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## 5G HarmoniseD Research and TrIals for serVice Evolution between EU and China

# D2.3: Final Report of Architecture and Use Case Implementation

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*Abstract*

The 5G-DRIVE project is the first international collaborative project in 5G applications between the EU and China. The present Deliverable D2.3 is a largely extended as well as a more detailed composition of the previously submitted “MS4” (“Milestone 4”) report, aiming to provide a more detailed summary of the work performed in the scope of WP2. The work mainly focuses upon the originally selected use cases that have been designed and developed around the two “core” scenarios of the 5G-DRIVE project (i.e. eMBB and V2X communications) structured on a per WP basis (following to dedicated requirements as these have been set in WP3 and WP4, *correspondingly*). The work reassesses the role of 5G as “enabler” for innovation and identifies specific actions promoted within the 5G-PPP framework, where the 5G-DRIVE project is also included. Then we discuss and evaluate the overall 5G-DRIVE concept and we further analyse the challenges appearing from the promoted eMBB and V2X applications, especially by correlating our effort to other prior -or still ongoing- EU-funded projects, especially those belonging to the 5G-PPP context. Our work also focuses on the essential technological enablers that support the progress of our project and of 5G System in a more generalised approach. The deliverable discusses the proposed use cases, evaluates their essential conceptual background by providing a wider descriptive framework and identifies their potential opportunities for growth in the global 5G environment and/or market, in parallel with supportive technologies or other means. In addition, the work takes into account the progress performed in the scope of the corresponding trials for each selected use case and presents the proposed architectural framework for each selected implementation.

 

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# Executive Summary

The present work is an extended and a more detailed composition of the previously submitted "MS4" ("Milestone 4") report, aiming to provide a more detailed summary of the work performed for the ongoing implementation of both original 5G-DRIVE scenarios by taking into account the progress of the use cases selected for both WP3 and WP4. Our work mainly focuses upon the originally selected use cases that have been designed and developed around the two "core" scenarios of the 5G-DRIVE project (i.e.: enhanced Mobile Broadband (eMBB) and Vehicle-to-Everything (V2X) communications).

5G-DRIVE is a completely innovative EU-funded project promoting research between the EU and China, upon two fundamental – and very much promising for development and growth – scenarios, relevant to the provision of: (i) eMBB in the 3.5 GHZ band which is a priority band in the two regions for (early) introduction of very high rate services, and; (ii) Internet of Vehicles (IoV) based on LTE-V2X using the 5.9 GHz band for Vehicle-to-Vehicle (V2V) and the 3.5 GHz band for Vehicle-to-Network (V2N), which implicate for remarkable business challenges in both regions, also taking into account recent regulatory progress and current market trends. The overall goal of the project effort has been to proceed to technical and business evaluation/assessment of the above fundamental scenarios, in real setups, by using innovative end-to-end 5G systems built on the outcomes of the previous phases of the broader 5G R&I (especially the progress performed at European level within the 5G-PPP research framework). More specifically, the optimisation of the band usage in multiple scenarios with different coverage is a key target both in the EU and China, so as the validation of the geographic interoperability of the 3.5 and 5.9 GHz bands for the related use cases; in fact, both bands implicate for the promotion of innovative solutions, able to respond to modern market needs for eMBB and V2X uses. In order to realize its expected aims as well as to offer assurance for achieving high impact on the market, the 5G-DRIVE consortium has involved 17 partners from 11 European countries, actively representing various critical sectors of the 5G evolving market (i.e., network and service providers, technology developers, the automotive sector, SMEs, research institutes and the academia). All partners have so participated to the work for the assessment of the two main scenarios that have correspondingly lead to the selection of four dedicated use cases, each one being able to promote innovative aspects and related services/facilities for the benefit of the EU market, within the wider 5G growth. The project has worked on 5G technologies and pre-commercial testbeds for eMBB and V2X services, with a significant part of the effort focused on trials and experimentation that have taken place in dedicated tests-beds in Finland, Italy and the UK, offered by some of the project partners. Several project activities were conducted in parallel with a Chinese twinning project so as to assess cross-regional interoperability and enhance validity of the obtained results.

The selection of the proposed use cases to serve the two fundamental 5G-DRIVE scenarios has taken place very carefully since the early beginning of the project, in a way to identify opportunities for development and growth in the 5G market (both in the EU and China) and with the aim of offering easy-to-implement and applicable solutions for the benefit of the market actors. As the 5G-DRIVE offers great opportunities strongly correlated to the introduction and applicability of 5G-based services in both regions, it was important to promote and/or enhance dedicated options based on the selected use cases, and identify the rising potential of innovation and commercialization.

Thus, D2.3 aimed to further elucidate the conceptual framework of the selected four use cases and correlate them to the wider 5G-PPP framework, especially to the activities for applied trials at the EU level. In addition, our work has further analysed progress and international trends coming from the applicability of eMBB and V2X communications as indispensable parts of the 5G global effort, to better "delineate" the intended market-oriented scope of each separate use case. The related architectures to serve the proposed use cases have also been discussed, with important KPIs and parameters for assessment, as the latter came from the trials.

The present deliverable D2.3 is structured on a per WP basis (following to dedicated requirements set in WP3 and WP4, *correspondingly*). The work reassesses the role of 5G as an "enabler" for innovation and identifies specific actions promoted within the 5G-PPP framework, where the 5G-DRIVE project is also included. Thus we "position" our 5G-DRIVE effort within the broader 5G European policy for growth and development, challenging a multiplicity of opportunities. Then we discuss and evaluate the overall 5G-DRIVE concept and we further analyse the benefits appearing from the promoted eMBB and V2X applications, especially by correlating our effort to other prior -or still ongoing- EU-funded projects, especially those belonging to the 5G-PPP context. Specific emphasis is provided on the ongoing joint European actions for 5G trials, aiming to the validation of the related cases. In parallel, we discuss the various technological enablers acting as supporters for the 5G implementation and realisation, especially within the context of the 5G System (5GS).

The work takes into account the progress performed in the scope of the corresponding trials for each selected use case; *furthermore*, it extends the related background by providing a wider descriptive framework via the inclusion of suitable information so that to elucidate the corresponding conceptual background, the insertion of supportive technologies and/or other means. The work also discusses the actual implementation taking place, by assessing outcomes originating from the trials performed in the selected European sites/test-beds and/or the joint collaborative actions with the "twin" Chinese project. In this scope, we also examine potential market relevance and appearing market applicability of the proposed use cases, so that to be able to assess them as real "5G enablers"; in fact, this is expected to be a quite reliable and innovative part of the entire project effort towards promoting feasible 5G-*based* solutions that will support growth and development. Meanwhile, reference is also made to the corresponding KPIs, *on a per use case basis*, as these have been identified and considered for the intended evaluation/assessment of the project technical progress. For the proposed use cases we also present the corresponding architectural framework that enables their implementation and further evaluation.

All these are included within a more generalised conceptual framework in order to strongly correlate our actual effort to the much promising 5G-based framework, in particular to the one appearing via the consideration of trials. Our work is around the following use cases developed around the two fundamental scenarios. The related use cases that are briefly described are as follows:

- **Cloud-assisted 3D Augmented Reality (AR):** As opposed to conventional gaming consoles or personal computers (which are highly dependent on the signal processing capabilities of the GPU), cloud-assisted AR enables users to stream video games or virtual contents from cloud servers like other streaming media. This new type of services offers an opportunity for more varied and interactive contents and makes user devices lighter and cheaper.
- **Indoor Positioning** supports navigation within building premises. However, this location information is also a valuable asset for providing and maintaining high quality eMBB services to end user devices. Positioning offers means to utilize location information to improve network communication reliability, reduce latency, and balance data loads. Since most of the network control components are fixed at specific locations, eMBB services to mobile end-user devices require also support for mobility.
- **GLOSA (Green Light Optimal Speed Advisory)** is a *Day-1* signage Cooperative Intelligent Transport Systems (C-ITS) service aimed at informing end users about the speed that needs to be sustained within applicable legal limits to reach an upcoming traffic light in green status. GLOSA provides end users with short-term information on upcoming traffic light status to optimise and smoothen traffic flows, help prevent speed limits violations, improve fuel efficiency and reduce pollution.
- The **Intelligent Intersection** use case deals with user safety on road intersections, focusing on infrastructure detection of situations that are difficult to perceive by the vehicles themselves. A good example is a situation where a vehicle wants to make a right turn while parallel vulnerable road users also have a green phase and right of way (permissive green for motorised traffic). When a pedestrian is detected in this sensitive area, a Decentralised

Environmental Notification Message (DENM) is broadcasted by the RSU, while the back-office "geocasts" this message to all vehicles in the vicinity.

Section 1 of the document serves as an extended introduction, discussing the fundamental role of 5G for the growth of the market. In this context we also discuss specific actions taken place in the 5G-PPP collaborative framework together with the respective initiative for Pan-European trials.

Section 2 "positions" the 5G-DRIVE project in the broader 5G arena. This discusses the overall concept together with the two fundamental scenarios covering eMBB and V2X communications. For each scenario we discuss past or ongoing EU-projects relevant to our approach. In addition, we provide the modern technical background for the 5G realisation via dedicated and distinct technologies, by discussing their basics. We also include some generalised KPIs, able to assess progress, in a broader scope.

Section 3 is purely dedicated to the eMBB scenario. We introduce the two corresponding use cases (cloud-assisted AR and indoor positioning) and we discuss their conceptual background, in parallel with actual implementation status. Based on the progress performed we introduce suitable KPIs for assessment, conformant to the related trials. We also present and discuss the related essential architecture, selected to serve each one among the use cases.

Section 4 follows a similar structuring, as the previous one. However, it discusses the more generalised V2X framework as a part of the 5G evolution and then focuses upon the two selected use cases (GLOSA and intelligent intersection). We also include an update of recent progress in radio frequency spectrum policy for C-ITS, as performed in the EU, China and the US. Furthermore, we analyse the main concept of each use case as well as the actual implementation status. Once again, we propose selected KPIs for assessment. Last but not least we discuss the related essential architectures as well as a "joint" architectural approach to serve both use cases, simultaneously.

The work finalizes with an extended set of bibliographical references, coming from various sources.

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## Abbreviations

| | |
|---|---|
| **2D, 2-D** | Two-Dimensional |
| **3D, 3-D** | Three-Dimensional |
| **3GPP** | The Third Generation Partnership Project |
| **4G** | The Fourth Generation of Mobile Communications |
| **5G** | The Fifth Generation of Mobile Communications |
| **5GAA** | 5G Automotive Association |
| **5GC** | 5G Core |
| **5GIC** | 5G Innovation Centre |
| **5GNR** | 5G New Radio |
| **5GS** | 5G System |
| **5G-PPP** | 5G Infrastructure Public Private Partnership |
| **5QI** | 5G QoS Identifier |
| **AAA** | Authentication, Authorisation and Accounting |
| **ACC** | Adaptive Cruise Control |
| **ACC** | Automatic Cruise Control |
| **ACCA** | Anticipated Cooperative Collision Avoidance |
| **ACI** | Adjacent-Channel Interference |
| **ACM** | Association for Computing Machinery |
| **AD** | Advanced Driving |
| **ADAS** | Advanced Driver Assistance System |
| **AF** | Application Function |
| **AI** | Artificial Intelligence |
| **AMF** | Access and Mobility Management Function |
| **AN** | Access Network |
| **AP** | Access Point |
| **AP** | Application Plane |
| **API** | Application Programming Interface |
| **AQMP** | Advanced Message Queuing Protocol |
| **AR** | Augmented Reality |
| **ARF** | Augmented Reality Framework |
| **ARGOS** | Advanced Research and Global Observation Satellite |
| **ARIB** | Association of Radio Industries and Businesses |
| **ARP** | Allocation and Retention Priority |
| **ASN.1** | Abstract Syntax Notation One |

| | |
|---|---|
| **ATIS** | Alliance for Telecommunications Industry Solutions |
| **AUSF** | Authentication Server Function |
| **AV** | Autonomous Vehicle |
| **BBU** | Base Station Baseband Unit |
| **BC** | Boundary Clock |
| **BLD** | Building |
| **BLER** | Block Error Rate |
| **BMS** | Broadcast/Multicast Service |
| **BS** | Base Station |
| **BSM** | Basic Safety Message |
| **BSP** | Basic System Profile |
| **BSS** | Business Support System |
| **C2C** | Car-to-Car |
| **C2C-CC** | Car-to-Car Communication Consortium |
| **C-ACC** | Cooperative Automatic Cruise Control |
| **C-ITS** | Cooperative Intelligent Transport Systems |
| **C-RAN** | Cloud-RAN |
| **C-V2X** | cellular V2X |
| **CA** | Collision Avoidance |
| **CA** | Cooperative Awareness |
| **CACC** | Cooperative Adaptive Cruise Control |
| **CAD** | Computer-Aided Design |
| **CAD** | Connected Automated Driving |
| **CAGR** | Compound Annual Growth Rate |
| **CALM** | Communications Access for Land Mobiles |
| **CAM** | Connected and Automated Mobility |
| **CAM** | Cooperative Awareness Message |
| **CAPEX, capex** | Capital Expenditure |
| **CAV** | Connected Automated Vehicle |
| **CAVE** | Cave Automatic Virtual Environment |
| **CBG** | Code Block Group |
| **CBR** | Channel Busy Ratio |
| **CBT** | Channel Busy Time |
| **CCAM** | Cooperative, Connected and Automated Mobility |
| **CCI** | Co-Channel Interference |

| | |
|---|---|
| **CCSA** | China Communications Standards Association |
| **CCSP** | Certified Cloud Security Professional |
| **CCTV** | Closed Circuit Television |
| **CDF** | Cumulative Distribution Function |
| **CDN** | Content Delivery Network |
| **CEF** | Connecting Europe Facilities |
| **CEN** | European Committee for Standardization |
| **CEPT** | European Conference of Postal and Telecommunications Administrations |
| **CFS** | Customer Facing Service |
| **CI** | Cooperative Intersection |
| **CICAS** | Cooperative Intersection Collision Avoidance Systems |
| **CMRI** | Cardiac Magnetic Resonance Imaging |
| **CN** | Core Network |
| **CoMP** | Coordinated Multipoint |
| **CP** | Collective Perception |
| **CP** | Control Plane |
| **CPE** | Customer Premises Equipment |
| **CPM** | Collaborative Perception Message |
| **CPM** | Collective Perception Message |
| **CPRI** | Common Public Radio Interface |
| **CPS** | Collective Perception Service |
| **CPU** | Central Processing Unit |
| **CQI** | Channel Quality Indicator |
| **CSI** | Communication Service Instance |
| **CSMA** | Carrier Sense Multiple Access |
| **CSMA-CA,**<br>**CSMA/CA** | Carrier Sense Multiple Access protocol with Collision Avoidance |
| **CSMF** | Carrier Sense Management Function |
| **CSP** | Communication Service Provider |
| **CU** | Central Unit |
| **CUPS** | Control and User Planes Separation |
| **D2D** | Device-to-Device |
| **D-FPAV** | Distributed Fair Power Adjustment for Vehicular networks |
| **D-NUM** | Distributed Network Utility Maximisation |
| **DDS** | Data Distributed Service |

 

| | |
|---|---|
| **DENM** | Decentralised Environmental Notification Messages |
| **DL** | Downlink, Down Link |
| **DM** | Domain Manager |
| **DN** | Data Network |
| **DP** | Data Plane |
| **DMRS** | Demodulation Reference Signal |
| **DOT** | Department of Transportation |
| **DPI** | Deep Packet Inspection |
| **DRx** | Discontinuous Reception |
| **DSM** | Digital Single Market |
| **DSRC** | Dedicated Short-Range Communications |
| **DU** | Data Unit |
| **E2E** | End-to-End |
| **E-UTRAN** | Evolved UMTS Terrestrial Radio Access Network |
| **EC** | European Commission |
| **EG** | Exposure Governance |
| **EGMF** | Exposure Governance Management Function |
| **EIP** | European ITS Platform |
| **EM** | Element Manager |
| **eMBB** | enhanced Mobile Broadband |
| **EN** | European Norm |
| **eNB** | evolved NodeB |
| **EPC** | Evolved Packet Core |
| **EPS** | Evolved Packet Switching |
| **ERM** | Electromagnetic Compatibility and Radio Spectrum Matters |
| **ES** | European Standard |
| **ETP** | European Technology Platform |
| **ETSI** | European Telecommunications Standards Institute |
| **EU** | European Union |
| **EuCNC** | European Conference on Networks and Communications |
| **F2F** | Face-to-Face |
| **FBR** | Flow Bit Rate |
| **FCAPS** | Fault, Configuration, Accounting, Performance, Security |
| **FCC** | Federal Communication Commission |
| **FD** | Frequency Division |
| **FD-LTE** | Frequency Division - Long Term Evolution |

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|---|---|
| **FDC** | Flat Distributed Cloud |
| **FEA** | Finite Element Analysis |
| **FHWA** | Federal Highway Administration |
| **FIF** | Future Internet Forum |
| **FiWi** | Fiber-Wireless |
| **FM** | Frequency Modulation |
| **FOT** | Field Operational Test |
| **FOV, FoV** | Fields of View |
| **FP7** | The Seventh Framework Programme |
| **FP** | Framework Programme |
| **fps** | frames per second |
| **FRP** | Filter Result Packet |
| **FSM** | Finite State Machine |
| **FTP** | File Transfer Protocol |
| **GA** | Grant Agreement |
| **Gbps** | Gigabit per second |
| **GBR** | Guaranteed Bit Rate |
| **GCDC** | Grand Cooperative Driving Challenge |
| **GFBR** | Guaranteed Flow Bit Rate |
| **GHz** | Giga Hertz |
| **GIS** | Geographic Information Systems |
| **GLOSA** | Green Light Optimal Speed Advisory |
| **gNB** | g NodeB [next generation NodeB] |
| **GNSS** | Global Navigation Satellite System |
| **GPU** | Graphics Processing Unit |
| **GPS** | Global Positioning System |
| **GSM** | Global System for Mobile Communications |
| **GSMA** | GSM Association |
| **GST** | Generic network Slice Template |
| **GUI** | Graphical User Interface |
| **GW** | Gateway |
| **H2020** | Horizon 2020 |
| **HAD** | Highly Automated Driving |
| **HD** | High Definition |
| **HDR** | High Data Rate |
| **IFA** | International Financial Architecture |

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|---|---|
| **HMD** | Head-Mounted Display |
| **HMI** | Human-Machine Interface |
| **HSPA** | High Speed Packet Access |
| **HTML** | Hypertext Markup Language |
| **HTTP, http** | HyperText Transfer Protocol |
| **HTTPS, https** | HyperText Transfer Protocol Secure |
| **HUD** | Heads-Up Display |
| **HW** | Hardware |
| **I2V** | Infrastructure-to-Vehicle |
| **IA** | Infrastructure Association |
| **IaaS** | Infrastructure as a Service |
| **IAB** | Integrated Access and Backhaul |
| **ICRW** | Intersection Collision Risk Warning |
| **ICT** | Information and Communication Technologies |
| **ICW** | Intersection Collision Warning |
| **ID** | Identifier |
| **IEC** | International Electrotechnical Commission |
| **IEEE** | Institute of Electrical and Electronic Engineers |
| **IETF** | Internet Engineering Task Force |
| **IMS** | IP Multimedia Subsystem |
| **IMT** | International Mobile Communications |
| **IMU** | Inertial Measurement Unit |
| **InP** | Indium Phosphite |
| **IoT** | Internet of Things |
| **IoV** | Internet of Vehicles |
| **IP** | Internet Protocol |
| **IPS** | Indoor Positioning System |
| **IPT** | Integrated Publishing Toolkit |
| **IQ, I/Q** | In-Phase and Quadrature |
| **IR** | Infrared |
| **ISG** | Industry Specification Group |
| **ISO** | International Organization for Standardization |
| **IT** | Information Technology |
| **ITF** | Intersection Topology Format |
| **ITS** | Intelligent Transport System |

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|---|---|
| **ITS-S** | ITS stations |
| **ITST** | Intelligent Transportation Systems Telecommunications |
| **ITU** | International Telecommunication Union |
| **ITU-R** | International Telecommunication Union – Radiocommunications Sector |
| **ITU-T** | International Telecommunication Union – Telecommunication Standardization Sector |
| **IVI** | In-Vehicle Information |
| **IVI** | In-Vehicle Infotainment |
| **IVIM** | In-Vehicle Infotainment Message |
| **IWF** | Interworking Function |
| **JSAC** | Journal on Selected Areas in Communications |
| **JSON** | JavaScript Object Notation |
| **KPI** | Key Performance Indicator |
| **KVM** | Kernel Virtual Machine |
| **LAN** | Local Area Network |
| **LBS** | Location Based Service |
| **LCS** | Location Services |
| **LCM** | Life Cycle Management |
| **LIDAR** | Light Detection and Ranging |
| **Li-Fi, LiFi** | Light Fidelity |
| **LoRa** | Long Range |
| **LoS** | Line of Sight |
| **LTE** | Long Term Evolution |
| **LTE-A** | Long Term Evolution – Advanced |
| **LTE-V2X** | LTE Vehicle-to-Everything |
| **LU** | Location Unit |
| **M2M** | Machine-to-Machine |
| **MAC** | Medium Access Control |
| **MANO** | Management and Orchestration |
| **MAP** | Map data, in conjunction with SPaT messages |
| **MAPEM** | MAP Extended Message |
| **MAVEN** | Managing Automated Vehicles Enhances Network |
| **MBB** | Mobile Broadband |
| **MBMS** | Multimedia Broadcast/Multicast Service |
| **Mbps** | Megabit per second |
| **MBS** | Multimedia Broadcast Service |
| **MC** | Mission Critical |

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|---|---|
| **MCC** | Mission Critical Communication |
| **MCL** | Maximum Coupling Loss |
| **MCM** | Manoeuvre Coordination Message |
| **MCS** | Manoeuvre Coordination Service |
| **MDAF** | Management Data Analytics Function |
| **MDP** | Meta-Data Protocol |
| **MEC** | Mobile Edge Computing |
| **MEC** | Multi-access Edge Computing |
| **MEP** | MEC Platform |
| **MEPM** | MEC Platform Manager |
| **MF** | Management Function |
| **MFBR** | Maximum Flow Bit Rate |
| **MIIT** | Ministry of Industry and Information Technology (of the People's Republic of China) |
| **MIMO** | Multiple-Input Multiple-Output |
| **MIoT** | Massive IoT |
| **ML** | Machine Learning |
| **MMC** | Massive Machine Communications |
| **mMIMO** | massive MIMO |
| **mMTC** | massive Machine Type Communications |
| **mmWave** | millimetre wave (band) |
| **MNO** | Mobile Network Operator |
| **MOST** | Ministry of Science and Technology (of the People's Republic of China) |
| **MOT** | Ministry of Transport (of the People's Republic of China) |
| **MPS** | Ministry of Public Security (of the People's Republic of China) |
| **MQ** | Message Queuing |
| **MQTT** | Message Queuing Telemetry Transport |
| **MR** | Mixed Reality |
| **MS** | Member State |
| **MVNO** | Mobile Virtual Network Operator |
| **N3IWF** | Non-3GPP Interworking Function |
| **NB-IoT** | Narrow Band IoT |
| **NBI** | North-Bound Interface |
| **NEF** | Network Exposure Function |
| **NEST** | Network Slice Template |
| **NF** | Network Function |
| **NFMF** | Network Function Management Function |

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|---|---|
| **NFV** | Network Function Virtualisation |
| **NFVI** | Network Function Virtualisation Infrastructure |
| **NFVO** | Network Function Virtualisation Orchestration |
| **NFVO** | Network Function Virtualisation Orchestrator |
| **NG** | Next Generation |
| **NGC** | Next Generation Core |
| **NGMN** | Next Generation Mobile Networks |
| **NLoS** | Non-Line of Sight |
| **NO** | Network Operator |
| **NOP** | Network Operator |
| **NR** | New Radio |
| **NRF** | Network Repository Function |
| **NS** | Network Service |
| **NS** | Network Slicing |
| **NSA** | Non-Standalone |
| **NSaaS** | Network Slicing as a Service |
| **NSI** | Network Slice Instance |
| **NSM** | Network and Service Management |
| **NSMF** | Network Slice Management Function |
| **NSSAAF** | Network Slice-Specific Authentication and Authorisation Function |
| **NSSF** | Network Slice Selection Function |
| **NSSI** | Network Slice Subnet Instance |
| **NSSMF** | Network Slice-Specific Management Function |
| **NWDAF** | Network Data Analytics Function |
| **OBFN** | Optical Beamforming Network |
| **OBU** | On-Board Unit |
| **ODL** | OpenDaylight |
| **OEM** | Original Equipment Manufacturer |
| **OFDM** | Orthogonal Frequency-Division Multiplexing |
| **OJ** | Official Journal |
| **ONAP** | Open Network Automation Platform |
| **ONF** | Open Networking Foundation |
| **OPEX, opex** | Operational Expenditure |
| **OPNFV** | Open Platform for NFV |
| **OS** | Operating System |

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|---|---|
| **OSI** | Open System Interconnection |
| **OSM** | Open Source MANO |
| **OSS** | Operations Support System |
| **OTDOA** | Observed Time Difference of Arrival |
| **OTT** | Over-the-Top |
| **P2P** | Point-to-Point |
| **PCAM** | Pedestrian Crash Avoidance Mitigation |
| **PCF** | Policy Control Function |
| **PDN** | Packet Data Network |
| **PDR** | Packet Detection Rule |
| **PDR-DCC** | Packet-count based Decentralised Data-Rate Congestion Control |
| **PDU** | Protocol Data Unit |
| **PER** | Packet Error Rate |
| **PGW** | Packet Data Network Gateway |
| **PHY** | Physical Layer |
| **PLMN** | Public Land Mobile Network |
| **PNF** | Physical Network Function |
| **PoP** | Point of Presence |
| **PPP** | Public-Private Partnership |
| **pRRU** | pico-Remote Radio Unit |
| **PT** | Public Transport |
| **PTP** | Precision-Time Protocol |
| **PULSAR** | Periodically Updated Load Sensitive Adaptive Rate |
| **QFI** | QoS Flow ID |
| **QI** | QoS Identifier |
| **QoE** | Quality of Experience |
| **QoS** | Quality of Service |
| **R&D** | Research and Development |
| **R&I** | Research and Innovation |
| **R&TTE** | Radio and Telecommunications Terminal Equipment |
| **RAB** | Radio Access Bearer |
| **RAM** | Random Access Memory |
| **RAN** | Radio Access Network |
| **RED** | Radio Equipment Directive |
| **RF** | Radio Frequency |
| **RGB** | Red, Green, Blue |

 

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| **RIA** | Research and Innovation Action |
| **RLAN** | Radio Local Area Network |
| **RLT** | Road and Lane Topology |
| **RM** | Resource Management |
| **ROI** | Return on Investment |
| **ROW** | Right-of-Way |
| **RRC** | Radio Resource Control |
| **RRH** | Remote Radio Head |
| **RRU** | Remote Radio Unit |
| **RSC** | Radio Spectrum Committee |
| **RSRP** | Reference Signal Received Power |
| **RSRQ** | Reference Signal Received Quality |
| **RSS** | Received Signal Strength |
| **RSU** | Road-Side Unit |
| **RT** | Real Time |
| **RTD** | Research and Technical Development |
| **RTPC** | Random Transmit Power Control |
| **RTT** | Round-Trip Time |
| **Rx** | Reception, Receiver |
| **S-NSSAI** | Single-Network Slice Selection Assistance Information |
| **SA** | Standalone |
| **SAE** | Society of Automotive Engineers |
| **SBA** | Service-Based Architecture |
| **SBI** | Service-Based Interface |
| **SCP** | Service Communication Proxy |
| **SD** | Slice Differentiator |
| **SDN** | Software Defined Network |
| **SDO** | Standard Development Organisation |
| **SDU** | Service Data Unit |
| **SE** | Spectral Efficiency |
| **SINR** | Signal-to-Interference and Noise Ratio |
| **SLA** | Service Level Agreement |
| **SLAM** | Simultaneous Localisation and Mapping |
| **SMARTER** | Study on New Services and Markets Technology Enablers |
| **SMB** | Service Message Bus |
| **SME** | Small- and Medium-sized Enterprise |
| **SMF** | Service Management Function |

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| **SMF** | Session Management Function |
| **SP** | Service Provider |
| **SPAT, SPaT** | Signal Phase and Timing |
| **SST** | Slice Service Type |
| **SW** | Software |
| **T&M** | Test and Measurements |
| **TaaS** | Test as a Service |
| **TC** | Technical Committee |
| **TC** | Transparent Clock |
| **TCO** | Total Cost of Ownership |
| **TCP** | Transmission Control Protocol |
| **TDD** | Time Division Duplex |
| **TG** | Technical Group |
| **TMC** | Traffic Management Centre |
| **TMV** | Test, Measurement, and KPIs Validation |
| **TPU** | Tensor Processing Unit |
| **TR** | Technical Report |
| **TRxP** | Transmission Reception Point |
| **TS** | Technical Specification |
| **TSDSI** | Telecommunications Standards Development Society of India |
| **TSG** | Technical Specification Group |
| **TTA** | Telecommunications Technology Association |
| **TTC** | Telecommunication Technology Committee |
| **TTG** | Time To Green |
| **TTI** | Time Transmission Interval |
| **TTI** | Traffic and Traveller Information |
| **TV** | Television |
| **Tx** | Transmission, Transmitter |
| **UAS** | Unmanned Aerial System |
| **UAV** | Unmanned Aerial Vehicle |
| **UAV** | Unmanned Aviation Vehicle |
| **UC** | Use Case |
| **UDM** | Unified Data Management |
| **UDP** | User Datagram Protocol |
| **UE** | User Equipment |

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| **UHD** | Ultra-High Definition |
| **UHDTV** | Ultra-High Definition Television |
| **UIO** | Unique Input/Output Sequence |
| **UL** | Uplink, Up Link |
| **uMTC** | ultra-reliable Machine Type Communications |
| **UMTS** | Universal Mobile Telecommunications System |
| **UP** | User Plane |
| **UPF** | User Plane Function |
| **URLLC** | Ultra-Reliable Low Latency Communications |
| **USDOT** | U.S. Department of Transportation |
| **USRP** | Universal Software Radio Peripheral |
| **UTDOA** | Uplink-Time Difference of Arrival |
| **UTM** | UAV Traffic Management |
| **V2C** | Vehicle-to-Cloud |
| **V2D** | Vehicle-to-Device |
| **V2G** | Vehicle-to-Grid |
| **V2I** | Vehicle-to-Infrastructure |
| **V2N** | Vehicle-to-Network |
| **V2P** | Vehicle-to-Pedestrian |
| **V2R** | Vehicle to the Road-side units |
| **V2S** | Vehicle-to-Sensors |
| **V2V** | Vehicle-to-Vehicle |
| **V2X** | Vehicle-to-Everything |
| **VE** | Virtual Environment |
| **VIAPA** | Video, Imaging and Audio for Professional Applications |
| **VIM** | Virtual Infrastructure Manager |
| **VM** | Virtual Machine |
| **VNF** | Virtual Network Function |
| **VNFM** | Virtual Network Function Manager |
| **VNO** | Virtual Network Operator |
| **VoD** | Video on-Demand |
| **VPN** | Virtual Private Network |
| **VPU** | Video Processing Unit |
| **VR** | Virtual Reality |
| **VRARA** | VR/AR Association |
| **VRU** | Vulnerable Road User |

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|---|---|
| **VZ** | Vision Zero |
| **WAT** | Wireless Access Technology |
| **WAVE** | Wireless Access in Vehicular Environments |
| **WDM** | Wavelength Division Multiplexer |
| **WI** | Work Item |
| **Wi-Fi, WiFi** | Wireless Fidelity |
| **WI** | Work Item |
| **WG** | Working Group |
| **WIMU** | Wireless Inertial Measurement Unit |
| **WLAN** | Wide Local Area Network |
| **WP** | Work Package |
| **WRC** | World Radio Communication Conference |
| **WWW, www** | World Wide Web |
| **XAPI** | Xen Project Management API |
| **xMBB** | extreme Mobile Broadband |
| **XR** | Extended Reality |

# 1 Introduction

## 1.1 Framework of Reference: Towards 5G Implementation

The socio-technical evolution in the last few decades has been significantly "driven" by the evolution of mobile communications and has contributed to the economic and social development of both developed and developing countries. Mobile communication has become closely integrated in the daily life of the society "as a whole" [2]. It is expected that the socio-technical trends and the evolution of mobile communications systems will remain tightly coupled together and will form a foundation for society in 2020 and beyond[3]. In the future, however, it is foreseen that new demands, such as more traffic volume, many more devices with diverse service requirements, better quality of (user) experience[4] (QoE) and better affordability by further reducing costs, will require an increasing number of innovative solutions.

In the same scope, mobile devices play various, continuously evolving roles in our everyday life. Future IMT systems should support emerging new use cases, including applications requiring very high data rate communications, a large number of connected devices, and ultra-low latency and high reliability applications. User devices will get enhanced media consumption capabilities, such as Ultra-High Definition (UHD) display, multi-view High Definition (HD) display, mobile 3D projections, immersive video conferencing, and Augmented Reality (AR) and mixed reality display and interface. This will all lead to a demand for significantly higher data rates. Media delivery will be both to individuals and to groups of users.

A connected society in the years beyond 2020 will imply to accommodate a comparable user experience for end-users on the move and when they are static (e.g. at home or in the office). To offer the best experience to highly mobile users and communicating machine devices, robust and reliable connectivity solutions are needed as well as the ability to efficiently maintain service quality with mobility. Maintaining high quality at high mobility will enable successful deployment of applications on user equipment located within a moving platform such as cars or high-speed trains. Connectivity on mobile platforms may be provided via IMT, Radio Local Area Network (RLAN) or another network on that platform using suitable backhaul.

Today, Internet and communication networks are "critical" tools for most areas and sectors of our modern societies and economies as they are transforming our world; actually, these networks constitute fundamental "pillars" for any evolutionary process supporting effort for growth and development. According to recent market trends as well as to actual European policy measures and/or related initiatives, it is assessed that the communication networks and the wider modern services/facilities environment of the year 2020 and beyond will be *"enormously richer and much more complex than that of today".*

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[2] Almost 16 years after the initial edition, it is still interesting to assess the context proposed in: International Telecommunication Union – Radiocommunications Sector (ITU-R): Recommendation M1645-0 (06/2003): "Framework and overall objectives of the future development of IMT-2000 and of systems beyond IMT-2000".

[3] See: International Telecommunication Union – Radiocommunications Sector (ITU-R): Report ITU-R M.2243 (11/2011): "Assessment of the global mobile broadband deployments and forecasts for International Mobile Telecommunications". This Report assesses the perspectives and needs of mobile broadband, to be supported by IMT during the decade 2012-2022. It also presents mobile traffic forecasts provided by a number of industry sources for the forecast up to 2015 and one source for the forecast between 2015 and 2020 taking into account the new market trends and market drivers.

[4] Quality of experience (QoE) measures total system performance using subjective and objective measures of customer satisfaction. It differs from quality of service (QoS), which assesses the performance of hardware and software services delivered by a vendor under the terms of a contract.

Within the forthcoming years it is also expected that the underlying (usually heterogeneous) network infrastructure will be able of "connecting everything" according to an extended multiplicity of application-specific requirements (thus including users, things, goods, computing centres, content, knowledge, information and processes), in a purely flexible, mobile, and quite powerful way[5]. Living within a fully converged environment, the number of smart terminals, machines, "things" (also including sensors and actuators) attached to current networks is growing exponentially and soon it will be possible to connect and operate an immense diversity of new forms of equipment (e.g. smart home gadgets, vehicles, drones and even robots) as well; this extends our ICT-based abilities and concepts far beyond our current experience of tablet and smartphone connectivity. In order to "face" these major challenges, such innovative aspects not only necessitate but also imply for the proper establishment and the effective operation of a relevant novel kind of infrastructure[6], able to provide network features and performance characteristics to assure progress and growth in all corresponding domains (i.e. technical, business, financial, regulatory, social, etc.). In this scope, the simultaneous (occasionally appearing as "gradual") "inclusion" of modern features (such as of virtualisation and of software-based network functionalities) in communications infrastructures is expected to support the corresponding transitional process via further strengthening network flexibility and reactivity[7].

Market actors intend to be strongly involved in such processes, whilst creating new opportunities for novelty and investments. These chances are so expected to take place within the forthcoming "fifth generation" – or 5G – of telecoms systems, that will be the most critical building block of our "digital society" in the next decade; 5G will not only be an evolution of mobile broadband networks[8] but will bring new unique network and service capabilities, creating a sustainable and scalable technology but also a proper ecosystem for technical and business innovation[9]. 5G represents a significant shift for the industry where mobility and computing converge and become indistinguishable. Wireless networks must transform to become more powerful, agile and intelligent to realize the potential for the IoT and enable richer experiences throughout daily life. Thus, 5G encompasses multiple application needs with different End-to-End (E2E) requirements (latency, throughput, security, mobility, etc.). It is not practical to implement separate networks for different QoS requirements hence 5G networks need to be flexible, scalable and reliable.

Among the above, reliability is a critical concern. Currently, communication systems beyond 2020 will need to be flexible enough to accommodate all the diverse use cases without increasing the complexity of management. Another reason that flexibility is the first key design principle of 5G is that any new technology or system we design for 5G needs to be future-proof and last at least until 2030. This means that it is unlikely that we can currently foresee all future use cases. However, we will need to design all new components of 5G in a way that makes it easy to extend them to accommodate these unknowable scenarios.

In fact, as a key design principle for 5G, reliability is strongly related to flexibility; with the flexible integration of different technology components, we will see a step away from best effort mobile

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[5] Andrews, J.G., Buzzi, S., Choi, W., et *al*. (2014): What Will 5G Be? *IEEE JSAC, Special issue on 5G Wireless Communications Systems*, **32**(6), 1065-1082.

[6] European Commission (2014): 5G: *Challenges, Research Priorities, and Recommendations – Joint White Paper*. European Commission, Strategic Research and Innovation Agenda.

[7] Chochliouros, I.P., Sfakianakis, E., Belesioti, M., Spiliopoulou, A.S., Dardamanis, A. (2016): *Challenges for Defining Opportunities for Growth in the 5G Era: The SESAME Conceptual Model*. In Proceedings of the EuCNC-2016 International Conference, pp.1-5. Athens, Greece, June 27-30, 2016.

[8] In fact, 5G is not conceived as a technology replacing 4G, but rather enhancing it and complementing it with new service capabilities. Based on this context, it is considered that the usage of 4G will continue for several years, before eventually 5G takes over completely. 5G will be designed to co-exist with 4G, and it is so expected to support the advent of multi-technology operations, with terminals having the capability to connect to the best available network, as a function of the service requirements of the application.

[9] 5G Public-Private Partnership (5G-PPP): 5G Vision (02/2015) [*https://5g-ppp.eu/roadmaps/*]

broadband towards truly reliable communication. Reliability is not only about equipment up-time, it also relates to the perception of infinite capacity and coverage that future mobile networks need to deliver. This in principle means that for all the use cases and the vast majority of the users, the required data will be received in the required time and will not be dependent on the technology used. Furthermore, reliability is becoming more critical as we start to relay on mobile communications for control and safety. A reliable connection can be defined as the probability of a certain data package being decoded correctly within a certain timeframe. This means that retransmission may be needed to ensure reception of a correct data package, which will inevitably delay the transmission. Therefore, even to obtain LTE latency numbers with higher reliability, a lower system delay will be required. Putting reliability as a key design principle for 5G means that: (i) in all concepts of system design focus should be put on fairness; (ii) the requirement is expressed in % of the users and not the locations/coverage, because even the reliable network needs to be cost-effective for the service providers; (iii) the mechanisms for trade-off between link reliability (so low packet error rate) and throughput and/or latency are introduced in a simple and efficient way; and (iv) multiple network layers and radio access technologies are used to provide the most reliable link based on the user's application needs, location and mobility.

5G is actually a commercial reality with approaching one hundred and fifty network deployments worldwide[10]. It is a force central to the development of the Fourth Industrial Revolution. 5G technologies are a major driver for a dizzying array of ground-breaking digital services and changes that will sweep across the world over the next decade. The transition to 5G is transforming our lives, our economy, our jobs, and our industries as evidence emerges each day. For instance, wearables, such as cellular smart watches or connected eyeglasses, are evolving to become self-contained mobile computing devices. Autonomous vehicles[11], one of the most highly anticipated 5G technologies, are expected to help us reclaim commute time for new activities in our lives. Healthcare is changing as services like remote monitoring and telemedicine provide new opportunities for care. Drones will be used for transportation, surveillance, and rescue operations. Robots and Artificial Intelligence (AI) will create new dynamics for both humans and machines. Cellular Vehicular-to-Everything (C-V2X) connectivity is expected to save lives and increase transportation efficiency. Automated end-to-end (E2E) manufacturing processes enabled by 5G connectivity will change the supply chain process in ways we have not witnessed. The scale of 5G's impact is expected to be staggering. One glance at industry-analyst forecasts[12] provides us with some insight:

- *5 Billion people forecast to be accessing the internet via mobile by 2025.*

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[10] Ericsson (2019): *Ericsson Report: This is 5G*. Available at: *https://www.ericsson.com/49df43/assets/local/newsroom/media-kits/5g/doc/ericsson_this-is-5g_pdf_2019.pdf*

[11] A self-driving car, also known as a robot car, autonomous car, or driverless car, is a vehicle that is capable of sensing its environment and moving with little or no human input.

Also see: Thrun, S. (2010): Toward Robotic Cars. *Communications of the ACM*, **53**(4), 99-106.

Autonomous cars combine a variety of sensors to perceive their surroundings, such as radar, computer vision, Lidar sonar, GPS, odometry and inertial measurement units. Advanced control systems interpret sensory information to identify appropriate navigation paths, as well as obstacles and relevant signage. Potential benefits include reduced costs, increased safety, increased mobility, increased customer satisfaction and reduced crime. Safety benefits include a reduction in traffic collisions, resulting injuries and related costs. Automated cars are predicted to increase traffic flow; provide enhanced mobility for children, the elderly, disabled and the poor; relieve travellers from driving and navigation chores; lower fuel consumption; significantly reduce needs for parking space; reduce crime, and facilitate business models for transportation as a service, especially via the sharing economy. Problems include safety, technology, liability, desire by individuals to control their cars, legal framework and government regulations; risk of loss of privacy and security concerns, such as hackers or terrorism; concern about the resulting loss of driving-related jobs in the road transport industry; and risk of increased sub-urbanisation as travel becomes more convenient.

[12] 5GAmericas (01/2021): *3GPP Release 16, 17 and Beyond - White Paper*. Available at: *https://www.5gamericas.org/3gpp-releases-16-17-beyond/*

- *5G coverage will roll out rapidly to cover 37 percent of the global population by 2025.*
- *5G will account for 29% of all connections by 2025.*
- *10.3 Billion mobile connections are forecast by 2025.*
- *25 Billion Internet of Things (IoT) devices globally in 2025. (11.4 Billion Consumer IoT; 13.7 Billion Industrial IoT)*
- *5G will add $2.2 Trillion to the global economy over the next 14 years.*

These are clearly enormous numbers. While the promise of 5G is high, analysts believe the expected results from 5G technology commercial deployments are in the initial development stages and will take time to evolve. The 5G architecture is standardised for today and tomorrow's network evolution. The wireless industry is transformational using technology enablers like Cloud-Native, Software Defined Radio (SDR), Network Function Virtualisation[13] (NFV) and Multi-Access Edge Computing (MEC)[14]. The mega-networks of billions of connected things and people of the future will require a major shift in network operations and management. These changes are enabled through the Long-Term Evolution (LTE) and 5G specifications created by the Third Generation Partnership Project (3GPP).

Multi-access Edge Computing (previously known as Mobile Edge Computing) technology is also being leveraged in 5G. MEC systems "bring" the service close to the network edge, therefore, close to the device's point of attachment. This entity contains the applications and a virtualisation infrastructure which provides compute, storage, and network resources, and also the functions needed by applications.

MEC has recently emerged as a promising technique[15]; MEC's core idea is to move computation closer to end-users, whereby small servers or micro-data centres that can host cloud applications are distributed across the network and connected directly to entities, such as cellular base stations, at the mobile network edge. MEC is also expected to be more robust than traditional centralised Cloud computing systems[16], because it is distributed and is thus less impacted by failures at a centralised

[13] NFV is a paradigm shift in how the networks that underpin today's service provider infrastructures are built and operated, and how the services they deliver are managed. New degrees of freedom are introduced to the network and its management as resources now may be added, changed, and removed dynamically. This change opens up a wave of new business opportunities. However, a new and highly agile operational approach is needed to take full advantage of these opportunities.

[14] Multi-access Edge Computing (MEC) makes no assumptions on the underlying radio infrastructure, which makes it a highly flexible element in the communications networks. As the delivery technology, together with the underlying hardware of the MEC platform, remains open, this enables new levels of adaptability to the chosen deployment scenario. Therefore, service providers (SPs) can use MEC as a revenue generator and application test-bed (including service producing applications) without being forced to wait for full ratification of the 5G standard and the associated capital investment. This approach enables SPs to offer third parties a cost effective way to trial their applications. Due to the virtualised characteristics of MEC, it is easy to monitor performance and resource needs of an application, which, in turn, enables more accurate pricing for operators towards application providers for hosting the applications, as well as dimensioning the edge equipment exactly as required for the application set proposed. Thus, MEC allows content, services and applications to be accelerated, increasing responsiveness from the edge. The mobile subscriber's experience can be enriched through efficient network and service operations, based on insight into the radio and network conditions.

For the fundamental technical scope, see more details in the scope of the discussion provided in section 1.2 of the present document.

[15] Taleb, T., Dutta, S., Ksentini, A., Iqbal, M., and Flinck, H. (03/2017): Mobile edge computing potential in making cities smarter. *IEEE Communications Magazine,* **55**(3), 38-43.

[16] Satyanarayanan, M., Lewis, G., Morris, E., Simanta, S., Boleng, J., and Ha, K. (10/2013): The role of cloudlets in hostile environments. *IEEE Pervasive Computing*, **12**(4), 40-49.

point. The idea of distributing cloud servers at the mobile network edge is also known as cloudlets[17], edge computing[18] and fog computing[19]. In all these techniques, each set of servers or each micro-data centre is responsible for a small geographical area, although some servers/micro-data centre may not be directly connected to the base station. The distinguishing feature of MEC, unlike other concepts, is the tight integration with RAN and the exchange of contextual information (radio conditions, user location and presence, etc.) and control of selective local breakout of user data flow to hosted applications. The MEC paradigm permits offering environments characterised by low latency, high bandwidth and location awareness that can be leveraged by applications; this also paves the way for the development of several new applications. It is generally agreed that the 5G mobile system will largely benefit from MEC in order to enable novel services from vertical industries, particularly those covering automotive industry (as the latter have several constraints that cannot be accommodated by the current 4G/4G+ mobile networks).

MEC helps to satisfy the demanding requirements for the 5G era in terms of expected throughput, latency, scalability and automation. By offering cloud-computing capabilities and an IT service environment at the edge of the network, MEC allows for ultra-low latency and high bandwidth. Furthermore, it can provide access to real-time network and context information. MEC also offers additional privacy and security and ensures significant cost efficiency. The integration of MEC into the 5G architecture will result in added-value, ensuring highly efficient network operation, service delivery and the ultimate personal experience. MEC and NFV are two different concepts and they can be implemented independently. That means they may share the same virtualisation infrastructure, or they may have independent ones, depending on the deployment option (MEC standalone or MEC in NFV environment). In any case, from a standardisation point of view, MEC technology reuses the NFV virtualisation infrastructure and the NFV infrastructure management to the largest extent possible.

At of the end of October 2020, there were 9.4 billion mobile connections globally, 61% of which were LTE. With 5.82 billion LTE connections, it vastly surpasses previous technologies of HSPA (1.8 billion) and GSM (1.4 billion) as the leader in global technologies. 5G network connection numbers are surging with 229 million 5G subscriptions and 236 million projected for the end of the year. This number is expected to increase to 1 billion by 2022 and over 3 billion at the end of 2025[20], which represents up to 37% of the world’s population. The first 5G smartphones were launched in December 2018 to coincide with the launch of 5G networks in South Korea which was the beginning of the initial device wave. The volume-device wave currently has 100 5G device models that use varied combinations of High-band, Mid-band or Low-band spectrum. Performance-optimised 5G devices should be available in 2021. All of this will contribute to rapid adoption and rapid growth of the 5G networks.

5G has the potential to deliver substantial performance and capacity improvements for personal, public and enterprise communications. It has the potential to provide a suitable communication solution basis for many vertical applications, as well as to offer new architectural concepts and value chains to efficiently support innovation and future needs[21],[22]. 5G is about the seamless interworking

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17 Ibid.

18 Davy, S., Famaey, J., Serrat, J., Gorricho, J.L., Miron, A., Dramitinos, M., *et al.* (01/2014): Challenges to support edge-as-a-service. *IEEE Communications Magazine,* **52**(1), 132-139.

19 Bonomi, F., Milito, R., Zhu, J., and Addepalli, S. (2012): *Fog computing and its role in the internet of things*. In Proceedings of the MCC 2012 Workshop on Mobile Cloud Computing, pp. 13-16. August 2012.

20 Global System for Mobile Communications (GSM) Association (GSMA) (2020): *GSMA Intelligence; Mobile World Congress Daily*.

21 El Hattachi, R., and Erfanian, J. (02/2015): *Next Generation Mobile Networks (NGMN): NGMN 5G White Paper v1.0*. Next Generation Mobile Networks Ltd. Available at: http://www.ngmn.org/fileadmin/ngmn/content/images/news/ngmn_news/NGMN_5G_White_Paper_V1_0.pdf

 

of different network technologies, mobile, fixed as well as satellite, and their co-existence within a common infrastructure of standardised and customer specific networks or IT functionalities, designed to fit vertical industries as well as consumers to broaden digital inclusiveness. It is expected that the development of 5G systems will be based on an ecosystem of a close cooperation between industry, SMEs and the research community to develop innovative solutions and to ensure the acceptance and exploitation of these solutions in global standards and markets[23].

As the industry builds upon the great work, which 3GPP has accomplished with defining New Radio[24] (NR) and Service Based Architecture (SBA), these aspects and others of 5G will simultaneously evolve in 3GPP Release 17[25] and beyond. 5G preserves the economy of scale benefits of a common network infrastructure and unified radio interface for various, even completely different applications, avoiding technology fragmentation, preventing energy and spectrum wastage and facilitating cross-sector innovation, thus improving the competitiveness of the economy. Thus, 5G can therefore facilitate connectivity, network access and service security of different vertical sectors and be instrumental to the management and automation of business assets and processes.


*Figure 1: 5G roadmap evolution towards 2020 and beyond26*

The above Figure 1 indicates the overlapping activities and timelines of organisations working on 5G at a number of layers, and in reality, many more could be added to that list, from Internet standards bodies like the IETF to evolutions in IT and cloud platforms.
The next figure, as below, illustrates the latency and bandwidth/data rate requirements of the various use cases (as proposed by GSMA Intelligence[27]) which have been discussed in the context of 5G to date.

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22 Warren, D., and Dewar, C. (12/2014): *Understanding 5G: Perspectives on future technological advancements in mobile.* GSM Association (GSMA) Intelligence. Available at: [https://www.gsmaintelligence.com/research/?file=141208-5g.pdf&download](https://www.gsmaintelligence.com/research/?file=141208-5g.pdf&download)

23 See, *for example,* the wider context discussed within: [https://5g-ppp.eu/](https://5g-ppp.eu/)

24 Holma, H., Toskala, A., and Nakamura, T. (12/2019): 5G technology: 3GPP new radio. Wiley.

25 For further information also see: [https://www.3gpp.org/release-17](https://www.3gpp.org/release-17)

26 Source: "*The 5G Infrastructure Public-Private Partnership*" – NET Features 2015 – 5G PPP Vision – 25.03.2015. [Presentation by Jean-Sebastien Bedo]. Available at: [https://5g-ppp.eu/wp-content/uploads/2015/07/BEDO-25Mar2015.pdf](https://5g-ppp.eu/wp-content/uploads/2015/07/BEDO-25Mar2015.pdf)

27 Global System for Mobile Communications (GSM) Association (GSMA) (2020): *GSMA Intelligence; Mobile World Congress Daily*.

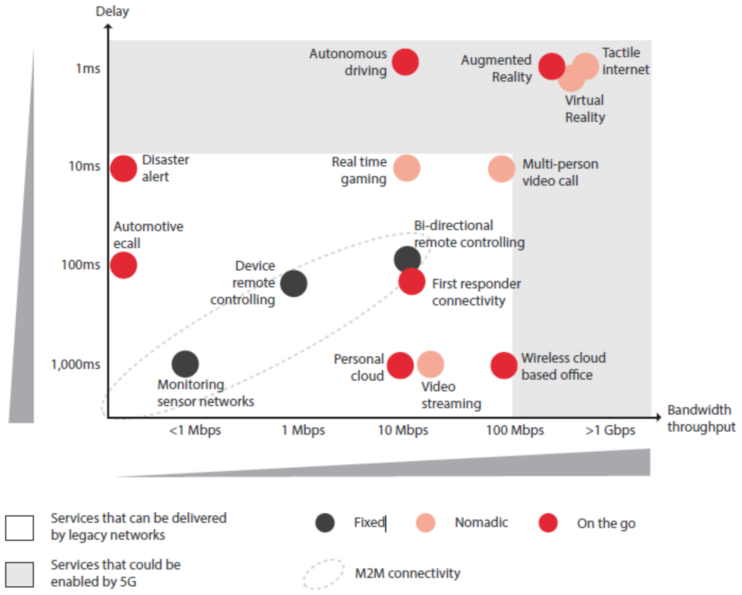


*Figure 2: Bandwidth and latency requirements of potential 5G use cases28*

The 5G communications network and service environment of "2020 and beyond" will be infinitely richer and more complex than today. The user experience will not only be more involving but also more immersive, supporting all aspects of social interaction, work communication, health monitoring, device and environment management, and even assisting our economic wellbeing, too. The challenge is to provide an appropriate 5G infrastructure that has the inherent capacity, capability, reliability, availability and security to provide this seamless life support in a timely and sustainable way. This new network infrastructure must be capable of connecting people, processes, computer centres, content, knowledge, information, goods, and other things at high speed according to a multiplicity of application specific requirements. And while the volume of communication each person does is expected to increase dramatically, the number of connected things communicating is expected to be 10 times higher than the number of connected human users by then. 5G is not just an evolution; it is a revolution and must be designed to handle this dramatic increase in communications from the start! Because of the recession and intense competition around the world, the European Union is committed to keep strengthening Europe's role in communications and to develop more European-built Internet infrastructure and services.

If history is any indicator, technology will likely continue to progress into another ITU-defined "IMT" into the 2030 timeframe. This will probably be marketed as "6G" (and succeeding, it will be a 7G, 8G, and so on each following a 10-year cycle). As of November 2020, there was no industry agreed definition or timeline for the successor to IMT-2020 or what will likely be called "IMT-2030" or 6G[29]. However, output from the work on this next "IMT" vision and the goals that the ITU has identified is expected to show progress within the next few years, as there are already projects underway, which impact technology evolution into the late 2020s and 2030s[30]. While 6G is expected to revolutionize radio, network technologies and architecture potentially based on new IMT requirements[31], it is not

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28 Source: Warren, D., and Dewar, C.: *Understanding 5G: Perspectives on future technological advancements in mobile.* GSM Association (GSMA) Intelligence (12/2014).

29 5G Americas (12/2020): *Mobile Communications Beyond 2020 – The Evolution of 5G Towards the Next G*. Available at: https://www.5gamericas.org/mobile-communications-beyond-2020--the-evolution-of-5g-towards-next-g/

30 Alsharif, M.H., Kelechi, A.H., Albreem, M.A., Chaudhry, S.A., et *al.* (2020): Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions. *Symmetry*, **12**(4), 676-697.

31 Akyldiz, I.F., Kak, A., and Nie, S. (07/2020): 6G and Beyond: The Future of Wireless Communications Systems. *IEEE Access*, **8**, 133995-134030.

likely this work will appear in a 3GPP release until after Release 19 or 20, nor be ready for commercial deployment until around 2030[32].

## 1.2 5G as "Enabler" of the European and of the Global Market

Current market growth via the development and exploitation of corresponding 5G networks and of related infrastructures "delineates" a purely innovative framework that drastically affect modern economies and societies. In any case, the concept of very high performance 5G networks results from a combination of different factors and by assessing a variety of features. Thus, we can distinguish several potential approaches among which important is the one proposed from the service and business perspective that is summarised as below:

- A significant growth in mobile video consumption will create a new framework that is assessed to require much higher traffic volumes per device in Europe after 2020, if compared to actual corresponding figures[33],[34]. Usage of video-on-demand (VoD) services will continue to grow and resolution of these videos will continue to increase. It is expected that people will want to watch high-resolution audio-visual content (HD/UHD), regardless of the way the content is delivered. The popularisation of cloud-delivered Media and Social Media content to smart devices implicates for supplementary limitations on the intermediate communication links, while ever richer content calls for significant capacity increase. Any relevant Virtual Reality (VR) applications are expected to require Gbps capability, whilst the generalisation of 8K[35] Ultra High Definition Television (UHDTV) and of corresponding streaming should necessitate capacities of more than 100 Mbps for a single user. From the 5G perspective, the corresponding services are called as "enhanced Mobile Broadband", also referred to as eMBB in the following text, and target applications with aggregated speeds higher than 10 Gbps.
- The expansion of Machine-to-Machine (M2M) communication with great numbers of connected devices (massive IoT[36]) used in professional and industrial applications and/or in smart cities with the deployment of large populations of sensors, implicates for highly efficient radio networks and very low energy consumption. From the 5G perspective, the corresponding services are called as "massive Machine-to-Machine Communication", also referred to as massive Machine-Type Communication[37] (mMTC) in the following text, and target applications with millions of devices per km². For future wireless systems, the design

[32] NTT DOCOMO Inc. (01/2020): *White Paper: 5G Evolution and 6G*.

[33] International Telecommunication Union - Radiocommunications Sector (ITU-R): Report ITU-R M.2370 (07/2015): *"IMT traffic estimates for the years 2020 to 2030"*. (This Report contains global IMT traffic estimates beyond 2020 from several sources. These estimates anticipate that global IMT traffic will grow in the range of 10-100 times from 2020 to 2030).

[34] Cisco: *Cisco Annual Internet Report (2018-2023) White Paper* (update: 09.03.2020) *http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html*

[35] "8K" refers to the number of "pixels" (picture elements) with 4 times better horizontal and vertical definition of an image compared to traditional High Definition TV standards (2K pixels for horizontal definition).

[36] In the (near) future, every object that can benefit from being "connected" will perform so through wired or wireless Internet technologies. Therefore, the number of connected devices will grow rapidly and it is expected to exceed the number of human user devices. These connected "things" can be smart-phones, sensors, actuators, cameras, vehicles, etc., ranging from low-complexity devices to highly complex and advanced devices. A significant number of connected devices are expected to use IMT systems.

[37] For further information see, *for example*: Pratas, N.K., Wunder, G., Saur, S., Navarro, M., Gregoratti, D., et *al.* (2018): Towards Massive Connectivity Support for Scalable mMTC Communications in 5G Networks. *IEEE Access*, **6**, 28969-28992.

of new applications is envisaged based on M2M communication with real-time constraints. Driverless cars, enhanced mobile cloud services, real-time traffic control optimisation, emergency and disaster response, smart grid, e-health or efficient industrial communications are examples of where low latency and high reliability can improve quality of life. Related use cases are characterised by requirements on very low device cost and very long device battery life, often also associated with a requirement on very-wide-area coverage.

- New time-demanding applications requiring immediate reaction (i.e. very low latency in the order of 1 ms), cannot be served by today's existing technology with the required guarantee of performance (where a typical LTE latency is approx. of 10 ms). Several "typical" applications comprise of remote surgery, connected cars (mainly for safety services and fast prediction of surrounding conditions), smart factories and robotics, or detection of faults in energy grids. These applications are typically associated with requirements for very high communication reliability and the possibility for very low latency. In most of the considered cases, these time-critical applications have to combine 5G connectivity with distributed (mobile) cloud technology so that to satisfy the required end-to-end (E2E) response times. From the actual 5G perspective, the corresponding services are called as "Ultra Reliable Low Latency Communications" also referred to as URLLC in the following text, and target applications with very low latency requirements.

From a technological perspective, several innovative and high-disruptive technologies are also expected to act as potential "enablers"[38]. In the following parts we briefly discuss several among them, *per case*:

- The *vision of economic fibre-like radio access* with data rates beyond 10 Gbps is within reach, notably through the usage of higher frequency bands above 6 GHz and related technologies. Today, spectrum allocations for wireless broadband are situated below 6 GHz. Higher frequency bands will offer larger capacities for disruptive capabilities, such as a large number of simultaneous communications with users/devices, and open the prospect for user data rates meeting the International Telecommunication Union (ITU) requirements for 5G (i.e. mainly for exceeding the rate of 10 Gbps). A multiplicity of realised industrial trials have led to speeds higher than 10 Gbps and up to 70 Gbps, achievable when using spectrum above 6 GHz[39],[40].

  *Network Function Virtualisation (NFV):* Open platforms offer better flexibility and scalability than the purpose-based hardware used in existing networks, so the 5G network is moving away from the traditional specialised hardware used in previous network generations and towards open platforms. Open platforms consist of COTS (Commercial off-the-Shelf) hardware, where applications are installed, forming what is called a Virtual Network Function (VNF). Network functions can be executed in any physical hardware, and therefore the physical location can dynamically change based on current demand and also the service

[38] International Telecommunication Union - Radiocommunications Sector (ITU-R): Report ITU-R M.2320 (11/2014): *"Future technology trends of terrestrial IMT systems"*. The above Report provides a broad view of future technical aspects of terrestrial IMT systems considering the timeframe 2015-2020 and beyond. It also provides information on technical and operational characteristics of IMT systems, including the evolution of IMT through advances in technology and spectrally-efficient techniques and their deployment.

[39] To this aim, a huge majority of vendors and operators aim at using spectrum around 30 GHz (25-32 GHz) for early 5G trials at high speeds, where commercial implementation may be feasible in the short term.

[40] International Telecommunication Union - Radiocommunications Sector (ITU-R): Report ITU-R M.2376 (07/2015): *"Technical feasibility of IMT in bands above 6 GHz"*.

 

requirements such as latency. This also enables cloud computing[41], where the network nodes share compute, storage and network resources, dynamically and independently of their physical location. The NFV process provides the possibility of realising and implementing specific network functions (such as, *for example*, Content Delivery Network (CDN), Customer Premises Equipment (CPE) management, etc.) in software running on generic hardware, without the need for costly hardware-specific machines. NFV enables the on-demand instantiation of functions in a format easier to load-balance, scale up/down, and allow for the movement of functions dynamically across distributed hardware resources in the network[42]. The anticipated benefits are: (i) A drastic reduction in capital expenditure (capex) and network management costs – operational expenditure (opex); (ii) reuse and sharing of the same functionality between several customers; and (iii) higher innovation capability through easy introduction of new software functionalities and creation of a "network app" market place. The trend towards virtualisation is profound in the industry. The great majority of market actors support the ETSI-NFV Industry Specification Group[43] (ISG) which is one of the leading bodies for NFV functional specifications.

Thus, NFV aims to transform the way that network operators architect networks by evolving standard IT virtualisation technology to consolidate many network equipment types onto industry standard high-volume servers, switches and storage, which could be located in a variety of NFVI-PoPs including data centres, network nodes and in end-user premises. High-level objectives of NFV are[44]: (i) Rapid service innovation through software-based deployment and operation of network functions and end-to-end services; (ii) improved operational efficiencies resulting from common automation and operating procedures; (iii) reduced power usage achieved by migrating workloads and powering down unused hardware; (iv) standardised and open interfaces between network functions and their management entities so that such decoupled network elements can be provided by different players; and (v) greater flexibility in assigning VNFs to hardware.

*Software Defined Networking (SDN):* Another new feature of 5G networks is what is called SDN which provides the separation of the control plane from the user plane. The usage of SDN allows for a high level of programmability, enabling the separation of the network in different slices within the same hardware. Each slice can then be dedicated to a different type of service. SDN is a complementary trend to NFV[45] that allows the control of network resources to be opened to third parties, with the possibility for these third parties to manage their own physical or virtual resources individually, as needed, with the required level of performance tailored to actual needs. SDN centrally configures and manages physical and virtual network devices in datacentres, such as routers, switches, and gateways. This possibility goes much beyond the management capabilities offered to today's Mobile Virtual

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41 Could computing has been gaining lots of momentum for its flexibility, elasticity, and cost-efficiency. The basic tenet of cloud computing is that users do not need to be concerned about the placement of their services nor the provisioning of the required resources; principally offered following the pay-per-use model.

Also see: Satyanarayanan, M., Lewis, G., Morris, E., Simanta, S., Boleng, J., and Ha, K. (10/2013): The role of cloudlets in hostile environments. *IEEE Pervasive Computing*, **12**(4), 40-49.

42 Mijumbi, R., Serrat, J., Gorricho, J.-L., Bouten, N., et *al.* (1st quart. of 2016): Network function virtualization: State-of-the-art and research challenges. *IEEE Communications Surveys and Tutorials*, **18**(1), 236-262.

43 Founded in November 2012 by seven of the world's leading telecoms operators, the ETSI INF ISG became the home of the try Specification Group for NFV. For more details see: *https://www.etsi.org/technologies/nfv*

44 European Telecommunications Standards Institute (ETSI): ETSI GR NFV 001 V1.2.1 (2017-05): *"Network Functions Virtualisation (NFV); Use Cases"*. Available at: *https://www.etsi.org/deliver/etsi_gs/NFV-MAN/001_099/001/01.01.01_60/gs_NFV-MAN001v010101p.pdf*

45 Li, Y., and Chen, M. (2015): Software-defined network function virtualization: A survey. *IEEE Access*, **3**, 2542-2553.

 

Network Operators[46] (MVNOs). The combination of NFV and SDN technologies[47] enables a lower capex as compared to traditional networks, accelerating time to market. According to recent research[48] businesses utilizing such technologies can implement new services 13 times faster than with traditional networks. Operational cost is also reduced due to automation and the scalability of such networks. Based on an analyst firm estimate[49], operational costs of running a network implemented with such technologies can be reduced by as much as the limit of 50%.

In the framework of actual 5G developments and with the pure aim of supporting *ad-hoc* digital business models of industrial users, SDN and NFV are often seen as "key and supplementary components" to allow these specific categories of professional users to control their network capabilities dynamically, according to their specific needs. As network resources are potentially available to third parties through open interfaces, they also open the possibility for smaller "actors" to innovate through development of specific service offers building on network resources made available for third party access and programmability. SDN and NFV are having an enormous impact on network operations today, the IoT with massive numbers of devices, the dynamic nature of the underlying networks and QoS requirements, and finally the end customers who continue to expect an improved level of communication experience. To unleash the benefits of virtualisation and software defined technologies, while increasing the efficiency of network operations, the industry must enhance Network and Service Management (NSM) automation. Developments in edge computing, low latency networks, Artificial Intelligence (AI), and Machine Learning (ML) offer additional benefits that again can only be realised with NSM automation. The introduction of 5G further raises the stakes towards a next generation NSM architecture. The evolution of network and control technology will enable more flexibility in service creation, capacity and change management as well as more efficient network operations.

The essential capabilities delineated above also implicate for progress and evolution overpassing current 4G/LTE capabilities, as of the following attributes:

- *Speed:* Currently, 4G data rates (reachable by multiple users) are at about 500 Mbps, which supports in average a maximum data rate of 50 Mbps per user.
- *Flexibility to accommodate demanding professional-grade applications:* 4G core network architectures and capability do not widely implement SDN-/NFV-based functions. This does not allow the resource allocation flexibility needed in scenarios where a radio access has to assist applications with very different requirements (e.g. connected vehicle users with very low latency requirements or video streaming users with very high downlink speed requirements). The lack of open interfaces also pre-empts the emergence of innovative service offers in the new domains.
- *Instant response time:* Core 5G application requirements such as low latency of 1 ms (10 to 20 ms for 4G), serving 1 million devices/km² (about 1000 device/km² for 4G) or fast deployment of new services in the order of 1-hour deployment time (measured in days with current technology) are not part of today's 4G technology.

Against the background, new 5G definition(s) and use cases have been developed by the industry.

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[46] A Mobile Virtual Network Operator (MVNO) operates resources contracted from a network operator owning physical and logical network infrastructure.

[47] Nguyen, V.-G., Brunstrom, A., Grinnemo, K.-J., and Taheri, J. (3rd quart. of 2017): SDN/NFV-based mobile packet core network architectures: A survey. *IEEE Communications Surveys and Tutorials*, **19**(3), 1567-1602.

[48] ZK Research (07/2015): *The Quantitative and Qualitative Benefits of the New IP Network*.

[49] Ibid.

The ITU Recommendation ITU-R M.2083-0[50], approved in September 2015, defines the overall objectives of the future development of IMT for 2020 and beyond. It calls for 5G system improvements that cover three generic classes of services, based on anticipated market developments. These are outlined in the broadly known as the "ITU triangle", as illustrated below (Figure 3):

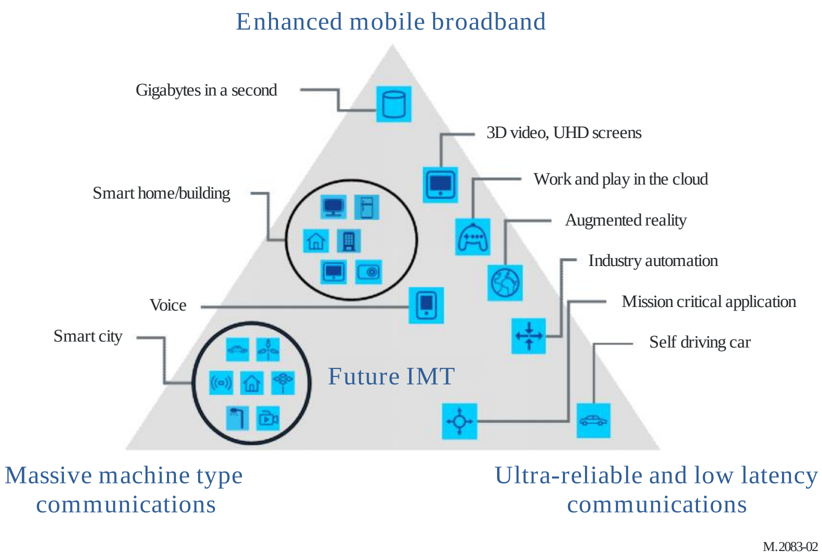


*Figure 3: Usage scenarios of IMT 2020 and beyond [Source: ITU-R Recommendation M.2083-0]*

IMT for 2020[51] and beyond is envisaged to expand and support diverse usage scenarios and applications that will continue beyond the current IMT. Furthermore, a broad variety of capabilities would be "tightly coupled" with these intended different usage scenarios and applications for IMT for 2020 and beyond[52],[53]. The usage scenarios for IMT for 2020 and beyond include:

- ***Enhanced Mobile Broadband (eMBB)***: Mobile Broadband (MBB) addresses the human-centric use cases for access to multi-media content, services and data. The MBB can be relevant for accessing multi-media content such as a 4K streaming on a mobile device or on-site live experiences. It is also relevant to 4K[54]/8K[55] TV, health wearables and home sensor services. It is the first use case for the applicability of 5G. The eMBB addresses traffic growth demands and higher consumer experience needs. It requires a significant increase in capacity over a macro-scale coverage area; at the same time, sites along highways in close proximity are needed to support connected vehicles as the smart car becomes even smarter as part of the evolution towards fully autonomous vehicles. The demand for mobile broadband will

[50] International Telecommunication Union – Radiocommunications Sector (ITU-R): Recommendation ITU-R M.2083-0 (09-2015): *"IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond"*.

[51] The term "IMT 2020" implicates for several requirements issued by the ITU Radiocommunications Sector (ITU-R) of the International Telecommunication Union (ITU) in 2015, for 5G networks, devices, and services.

[52] Popovski, P., Trillingsgaard, K.F., Simeone, O., and Durisi, G. (2018): 5G Wireless Network Slicing for eMBB, URLLC, and mMTC: A Communication-Theoretic View. *IEEE Access*, **6**, 55765-55779.

[53] Anand, A., Veciana, G. de, and Shakkottai, S. (2017): *Joint scheduling of URLLC and eMBB traffic in 5G wireless networks*. Available at: https://arxiv.org/abs/1712.05344.

[54] 4K resolution, also called as 4K, refers to a horizontal display resolution of approximately 4,000 pixels. More relevant information can be found, among others at: https://en.wikipedia.org/wiki/4K_resolution

[55] 8K resolution refers to an image or display resolution with a width of approximately 8,000 pixels. The 8K display resolution is the successor of the 4K resolution. For further details also see, *among others*: https://en.wikipedia.org/wiki/8K_resolution

continue to increase, thus leading to eMBB. The eMBB usage scenario comes with new application areas and requirements in addition to existing Mobile Broadband applications for improved performance and an increasingly seamless user experience. This usage scenario covers a range of cases, including wide-area coverage and hotspot, which have different requirements. For the hotspot case (i.e. for an area with high user density) very high traffic capacity is needed, while the requirement for mobility is low and user data rate is higher than that of wide area coverage. For the wide area coverage case, seamless coverage and medium to high mobility are desired with much improved user data rate compared to existing data rates. However, the data rate requirement may be relaxed compared to hotspot. In general, the eMBB use cases have requirements for higher data rates and better coverage. For example, mobile broadband requires a significant increase in capacity over a macro-scale coverage area. At the same time, sites along highways in close proximity are needed to support connected vehicles as the smart car becomes even smarter as part of the evolution towards fully autonomous vehicles.

- ***Ultra-Reliable and Low Latency Communications (URLLC):*** This use case has stringent requirements for capabilities such as throughput, latency and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc. As evident, the related use cases have very strict requirements on latency and reliability. URLLC supports low-latency transmissions of small payloads with very high reliability from a limited set of terminals, which are active according to patterns typically specified by outside events, such as alarms[56].
- ***Massive Machine-Type Communications (mMTC):*** This use case is characterised by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data[57]. Devices are required to be low cost and have a very long battery life. The definition of machine-type communications is somewhat elusive, as it has to include a large variety of emerging concepts, such as the Internet of Things (IoT), Internet of Everything (IoE), Industry 4.0, Smart "X", etc. Each adds new scenarios with differing assumptions and requirements, ranging from long term environmental observation involving limited energy consumption, over smart cities with millions of sensors, to fully wireless factories with very strict requirements on latencies and reliabilities of the wireless connection. A 5G design needs to consider all this in order to really fulfil the role of a universal enabler for emerging and future industries. The related uses cases generally have requirements to support a very large number of devices in a small area, therefore, very large device density. The main challenge in mMTC is scalable and efficient connectivity for a massive number of devices sending very short packets, which is not done adequately in cellular systems designed for human-type communications. Furthermore, mMTC solutions need to enable wide area coverage and deep indoor penetration while having low cost and being energy efficient.

Additional use cases are expected to emerge, which are currently not foreseen. For future IMT, flexibility will be necessary to adapt to new use cases that come with a wide range of requirements. Future IMT systems will encompass a large number of different features. Depending on the circumstances and the different needs in different countries, future IMT systems should be designed in a highly modular manner so that not all features have to be implemented in all networks.

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56 Also see, for further study: Fehrenbach, T., Datta, R., Göktepe, B., Wirth, T., and Hellge, C. (2018): *uRLLC Services in 5G Low Latency Enhancements for LTE networks*. In Proceedings of the 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), pp.1-6. Chicago, IL, USA.

57 See, *for example*: Bockelmann, C., Pratas, N., Nikopour, H., Au, K., Svensson, T., et *al.* (09/2016): Massive machine-type communications in 5G: Physical and MAC-layer solutions. *IEEE Communications Magazine*, **54**(9), 59-65.

With such a large variation in performance attributes, it may be more useful to consider these very different use cases in terms of their types of interaction: between people, between machines, or between people and machines. Considering this classification, and grouping the use cases by the primary categories that 5G will affect (i.e., extreme mobile broadband, massive scale communication and ultra-reliable low latency service), leads to the consideration of a powerful alternative visualisation. This, in particular, enables a vision of the way certain use cases will span across multiple types of interaction and various performance requirements[58]. Figure 4, below, illustrates this sort of taxonomy for some 5G use cases.

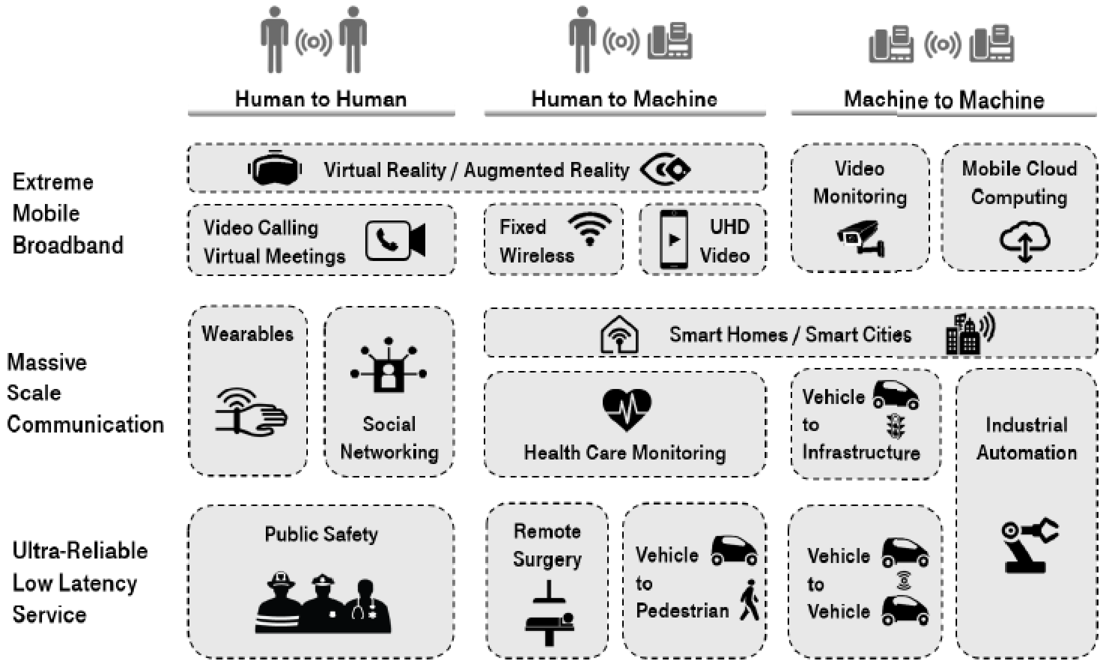


*Figure 4: Some 5G use cases grouped, according to 5G Americas [Source: 5G Americas (2017): 5G Services and Use Cases – A White Paper]*

### 1.2.1 Specific Actions promoted by the EU in the 5G-PPP Context

The European Commission (EC) launched in 2013 a Public-Private-Partnership[59] (5G-PPP) backed by 700 million euro of public funding with the aim of making sure that 5G technology is available in Europe by 2020. However, research efforts alone will not be sufficient to ensure Europe's leadership in 5G. A wider effort and a more detailed approach are so expected to make 5G and the services that will flow from it a reality, in particular for the appearance of a European "home market" for 5G. The future European Electronic Communications Code[60] will support the deployment and take-up of 5G networks, particularly as regards assignment of radio spectrum, investment incentives and favourable framework conditions, while the recently adopted rules on open Internet[61] provide legal certainty as regards the deployment of 5G applications. This communication complements and

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[58] 5G Americas (2017): *5G Services and Use Cases – A White Paper*. Available at: https://www.5gamericas.org/5g-services-use-cases/

[59] More details can be found at: https://5g-ppp.eu/

[60] For further information also see: https://ec.europa.eu/digital-single-market/en/connectivity-european-gigabit-society

[61] See, *for example*: Regulation (EU) 2015/2120 of the European Parliament and of the Council of 25 November 2015 *on laying down measures concerning open Internet access and amending Directive 2002/22/EC on universal service and users' rights relating to electronic communications networks and services and Regulation (EU) No.531/2012 on roaming on public mobile communications networks within the Union.* Official Journal (OJ) L310, 26.11.2015, pp.1-18.

 

leverages this new regulatory framework through a set of targeted actions[62].

The EC will assist EU Member States in the context of their national broadband plans and the Future Internet Forum (FIF) and in collaboration with industry through the 5G-PPP to establish common objectives and concrete steps for testing and deploying commercially available 5G solutions.

As major research efforts are taking place at a universal level, it is critical to avoid any sort of “unsuited” 5G standards, evolving in different regions and, occasionally, promoting different aspects. This challenge implicates for a more “coordinated” approach to be performed at EU level, aiming to structure an explicit consensus as of the choice and usage of technologies, spectrum bands and in order to establish effective 5G applications. The promotion of commercial 5G services in the market will also implicate for considerable investments, for the availability of a “suitable” amount of the radio spectrum as well as for close and interactive collaboration between telecom players and “key” user industries, not necessarily within the EU borders only. In fact, any option for international collaboration will strengthen the intended actions and will support development and growth, together with clear technological prospects and a reliable regulatory framework. Legislative and regulatory actions can remove barriers, improve competitive incentives, deliver greater predictability for investors, as well as lower costs for network deployment. In this framework, an absence of coordination between national European approaches concerning the roll-out of 5G networks could generate an important risk of fragmentation as of spectrum disposal, service continuity across borders (e.g. connected vehicles) and reliable implementation of standards. Consequently, this could prevent from establishing a critical mass for 5G-based innovation in the European Digital Single Market[63] (DSM).

The Commission has identified the following key elements in order to support a proper development of the European market in view of the expected 5G[64] innovative features:

- Alignment of road-maps and priorities for a coordinated 5G deployment across all EU Member States, targeting early network introduction by 2018, and moving towards commercial large-scale introduction by the end of 2020, at the latest.
- Making provisional spectrum bands available for 5G ahead of the 2019 World Radio Communication Conference (WRC-19), to be complemented by additional bands as quickly as possible, and work towards a recommended approach for the authorisation of the specific 5G spectrum bands above 6 GHz.
- Promotion of early deployment in major urban areas and along major transport paths.
- Promotion of pan-European multi-stakeholder trials as “catalysts” to turn technological innovation into full business solutions[65].
- Facilitation of the implementation of an industry-led venture fund in support of 5G-based innovation.

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[62] To deliver appropriate incentives for investment in Internet connectivity, the proposed Code makes targeted changes to market regulation designed to enable adequate returns on new investments relative to risks, giving Europe-wide predictability to the international investment community, while leaving adequate scope for adaptation to localised network conditions.

[63] The Digital Single Market designates the 2014-2019 strategy of the European Commission for the best possible access to the online world for individuals and businesses. A DSM is one in which the free movement of persons, services and capital is ensured and where the individuals and businesses can seamlessly access and engage in online activities under conditions of fair competition, and a high level of consumer and personal data protection, irrespective of their nationality or place of residence. The 2014-2019 strategy of the Commission had identified the completion of the DSM as one of its 10 political priorities.

[64] 5G refers to the next generation of network technologies offering prospects for new digital economic and business models.

[65] Within this specific scope, the 5G Pan-European Trials Roadmap supports global European leadership in 5G technology, networks deployment and profitable business. It validates the benefits of 5G to vertical sectors including public sector, businesses and consumers. It also promotes a clear path to successful and timely 5G deployment in Europe.

- Support of leading market actors in working together, towards the promotion of global standards.

In addition to progressively challenging connectivity for media applications, professional-grade communications in industrial and service domains such as automotive, transport, manufacturing, health as well as next generation safety and emergency services will necessitate for a seamless, shared, fixed and wireless infrastructure, which offers a range of customer-controlled levels of reliability and quality of service (QoS), tailored to specific business needs. The foreseen services will share infrastructure and a common 5G technology and will allow users and objects "on the move"[66] to remain fully connected at all times, in urban transport, along inter-city corridors, or even in the air (e.g. drones for logistics). Industrial zones, road corridors and train connections are expected to be the key areas for the first phase of new applications[67]. The viability of some of these new applications will require the availability of 5G services simultaneously in all Member States to enable service continuity across borders and sufficient economies of scale. Thus, the Commission supports a common intermediate objective to promote a common timetable for network deployment proposed in the 5G action plan. This Action Plan aims to foster a coordinated approach for the deployment of 5G infrastructures, which shall affect Europe's future Internet connectivity and opens up entirely new opportunities to innovate, not only in the communications sector, but also throughout the whole economy and society. Establishing the new 5G infrastructure requires an appropriate degree of coordination between Member States and between relevant sectors to stimulate investments. The action plan aims to realise such coordination based on a number of targeted actions, largely of a voluntary nature. Together with the proposed Code, it should give Europe the tools to lead the 5G race for the benefit of its international competitiveness.

5G will be different to previous generations. Its specific goals include the creation of enabling solutions for vertical industries such as automotive, healthcare, transport and utilities. Vertical Industries are going through a new wave of generational transformation driven by multiple factors including societal changes, economic challenges and aging of populations. In the next decade, many industries are evolving towards distributed production, connected goods, low energy processes, increasing automation, collaborative robots, integrated manufacturing and logistics[68]. The vertical industries as well as the ICT industry will also benefit from globally accepted standards and harmonised frequency spectrum. This will enable economy of scale for affordable cost and ensures roaming by interoperability. While it cannot be denied that wireless through its generations has delivered enormous socioeconomic value almost beyond measure, no generation has ever set out with this fundamental goal as a priority. In this respect 5G will be quite different. It will be the first generation to explicitly target delivering socio-economic benefits and, as a result, many new 5G capabilities are anticipated. Among other capabilities, the 5G will enable a diversity of working solutions on planes, trains and cars.

More specifically, within the context of the ICT-17-2018 Call[69] ("5G E2E Facility") the main challenges have been towards establishing and providing a suitable end-to-end facility that can: (i) demonstrate that the "key" 5G-PPP network KPIs can be adequately met; (ii) be validated, accessed and used by vertical industries to set up research trials of innovative use cases, to further validate core 5G KPIs in the context of concurrent usages by multiple users and thus supporting market growth.

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66 In this context it is expected that 5G will co-exist seamlessly with complementary technologies already being deployed, e.g. for short-range communication for vehicle-to-vehicle and vehicle-to-infrastructure.

67 For terrestrial transport paths, and depending on the considered transport service, account will be taken of ongoing investments in C-ITS technologies while ensuring coordination with relevant stakeholders.

68 The 5G Public Private Partnership (5G-PPP) (04/2016): *5G Empowering Vertical Industries – White Paper*. Available at: https://5g-ppp.eu/roadmaps/

69 For more details also see the exact framework included in the following website: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ict-17-2018

### 1.2.2 The Pan-European Trials Roadmap

The 5G Pan-European Trials Roadmap[70] is covering a broader scope than the 5G Action Plan (5GAP) and the 5G Infrastructure PPP Phase 3 (2018-20+). Most of the Roadmap implementation is and will be covered by the industry on a private basis[71], with part of this implementation supported by EC through the 5GAP, EC 5G Infrastructure PPP Phase 3, EC 5G Investment Fund and by Member States through specific National programmes. Developing and aggregating a "critical mass" of 5G experimental facilities has to, foremost, support the visions that major stakeholders are proposing for 5G, in order to allow proper interoperability testing and comparison of the different architectural frameworks. This should have the ambition to let European companies create the basis for a shared vision on what 5G will really be, not only from the technological viewpoint, but also from a business sustainability and regulations perspectives. Furthermore, proper integration needs to be sought in order to create a hierarchical experimental ecosystem with interoperable coordination and management.

The main objectives of the 5G Pan-European Trials Roadmap are to: (i) Support global European leadership in 5G technology, networks deployment and profitable business; (ii) validate benefits of 5G to vertical sectors including public sector, businesses and consumers; and (iii) stimulate a clear path to successful and timely 5G deployment in Europe. To that end, it expands commercial trials and demonstrations as well as national initiatives, with a clear focus on activities revolving around EU cities. It is expected that 5G activities centered on major EU cities will contribute to meeting the challenge of making 5G a reality for all citizens and businesses in Europe.

The 5G Pan-European Trials Roadmap has been elaborated and reviewed by the Trials Working Group Member organisations, coordinated by the 5G Infrastructure Association (5G-IA). It is addressing several of the 5GAP key elements and targets to develop the necessary synergies between these elements.

The main objectives of the Roadmap are to: (i) Support global European leadership in 5G technology, 5G networks deployment and profitable 5G business; (ii) validate benefits of 5G to vertical sectors, public sector, businesses and consumers; (iii) initiate a clear path to successful and timely 5G deployment, and; (iv) expand commercial trials and demonstrations as well as national initiatives. The overall 5G Pan-EU Trials Roadmap time plan and relevant standardisation, regulatory and ecosystems time plan are summarised in the following Figure 5.

[70] The 5G Pan-European Trials Roadmap has been elaborated and is supported by the Trials Working Group (WG) Members organizations. It is coordinated by the 5G Infrastructure Association (5G-IA), expanding the work initiated by the Industry and the European Commission (EC) in the context of the 5G Manifesto (see: *http://ec.europa.eu/newsroom/dae/document.cfm?action=display&doc_id=16579*) and of the 5G Action Plan (5GAP) (see: *http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=17131*)

For more details also see: *https://5g-ppp.eu/5g-trials-roadmap/*

[71] As detailed in the previous versions of the 5G Pan-EU Trials Roadmap, the core part of the 5G trials and pilots is and will be achieved through private trials (commercial and pre-commercial) between network operators and manufacturers/vendors and is increasingly involving vertical stakeholders.

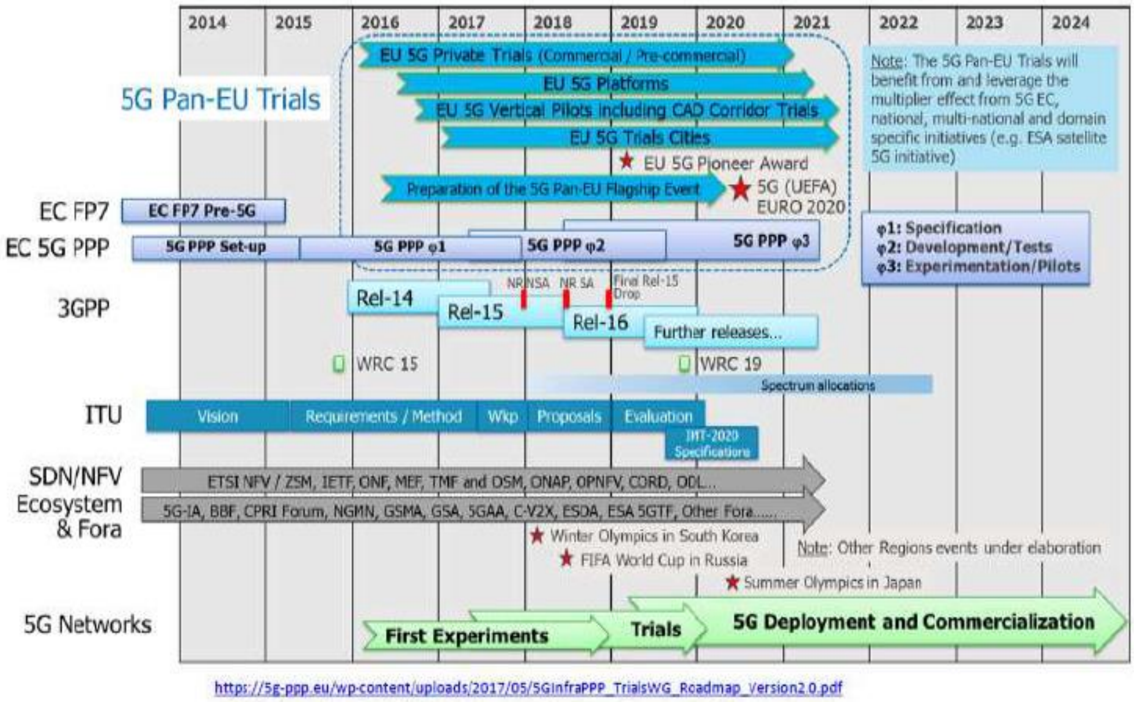


*Figure 5: 5G Pan-EU Trials Roadmap – Time Plan [Source: https://5g-ppp.eu/5g-trials-roadmap/]*

Experimental platforms for 5G developments and trials in EU are the results of private and public efforts at national and EU level. Accelerating trial capabilities and other pilots, the platforms remain subject to continuous efforts targeting the full 5G picture and future evolutions[72]. As such, the future roadmap of actual 5G infrastructure deployment is highly dependent on the capability to up-date existing or deliver a new relevant and comprehensive set of platforms addressing the remaining gaps and challenges. One should also consider platforms as valuable and demonstrated set of 5G enablers, beyond trial objectives. In order to increase the complementarity of the available platforms and the forthcoming developments, tight coordination is need, including first in the documentation of the platforms. It is of tremendous importance to describe the matching elements of each platform compared to the complete 5G landscape. This documented orientation helps 3rd parties to assign their interests to the respective platform purpose. To boost access to 5G platforms, it is necessary to help different stakeholders on their knowledge level to identify the right platform targeting their interests Therefore a common classification and documentation for 5G platforms addressing different target groups is mandatory. Consistent data structures and unified meta-information like name of the platform, countries where the platform is deployed and additional information on features and capabilities is fundamental. The data collections provided by platforms have to support questions from diverse stakeholders including research, public sector or industry.

A large-scale and hierarchical aggregation of experimental facility for 5G should fulfil a number of requirements; it should be:

- *flexible* enough in order to accommodate many different options in terms of technologies (including separate physical layers, frequency bands, etc.) at the different layers and components of the network;
- easily *reconfigurable* so that experimenters can shape it for the sake of testing their own solutions;

[72] The acceleration of 5G in EU is also happening thanks to a specific joint strategy between Industry (hand in hand with Research Centres, Academics and local communities), EC and EU member states (MSs) and Domains specific initiatives. The EU 5G strategy is clearly targeting large scale adoption of 5G by vertical sector (also see: https://5g-ppp.eu/wp-content/uploads/2016/02/BROCHURE_5PPP_BAT2_PL.pdf).

- based on *open source* solutions, to magnify its potential exploiting the competences of the largest possible scientific community;
- able to provide *reproducible* results, in order to guarantee fair and scientific testing and comparison of separate technologies (this might require the inclusion of emulation components);
- *complete,* to allow the inclusion of all components of the 5G ecosystem, from the MNO to the virtual operator, from the end-user to the M2M application field and the IoT, etc.;
- *heterogeneous* in terms of radio and optical interfaces tested, as well as of contexts, including body centric communications, vehicular networks, advanced robotics, etc.;
- *site-agnostic,* as far as this is possible, in order to test technologies and solutions in different contexts and to be easily accessible by researchers throughout all Europe;
- *topology-agnostic,* in order to cover all wireless solutions (including cellular and satellite technologies) and topologies (from small cells to macro-cells);
- *pan-European,* crossing several countries in Europe and serving stakeholders and research centres from all EC countries and beyond.

Moreover, it should constitute the basis for the development of 5G technologies in Europe, as well as for *training* a new generation of engineers and researchers prepared to such development. And above all, it should create concrete socio-economic impacts. In terms of *performance* the experimental facility should be able to allow testing of 5G technologies having in mind the need to "meet" some expected levels for KPIs to be properly defined.

5G Infrastructure PPP Phase-3[73] includes three platforms projects (through the ICT-17 call[74] that have started their work in July 2018. The projects, namely 5G EVE, 5GENESIS and 5G-VINNI are providing large-scale end-to-end 5G validation network infrastructures. They cover about 20 European sites and nodes on a pan-EU basis and will be operational until 2021. Their infrastructure provides an adequate level of openness to make it possible for vertical industries to test their innovative 5G business cases[75]. As 5G networks aim to support the vertical industries, a set of seven Vertical Pilot projects (through the ICT-19 call[76]) have started their activities in June 2019. They demonstrate advanced 5G validation trials across multiple vertical industries. These projects take advantage of the abovementioned ICT-17 projects and interwork with them. In the following paragraphs we provide a brief description of each one among the three platforms projects, in order to better "delineate" their conceptual scope.

**5G-EVE[77]:** The 5G EVE concept is based on further developing and interconnecting existing European sites to form a unique 5G end-to-end (E2E) facility. The four interworking sites are located in France, Greece, Italy and Spain and provide both indoor and outdoor facilities. Each site is operated by a telecoms network operator. The four sites are interconnected to provide a seamless single platform experience for experimenters from vertical industries. The 5G EVE end-to-end facility enables

[73] For more details see: https://5g-ppp.eu/5g-ppp-phase-3-projects/

[74] Horizon 2020 (H2020) Framework Programme (H2020): *5G End to End Facility*. Available at: https://ec.europa.eu/info/fundingtenders/opportunities/portal/screen/opportunities/topic-details/ict-17-2018

[75] A summary of their activities can be found in the publication: 5G-PPP (2020): 5G network support of vertical industries in the 5G Public-Private Partnership ecosystem, brochure. Available at: https://5g-ppp.eu/wpcontent/uploads/2020/02/Vertical-industries-in-the-5G-PPP.pdf

[76] Horizon (H2020) 2020 Framework Programme: *Advanced 5G validation trials across multiple vertical industries*. Available at: https://ec.europa.eu/info/fundingtenders/opportunities/portal/screen/opportunities/topic-details/ict-19-2019

[77] 5G-VINNI: 5G Verticals INNovation Infrastructure (GA No.815279). More details can be found at: https://www.5g-vinni.eu/

experimentation and validation with full sets of 5G capabilities – initially 3GPP Release 15[78] compliant and by the end of the project Release 16[79] compliant. The 5G-EVE facility enables experiments with: (i) heterogeneous access, including NR, licensed/unlicensed spectrum, advanced spectrum management; (ii) Mobile Edge Computing, backhaul, core/service technologies; and (iii) means for site-interworking and multi-site/domain/technology slicing/orchestration. The project team has performed a systematic analysis of the KPI performance requirements of all use cases by verticals participating in 5G EVE as well as a number of vertical use cases from the approved ICT-19 projects interested in leveraging 5G EVE platform. In addition, the project team has specified the overall 5G-EVE architecture for supporting the various use case requirements. Each site has already deployed the required 5G capabilities (up to Release 15), validation tools and systems, and the secure connectivity for enabling the initial experimentation of use cases on them. The first development of 5G-EVE's innovative framework features for advanced and intent-based validation, KPI monitoring/analysis/validation, basic interworking and openness support has been completed and released. The French site facility has integrated and tested the two use cases one of which was about a 360° video virtual visit (eMBB) which aimed at immersing the visitor in a VR scene located in a real environment.

**5G-VINNI**'s[80] main objective is to provide and enable the longer term evolution of an E2E 5G facility demonstrating that the key 5G PPP network KPIs can be met, accessed and used by vertical industries to set up research trials, to further validate core 5G KPIs in the context of concurrent usages by multiple users, by serving end users with flexible and reliable services ranging from low bit rate high latency services to high bitrate low latency services and everything in between. 5G-VINNI adopts Network Slice as a Service (NSaaS) delivery model to offer customised service experience to verticals, basing its architecture on guidelines from telecom industry organisations and the normative specifications from standards bodies to ensure interoperability and reproducibility. For validating the NSaaS model, 5G-VINNI has assembled an E2E facility with the latest 5G technologies for radio access, backhaul, core networks, leveraging the most advanced virtualisation technologies and optimisation algorithms to test the model with demanding vertical sector driven applications and services. The resources and functional layer of the 5G-VINNI E2E facility is comprised of the RAN, Backhaul, Mobile Core and Cloud Computing facilities, Edge or Centralised Clouds. The resources & functional level will provide the physical resources to host the Service Level and Network Level elements (e.g. VNFs). These elements are interconnected to build dedicated logical networks, customised to the respective telco services (e.g., eMBB, V2X, URLLC, mMTC).

**5GENESIS**[81]: The main goal of 5GENESIS is to validate 5G KPIs for various 5G use cases, in both controlled set-ups and large-scale events. This will be achieved by bringing together results from a considerable number of EU projects as well as the partners' internal R&D activities in order to realise an integrated End-to-end 5G Facility. The 5GENESIS Facility, as a whole, will: (i) implement and verify all evolutions of the 5G standard, via an iterative integration and testing procedure; (ii) engage a wide diversity of technologies and chain innovations that span over all domains, achieving full-stack coverage of the 5G landscape; (iii) unify heterogeneous physical and virtual network elements under a common coordination and openness framework exposed to experimenters from the vertical industries and enabling end-to-end slicing and experiment automation; and (iv) support further experimentation projects, in particular those focused on vertical markets.

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[78] Also see**,** *among others*: 3GPP TR 21.915 V1.1.0 (2019-09): *"Release 15 Description; Summary of Rel-15 Work Items (Release 15)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/21_series/21.915/

[79] Also see, *among others*: 3GPP TR 21.916 V1.1.0 (2020-12): *"Release 16 Description; Summary of Rel-16 Work Items (Release 16)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/21_series/21.916/

[80] 5G-EVE: 5G European Validation platform for Extensive trials (GA No.815074). More details can be found at: https://www.5g-eve.eu/

[81] 5GENESIS: 5th Generation End-to-end Network, Experimentation, System Integration, and Showcasing (GA No.815178). More details can be found at: https://5genesis.eu/

# 2 The 5G-DRIVE Positioning

## 2.1 Overall Concept

5G-DRIVE's overall concept is illustrated in Figure 6, which shows the three "core" streams and depicts the flow from research, to adaptation into existing test-beds and commercial test-bed deployments, to the real-world trials of the 5G radio access network (RAN) and of the wider 5G network. The project "brings together" solid research competence, commercial grade test-beds, and some of the stakeholders who will eventually become major customers of 5G systems.

In the 5G-DRIVE context there are partners with rather extensive 5G test-bed installations – these are three facilities that have been defined, specified and deployed to meet the individual requirements of the three research organisations (i.e.: UoS, VTT and JRC). While all three test-beds are set up with commercial grade equipment, each one has a special focus: the Surrey test-bed can support capacity provision in very dense deployments over a 4 km² area; the Espoo test-bed demonstrates the use of slicing and V2X (Vehicle-to-Everything); the JRC facility allows the testing of new technologies in any part of the network in a fully-controlled environment. All test-beds are defined in an evolutionary approach and allow the gradual introduction and testing of new equipment, as well as new mechanisms, algorithms and protocols.

These characteristics have been exploited in the entire 5G-DRIVE's context. In the research stream, the project aimed to investigate network and RAN slicing, mobile edge computing (MEC), massive MIMO[82] for the 5G NR[83], as well as SDN and network function virtualisation (NFV) techniques applied to different traffic and load scenarios. Techniques and mechanisms in the research stream of the project have been integrated into the most appropriate test-bed. Wherever possible, we endeavoured to deploy such new mechanisms into all three test-beds.

The proposed experimental test-beds/facilities for 5G are able to fulfil a number of requirements[84]. Thus, they are: (i) flexible enough in order to accommodate many different options in terms of technologies (including separate physical layers, frequency bands, etc.) at the different layers and components of the network; (ii) easily reconfigurable so that experimenters can shape it for the sake of testing their own solutions; (iii) based on open source solutions, to magnify its potential exploiting the competences of the largest possible scientific community; (iv) able to provide reproducible results, in order to guarantee fair and scientific testing and comparison of separate technologies; (v)

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[82] Massive Multiple-Input and Multiple-Output (MIMO) is the combination of MIMO and beamforming with large number of antenna elements – to improve both throughput and energy efficiency.

MIMO wireless systems, in general, allow network capacity to increase in terms of higher data rates and a higher number of users served. The multiple transceivers can be employed to provide spatial diversity, or improve the received signal strength by employing, for example, beamforming. When the number of antennas at the base station is increased to a hundred or a thousand elements, the term massive MIMO is employed. Massive MIMO are also known as Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO, Full-Dimension MIMO and Advanced Research and Global Observation Satellite (ARGOS).

Massive-MIMO proposes utilizing a very high number of antennas to multiplex messages for several devices on each time-frequency resource, focusing the radiated energy towards the intended directions while minimizing intra- and inter-cell interference. Massive-MIMO may require major architectural changes, in particular in the design of macro base stations (BSs), and it may also lead to new types of deployments.

[83] 5G New Radio (NR) is the radio access interface that became the foundation for the next generation of mobile networks. Also see: Also see: 3GPP TS 38.300 V16.4.0 (2021-01): *"NR; NR and NG-RAN Overall description; Stage-2"*. Available at: https://www.3gpp.org/ftp/Specs/archive/38_series/38.300/

[84] Verdone, R., and Manzalini, A. (2016): *5G Experimental Facilities in Europe – White Paper, Version 11.0.* NetWorld 2020 ETP. Available at: https://www.networld2020.eu/wp-content/uploads/2016/03/5G-experimentation-Whitepaper-v11.pdf

complete, to allow the inclusion of all components of the 5G ecosystem, from the MNO to the virtual operator, from the end-user to the M2M application field and the IoT, etc.; (vi) heterogeneous in terms of radio and optical interfaces tested, as well as of contexts, including body centric communications, vehicular networks, advanced robotics, etc.; (vii) site-agnostic, as far as this is possible, in order to test technologies and solutions in different contexts; (viii) topology-agnostic, in order to cover all wireless solutions (including cellular and satellite technologies) and topologies (from small cells to macro-cells).

The core objective of the project is to extensively trial eMBB and V2X service delivery under real world conditions. The stringent requirements for the delivery of such services should be defined jointly with the mobile operators in the consortium (Orange, OTE), as well as stakeholders form the automotive and intelligent transports markets (BMW, Vedia, Dynniq, ERTICO). These partners were involved in the use case and trial requirements definition, as well as in its subsequent implementation and analysis. The inclusion of these stakeholders was imperative to ensure that the trials and solutions "do meet" the requirements from the vertical domains.

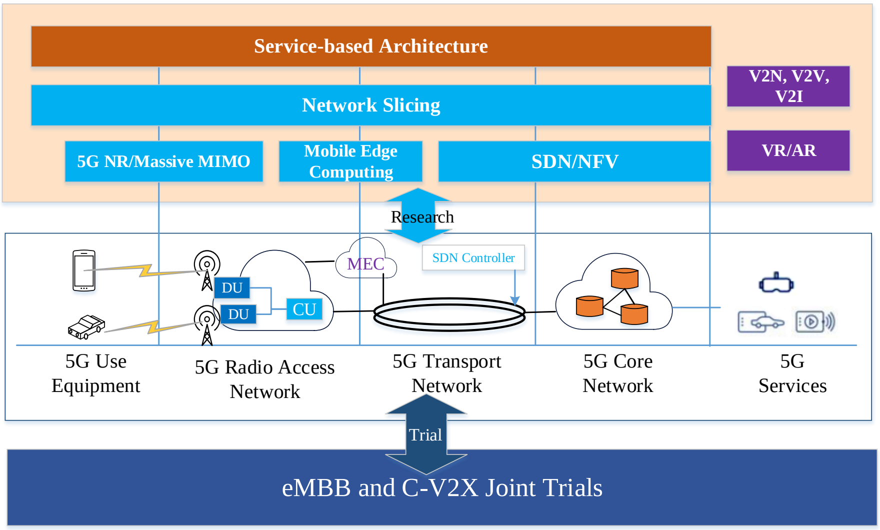


*Figure 6: Overall concept of the 5G-DRIVE project*

The 5G-DRIVE effort is based upon the existing and currently under design 5G standards, namely the 3GPP Releases 13-14, and any relevant findings should be fed back into appropriate standardisation organisations and/or working groups. The project exploits three already-existing 5G test-beds (Espoo, Surrey, and Ispra – details can be found further down in this section), which have been set up with commercial-grade and experimental equipment and are being used to test new research outcomes and new services.

Furthermore, the 5G-DRIVE has collaborated with projects from the ICT-17-2018 Call, aiming to further enhance the test-bed capabilities and the availability for the joint EU-China trials as implemented in its specific framework.

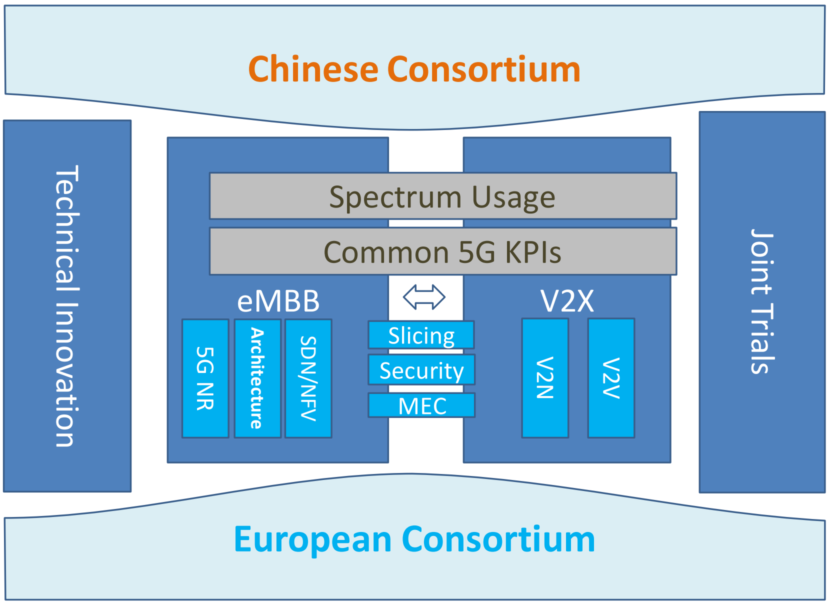


*Figure 7: EU-China 5G collaboration targets*

In order to achieve this goal, the 5G-DRIVE develops "key" 5G technologies and pre-commercial test-beds for eMBB and V2X services in collaboration with the "twinned" Chinese project led by China Mobile. Trials for testing and validating key 5G functionalities, services and network planning are conducted in eight cities across the EU and China. The main targets of this collaboration are illustrated in Figure 7, as depicted above.

## 2.2 Specific Objectives to Support a Generalised Socio-Technical Development

The global socio-technical development in the latest few decades has been critically driven by the growth of mobile communications and this sort of development has also supported towards improving the economic and social development of both developed and developing countries. Mobile communications have so become an indispensable part of our every-day life of the whole society. It is assessed that the socio-technical trends and the evolution of mobile communications systems will remain strongly coupled and will "compose" a foundation for society in 2020 and beyond. Nevertheless, in the future it is predicted that new sorts of "demands" (such as more traffic volume, many more devices with diverse service requirements, better quality of user experience (QoE) and better affordability by further reducing costs), will implicate for a growing number of innovative solutions to be developed and adopted.

Future International Mobile Telecommunications (IMT) systems[85] should support emergent new use cases, including applications necessitating very high data rate communications, a large number of connected devices and ultra-low latency and high reliability applications. IMT for 2020 and beyond is envisaged to expand and support diverse usage scenarios and applications that will continue beyond the current IMT. Furthermore, a broad variety of capabilities would be tightly coupled with these intended different usage scenarios and related applications. The usage scenarios for *IMT for 2020 and beyond* include eMBB, URLLC and mMTC as discussed in Section 1.2 (for more details also see Figure 8).

The 5G-DRIVE project performs a "close" collaboration between EU and China to synchronise 5G

[85] IMT systems serve as a communication tool for people and a facilitator, which assists the development of other industry sectors, such as medical science, transportation, and education.

technologies and spectrum issues before the final rollout of 5G in order to "address" two most promising 5G deployment scenarios, namely eMBB and V2X communications[86].

### 2.2.1 Enhanced Mobile Broadband (eMBB)

***Enhanced Mobile Broadband (eMBB)*** is one of three primary 5G New Radio (NR) use cases defined by the 3GPP[87] as part of its SMARTER (Study on New Services and Markets Technology Enablers) project[88].

The objective behind SMARTER was to develop high level use cases and identify what features and functionality 5G would need to deliver to enable them. It began in 2015 and resulted in over 70 use cases, initially grouped into five essential categories which have been later trimmed to three. They are characterised by the performance attributes the particular use cases will require, although there is some overlap.

The three fundamental sets of use cases are as discussed in Section 1.2. The above context structures the so called as the "future IMT scope[89] and this is schematically depicted in the following Figure 8.

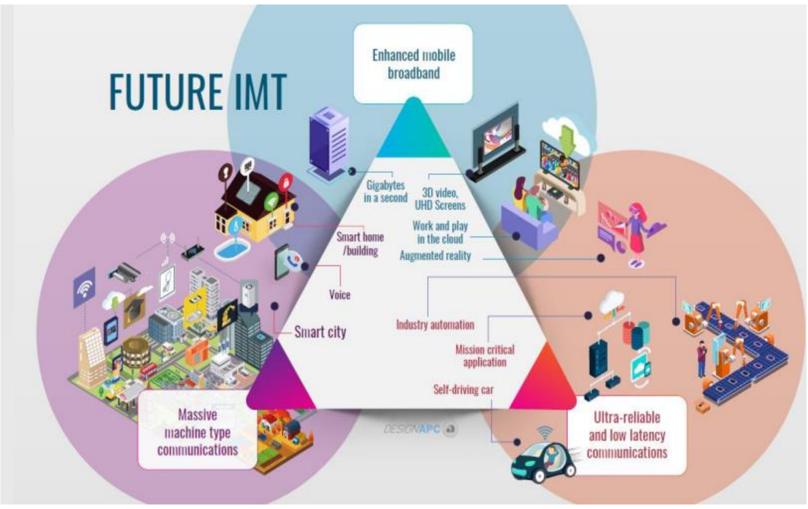


*Figure 8: The future IMT scope. [Source: ITU-R Recommendation M.2083-0]*

86 The 5G-DRIVE EU-funded project falls within the original H2020-ICT-2018-1 framework under the topic ICT-22-2018 (EU-China 5G Collaboration). More detailed related information about this initiative can be *found at:* https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/ict-22-2018.html

87 The 3rd Generation Partnership Project (3GPP) is a global initiative that unites seven telecommunications standard development organizations – SDOs (i.e. ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as "Organizational Partners" and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. The project covers cellular telecommunications network technologies, including radio access, the core transport network, and service capabilities – including work on codecs, security, quality of service – and thus provides complete system specifications. The specifications also provide hooks for non-radio access to the core network, and for interworking with Wi-Fi networks. The 3GPP qualifies ultra-fast mobile broadband as mobile systems capable of delivering speeds of 20 gigabits per second, at least uni-directionally, and without specific latency requirements. More information can be found at: http://www.3gpp.org/about-3gpp. For further informative purposes also see*, inter alia*: https://en.wikipedia.org/wiki/3GPP

88 For further details about the SMARTER project see the content of the 3GPP Specification 22.891: *"Study on New Services and Markets Technology Enablers – Technical Report (TR) – Release 14"*. Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2897

89 Also see: International Telecommunication Union – Radiocommunication Sector (ITU-R): Recommendation M.2083-0 (09/2015): *"IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond"*. ITU, Geneva, Switzerland.

We can assess eMBB as an extension to existing 4G services and amongst the first 5G services which could be offered commercially as early as 2019. In fact, based on estimations set by Ericsson[90] it is expected that there will be one billion 5G subscriptions for eMBB globally by 2023, with Asia and North America likely to be the first adopters.

To allow the early deployment of eMBB services, in March 2017 the 3GPP's RAN Group[91] committed to finalise the Non-Standalone (NSA) 5G NR variant by March 2018. In fact, the standard was approved in December 2017[92],[93]. The NSA mode uses the existing 4G network, supplemented by 5G NR carriers to boost data rates and reduce latency[94]. This is reported to speed-up 5G adoption; however, some operators and vendors have criticised prioritizing the introduction of 5G NR NSA on the grounds that it could hinder the implementation of the standalone (SA) mode of the network[95].

The SA variant was finalised in June 2018 for the new 3GPP 5G core[96] network architecture. The SA mode of 5G NR refers to using 5G cells for both signalling and information transfer. It includes the new 5G Packet Core architecture instead of relying on the 4G Evolved Packet Core[97], to allow the deployment of 5G without the LTE network[98]. It is expected to have lower cost, better efficiency, and to assist development of new use cases.

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90 For more informative details also see: *https://www.ericsson.com/en/press-releases/2017/11/ericsson-predicts-1-billion-5g-subscriptions-in-2023*

91 More information about the 3GPP'S Technical Specification Group (TSG) Radio Access Network (RAN) can be found at: *http://www.3gpp.org/specifications-groups/ran-plenary*

92 For further detailed information, also see: *http://www.3gpp.org/news-events/3gpp-news/1929-nsa_nr_5g*

93 A very interesting press release "depicting" the way how several major and global industrial "actors" have supported the 3GPP NR announcement, can be found at: *http://www.3gpp.org/news-events/3gpp-news/1931-industry_pr_5g*

94 For further discussion also see, *among others*: *https://www.rfwireless-world.com/Terminology/5G-NR-deployment-scenarios-or-modes.html*

95 See, *for example*: Teral, S. (2019): *5G best choice architecture- White Paper*. IHS Markit Technology. Available at: *https://technology.ihs.com/610777/5g-best-choice-architecture*

96 The 5G core network (5GC) architecture is defined to enable the deployments to use techniques such as NFV, MEC and SDN. The architecture leverages service-based interactions and separates the User Plane (UP) functions from the Control Plane (CP) functions. This separation allows for independent scalability, evolution and flexible deployments, for example, centralised location or distributed (remote) location. The architecture is also defined with a converged core network with a common interface between Access Network (AN) and the Core Network (CN). This minimizes the dependencies between the AN and the CN, and allows for the integration between different 3GPP and non-3GPP access types. Network functions tend to be Central Processing Unit (CPU) intensive, and in some cases memory intensive but not storage intensive, thereby allowing resources to be allocated efficiently, for example, store configuration and logs in a separate location than the network function. In the control plane, the mobility management and session management functions are split between two different network functions: the AMF (Access and Mobility Management Function) and the SMF (Session Management Function). The NEF (Network Exposure Function) provides an interface for outside applications to communicate with the 3GPP network. Unified Data Management (UDM) is responsible for access authorization and subscription management. Network Repository Function (NRF) and Policy Control Function (PCF) contains the policy rules. Authentication is handled by the AUSF (Authentication Server Function). In the user plane, the User Plane Function (UPF) is responsible for handling the packets, such as buffering packets, packet filtering, packet routing, etc. The Data Network (DN) provides operator services, 3rd party services, or access to the Internet. In order to support traffic offloading for Edge Computing the SMF may control the data path of a PDU (Packet Data Unit) session so that the PDU session may simultaneously correspond to multiple N6 interfaces (interface with the application server). In cases where the offload starts in the RAN, then the AMF and SMF have to coordinate the data path diversion in the RAN.

For further details see: 3GPP TS 23.501 V16.3.0 (2019-12): "*System Architecture for the 5G System (5GS); Stage 2 (Release 16)*". Available at: *https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/*

97 Very interesting is the discussion that has been proposed in: *https://www.lightreading.com/mobile/5g/standalone-or-non-standalone-5g-trials-will-help-orange-decide/d/d-id/744057*

98 For further reading, also see: Brown G. (02/2017): *Designing Cloud-Native 5G Core Networks (A Heavy Reading White Paper produced for Nokia)*. Heavy Reading.

 

Thus, eMBB can be seen as the first phase of 5G, which has been incorporated in the 3GPP Release 15[99] standards update due for completion within 2018. Release 15, finalised in June 2018, has included the first version of the 5G/NR technology together with a set of new features as part of the LTE evolution.

5G Phase 2 goes beyond eMBB services to more transformational URLLC and mMTC applications and is included in Release 16[100]. Release 16 included several major enhancements and extensions to NR as part of the first step in the NR evolution, together with additional LTE extensions and enhancements. Finalisation of Release 16 was initially targeted for March 2020, with the physical layer specifications already finalised in December of 2019. However, the overall finalisation was delayed by one quarter due to the Covid-19 situation, which has prevented 3GPP face-to-face (F2F) meetings for the majority of 2020.

Release 17[101] is the main 3GPP activity for the later part of 2020 and for 2021. Release 17 was initially targeted for finalisation in July 2021. However, the finalisation of Release 17 has been delayed by a half year, as it was decided by 3GPP RAN in December 2020. As the industry builds upon the great work 3GPP has accomplished with defining New Radio (NR) and Service-Based Architecture (SBA), it will simultaneously evolve these aspects and others of 5G in 3GPP Release 17 and beyond. In the scope of the initiated Release 17 among the included features is to look out for include new work and enhancements for: URLLC for industrial IoT over NR, NR support over non-terrestrial networks, MIMO, integrated access and backhaul (IAB), MBS positioning, NR multicast and broadcast services, RAN slicing for NR, NR side link, multi-RAT dual-connectivity, support for multi-SIM devices for LTE/NR, NR small data transmissions in inactive state and multimedia priority service, to name a few.

Release 18 has already been started[102]. Its timeline has not been defined yet, except the expected approval of the scope by the end of 2021. However, some Stage 1 studies are underway and the fundamental document on 5G system service requirements has already been upgraded to version 18[103].

Enhanced mobile broadband is important for 5G development. 5G should help to accommodate satisfactorily the huge increase of mobile traffic (more than 15 additional exabytes[104]) per year in Europe by 2020 and beyond) at a reasonable cost. Moreover, 5G will improve the mobile broadband experience in all situations: at cell borders, at stadiums, in shopping malls, on trains, airplanes, etc. Beyond that, the network should bring to the end-user a seamless connectivity experience – meaning a seamless handover to the best access network – regardless of the device used. This *“Any Time, Any Where, Any Device paradigm”* will pave the way for business growth. Key 5G opportunities however exist beyond the sole eMBB case. In 2020 and further on, Internet of Things will not be a niche market anymore. Ericsson[105] and Machina[106] estimate that there will be about 25 billion connected devices by 2020 and further on, much more than smartphones. 5G will help to scale up this business preparing the world for the next trillion connected objects by offering a global standard for low

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99 For more details see: *http://www.3gpp.org/release-15.*

100 For more details see: *http://www.3gpp.org/release-16*

101 For more details see: *https://www.3gpp.org/release-17*

102 For more details see: *https://www.3gpp.org/release18*

103 3GPP TS 22.261 V18.1.1 (2021-01): “*Service requirements for the 5G system; Stage 1*”. Available at: *https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/*

104 1 exabyte = $10^{18}$ bytes.

105 Ericsson Mobility Report (11/2015). Available at: *http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-nov-2015.pdf*

106 GSM Association (GSMA) (2013): *The connected life*. Available at: *http://www.gsma.com/connectedliving/wp-content/uploads/2013/03/JimMorrish_GSMA-Connected-Life-20130624-v4.pdf*

 

power and large coverage connectivity. Standards based solutions, like 5G, can bring economies of scale compared to proprietary solutions.

Taking connected cars as an example, the first phase of eMBB services involves enhanced in-vehicle infotainment, like real-time traffic alerts, high-speed internet access, streaming real-time video or playing games involving 3D 4K[107] video. The second phase would be autonomous vehicles on a mass scale able to connect to and interact with other vehicles and the surrounding road infrastructure.

The eMBB can so be assessed as a sort of natural evolution of existing 4G networks that offers faster data rates and, consequently, a more enhanced and improved user experience than existing mobile broadband services. Nevertheless, it provides the opportunity to realise significantly faster downloads so that to contribute towards an increasingly seamless user experience that will improve the status of the quality of service we are currently experiencing from existing broadband technologies. Moreover, it is expected that eMBB will support the provision of 360° video streaming, VR and AR applications and much more. Within the context of eMBB and for the proper offering of the related use cases in the market sector, there are three distinct attributes/features that 5G has to assure, listed as follows:

- *Higher capacity:* this implicates that the intended broadband access has to be adequately available in densely populated areas, both indoors and outdoors (such as the cases of city centres, office buildings or public venues like stadiums or conference centres). This has also relevance to the necessary deployment of the underlying network infrastructures in order to support the expected coverage.
- *Enhanced connectivity:* this implicates that broadband access has to be offered "everywhere", in order to deliver a reliable user experience.
- *Higher user mobility*: this implicates that it will also predict to enable mobile broadband services in moving vehicles (including cars, buses, trains and/or planes).

The above purely implicate for diverse groups of use cases, with different requirements. For example, in the case of a "hotspot" where many users are potentially involved such as an event in a stadium, priority is expected to be given to assurance of very high traffic capacity so that to fulfil related users' needs; however, as users are expected as static or moving slowly, the corresponding requirement for mobility will be low. On the contrary, providing eMBB services to passengers in a high-speed vehicle will imply for a significantly higher degree of mobility, although the traffic capacity would be lower than that of the previous case of the hotspot. As a sort of an "average" approach among the two above scenarios, the intended coverage of a wide area will imply for a "medium" level of mobility and, while the data throughput would be higher than is currently possible, it may not need to be as high as in a hotspot. They key criteria here is seamless coverage. In order to deliver these requirements and depending upon the selection of suitable parameters to describe reliable KPIs, it is expected that 5G will be able to provide:

- Traffic capacity of 10 Mbps per square metre in hotspot areas;
- Data transfer rates experienced by the user of up to 1Gbps, with peak data transfer rates of tens of Gbps and whole traffic volume of at least 1 Tbps per square kilometre;
- Latency of 1 ms for user experienced data exchange;
- Connection density of up to one million connections per square kilometre;
- High mobility up to 500 km/h in high-speed trains and up to 1,000 km/h in airplanes, with enhanced user experience.

[107] 4K resolution, also called as 4K, refers to a horizontal display resolution of approximately 4,000 pixels. More relevant information can be found, among others at: *https://en.wikipedia.org/wiki/4K_resolution*

Some primary eMBB use cases focus on the consumer market and the necessity for better and faster connectivity to handle higher quality video content, the growth in user-generated content and our prospects of being able to stream our data content when and where requested, without needing to log onto a WiFi network.

However, among the core priorities of 5G is to provide the services we already experience but in a "better way", implicating that we will not experience latency issues, irregular connectivity or dropped connections, even in network conditions like crowded locations or when being in moving vehicles. In any case, the eMBB has not only to be assessed as simply the consumption of multimedia content for entertainment purposes. In contrast, it will support an extended set of (cloud-based) applications and of related facilities affecting our digital experiences via a great diversity of devices and/or equipment wirelessly and seamlessly connected. Moreover, it will also support applications from fully immersive VR and AR to real-time video monitoring and virtual meetings with 360º video, real-time interaction and even real-time translation for participants speaking different languages.

### 2.2.2 EU-funded Projects related to eMBB

Although the case of eMBB has been among the core priorities of the original H2020-ICT-2018-1 framework under the topic ICT-22-2018 (EU-China 5G Collaboration)[108], in several past 5G-PPP projects there has been relevance either to the scope of Mobile Broadband (MBB) or directly to eMBB.

The H2020 ICT-22-2018 Call aimed at performing a close collaboration between EU and China to synchronise 5G technologies and spectrum issues[109] before the final roll-out of 5G. The main scope has been about conducting 5G trials addressing two specific scenarios, one of which was the case of **enhanced Mobile Broadband (eMBB)** on the 3.5 GHz band, which is a priority band in the two regions for early introduction of very high data rate services. Thus, in the 5G-DRIVE approach, the overall goal has been to evaluate in real setup innovative end-to-end 5G systems built on the outcomes of the previous phases of the 5G R&I; more specifically, the optimisation of the band usage in multiple scenarios with different coverage has been a key target, so as the validation of the geographic interoperability of the 3.5 GHz band for the respective use cases. The 5G-DRIVE eMBB scenario has been implemented in both regions (EU and China) through appropriate test-beds and with suitable trials[110]. The applications used to test and validate the use of eMBB in the 3.5 GHz band have been typical mobile broadband services such as indoor positioning as well as cloud-assisted Augmented Reality (AR).

Under a broader conceptual perspective, MBB focuses on mobile broadband services supposing increased capacity, efficiency and data transmission rates. Mobile broadband typically demands high data rates, but also flexible scheduling of smaller payloads, and thus requires a scheduling framework that supports a high dynamic range of scheduled payload sizes. Typical use cases corresponding to MBB are multimedia streaming, combinational services including Voice over IP (VoIP) as one of the services, internet browsing, videoconferencing, file downloads and uploads to the cloud, some gaming services, etc. In the following, we list several among these projects.

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108 Also see*:* *https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/ict-22-2018.html*

109 Also see: 5G-DRIVE Project (04/2019): Deliverable 2.2: *"Joint Architecture, Use Cases and Spectrum Plan"*. Available at: *https://5g-drive.eu/resources-and-results/project-deliverables/*

110 According to the ICT-22-2018 Call the expectations have been that the underlying trials' testing facilities shall implement the latest mature and broadly commonly agreed 5G systems, network architectures and technologies spanning from the core/transport networks, the radio access, up to the service, orchestration, management and security components. The trial facility would not be restricted to innovative 5G radio access technology, but should include and enable the evolution of 5G networks innovations in network slicing, virtualisation, cross-domain orchestration, in view of supporting resource control from multiple tenants. These concerns have been fully taken into account in the involvement of the EU participating trial sites for the eMBB scenario (UoS in Surrey, UK, and VTT in Finland).

**FANTASTIC-5G**[111] (Flexible Air iNTerfAce for Scalable service delivery wiThin wIreless Communication networks of the5th Generation): The main challenge for FANTASTIC-5G has been to develop a modular air interface, being able to support all the anticipated use cases with highest efficiency and scalability without being overly complex on the network side. To this end, the project has developed the technical AI components (e.g. flexible waveform and frame design, scalable multiple access procedures, adaptive retransmission schemes, enhanced multi-antenna schemes with/without cooperation, advanced multi-user detection, interference coordination, support for ultra-dense cell layouts, multi-cell radio resource management, device-to-device) and integrate them into an overall AI framework where adaptation to the high degree of heterogeneity 5G will face, is accomplished. Projects' work has also comprised intense validation and system level simulations. The ambition has been to outperform a system involving dedicated air interfaces.

5G has been mainly about two ambitions, that is to: (i) Respond to the strong growth of requested data rates (evolutionary effect); and (ii) enhance the business model of operators by widening the pool of services (revolutionary target). While supporting the former, FANTASTIC-5G targeted to make the latter a reality. For doing so, the project has set up 5 core-services, which either in itself or by combination realize real-world use cases. The key differentiator between these core services have been in the respective service defining KPIs, as follows: (i) Mobile Broadband (MBB): throughput/user rate, latency, mobility; (ii) Mission Critical Communications (MCC): latency, reliability/availability; (iii) Massive Machine Communications (MMC): number of connected devices, low cost, low energy; (iv) Broad- and Multicast Services (MBS): number of connected devices; and (v) Vehicle-to-Vehicle and Vehicle-to-Infrastructure Services (V2X): high mobility.

FANTASTIC-5G's research on radio link design has focused on solutions on PHY and MAC layer towards a holistic air interface design, which was intended to enable the system to flexibly adapt its current configurations in response to the diverse requirements of the various service types to be supported by the 5G system. In contrast to 3GPP, where these service types have been defined as eMBB, mMTC and uMTC[112], the project defined five so-called "core services", namely MBB, massive machine communication (MMC), mission critical communication (MCC), vehicular to anything (V2X) and broadcast/multicast service (BMS); however, those can be clearly mapped to the former service types defined by 3GPP.

**METIS-II**[113] (Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II) aimed to provide an overall 5G RAN design, describing an overall protocol stack architecture with all the functionalities and interfaces needed to fulfil the 5G vision. The overall 5G RAN design has been built upon the following key innovation pillars: (i) A holistic spectrum management architecture addressing the spectrum crunch; (ii) a holistic air interface harmonisation framework enabling an efficient integration of new and legacy air interfaces; (iii) an agile Resource Management (RM) framework providing the dynamics required to efficiently adapt the integrated 5G air interfaces and radio concepts to the varying traffic demand and service requirements; (iv) a cross-layer and cross-air-interface system access and mobility framework ensuring an ubiquitous access continuum; and (v) a common control and user plane framework providing the means for an efficient support of the broad versatility of services expected for 5G as well as a future-proof and cost-

[111] FANTASTIC-5G: Flexible Air iNTerfAce for Scalable service delivery wiThin wIreless Communication networks of the5th Generation (GA No.671660). For more details also see: *http://fantastic5g.com/*

[112] The mMTC (massive Machine Type Communications) is about wireless connectivity to tens of billions of machine type terminals, uMTC (ultra-reliable Machine Type Communications) is about availability, low latency, and high reliability. The main challenge in mMTC is scalable and efficient connectivity for a massive number of devices sending very short packets, which is not done adequately in cellular systems designed for human-type communications. Furthermore, mMTC solutions need to enable wide area coverage and deep indoor penetration while having low cost and being energy-efficient.

[113] METIS-II: Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II (GA No.671680). More details can be found at: *https://metis-ii.5g-ppp.eu/*

 

efficient implementation of the 5G integration. METIS-II has defined an essential set of 5G use cases, capitalizing on use cases of METIS, other EU projects and organisations like NGMN and ITU-R. To this end, a methodology has been adopted: The use cases from literature have been grouped with regards to the three major 5G services (xMBB, mMTC, uMTC), forming three families of use cases. Then, a small number of representative use cases have been selected from each family of use cases. A selected use case had to fulfil the following requirements: (i) it represents perfectly the use case family it belongs to, from services and requirement points of view; (ii) it has stringent QoS and traffic requirements; and (iii) the technical solutions needed for covering this use case also serve other similar use cases. The requirements of the identified use cases have then been updated following the NGMN requirements.

The overall objective of **NRG-5**[114] has been to guarantee optimal communications of the energy grid, which is believed to be the most complex, heterogeneous and gigantic machine ever made in human history, deploying, operating and managing existing and new 5G communications techniques and energy infrastructures (in the context of the Smart Energy as a Service) easier, safer, more secure and resilient from an operational and financial point of view. Thanks to its ambitious objectives, NRG-5 aimed at defining and specifying some vertical additional use cases focusing on utilities domain, mainly gas and energy. The Use Cases described in NRG-5 fell within a small set of basic 5G service classes, which have been consolidated and agreed in the context of 5G-PPP as follows: (i) Enhanced Mobile Broadband (eMBB), also called Extreme Mobile Broadband (xMBB); (ii) Ultra-Reliable Machine Type Communications (uMTC), also called Ultra-Reliable and Low Latency Communications (URLLC); and (iii) massive Machine Type Communications (mMTC). NRG-5's solution within a dedicated project use case about "Enabling aerial predictive maintenance for utility infrastructure", guarantees xMBB communications for video streaming from the drones and analysis to the local mobile edge processing node and the utility control centre, and uMTC for stringent real-time control of the flight of drones. The use case's ultimate objective has been to bring a way of supporting current activities responsible as maintenance director and security/Safety officer to improve the cost efficiency of their job and reduce the risks for the human. The current limitation, in terms of data streaming performance, is blocking the generalisation of drone's use.

**ONE5G**'s[115] main ambition has been to investigate and propose new features and advancements (focusing on the RAN) for moving 5G towards 5G-advanced. The areas of the project effort have been advanced multi-link access and interference management supported by massive MIMO and E2E-aware performance optimisation through advanced radio resource allocation and multimode connectivity orchestration, load balancing, spectrum management and D2D. The main objective of the ONE5G project has been about to: (i) propose the necessary 5G extensions, to address the two selected scenarios ("megacities" and "underserved areas"); (ii) build consensus on new features and provide technical recommendations for moving 5G towards "5G advanced (pro)"; (iii) propose advanced link technologies and enhancements beyond Release 15 to enable multi-service operation and practical implementation of "5G advanced (pro)", with future-proof access schemes, advanced massive MIMO enablers and link management; (iv) research and deliver highly generic performance optimisation schemes, in order to achieve successful deployment and operation, including optimisations for both the network operator and the E2E user-experienced performance; (v) identify the cost driving elements for the roll-out and operation and to propose adaptations to allow sustainable provision of wireless services in underserved areas under constrained circumstances; and (vi) validate the developed extensions and modifications through different approaches: analytically, by means of extensive simulations and with the help of proof-of-concepts for selected aspects.

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114 NRG-5: Enabling Smart Energy as a Service via 5G Mobile Network advances (GA No.762013): More details can also be found at: http://www.nrg5.eu/

115 ONE5G: E2E-aware Optimizations and advancements for the Network Edge of the 5G NR (GA No.760809). More details can be found at: https://one5g.eu/

ONE5G also leverages on mobility optimisation and dynamic spectrum management to improve the E2E performance. For mobility-related optimisations, advanced traffic steering and load balancing schemes have been developed. Among others, it has been proposed to migrate from traditional re-active schemes that aim for load equalisation between cells, towards more promising context-aware proactive schemes that equalise the Quality of Experience (QoE) between the cells instead. Social data, such as information on social events, has been exploited to forecast traffic demand and pro-actively perform traffic steering to minimise the impact of the large social gatherings on the QoE of the involved users. For spectrum management, solutions have been derived for dynamic spectrum aggregation and exploitation of both licensed and unlicensed frequency bands to meet requirements from multiple services, mainly to boost the capacity and user data rates for eMBB services. Finally, ONE5G has developed enhanced D2D solutions. These include both solutions for eMBB capacity boosting and relay-based schemes for coverage enhancement and for reduced power consumption to better serve mMTC in coverage challenging environments such as underserved scenarios.

**5G-PHOS**[116] aimed at the development of novel 5G broadband fronthaul architectures and the production of a powerful photonic integrated circuit technology toolkit that will exploit the recent advances in optical technologies. It aimed to capitalise on novelties in InP[117] transceiver, Triplex optical beam-formers and multi-bitrate optical communications into next generation fronthaul in order to migrate from CPRI-based to integrated Fiber-Wireless packetised C-RAN fronthaul supporting mm-Wave massive MIMO communications. More specifically, 5G-PHOS focused on creating an integrated Fiber-Wireless (FiWi) packetised SDN-programmable 5G fronthaul that supports 64x64 MIMO antennas in the mm-Wave band offering: (i) up to 400 Gbps wireless peak data rate in ultra-dense networks, adopting optical Spatial-Division-Multiplexed solutions on top of the emerging 25 Gbps PON and; (ii) 100 Gbps wireless peak data rate in Hotspot areas, showcasing the benefits of WDM technology and packetised fronthauling in private C-RAN solutions. Benefiting from the partners' assets and expertise, lab/test-bed experiments and field trials have been conducted towards the evaluation of the project outcomes for Dense, Ultra-Dense and Hotspot areas. Among the project activities has been the design of novel Optical Beamforming Networks (OBFNs) providing dynamic, accurate and sufficient coverage and capacity for eMBB services.

The main objective of **SLICENET**[118] has been to remove the limitations of current network infrastructures by achieving full softwarisation-friendly 5G infrastructures, and address the associated challenges in managing, controlling and orchestrating the new services for verticals, thereby maximizing the potential of 5G infrastructures and their services based on advanced software networking and cognitive network management. SLICENET has implemented a verticals-oriented, QoE-driven 5G network slicing framework focusing on cognitive network management and control, for end-to-end slicing operation and slice-based services, across multiple operator domains, in 5G networks enabled by SDN/NFV, whilst offering flexibility and capabilities to the vertical users of the services. SLICENET has demonstrated how it facilitates vertical business added value by implementing use cases exploiting the 3GPP defined requirements, URLLC, mMTC and eMBB. The innovative, verticals-oriented, network slicing framework have been demonstrated through selected 5G use cases featuring these service requirements and targeting three different vertical industries, that is: smart-grids, e-health, and smart-cities. The eHealth use case considered eMBB, requiring both extremely high data rates and low-latency communication in some areas and reliable broadband access over large coverage areas.

[116] 5G-PHOS: 5G integrated Fibre-Wireless networks exploiting existing photonic technologies for high-density SDN-programmable network architectures (GA No.761989). More details can be found at: http://www.5g-phos.eu/

[117] Indium phosphide (InP) is a binary semiconductor composed of indium and phosphorus. More details can be found, *for example*, at: https://en.wikipedia.org/wiki/Indium_phosphide

[118] SLICENET: End-to-End Cognitive Network Slicing and Slice Management Framework in Virtualised Multi-Domain, Multi-Tenant 5G Networks (GA No.761913). More details can be found at: https://slicenet.eu/

**5G-SMART**[119] 5G for smart manufacturing aims at demonstrating how 5G can improve manufacturing through its work on industry field trials, business models and research concepts. Within three 5G-enabled industry field trials, 5G-SMART aims to demonstrate, evaluate and validate 5G systems for manufacturing applications in real manufacturing environments. The business model activities in 5G-SMART are exploring the 5G ecosystem while investigating regulatory and spectrum aspects, including also mobile network operator engagement options. The concept work in 5G-SMART aimed to contribute to the future evolution of 5G with a focus on 5G features to be developed targeting the manufacturing sector. This includes, for instance, the integration of 5G with time-sensitive networking, and critical cloud platforms enabling flexible software development while providing low latency and high reliability. At three different trial sites 5G-SMART aims to test most advanced 5G integrated manufacturing applications such as digital twins, industrial robotics and machine vision based remote operations. The trial sites are: An Ericsson factory in Kista (Sweden), a Fraunhofer IPT shop-floor in Aachen (Germany) and a Bosch semiconductor factory in Reutlingen (Germany). On site, the project has evaluated different 5G services (URLLC, eMBB, mMTC).

**5G-SOLUTIONS**[120] aims at proving and validating that 5G provides prominent industry verticals with ubiquitous access to a wide range of forward-looking services with orders of magnitude of improvement over 4G, thus “bringing the 5G vision closer to realisation”. The project intends to setup several living labs to cover the majority impact of 5G revolution. Each of said living labs is to be organised in different use cases. The project, among others, includes use cases to be validated in the Smart City and Ports Living Lab. Through the use of digital and telecommunication technologies, traditional networks and services become more efficient for the inhabitants, businesses and ports benefit. It is estimated that a large proportion of communications will occur between machines and not humans. In this respect, 5G supporting mMTC, eMBB, URLLC, virtualisation and slicing will be able to respond to the smart cities and ports of the future.

The main goal of **5G-VICTORI**[121] is to conduct large-scale trials for advanced use case (UC) verification in commercially relevant 5G environments for a number of verticals. These include Transportation, Energy, Media and Factories of the Future, as well as some specific UCs involving cross-vertical interaction. The project will exploit extensively the existing ICT-17 5G Test-bed Infrastructures interconnecting main sites of all ICT-17 infrastructures, namely 5G-VINNI, 5GENESIS and 5G-EVE and the 5G UK test-bed in a Pan-European Network Infrastructure. Minor enhancements will be provided to these infrastructures, extending their coverage towards the integration of the 5G-VICTORI UCs. There is a prescribed trial for eMBB under high speed mobility. The goal of this trial is to demonstrate eMBB functionality through heterogeneous access technologies for on-board network connectivity in a high mobility railway environment. Wireless transport network devices will be managed and controlled to facilitate interconnection of on-board devices with the trackside, and the trackside with the core network. Both infotainment and critical operations data (e.g. data from on board CCTV systems) will be efficiently managed from the operator’s perspective in order to allow their successful and timely transmission to the edge/core network.

**5G-CLARITY**[122] puts forward a beyond 5G architecture for private networks, which features a novel access network integrating 5G, WiFi, and LiFi, compute and transport resources, and novel management components to enable AI driven network automation. Based on this architecture, 5G-CLARITY will define communication services that deliver measurable enhancements with respect to

[119] 5G-SMART: 5G for smart manufacturing (GA No.857008). More details can be found at: https://5gsmart.eu/

[120] 5G-SOLUTIONS: 5G Solutions for European citizens (GA No.856691). More details can be found at: https://www.5gsolutionsproject.eu/

[121] 5G-VICTORI: VertIcal demos over Common large scale field Trials fOr Rail, energy and media Industries (GA No.857201). More details can be found at: https://www.5g-victori-project.eu/

[122] 5G-CLARITY: Beyond 5G multi-tenant private networks integrating Cellular, Wi-Fi, and LiFi, Powered by ARtificial Intelligence and Intent Based PolicY (GA No.871428). More details can be found at: https://5g-ppp.eu/5g-clarity/

the eMBB and URLLC services defined by 3GPP in Release 16, in terms of low latency, area capacity, reliability and accurate positioning and synchronisation capabilities. In addition, 5G-CLARITY will develop a management plane featuring SDN/NFV components together with an AI engine that will automate network management by receiving high level intent policies from the network administrator. 5G-CLARITY investigates how the concept of private 5G networks should evolve beyond the 3GPP Release 16, by bringing innovation in two main pillars: The first pillar constitutes a heterogeneous wireless access network that integrates 5GNR, Wi-Fi, and LiFi[123]. The proposed multi-connectivity framework enables an intelligent aggregation of the 5G/Wi-Fi/LiFi interfaces, resulting in eMBB and URLLC services.

The H2020 **5G!Drones[124]** project is devoted to trials of several Unmanned Aviation Vehicle (UAV) use cases covering eMBB, URLLC, and mMTC 5G services and to validate 5G KPIs for supporting these use-cases as well as formulating recommendations for further UAV-related improvements on 5G and aviation domain standards. Its specificity lies primarily in the integration of the telecommunications environment with the aviation environment, including e.g. UAV traffic management (UTM) systems, remote UAV control systems with First Person View (360 degrees high-quality real-time media enabling the virtual remote presence of the UAV pilot on board of the UAV), GIS-based 3D flight visualisation systems for flight trajectory planning and real time flight steering support. In this combined ecosystem where the telecommunications and aviation business domains permeate and multilaterally exchange information, it will be possible to perform comprehensive and multi-faceted validation of 5G UAV services (at the technical level and E2E level of business processes life-cycle) in the context of: (i) UAV traffic management (UTM, command and control, 3D map and supporting visualisation/analysis software, UAV logistics); (ii) public safety (monitoring a wildfire, disaster recovery, public security including counter-UAS); (iii) situational awareness (infrastructure inspection, UAV-enhanced IoT data collection, location of UE in non-GPS environments, multimedia); and (iv) connectivity extension and offloading (mobile base station on-board the UAV).

The trials will be implemented *inter-alia* on 5G-EVE and 5GENESIS test-bed facilities, using the special software layer (trial controller), acting also as a business service orchestrator, which exposes a high-level API for vertical's software ecosystem to enable implementation of 5G services offered by specific underlying 5G facilities. At the same time, special aviation domain-belonging UAV service enablers will be embedded in the 5G facilities and integrated with 5G network mechanisms. The 5G!Drones project may benefit of the 5G-DRIVE outcomes in the domains of eMBB services trials (especially VR/AR), network slicing, new radio access techniques for network capacity enhancement, energy efficiency increase and latency reduction, beamforming, and – to some extent – with V2X services trials, when the results are applicable to aviation vehicles.

The H2020 **MonB5G[125]** project is devoted to the distributed management of Network Slices in beyond 5G. The maturing and massive roll-out of the 5G technology will cause a necessity to support massive numbers of coexisting network slices, with different performance requirements, functionality, and timespans. These challenges cannot be faced with existing centralised and manually operated management systems, and MonB5G aims to provide zero-touch management and orchestration in a novel autonomic framework, heavily leveraging hierarchical distribution of operations together with state-of-the-art data-driven AI-based mechanisms. MonB5G will extend the ETSI MANO and MEC frameworks with embedded cognitive capabilities. It will also develop trust mechanisms tailored to the targeted multi-stakeholder environment, for secure and trustworthy cross-domain operations. MonB5G plans to trial two use cases, featuring automated, zero-touch slice

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[123] LiFi is a high data-rate technology supporting the full-duplex operation, mobility, and extremely high area capacity.

[124] 5GDrones!: Unmanned Aerial Vehicle Vertical Applications' Trials Leveraging Advanced 5G Facilities (GA No.857031). For further information see: https://5gdrones.eu/

[125] MonB5G: Distributed management of Network Slices in beyond 5G (GA No.871780). For more details also see: https://www.monb5g.eu/

management and orchestration across technical and administrative domains, enabling network operators to ensure end-to-end cross-domain SLAs, as well as AI-assisted policy-driven security monitoring and enforcement. The MonB5G project may benefit of the 5G-DRIVE outcomes in the domains of eMBB and also V2X services trials (observed phenomena may feed the algorithms of automated slices management), network slicing (including slicing framework KPIs), MEC and sliced 5G integration, network/service orchestration, and 5G network security.

### 2.2.3 Vehicle-to-Everything (V2X) Communication

***V2X communication*** is the transfer of information from a vehicle to any "entity" that may affect the vehicle, and *vice versa*. It is a vehicular communication system that integrates other more specific types of communication as V2I (Vehicle-to-Infrastructure), V2N (Vehicle-to-Network), V2V (Vehicle-to-Vehicle), V2P (Vehicle-to-Pedestrian), V2D (Vehicle-to-Device), V2G (Vehicle-to-Grid) and V2R (Vehicle-to-Road-side units). Thus, V2X can be assessed as a wireless technology aimed at enabling data exchanges between a vehicle and its surroundings.

The core motivations for V2X are road safety, traffic efficiency, and energy savings. By sharing data, such as their position and speed, to surrounding vehicles and infrastructures, V2X systems improve driver awareness of upcoming potential dangers and significantly improve collision avoidance, resulting in heavily reduced fatalities and injury severity. In addition, the technology will enhance traffic efficiency by providing warnings for upcoming traffic congestions, proposing alternative routes and ensuring eco-friendly driving, reducing $CO_2$ emissions through adaptive cruise control and a smarter transportation management.

There are two types of V2X communication technology depending on the underlying technology being used, that is: (i) WLAN-*based*, and (ii) cellular-based.

The IEEE first published the specification of WLAN-*based* V2X (IEEE 802.11p[126]) in 2012. The 802.11p is an extension of 802.11a (Wi-Fi), and was standardised by the IEEE in 2009. In 2012, 802.11p was included in the overall IEEE 802.11 standard, but the informal term, 802.11p, is in general use. The 802.11p multiple access mechanism (Carrier Sense Multiple Access protocol with Collision Avoidance, CSMA-CA) is a statistical protocol for direct communications and connecting V2V and V2R[127].

The original V2X communication uses WLAN technology and works straight directly between vehicles, which compose a so called as vehicular *ad-hoc* network as two V2X senders come within each other's range. Therefore, it does not necessitate any infrastructure for vehicles to communicate, which is fundamental requirement to guarantee safety in remote -or little developed- areas. WLAN is particularly suitable for V2X communication, due to its low latency. It transmits messages known as Cooperative Awareness Messages[128] (CAM), Decentralised Environmental

[126] For more details see: IEEE 802.11p-2010: *IEEE Standard for Information Technology (IT) – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*. Available at: https://standards.ieee.org/standard/802_11p-2010.html

[127] Also see: 5G Automotive Association (5GAA) (2017): *An assessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safety in the EU*. Available at: http://5gaa.org/wp-content/uploads/2017/12/5GAA-road-safety-FINAL2017-12.05.pdf

[128] The Cooperative Awareness Message (CAM) is a message created by the Cooperative Awareness (CA) service residing at the Facilities layer of the ETSI ITS communication architecture stack described in ETSI EN 302 665 V1.1.1 (2010-09): *"ITS Communication Architecture"*.

The Cooperative Awareness service is described in the context of the work included in ETSI EN 302 637-2 V1.4.1 (2019-04): *"Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service".* Available at: https://www.etsi.org/deliver/etsi_en/302600_302699/30263703/01.02.01_30/en_30263703v010201v.pdf

 

Notification Messages[129] (DENM) or Basic Safety Message[130] (BSM) and others. The data volume of these messages is very low. The radio technology is part of the WLAN IEEE 802.11 family of standards and known in the US as Wireless Access in Vehicular Environments (WAVE[131]) and in Europe as ITS-G5[132].

The 3GPP started standardisation work of cellular V2X (C-V2X) in Release 14[133] in 2014. It is based on LTE as the underlying technology. Specifications were published in 2016. Because this C-V2X functionalities are based on LTE, it is often referred to as "cellular V2X" (C-V2X) to "differentiate" itself from the 802.11p based V2X technology. The scope of functionalities supported by C-V2X includes both direct communication (V2V, V2I) as well as wide area cellular network communication (V2N).

In Release 15, 3GPP continued its C-V2X standardisation to be based on 5G. To indicate the underlying technology, the term NR-V2X (New Radio V2X) is often used in contrast to LTE-based V2X

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CAMs are exchanged between C-ITS stations equipped with V2X technology (i.e. vehicles, infrastructure stations, etc.) to create and maintain awareness of each other and to support cooperative performance of vehicles using the road network. CAMs provide information about presence, position, dynamics and basic attributes of the originating station. The received information can be used to support several C-ITS applications. For example, by comparing the position and dynamics of the originating station with its own status, a receiving station is able to estimate a collision risk. A CAM is composed of a common ITS PDU header and multiple containers.

[129] Decentralised Environmental Notification Message (DENM) is a facilities layer message that is mainly used by ITS applications in order to alert road users of a detected event using ITS communication technologies. DENM is used to describe a variety of events that can be detected by ITS stations (ITS-S). The construction of a DENM is triggered by an ITS-S application. A DENM contains information related to a road hazard or an abnormal traffic conditions, such as its type and its position.  Upon detection of an event an ITS-S transmits a DENM in order to disseminate the information about this event to other ITS-Ss located inside an area of relevance. Then the ITS-S that transmits DENM is denoted as originating ITS-S. DENM transmission is initiated and terminated by an ITS-S application at the ITS application layer. DENM transmission is initiated and terminated by an ITS-S application at the ITS application layer. The transmission of a DENM may be repeated. DENM transmission may persist as long as the event is present. The termination of DENM transmission is either automatically achieved by the facilities layer, i.e. the DEN (the Decentralised Environmental Notification (DEN) basic service is an application support facility provided by the facilities layer) basic service of the originating ITS-S when a predefined expiry time is reached, or by an ITS-S application that requests the generation of a DENM to inform that the event has terminated. An ITS-S, which receives a DENM, processes the information and may decide to present an appropriate warning or information to user, as long as the information in the received DENM is relevant to the ITS-S. This ITS-S is denoted as receiving ITS-S. Also see: European Telecommunications Standards Institute (ETSI): ETSI EN 302 637-3 v1.2.2 (2014-11): *"Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralised Environmental Notification Basic Service"*. Available at: https://www.etsi.org/deliver/etsi_en/302600_302699/30263703/01.02.02_60/en_30263703v010202p.pdf

[130] See, *for example*: Saxena, S., and Isukapati, I.K. (2019): *Simulated Basic Safety Message: Concept & Application*. In Proceedings of the IEEE Intelligent Vehicles Symposium 2019 (IV-2019), pp.2450-2456.

[131] Also see, *among others*: Eichler, S. (10/2007): *Performance evaluation of the IEEE 802.11p WAVE communication standard*. In Proceedings of the 2007 66th Vehicular Technology Conference (VTC2007-Fall), pp.2199-2203. IEEE, Baltimore, MA, September 30 - October 03, 2007.

[132] "ITS" is the acronym for Intelligent Transport System. The "G5" is a standard for car-to-car communications and should not be confused with "5G". ITS comprise several combinations of communication, computer and control technology developed and applied in the domain of transport to improve system performance, transport safety, efficiency, productivity and level of service, environmental impacts, energy consumption, and mobility. For further information also see, *among others*: European Telecommunications Standards Institute (ETSI): ETSI ES 202 663 V1.0.0 (2010-01): "*Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band".* Available at: https://www.etsi.org/deliver/etsi_es/202600_202699/202663/01.01.00_60/es_202663v010100p.pdf

Also see, *inter-alia*: Eckhoff, D., Sofra, N., and German, R. (2013): *Performance Study of Cooperative Awareness in ETSI ITS G5 and IEEE WAVE*. In Proceedings of the 2013 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS), pp. 196-200. IEEE, Banff, AB, Canada, March 18-20, 2013.

[133] Also see**,** *among others*: 3GPP TR 21.914 V14.0.0 (2018-05): ***"****Release 14 Description; Summary of Rel-14 Work Items (Release 14)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/21_series/21.914/

(LTE-V2X). Either case, C-V2X is a generic term used to refer to cellular-based V2X communications, irrespective of the specific underlying mobile communications generation being used (4G or 5G).

In Release 16, 3GPP further enhances the C-V2X functionality. This work is currently in progress. Its main goal is to provide enhanced data rates and advanced ITS services and is, *therefore*, considered as part of the future landscape of vehicular telecommunication.

### 2.2.4 EU-funded Projects related to V2X

The development and large-scale deployment of Connected and Automated Mobility[134] (CAM) provides a unique opportunity to make our mobility system safer, cleaner, more efficient and more user-friendly. With the evolution of digital technologies, such as robotics, internet of things, artificial intelligence, high-performance computers and powerful communication networks, vehicles in general, and cars in particular, are quickly changing. Therefore, policies and legislation relating to digital technology, including cybersecurity, liability, data use, privacy and radio spectrum/connectivity are of increasing relevance to the transport sector. These aspects need coordination at the European level in order to ensure that a vehicle may remain connected when crossing borders.

The EU member States, industry and the European Commission collaborate to achieve the EU's ambitious vision for connected and automated mobility in a Digital Single Market (DSM), taking into consideration public authorities, citizens, cities and industry interests. The 2014-2019 Commission strategy had identified the completion of the DSM as one of its 10 political priorities[135] and the DSM Strategy was built on three pillars: (i) Access: implicating for better access for consumers and businesses to digital goods and services across Europe. (ii) Environment: aiming to create the right conditions and a level playing field for digital networks and innovative services to flourish. (iii) Economy and Society: aiming to maximise the growth potential of the digital economy.

The special framework of the H2020 ICT-22-2018 Call aimed at performing a close collaboration between EU and China to synchronise 5G technologies and spectrum issues[136] before the final roll-out of 5G. The main scope has been about conducting 5G trials addressing two specific scenarios, the second of which was the case of **Internet of Vehicles (IoV)** based **on LTE-V2X using the 5.9 GHz band for Vehicle-to-Vehicle (V2V)** and the **3.5 GHz band for Vehicle-to-Network (V2N)**. Both these bands are priority bands in the two regions for early introduction of very high data rate services. Thus, in the 5G-DRIVE approach, the overall goal has been to evaluate in real setup innovative end-to-end 5G systems built on the outcomes of the previous phases of the 5G R&I; more specifically, the optimisation of the bands usages in suitable scenarios has been a key target, so as the validation of the interoperability of the 3.5 GHz and the 5.9 GHz bands for the respective use cases. The 5G-DRIVE IoV scenario has been implemented in both regions (EU and China) through appropriate test-beds and with suitable trials[137]. The applications used to test and validate the use of LTE-v2x in the 5.9 GHz

[134] Connected and Automated Mobility (CAM) refers to autonomous/connected vehicles or self-driving cars (vehicles that can guide themselves without human intervention).

[135] For more details see: https://ec.europa.eu/digital-single-market/en/shaping-digital-single-market

[136] Also see: 5G-DRIVE Project (04/2019): Deliverable 2.2: *"Joint Architecture, Use Cases and Spectrum Plan"*. Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

[137] According to the ICT-22-2018 Call the expectations have been that the underlying trials' testing facilities shall implement the latest mature and broadly commonly agreed 5G systems, network architectures and technologies spanning from the core/transport networks, the radio access, up to the service, orchestration, management and security components. The trial facility would not be restricted to innovative 5G radio access technology, but should include and enable the evolution of 5G networks innovations in network slicing, virtualisation, cross-domain orchestration, in view of supporting resource control from multiple tenants. These concerns have been fully taken into account in the involvement of the EU participating trial sites for the IoV scenario (JRC in Ispra, Italy and VTT in Finland).

 

band for V2V applications and the use of 3.5 GHz band for V2N applications. The selected uses vases have been the CLOSA (Green Light Optimal Speed Advisory) and the intelligent intersection.

In the following sections, we provide an overview of either on-going and/or past EU projects related to the wider scope of V2X communications[138].

The 29 signatory countries of a Letter of Intent signed at Digital Day 2017 agreed to designate 5G cross-border corridors[139], where vehicles can physically move across borders and where the cross-border road safety, data access, data quality and liability, connectivity and digital technologies can be tested and demonstrated[140]. The European Commission's ambition is to focus on these corridors in future EU automated driving projects in the area of digital policies, with links to cybersecurity, privacy, 5G, internet of things, data economy, free flow of data, etc. The EU supports 3 projects (these are the 5GCroco project, the 5G-CARMEN project and the 5G-MOBIX project). All are running as part of the European Commission's 5G Public Private Partnership[141] which will set up 5G trials over more than 1000km of highway including four cross-border corridors: Metz-Merzig-Luxembourg, Munich-Bologna via the Brenner Pass, and Porto-Vigo and Evora-Merida, both between Spain and Portugal. In addition, a short cross-border segment between Greece and Turkey has been proposed for deployment, to serve testing as well. These trials will be crucial to the development of 5G-enabled connected and automated mobility. The areas they cover are among ten 5G cross-border corridors already agreed between EU countries. 5G technology will allow autonomous vehicles to connect in real time to each other, to pedestrians, to road infrastructure as well as to public telecom networks and resources in the cloud. This will help to avoid accidents and optimize traffic efficiency and therefore improve road safety, reduce traffic congestion, and lower greenhouse gas emissions. The three make possible to test and demonstrate connected and automated mobility services such as automated change of lanes ("lane merge") and trucks driving in platoons partly without need for drivers ("truck platooning"). They will also help the automotive and telecom industries to develop new business models, making use of 5G to transform online maintenance, fleet management and infotainment.

**5GCroco**[142] aims to trial 5G technologies over highways between Metz, Merzig and Luxembourg, crossing the borders of France, Germany and Luxembourg. It intends to test and refine advanced 5G network technologies such as mobile edge computing and network slicing, as well as to test tele-operated driving, high definition maps for autonomous vehicles, and Anticipated Cooperative Collision Avoidance (ACCA).

In addition, 5GCroCo also aims at defining new business models that can be built on top of this unprecedented connectivity and service provisioning capacity. Ultimately, 5GCroCo will impact relevant standardisation bodies from the telco and automotive industries. The possibility of providing connected, cooperative and autonomous mobility (CCAM) services along different countries when vehicles traverse various national borders has a huge innovative business potential. However, the seamless provision of connectivity and the uninterrupted delivery of services along borders also

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138 With the evolution of digital technologies, such as robotics, internet of things, artificial intelligence, high-performance computers and powerful communication networks, vehicles in general, and cars in particular, are quickly changing. Therefore, policies and legislation relating to digital technology, including cybersecurity, liability, data use, privacy and radio spectrum/connectivity are of increasing relevance to the transport sector. These aspects need coordination at the European level in order to ensure that a vehicle may remain connected when crossing borders.

139 Also see: *https://ec.europa.eu/digital-single-market/en/cross-border-corridors-connected-and-automated-mobility-cam*

140 Creating cross border pilots and jointly addressing data transmission and liability will give the EU automotive, tech and telecoms industries the advantage of a harmonised and unified market of 500 million consumers. It will also help the automotive industry maintain its global lead in the area of connected and automated cars.

141 For more informative details about this initiatives also see: *https://ec.europa.eu/digital-single-market/en/news/5g-public-private-partnership-next-generation-broadband-infrastructure*

142 5GCroCo: 5G Cross-Border Control (GA No.825050). More details can be found at: *https://5gcroco.eu/*

 

poses interesting technical challenges. The situation is particularly challenging given the multi-country, multi-operator, multi-telco-vendor, and multi-vehicle-OEM scenario of any cross-border layout. Motivated by this, 5GCroCo brings together a strong consortium from both, European automotive and mobile communications industries, with the explicit support of road traffic authorities and the respective national governments (through letters of support), to develop innovation at the intersection of these two industrial sectors. The aim is to define a successful path towards the provision of CCAM services along cross-border scenarios and reduce the uncertainties of a real 5G cross-border deployment. 5GCroCo aims at trialling 5G technologies in the cross-border corridor connecting the cities of Metz-Merzig-Luxembourg, traversing the borders between France, Germany and Luxembourg. The objective is to validate advanced 5G features, such as New Radio, MEC-enabled distributed computing, Predictive QoS, Network Slicing, and improved positioning systems, all combined together, to enable innovative use cases for CCAM. 5GCroCo aims at defining new business models that can be built on top of this unprecedented connectivity and service provisioning capacity, also ensuring that relevant standardisation bodies from the two involved industries are impacted[143].

**5G-CARMEN[144]** intends to conduct extensive trials across an important north-south corridor from Bologna to Munich via the Brenner Pass, spanning 600 km of roads, connecting three European regions, Bavaria (Germany), Tirol (Austria) and Trentino/South-Tyrol (Italy). It focuses on vehicle manoeuvre negotiation, infotainment, and emissions control in sensitive areas. The goal of 5G-CARMEN is to create new and realistic opportunities for generating competitive advantages for the European ICT, as well as the automotive, and road equipment manufacturing sectors. The vision of connected vehicle will transform the automotive industry that will benefit from the same level of agility as what is available today in the IT world: Time to market for new innovative services will be significantly improved, and overall Total Cost of Ownership (TCO) will be reduced. In the commercial field, 5G-CARMEN will help to open the market to new actors and will provide more compelling competitions over service availability and proper handover/roaming between worldwide operators[145]. Cooperative manoeuvring, situation awareness, video streaming, and green driving are the cross-border use cases targeted by 5G-CARMEN pilots in order to maximize the project commercial, societal, end environmental impact.

**5G-MOBIX[146]** aims to test connected and automated mobility applications along two cross-border corridors between Spain and Portugal, a short corridor between Greece and Turkey, and six national

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[143] 5GCroCo started on 1st November 2018. Since then, the use cases and user stories that will be trialed have been specified. Also, the test cases and test sites have been identified. The initial end-to-end architecture for cross-border network handover, end-to-end Quality of Service (QoS) with network slicing, Mobile Edge Computing/Cloud and positioning architecture, have been also defined. Furthermore, an initial application architecture has been defined and described and responsibilities for component development have been agreed. 5GCroCo business potentials have also been described. Besides, ethical issues regarding human participation in trials have been considered. In addition, a set of procedures have been established to maximize safety during the execution of the trials and to provide an informed consent for research participants. Protection of personal data ethical issues has been also evaluated in order to minimize personal data used during the execution of the project.

[144] 5G-CARMEN: 5G for Connected and Automated Road Mobility in the European unioN (GA No.825012). More details can be found at: *https://5gcarmen.eu/*

[145] The 5G-CARMEN use cases have been refined and specified. Also, the 5G KPIs have been identified and the architecture for cross-border network have been defined. A survey of existing inter-operator cross-border solutions in Italy, Austria and Germany is ongoing including MNO's 5G roadmap. The use of Geoservice and AQMP (Advanced Message Queuing Protocol) server are being discussed across several use cases. Cloud Services as well as the inter-MEC connectivity requirements are under evaluation against the use case requirements. Fundamental improvements to the network implementations and configurations are being defined in cooperation with the 5GAA. Priority has been given to enable seamless connectivity when entering the border are and switching from one PLMN to another. Deployment locations for 5G gNBs at the Italian/Austrian Border have been defined.

[146] 5G-MOBIX: 5G for cooperative & connected automated MOBIility on X-border corridors (GA No.824496). For more details see: *https://www.5g-mobix.com/*

 

urban sites in Versailles (France), Berlin and Stuttgart (Germany), Eindhoven-Helmond (Netherlands) and Espoo (Finland). In addition to technical validation and advanced use cases, the trials will make it possible to define cooperation models and include cost/benefit analysis. They will explore new business opportunities for 5G-enabled connected and automated mobility services and provide recommendations and options for deployment. 5G-MOBIX aims at executing CCAM trials along x-border and urban corridors using 5G core technological innovations to qualify the 5G infrastructure and evaluate its benefits in the CCAM context as well as defining deployment scenarios and identifying and responding to standardisation and spectrum gaps. The project will first define the critical scenarios needing advanced connectivity provided by 5G, and the required features to enable those advanced CCAM use cases. The matching between the advanced CCAM use cases and the expected benefit of 5G will be tested during trials on 5G corridors in different EU countries as well as China and Korea. Those trials will allow running evaluation and impact assessments and defining also business impacts and cost/benefit analysis. As a result of these evaluations and also international consultations with the public and industry stakeholders, 5G-MOBIX will propose views for new business opportunity for the 5G enabled CCAM and recommendations and options for the deployment. Also, the 5G-MOBIX finding in term of technical requirements and operational conditions will allow to actively contribute to the standardisation and spectrum allocation activities. 5G-MOBIX will evaluate several CCAM use cases, advanced thanks to 5G next generation of Mobile Networks. Among the possible scenarios to be evaluated with the 5G technologies, 5G-MOBIX has raised the potential benefit of 5G with low reliable latency communication, enhanced mobile broadband, massive machine type communication and network slicing. Several automated mobility use cases are potential candidates to benefit and even more be enabled by the advanced features and performance of the 5G technologies, as for instance, but limited to: cooperative overtake, highway lane merging, truck platooning, valet parking, urban environment driving, road user detection, vehicle remote control, see through, HD map update, media & entertainment.

Other EU-funded projects and European initiatives have already covered different aspects for business modelling in the intersection of both automotive and ICT fields.

The Knowledge Base on Connected and Automated Driving (CAD) is the one-stop shop for data, knowledge and experiences on CAD in Europe and beyond[147]. The sharing of knowledge, data and experiences is essential for the development of connected and automated driving. Combining the knowledge sources enables all stakeholders to get a clearer picture of what the future impacts of road automation will be[148]. Thus, we consider the following:

**5GCAR[149]** was devoted to conduct research in the area of V2X communications for and the automotive vertical sector towards the adoption of 5G technologies. Main objectives within the 5GCAR project have been: (i) Development of an overall 5G system architecture providing optimised end-to-end V2X network connectivity for highly reliable and low-latency V2X services, which supports security and privacy, manages quality-of-service and provides traffic flow management in a multi-RAT and multi-link V2X communication system; (ii) interworking of multi-RATs that allows embedding existing communication solutions and novel 5G V2X solutions; (iii) development of an efficient, secure and scalable side-link interface for low-latency, high-reliability V2X communications; (iv) proposition of 5G radio-assisted positioning techniques for both vulnerable road users and vehicles to increase the availability of very accurate localisation; (v) identification of business models and

[147] A detailed list of all CAD projects at EU-level or at national level can be found at: https://knowledge-base.connectedautomateddriving.eu/projects/findproject/

[148] Developed as part of the Horizon 2020 Action ARCADE (Aligning Research & Innovation for Connected and Automated Driving in Europe), the Knowledge Base gathers the scattered information among a broad network of CAD stakeholders to establish a common baseline of CAD knowledge and provide a platform for a broad exchange of knowledge.

[149] 5GCAR: Fifth Generation Communication Automotive Research and Innovation (GA No.761510). More details can be found at: https://5gcar.eu/

 

spectrum usage alternatives that support a wide range of 5G V2X services; (vi) demonstration and validation of the developed concepts and evaluation of the quantitative benefits of 5G V2X solutions using automated driving scenarios in test sites. The 5GCAR project investigated and proved the added value of C-V2X 5G focus for connected cars, studying the domain from multiple perspectives, including business models, spectrum matters, and contributing to the conception of innovative solution for the radio access network, the system architecture, and the security and privacy framework. Multiple cooperative Intelligent Transport Systems (C-ITS) use cases, which benefit from 5G features, were demonstrated. Moreover, the scientific work within the project impacted standardisation by means of project partner contributions. The 5GCAR results addressed a wide range of C-V2X challenges, ranging from use case and requirement definitions, investigation of business and spectrum related aspects, development of cellular link (both regular cellular link and side link) and position technical enablers as well as architectural components. The technical work was the foundation of the final four demonstrations of the related use cases. The demonstration findings have shown that connected driving has a huge potential for more safety and comfort (assisted and automated) driving use cases.

Some past EU-funded projects, having a conceptual relevance, are also briefly mentioned as follows:

**COMPANION**[150]: The objective of this project has been to develop co-operative mobility technologies for supervised vehicle platooning, in order to improve fuel efficiency and safety for goods transport. The potential social and environmental benefits inducted by heavy-duty vehicle platoons (or road trains) have been largely proven. The proposed idea has been to develop a new energy-efficient and user-friendly integrated framework to coordinated driving of heavy-duty vehicles. The project has proposed a new real-time coordination system, to define an optimised flow of vehicles in order to dynamically create, maintain and dissolve platoons according to an online decision-making mechanism, taking into account also historical and real-time information about the state of the infrastructure. With such a technology, platoons could be no more composed just of vehicles with common origins and destinations, but they could be created dynamically on the road, by merging vehicles (or sub-platoons) that share also only subparts of their routes.

**AutoNet2030**[151] has extended the specifications of control algorithms and messages to support cooperative automated driving use cases, while using decentralised control system with 802.11p-based communications. AutoNet2030 aimed to develop and test a co-operative automated driving technology, based on a decentralised decision-making strategy which is enabled by mutual information sharing among nearby vehicles. The project aimed for a 2020-2030 deployment time horizon, taking into account the expected preceding introduction of co-operative communication systems and sensor-based lane-keeping/cruise-control technologies. By taking this approach, a strategy has been realised for the gradual introduction of fully automated driving systems, making the best use of the widespread existence of co-operative systems and making the deployment of fully automated driving systems beneficial for all drivers already from its initial stages. The main idea had been to achieve intelligent decision-making in fully automated vehicles through local group formation, by using co-operative communications to exchange input data and manoeuvring control commands. Such co-operation did not mean not only among automated vehicles, but has been extended also to manually driven vehicles; automated vehicles could locally coordinate the manoeuvring of all surrounding vehicles, making driving thereby more predictable and safer also for manually driven cooperative vehicles. This system has been optimised to make safe, predictable and efficient manoeuvring decisions.

150 COMPANION: Cooperative dynamic formation of platoons for safe and energy optimised goods transportation (GA No.610990). More details can be found at: [www.companion-project.eu](www.companion-project.eu)

151 AutoNet2030: Co-operative Systems in support of Networked Automated Driving by 2030 (GA No.610542). More details can be found at: [http://www.autonet2030.eu/](http://www.autonet2030.eu/)

 

The **GCDC**[152] project aimed to speed up real-life implementation and interoperability of wireless communication based automated driving. The objective of i-GAME had been to develop technologies that speed-up the real-life implementation of automated driving, which is supported by communication between the vehicles and between vehicles and road-side equipment. These automated systems need to be safe and able to cope (to a certain extend) with different circumstances. And the technology need not be too specific to be able to be used in a wide range of vehicles and traffic scenarios. For the i-GAME, the solution has been found in so-called supervisory control, providing both event-driven control to initiate vehicle manoeuvres (e.g. a car wants to merge on a highway) and real-time control to execute the manoeuvres (i.e. vehicles make a space for the merging vehicle and the merging vehicle steers into the empty space). These kinds of scenarios require that the participating vehicles and road-side equipment are able to communicate and cooperate with each other, which is called interoperability. The interoperability in i-GAME has been ensured *on the one hand* by a reference group of OEM's and suppliers, and, *on the other hand*, through the participating (university) teams in a second edition of the Grand Cooperative Driving Challenge. For the design and setup or the automated systems i-GAME has used a parallel approach. Firstly, a functional architecture has been developed. The components of the system (like the communication and the overall supervisory control system) have been developed on simulation level first and then tested in practice using benchmark vehicles. Secondly, to focus on interoperability and thus speed up real-life implementation, a series of verification and validation workshops has been held, having its climax in the final challenge on cooperative automated driving, together with leading RTDs, and supported by OEMs and suppliers. Typical examples of multi-vehicle platoon manoeuvres were platoon forming, priority and speed adaptation (including stop) at a traffic light, and automatic or supported vehicle merging based on fusion of in-vehicle and on-roadside information. This open approach created a multi-vendor playground and should catalyse the scale-up and commercial roll out of vehicles equipped with the automated solutions.

The **HIGHTS** [153]project aimed to achieve high precision positioning system with the accuracy of 25 cm, for applications such as highly automated driving, cooperative automatic cruise control and vulnerable road users (VRUs). The HIGHTS project has developed Cooperative Intelligent Transport System (C-ITS) to enable the localisation of any vehicle on the road with a positioning precision of 0.25 meters. This has improved the safety levels considerably for drivers and VRUs, as well as open the way to highly automated driving (HAD) applications. C-ITS applications rely on knowledge of the geographical positions of vehicles. Unfortunately, satellite-based positioning systems (e.g. GPS and Galileo) are unable to provide sufficiently accurate position information for many important applications and in certain challenging but common environments (e.g., urban canyons and tunnels). The HIGHTS platform aimed to increase the safety level of vulnerable road users (motorcycles, scooters, pedestrians) through bi-directional danger detection and by detecting slight deviations from driving courses, thus detecting danger before it occurs. Safety is a huge challenge for today's road scenario and it will be even more challenging in the future, with the progressive introduction of HAD applications such as C-ACC (Automatic Cruise Control that interacts with infrastructure).

**AUTOPILOT**[154] is another project in the context of connected and autonomous driving. The overall objective of AUTOPILOT has been to bring together relevant knowledge and technology from the automotive and the Internet of Things (IoT) value chains in order to develop IoT-architectures and platforms, which bring AD towards a new dimension. This IoT-architecture is said to enhance the security and comfort of the autonomous driving services. AUTOPILOT project has focused on the

[152] GCDC: Interoperable GCDC Automation Experience (GA No.612035). This is also known as i-GAME project. For more details see: *http://www.gcdc.net/en/i-game*

[153] HEIGHTS: High precision positioning for cooperative ITS applications (GA No.636537). For further information also see: *https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/intelligent-transport-systems/hights*

[154] AUTOPILOT: AUTOmated driving Progressed by Internet Of Things (GA No.731993). More details can be found at: *https://autopilot-project.eu/*

following use cases: automated valet parking, highway pilot, platooning, urban driving and car sharing.

The Connecting Europe Facilities (CEF)-funded Connected Corridor for Driving Automation (**CONCORDA**)[155] project evaluated connected services and facilities. Use cases considered were high-density truck platooning and highway chauffeur automated driving on motorways. It evaluated ITS-G5 and C-V2X (short-range and long-range) communication technologies[156] aiming at overcoming fragmentation and assuring backward interoperability between Cooperative ITS (C-ITS) services and technologies providing them. Trials were conducted in Netherlands, Belgium, France, Germany and Spain. Interoperability for system architecture and communication technologies, services, and actual implementation has been evaluated between the sites. Besides communication aspects, CONCORDA also evaluated enablers such as precise positioning and the non-technical aspects of cost-efficient realisation of services. Especially the latter will allow findings from CONCORDA regarding ecosystem and business aspects to be considered for 5GCroCo once the respective CONCORDA deliverables become public.

**CODECS**[157] aimed for a concerted roll-out of C-ITS applications across Europe. In close cooperation with an established open C-ITS stakeholder network of interested experts, CODECS followed a bottom-up approach based on three phases: collecting information, consolidating results and developing guidelines. The findings and outcome of CODECS have been shared with the C-ITS stakeholder network and important groups such as the Amsterdam Group, the C-ITS Deployment Platform and the standards setting organisations ETSI (ITS Technical Committee). During its lifetime CODECS has focused on: (i) Fostering knowledge exchange on initial C-ITS deployment initiatives; (ii) laying the foundation for road mapping beyond the initial deployment phase; (iii) enhancing knowledge building with respect to technical challenges beyond the initial deployment phase; (iv) progressing on strategy alignment of C-ITS deployment actors; (v) broadening and deepening awareness and understanding of opportunities for cities from C-ITS deployment networking and coordinating initial deployment activities.

During 2008, the projects **SAFERIDER**[158] and **TeleFOT**[159] were funded by EU under FP7 (Framework Programme). SAFERIDER provided ADAS and IVI systems in motorcycles, while TeleFOT conducted FOTs for IVS and aftermarket vehicle devices.

The **INTERACTION**[160] project addressed the understanding of driver interactions.

The **PRE-DRIVE C2X**[161] project developed a primary common European architecture for I2V systems, while Germany, through the projects **simTD**[162] and DIAMANT, envisioned increasing traffic efficiency and road safety.

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155 CONCORDA: Connected Corridor for Driving Automation. For further details about this project also see: *https://i-sense.iccs.gr/projects/ongoing-projects/item/1317-concorda*

156 For further reading also see, *among others*: Mannoni, V., Berg, V., Sesia, S., and Perraud, E. (2019): *A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X*. In Proceedings of the 2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring), pp.1-5. IEEE, Kuala Lumpur, Malaysia, April 28 – May 01, 2019.

157 CODECS: Coordination and Support Action **Co**operative ITS DEployment **C**oordination **S**upport (GA No. 653339). More details can be found at: *https://www.codecs-project.eu/index.php?id=5*

158 Advanced telematics for enhancing the SAFEty and comfort of motorcycle RIDERs (GA No.85335). More details can be found at: *http://www.saferider-eu.org/*

159 Field Operational Tests of Aftermarket and Nomadic Devices in Vehicles (GA No.224067). For more details also see: *www.telefot.eu*

160 Differences and similarities in driver INTERACTION with in-vehicle technologies (GA No. 218560). For more details also see: *https://interaction-fp7.eu/*

161 Preparation for Driving Implementation and Evaluation of C2X Communication Technology (GA No. 224019). For more details also see, *among others*: *www.pre-drive-c2x.eu*

 

In 2009 the EC launched the **FREILOT**[163] project, which developed C-ITS services for road goods transport.

The projects **SISCOGA**[164], **eCoMove**[165], **interactIVe**[166], **OVERSEE**[167] and **COSMO**[168] were launched in 2010, aiming to foster energy efficiency by developing various C-ITS services. France introduced a national FOT (Field Operational Test) for C-ITS standards, titled SCORE@F, while The Netherlands introduced the CCC project[169], with the objective of developing a cruise control system.

A series of three projects, funded by FP7, were introduced in 2011: **DRIVE C2X**[170], **PRESERVE**[171] and **COMeSafety2**[172]. The projects ambitioned respectively the assessment of C-ITS through FOTs in Europe, the provision of a security subsystem for V2X communication systems and the coordination of European activities. In the field of FOTs, EC launched the **FOTsis**[173] project and the **ITSSv6**[174] project. Another three projects, **Co-Cities**, **HeERO**[175] and **COBRA**[176], were founded during the same period by the EU, while the Austrian Testfeld Telematik project and the ParckR (Dutch Brabant In-Car II) project aimed for developing and operating C-ITS services at a national level.

A more recent very interesting project is the case of the **MAVEN**[177] project: For management of automated vehicles at signalised intersection and corridors, the MAVEN (Managing Automated Vehicles Enhances Network) project has developed infrastructure-assisted platoon organisation and negotiation algorithms. These extended and connected vehicle systems for trajectory and manoeuvre planning and infrastructure systems for adaptive traffic light optimisation. Traffic lights adapting their signal timing to facilitating the movement of organised platoons and reversely have offered substantial better utilisation of infrastructure capacity, reduction of vehicle delay and reduction of emission. The MAVEN project has built a system prototype for both field tests and extensive modelling for impact assessment, contribute to the development of enabling technologies such as communication standards and high-precision maps, and develop ADAS techniques for

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[162] Safe and Intelligent Mobility - Test Field Germany. More details can be found at: *https://www.as-p.com/projects/project/simtd-sichere-intelligente-mobilitaet-testfeld-deu-94/show/*

[163] FREILOT: CT for adaptive urban transport management infrastructure and services (GA No.238930). Also see: *https://www.up2europe.eu/european/projects/urban-freight-energy-efficiency-pilot_3084.html*

[164] SISCOGA: Smart Corridor in European Projects.

[165] eCOMove: Cooperative Mobility Systems and Services for Energy Efficiency (GA No.247908). More details can be found at: *http://www.ecomove-project.eu/*

[166] interactIVe: Accident avoidance by active intervention for Intelligent Vehicles (GA No.246587). More details can be found at: *https://www.interactive-ip.eu/*

[167] OVERSEE: Open VEhiculaR SEcurE platform (GA No.248333). For more details see: *https://www.oversee-project.com/*

[168] COSMO: Energy efficient co-operative transport management systems (GA No.270952).

[169] Also see: *https://www.cccresearch.nl/2017/07/02/ccc-project-from-maastricht-university/*

[170] DRIVE C2X: ICT for mobile of the future (GA No.270410).

[171] PRESERVE: Preparing Secure V2X Communications Systems (GA No.269994). For more details also see: *https://www.preserve-project.eu/www.preserve-project.eu/index.html*

[172] COMeSafety2: Communications for eSafety2 (GA No.270489).

[173] FOTsis: Field Operational Tests on Safe, Intelligent and Sustainable Road Operation (GA No.270447). Also see: *www.fotsis.com*

[174] ITSSv6: IPv6 ITS Station Stack for Cooperative ITS FOTs (GA No.210519). Also see: *http://www.itssv6.eu/*

[175] HeERO: Harmonised eCall European Pilot (GA No.270906). Also see: *http://www.heero-pilot.eu/view/en/home.html*

[176] GA No.282991. Also see: https://www.cobra-network.eu/the-project/

[177] MAVEN: Managing Automated Vehicles Enhances Network (GA No.690727). For more details see: *http://www.maven-its.eu/*

inclusion of vulnerable road users.

Other V2X-related information has originated from the following sources covering on-going initiatives and/or related actions. These are briefly summarised as follows:

The **5G-PPP Automotive WG**[178] released two white papers at the Mobile World Congress 2018 and 2019, respectively. They are presented as different versions (Version 1[179] and Version 2[180]) with the same purpose, that is to provide a first approach on a business case for 5G V2X deployment using a highway as an example. Both papers are providing figures about the costs and possible incomes related to Connected Automated Driving (CAD) services and connectivity needs. The second version goes deeper into different deployment scenarios exploring different network sharing options and revenue share between several MNOs, which will affect the CAD business case.

**The 5G Automotive Association (5GAA)**[181] was created on September 2016 and is a global cross-industry organisation that promotes the development of end-to-end specifications for future transportation and mobility services. So far, more than 110 companies have joined 5GAA. The 5GAA White Paper "C-ITS Vehicle to Infrastructure Services: How C-V2X technology completely changes the cost equations for road operators"[182], published in January 2019, shows how the business model and business case definition methodologies described earlier in this report are used to evaluate the business impact of new solutions[183]. The different cost-aspects of C-V2X technologies are evaluated based on capital expenses (CAPEX) and operational expenses (OPEX) and stated in different delivery models, which road authorities can use to reduce the implementation and operating costs of the technologies.

## 2.3 5G System as a Fundamental Enabler for 5G-DRIVE Objectives

The 5G System (5GS) defined by the 3GPP, "addresses" the needs and requirements of above-mentioned classes of services. The definition of the 5GS is based on experiences of mobile cellular systems development, especially lacks, gaps and shortages of previous generations of mobile systems. The 3GPP prefers evolutionary approach of mobile systems development. However, within the detailed concept of the 5GS, there are essential changes which may be considered as a sort of disruptive architectural changes, having major impact on 5GS capabilities in the context of 5G-DRIVE project.

### 2.3.1 Telco Network Softwarisation and Virtualisation

The 5GS is founded on the ETSI NFV[184] concept of implementation of telco network as a virtualised "network service", which is built with softwarised network functions (NFs), that is: specialised software applications realizing the specific NFs of the architectural framework of mobile network. Decoupling of NFs' software and hardware layers has serious consequences not only due to

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178 5G-PPP Working Groups, For more details see: https://5g-ppp.eu/5g-ppp-work-groups/

179 5G-PPP Automotive Working Group (02/2018): *A study on 5G V2X Deployment*. Available at: https://5g-ppp.eu/wp-content/uploads/2018/02/5G-PPP-Automotive-WG-White-Paper_Feb.2018.pdf

180 5G-PPP Automotive Working Group (02/2019): *Business Feasibility Study for 5G V2X Deployment*. Available at: https://bscw.5g-ppp.eu/pub/bscw.cgi/d293672/5G%20PPP%20Automotive%20WG_White%20Paper_Feb2019.pdf

181 For further details see: https://5gaa.org/about-5gaa/about-us/

182 See: https://5gaa.org/wp-content/uploads/2019/01/5GAA-BMAC-White-Paper_final2.pdf

183 See: https://5gaa.org/5gaa-in-motion/news/

184 For more details also see, *inter-alia*: https://www.etsi.org/technologies/nfv.

separation of their lifecycles, but also due to the advantage of using the ability of autonomous scaling of underlying virtualisation infrastructure, following the traffic load of individual NFs. This way, the load balancing at the communication network level may be replaced (to some extent) by scaling the resources, which contribute to run-time environment of specific communication network functions. Additionally, the internal mechanisms of the virtualisation environment may support roaming (relocation) of running communication network functions to follow the spatial traffic demand and distribution.

As, by principle, the ETSI NFV environment is implemented on a commodity IT hardware (e.g. x86[185]-based), which can be used for purposes other than implementation of communication network, the Network Operator (NO) can implement different optimisation strategies for maximizing a synergy and utilisation of IT resources supporting both telco network and other IT processes. It means that the appropriate and dynamically changing use of load balancing strategies both at the level of virtualisation resources and communication network architecture, in order to achieve the highest possible overall efficiency of resources.

Initially, the ETSI NFV was defined for virtual machines (VMs), but currently the ETSI NFV Group[186] works on the extension of the concept and its standardisation also to more lightweight containerisation technology. The latter one supports better a trend of higher granularity of functional decomposition of mobile network architecture.

The telecommunications network softwarisation and virtualisation are two twin concepts, which are so closely related that they are often confused with each other. The first of them assumes the implementation of a certain architectural function in the form of software (application) run on generic IT hardware, instead of the form of a monolithic solution on hardware specifically designed and dedicated to the function. The second one abstracts the application layer from the hardware layer by addition of the virtualisation layer supported by Hypervisor; this way the softwarised function, which is run within some environment (operating system, memory, storage, processing resources) is decoupled from the hardware aspect of this environment, thus the life cycles of both of them are also decoupled, then enabling this independent infrastructure management (scaling, extension, relocation, reconfiguration, etc.) without affecting the software, which is running on top of the infrastructure.

The reference framework for Network Functions Virtualisation (NFV) has been standardised by ETSI[187]. The Management and Orchestration (MANO) architecture has been specified in the ETSI NFV-MAN 001 document[188] (see Figure 9, below), where:

- The Virtualised Infrastructure Manager (VIM) manages and exposes the NFV Infrastructure (computational, memory and storage resources) within which the Virtual Network Functions (VNFs) reside;
- the role of the VNF Manager (VNFM) is to provide the conditions for the runtime existence of

[185] The x86 is a family of backward compatible instruction set architectures based on the Intel 8086 CPU and its Intel 8088 variant. More related information can be found, *for example*, at: https://en.wikipedia.org/wiki/X86.

[186] The ISG NFV has developed over 80 different reports and specifications for the virtualisation of network functions. NFV publications describe and specify virtualisation requirements, architecture framework, functional components and their interfaces, as well as the protocols and the APIs for these interfaces. ISG NFV also studies VNF performance, reliability and resilience matters, analyses the security challenges linked to virtualisation (trust, attestation and regulation). NFV specifies requirements for Management and Orchestration (MANO), for hardware acceleration, etc. For further details also see: https://www.etsi.org/committee/nfv. Virtual Network Functions (VNF) describe telecom core functions like packet core, IP Multimedia Subsystem (IMS) and Subscriber data management when implemented as software on cloud-based hardware platforms. The software is optimised for the cloud environment.

[187] See: https://www.etsi.org/technologies/nfv

[188] For further information see: ETSI GS NFV MAN V1.1.1 (2014-12): *"Network Functions Virtualisation (NFV); Management and Orchestration"*. Available at: https://www.google.com/search?client=firefox-b-d&q=etsi+nfv+mano

 

the individual VNFs; to this end, the VNFM exchanges information on the "well-being" of the VNF with it or its Element Manager (EM);

- the NFV Orchestrator (NFVO), located on top of the MANO stack, is a global manager-coordinator, aware of the big picture:
  - The VNF prototypes including the information about the environmental requirements for their execution;
  - the interrelations and interconnections between the individual VNFs, both at the level of templates (the defined, use case-driven constellation of some specific VNF prototypes is named a "Network Service", i.e. NaaS) and their implemented instances;
  - the NFVI Resources, both exposed and utilised by instantiated Network Services (NSs);
  - the overall view of events and performance of all underlying objects as well as needed rescaling operations both at VNF, Network Service and NFVI levels (scaling of resources or cloning of individual VNFs).

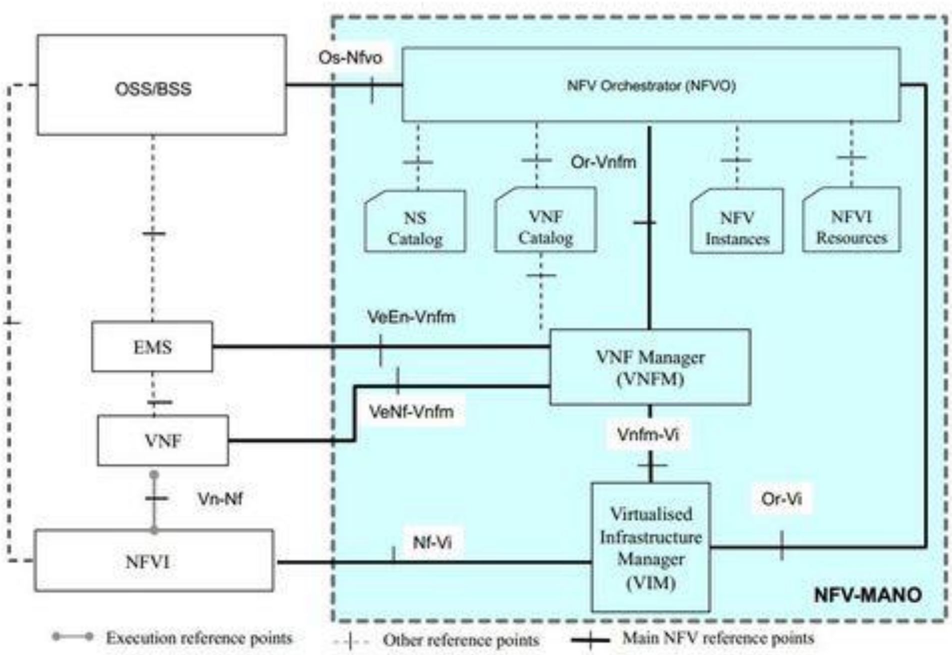


*Figure 9: ETSI NFV MANO framework [Source: ETSI NFV MAN 001]*

The ETSI NFV MANO stack is also capable of accommodating more complex architectural scenarios (multi-VIM, multi-VNFM, multi-NFVO, umbrella NFVO and umbrella Resource Orchestrator over multiple VIMs)[189]. However, it has to be noted that NFV framework and especially the MANO area of concern is limited to the software dimension of VNFs and Networks Services built upon them, only. Thus, they are both completely agnostic to the functional aspect of individual applications (VNFs) as well as entire network services. The "business" functions are recognised and managed by the OSS/BSS and EMs. The latter may be also implemented as VNFs or their components (either separate or embedded in the "business" VNFs).

Currently the most popular implementations of the NFV concept are based on the OpenStack

[189] For more details see: ETSI GS NFV-IFA 009 V1.1.1 (2016-07): *"Network Functions Virtualisation (NFV); Management and Orchestration; Report on Architectural Options"*. Available at: https://www.etsi.org/deliver/etsi_gs/nfv-ifa/001_099/009/01.01.01_60/gs_nfv-ifa009v010101p.pdf

project[190] (multi-tenant VIM) capable of management of various Hypervisor[191] solutions (KVM[192], VMWare vSphere[193], Xen[194], XenServer[195] or Microsoft Hyper-V). The higher layers of MANO stack is implemented using either proprietary or open-source solutions like ETSI OSM[196] or ONAP[197] (which plays also a role of OSS/BSS).

One of drawbacks of virtualisation is the resources overhead needed to support the entire VNF, which is the "business application" together with its own separated run-time environment (i.e. a complete operating system). Even if the operating system is slimmed down to the bare minimum required by an application implementing a network architecture function, the overhead is still significant and requires a correspondingly larger underlying hardware environment (implying increase of investment costs). The response to this issue is the concept of containerisation.

Containerisation is a concept of deployment application as portable, self-sufficient containers that can be run in the cloud or locally. It is applied by a technique of running processes in environments isolated from the rest of the system, so that each process running in its container is unaware of other, both non-containerised and containerised processes running next to it. Containerisation is also associated with the limitation of allocated system resources (CPU, memory, and disk) for an environment of a given container. An important distinguishing feature of containerisation, in opposite to full virtualisation, it is that containers share the same operating system and its resources, and also virtualize only selected elements. Containerisation is therefore a technique based on and built on top of the multitasking mechanisms of operating systems. Finally, an application together with its dependencies wrapped in a standardised container is much more lightweight than VNF.

Currently the most popular containerisation solution is Docker[198] that is implemented as a system

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[190] OpenStack controls large pools of compute, storage, and networking resources, all managed through APIs or a dashboard. Beyond standard infrastructure-as-a-service functionality, additional components provide orchestration, fault management and service management amongst other services to ensure high availability of user applications. For further details see: https://www.openstack.org/

[191] A hypervisor is a crucial piece of software that makes virtualisation possible**.** It abstracts guest machines and the operating system they run on, from the actual hardware. Hypervisors create a virtualisation layer that separates CPU/Processors, RAM and other physical resources from the virtual machines a user creates.

[192] Kernel-based Virtual Machine (KVM) is a virtualisation module in the Linux kernel that allows the kernel to function as a hypervisor. It was merged into the Linux kernel mainline in kernel version 2.6.20, which was released on February 5, 2007. KVM requires a processor with hardware virtualisation extensions, such as Intel VT or AMD-V. For more details see, *for example*: https://en.wikipedia.org/wiki/Kernel-based_Virtual_Machine

[193] For more details also see, *inter-alia*: https://www.vmware.com/products/vsphere.html

[194] The Xen Project is focused on advancing virtualisation in a number of different commercial and open source applications, including server virtualisation, Infrastructure as a Services (IaaS), desktop virtualisation, security applications, embedded and hardware appliances, and automotive/aviation. For more details also see: https://xenproject.org/

[195] Citrix Hypervisor (formerly known as the XenSever) is the leading open source virtualisation platform, powered by the Xen Project hypervisor and the XAPI toolstack. It is used in the world's largest clouds and enterprises. For more details also see: https://xenserver.org/

[196] OSM is developing an open source Management and Orchestration (MANO) stack aligned with ETSI NFV Information Models. As a community-led project, OSM delivers a production-quality MANO stack that meets operators' requirements for commercial NFV deployments. For further details see: https://osm.etsi.org/

[197] ONAP is a comprehensive platform for orchestration, management, and automation of network and edge computing services for network operators, cloud providers, and enterprises. Real-time, policy-driven orchestration and automation of physical and virtual network functions enables rapid automation of new services and complete lifecycle management critical for 5G and next-generation networks. For more details see: https://www.onap.org/

[198] Docker is an open platform for developing, shipping, and running applications. Docker enables the user to separate his/her applications from his/her infrastructure so he/she can deliver software quickly. With Docker, a user can manage his/her infrastructure in the same ways he/she manages his/her applications. For more details also see: https://www.docker.com

daemon together with a client, which aids containers management. In other words, it is a service responsible for the creation, management and destruction of containers. Docker employs two features of the Linux kernel:

- *cgroups* – resource limiting mechanism (memory, CPU usage, number of disk operations or the maximum number of processes in a given group) and counting all types of operations on these resources;
- *namespaces* – a mechanism for the logical isolation of processes by split between different abstract universes, making processes "think" that they are the only processes running on the system; namespaces also enable creation of individual virtual networks, which is essential for applications running inside the containers.

Container orchestrators were created to automate container management, including creation of abstract layer above the containers, and especially to solve certain specific problems inherent in the containerisation technique (ephemeral character of containers *vs.* the need to permanently save data from containerised databases, the need for a deterministic allocation of IP addresses to containers, High Availability support by placing copies of the same container on different hosts, scaling the abstract service by creating parallel copies of the same container with load balancing support, propagation of changes in the container prototype to selected running instances, etc.). The most popular Docker container orchestrators are: Kubernetes[199] (developed very actively), Docker Swarm[200], and Apache Mesos[201]. Additionally, the support of containerisation has been included to ETSI NFV framework within the Release 4[202], while the latest releases of OSM also support Docker container orchestration.

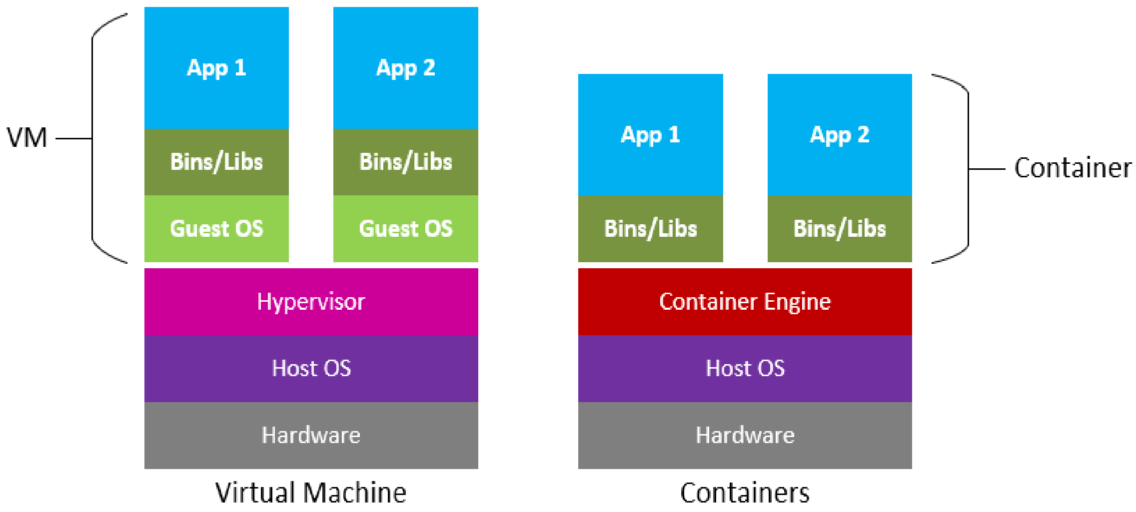


*Figure 10: Comparison of VM and containerisation techniques*

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[199] Kubernetes, also known as K8s, is an open-source system for automating deployment, scaling, and management of containerised applications. It groups containers that make up an application into logical units for easy management and discovery. Kubernetes builds upon 15 years of experience of running production workloads at Google, combined with best-of-breed ideas and practices from the community. For more details also see: https://kubernetes.io/

[200] Docker swarm is a container orchestration tool, meaning that it allows the user to manage multiple containers deployed across multiple host machines. One of the key benefits associated with the operation of a docker swarm is the high level of availability offered for applications. Also see: https://docs.docker.com/engine/swarm/

[201] Apache Mesos is an open-source project to manage computer clusters. For more details also see, *among others*: http://mesos.apache.org/ and/or https://en.wikipedia.org/wiki/Apache_Mesos

[202] For more details also see the context presented in ETSI GS NFV-IFA 040 V4.1.1 (2020-11): *"Network Functions Virtualisation (NFV) Release 4; Management and Orchestration; VNF Descriptor and Packaging Specification"*. Available at: https://www.etsi.org/deliver/etsi_gs/NFV-IFA/001_099/011/04.01.01_60/gs_NFV-IFA011v040101p.pdf

VM and containerisation techniques are compared illustratively in Figure 10. It should be noted that in case of containerisation there are serious concerns about hermeticity of mutual isolation of containers provided by the Container Engine (e.g. Docker), especially when some libraries are shared. Additionally, a hybrid solution is also possible where the Container Engine is running on top of VM.

It has to be also noted that both virtualisation and containerisation introduce an additional network delay, due to the introduction of an additional layer, which manifests itself in the increased E2E latency of communication between VMs/containers.

### 2.3.2 Separation of Control Plane and User Plane

Another fundamental change of architectural paradigm is a separation of Control Plane (CP) and User Plane (UP)[203], which can additionally be implemented to NFV. The former mobile network design, which was based on "nodes" (hardware boxes supporting high-level functions of the mobile network architecture) inherently implied concentration of both planes in these boxes. With communication network softwarisation, both planes – implemented in virtualisation environment – can be spatially distributed and located in more efficient way following the different traffic demands existing in each plane.

Additionally, the UP vision of the 3GPP 5GS defines a User Plane Function (UPF) as a distributed chain of various functions processing the UP traffic according to the needs of specific service or users' group. Unlike in the 4G and earlier systems, the UPF is no more a wireless mobility-supporting tunnel anchored at the gateway point to the IP network (e.g. the public Internet or private networks). Now, the chain may incorporate other traffic processing functions, which so far had to be implemented in the vestibule of the mobile network (in so called SGi-LAN[204]). The counter-partners of UPFs in the CP are their specific Session Management Functions (SMFs).

Control and User Planes Separation[205] (CUPS) is a fundamental architectural paradigm and one of the key features of the 5G architecture. It is enabled and tightly interrelated with the idea of telecommunications network softwarisation and virtualisation. Introduced initially for LTE within the Release 14[206], it has been incorporated to the set of architectural assumptions of the 3GPP 5G System. As a result of relinquishing of the vision of networks as sets of monolithic devices in favour of a constellation of programmable functions implementing the E2E mechanisms of telecommunications networks, the user data session control layer and the layer in which the user data transmission occurs directly were separated. In case of the LTE network, the S/P-GW nodes are split to S/PGW-C (Control) and S/PGW-U (User). The 5G System architectural framework defines the pairs of User Plane Functions (UPFs) under control of their Session Management Functions (SMFs)[207]. The consequences of CUPS are manifold:

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[203] For more details also see: 3GPP TS 23.501 V16.3.0 (2019-12): "*System Architecture for the 5G System (5GS); Stage 2 (Release 16)*". Available at: https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/

[204] For SGi-LAN (SGi Local Area Network) is network infrastructure connected to a 3GPP LTE (Long-Term Evolution) network over the SGi or Gi reference point (i.e. interface) that provides different value-added IP-based services to user data as it flows through the network. Also see, *inter-alia*: http://4g5gworld.com/ltefaq/what-are-lte-interfaces

[205] The term CUPS stands for Control and User Plane Separation of EPC (Evolved Packet Core) nodes and provides the architecture enhancements for the separation of functionality in the Evolved Packet Core's SGW, PGW and TDF. This enables flexible network deployment and operation, by distributed or centralised deployment and the independent scaling between control plane and user plane functions - while not affecting the functionality of the existing nodes subject to this split. Also see: https://www.3gpp.org/cups

[206] 3GPP TS 23.214 V14.6.0 (2018-03): "*Architecture enhancements for control and user plane separation of EPC nodes; Stage 2 (Release 14)*". Available at: https://www.3gpp.org/ftp//Specs/archive/23_series/23.214/

[207] For more details also see: 3GPP TS 23.501 V16.3.0 (2019-12): "*System Architecture for the 5G System (5GS); Stage 2 (Release 16)*". Available at: https://www.3gpp.org/ftp//Specs/archive/23_series/23.501/

 

- Spatial (geographical) separation of both planes: Control Plane (CP) functions may be placed in a centralised location, while the User Plane can be implemented at the closest possible location to the user or application it is supporting (e.g. for latency minimisation).
- Independent scaling of both planes, more flexible design, deployment and dimensioning of the network, dynamic optimisation of UP traffic distribution, gains on transport layer.
- Enabling the flexible UP programmability and incorporation of LTE SGi[208] LAN functionality into the UPF, e.g. firewall, Deep Packet Inspection (DPI), selective marking or altering, encapsulation, classification, forwarding or redirection of user traffic, anti-virus protection, parental control, etc.
- Enabling the network slicing in UP, i.e. service- or use case-driven differentiation of UPF architecture.
- Enabling the further integration with the Software Defined Networking paradigm (three-tier architecture), by introducing a **Network Controller** between the SMF and UPF, thus abstracting UP from CP. This way, SMF requests high-level policies for user traffic, and the Network Controller selects the data path, specific UP nodes and enforces these policies, thus delivering a requested UPF.

### 2.3.3 Service-Based Architecture of Control Plane and its Flexibility

The 5GS CP architecture is founded on the Service-Based Architecture (SBA) principle, i.e. instead of direct connection of CP NFs, the common CP communication bus is defined (Service Communication Proxy – SCP[209]). Moreover, the service bus-based architecture enables flexible extension of CP in response to specific needs of 5G mobile network services. The 5G CP can be partitioned into generic and specific functional sets, with functional differentiation of slice-specific partitions (i.e. common and dedicated CP slices).

The concept of "lightweight CP" assumes a fundamental, generic set of CP NFs, common for all types of services. On top of the lightweight CP, the service-specific and non-shared CP NFs can be implemented as add-ons, in the context of these services only.

The CP of the 5GS is inherently open to upper layer systems via its North-Bound Interface[210] (NBI), which has been defined in the 3GPP architectural framework as the Network Exposure Function[211] (NEF). Additionally, the 5GS architecture defines a generic Application Function (AF), which is a way of embedding OTT service-specific or Application Plane (AP) functions (e.g., IMS). These functions will be also exposed through the NBI-NEF, but due to being embedded within the CP, they may interact

[208] The SGi interface is defined between the P-GW and external networks, for example, Internet access, corporate access, etc.

[209] For more details also see: 3GPP TS 23.501 V16.7.0 (12/2020): *"System Architecture for the 5G System (5GS); Stage 2"*. Available at: https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/

[210] In computer networking and computer architecture, a northbound interface (NBI) of a component is an interface that allows the component to communicate with a higher level component, using the latter component's southbound interface. The northbound interface conceptualizes the lower level details (e.g., data or functions) used by, or in, the component, allowing the component to interface with higher level layers. In architectural overviews, the northbound interface is normally drawn at the top of the component it is defined in; hence the name northbound interface. A southbound interface decomposes concepts in the technical details, mostly specific to a single component of the architecture. For more details relevant to the dedicated 3GPP scope and about the corresponding approach also see, *among others*: https://www.3gpp.org/news-events/1854-common_api

[211] The Network Exposure Function (NEF) is related to the 3GPP 5G Architecture. This function provides a means to securely expose the services and capabilities provided by 3GPP network functions. Related examples would include: 3rd party, internal exposure/re-exposure. Also see the scope in 3GPP TS 29.522 V17.0.0 (2020-12): *"5G System; Network exposure Function Northbound APIs; Stage 3"*. Available at: https://www.3gpp.org/ftp/Specs/archive/29_series/29.522/

with low delay, securely and efficiently with native CP NFs of 5GS. The Application Function using the Service Message Bus (SMB) can be used for implementation of the context-aware services. The AF using can subscribe some information from the other components of the control plane and also can publish information that can be consumed by other functional entities of the control plane. This mechanism can be used, *for example*, for identification of group of users or cars (in case of V2X) that can be handled together, etc.

The Service-Based Architecture (SBA) of the 5G CP is another fundamental architectural assumption of the 5GS. The general concept of SBA is based on utilisation of a common message bus for exchange of messages between given functional entities. Instead of predefined point-to-point interfaces between communicating parties, a different model is used, in which the exchange occurs via a common message broker. The basic scheme of the mentioned communication architecture consists of sets of publishers, sets of subscribers and a message broker (a logical message bus), which organizes messages into specific queues (“topics”). The mentioned sets of publishers and subscribers are defined per specific topics. Every message belonging to a given topic, published by any publisher is eligible for delivery into any client session of subscription to this specific topic. The SBA-based communication enables flexible distribution of functional blocks and provides scalable, reliable and lightweight communication standard between them, especially delegating the responsibility for the exchange robustness on a specialised broker instead of individual implementation of mechanisms to ensure the successful communication at end-points of each possible mutual exchange. SBA of a given system may be however translated into traditional reference point architecture, represented by a diagram in which all point-to-point interactions are indicated.

The introduction of the SBA paradigm within the 5G CP is motivated by the following factors:

- Modularity – CP functions are loosely coupled with each other, hence they may be individually upgraded or scaled with minimum impact on other CP functions;
- Extensibility – new interactions between CP functions can be easily implemented, as the SBA message bus potentially enables exchange between all connected entities;
- Reusability – common communication mechanism and implementation of CP functions as services, which can be invoked by other services and their output can be further and flexibly reused;
- Openness – through usage of generic communication mechanisms, without need of protocol conversion, the CP services can be further exposed, with additional AAA mechanisms, to trusted 3rd parties, like verticals.

Application of SBA in the 5G System architecture is based on the following assumptions:

- Definition of the 5G System as the Network Function Service Framework, which functionalities include basic mechanisms of service registration/de-registration, consumer authorisation, service discovery, and standardised inter-service communication options (direct/indirect exchange, direct/delegated service discovery and selection).
- Network Function (NF) service (single or multiple per NF) is exposed by NF (Service Producer) to another authorised NF (Service Consumer) through a Service-Based Interface (SBI), which supports two mechanisms of the end-to-end interactions between Consumers and Producers: “Request-Response” and “Subscribe-Notify”.
- The special function Service Communication Proxy (SCP) is defined, which may be deployed in a distributed manner and supports the following functionalities: indirect communication, delegated service discovery, message forwarding and routing, communication security (Consumer authorisation to access the Producer’s service), exchange monitoring, load balancing and overload control. In a general case, multiple SCP instances may exist in the same network, and the Producer-Consumer interaction may traverse a chain of several SCP instances.

- Mechanisms of service discovery are implemented via the Network Repository Function (NRF) located in the 5G System CP. This function may be collocated with SCP. Unless the expected NF and NF service information is locally configured on the requester NF, it may be retrieved from NRF, provided that the NF instance has previously been registered in NRF.
- Mechanisms of service Consumer authorisation (both in case of intra- and inter-operator interactions) are based on policies and may entail NF instance/service discovery permission and service access permission.
- For SBI CP exchange the following protocols have been selected: RESTful framework (API) based on JSON (serialisation), HTTP/2 (application layer), and TCP (transport).
- In case of non-native (e.g. Application Functions – AFs) and/or untrusted CP functions connected to CP message bus as well as systems external to the 5G System CP, the CP services shall be exposed through a special CP gateway function, Network Exposure Function (NEF).

### 2.3.4 Network Slicing

Network slicing, first envisioned by the NGMN approach[212] and enabled by aforementioned telecommunications network softwarisation and virtualisation, is also incorporated in the 3GPP 5G System foundations. The common perception of this concept focuses on the feature of the implementation of multiple parallel communication networks, architecturally oriented towards the specificity of requirements of a given service, on a shared network resource environment. Indeed, network slicing is associated with the flexibility of dynamically creating dedicated networks that do not interfere with each other, optimizing the use of shared resources, and agile network reconfiguration mechanisms in response to changing loads and traffic demand. However, these are the advantages of virtualisation and softwarisation. The idea of resources sharing is also very old; network operators have been offering infrastructure services for years (e.g. leased lines, dark fibres, copper pairs, etc.), so their resources were used to build independent and separate communication solutions. In some telecommunications markets, especially in the European Union and USA, administrative mechanisms to counter telecommunications monopoly or single operator dominance have even been introduced, forcing infrastructure owner-operators to share resources with competing operators, e.g. Local Loop Unbundling or Bit-Stream Access mechanisms.

The usage of Network Slicing (NS) allows for the creation of multiple virtual networks and network resource pools within the same physical network[213],[214]. The parameters for each network slice are optimised according to different criteria and possibly used by different tenants or organisations. Each slice can then be optimised based on the characteristics of the services being provided in that slice and the applications that can be delivered on it. A slice can be thought of as a dynamic Infrastructure as a Service (IaaS) custom made for a service[215]. Network slices can be viewed as "on demand" networks. Slicing may also include a fine-grained allocation of resources, such as compute, memory and disk space, in addition to network separation. In this view, the slice can represent a dynamic and logically independent application delivery infrastructure (IaaS). If an operator wishes to save costs by

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[212] Next Generation Mobile Networks (NGMN) Alliance (2016): *Description of Network Slicing Concept, V1.0*. Available at: https://www.ngmn.org/wp-content/uploads/160113_NGMN_Network_Slicing_v1_0.pdf

[213] Afolabi, I., Taleb, T., Samdanis, K., Ksentini, A., et *al.* (2018): Network Slicing and Softwarization: A Survey on Principles Enabling Technologies and Solutions. *IEEE Communications Surveys and Tutorials*, **20**(3), 2429-2453.

[214] Foukas, X., Patounas, G., Elmokashfi, A., and Marina, M.K. (2017, May): Network slicing in 5G: Survey and challenges. *IEEE Communications Magazine,* **55**(5), 94-100.

[215] Chochliouros, I.P., Spiliopoulou, A.S., Lazaridis, P., Dardamanis, A., Zaharis, Z., and Kostopoulos, A. (2020): *Dynamic Network Slicing: Challenges and Opportunities*. In Proceedings of the AIAI-2020 International Conference (I. Maglogiannis, L. Iliadis and E. Pimenidis (Eds.)), IFIP WG 12.5, AICT, vol.585, pp.47-60. Springer Nature Switzerland AG.

sharing slice resources (for example, oversubscribing slice resources) then it is possible, and a cost/risk study has to be conducted for each use case. However, at the management layer the resources are always logically separated. Slicing can be enabled by combining cloud technologies with SDN and NFV capabilities.

NS, which is often overlooked, means *per se* the splitting of one universal, multi-purpose communication network supporting all types of services (as it was designed until the 4G) – and therefore not optimal from the point of view of conflicting requirements of different services with completely different characteristics – into separate, yet operating in parallel component networks providing services of a specific class, where the architecture of each component network is individually tailored and tuned to the specifics of requirements for the class of service it supports. What is the most important, the same user, or more precisely the same terminal of this user, is able to be simultaneously connected to some or all of these networks, using a unified mechanism of authentication, subscription management, and can even be directed to a certain service network by another, based on the identification of his current needs and service requirements. Thus, the communication network, after its slicing, becomes a federation of service-differentiated networks that are capable of rightly taking over handling of dynamically changing user requirements.

The definition of the 5G System in the aspect of network slicing is based on the standardised set of requirements[216]. They include the following features:

- Network slice life cycle management (network slice existence, from the management point of view, is characterised by specific phases, during which it is subject to some tasks, cf. Figure 11).
- Configurable set of services supported by a network slice.
- Slice-specific policy control, differentiated functionality and performance.
- Configurable association and access of User Equipment (UE) to a network slice or multiple slices of the same PLMN (Public Land Mobile Network).
- Creation, modification, scaling and deletion of one network slice as well as its traffic and services with no impact on traffic and services of other network slices (mutual isolation).
- Configurable minimum/maximum capacity of slice and slice scaling.
- Configurable resource allocation priority for slices.
- Hosting of private (non-public) networks as slices by the PLMN.
- Prevention against unauthorised UE access to radio resources dedicated to a specific private slice.
- Cross-network slice coordination – support of services spanning slices of multiple 5G networks (both non-public and PLMN).
- Possible limiting of slice accessibility to some specified geographical area.

[216] See: 3GPP TS 22.261 V17.1.0 (2019-12): *"Service requirements for the 5G system; Stage 1; (Release 17)"*. Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/

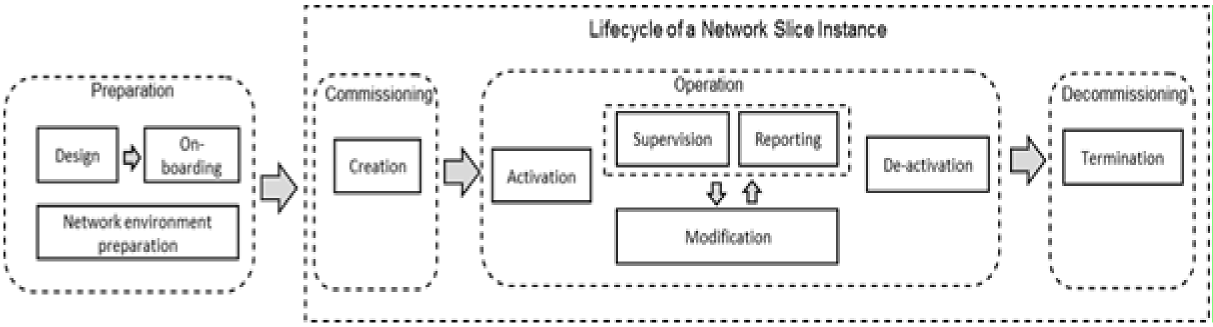


*Figure 11: Management aspects of network slicing [Source: 3GPP TS 28.530217]*

The architectural framework of the 3GPP 5G System[218] provides the key functions and mechanisms supporting network slicing (cf. Figure 12):

- Access and Mobility Management Function (AMF) – coordination of the entire UE-related signalling procedures, especially during the UE attach.
- The signalling between UE and CN-gateway point (AMF) is labelled with the Single-Network Slice Selection Assistance Information (S-NSSAI) parameter, which sets each exchange in the context of specific Network Slice Instance (NSI); S-NSSAI is composed of 8-bit Slice Service Type (SST) and optional 24-bit Slice Differentiator (SD) which provides unique identifier of NSI within the PLMN. Currently 3GPP defines 4 types of SST, indicating a basic breakdown of service groups: eMBB; URLLC; Massive IoT (MIoT), as defined by ITU-R IMT-2020, and V2X (added in June 2019, as it was considered as appropriate to distinguish this group of 5G use cases); but the list may be further extended in the future. SD may also code some more detailed properties of specific network slice template, its purpose, associated service profile (e.g. derived from service level specification related to standardised requirements for specific use cases, cf. section *2.3.6 Support of demanding QoS*, or driven by some specific SLA), tenant, etc., according to naming convention policy of MNO.
- Network Slice Selection Function (NSSF) – determining the availability of specific NSI on a per Tracking Area basis and support of selection or substitution (in case of unavailability) of requested NSI and AMF to serve the requesting UE.
- Network Slice-Specific Authentication and Authorisation Function (NSSAAF) – support of UE access authentication and authorisation to specific slice, in cooperation with Authentication, Authorisation and Accounting (AAA) server, which may belong to the 3rd party and be located outside the PLMN (to be contacted via AAA proxy).
- Unified Data Management (UDM) – management of UE profile, also in the context of subscribed/allowed network slices.
- Network Repository Function (NRF) – support of NF service discovery function, maintaining the NF profile with available NF instances, their supported services and health status; individual NRF instances may be deployed at several information scope levels: the whole PLMN, shared-slice (a set of Network Slices), slice-specific (individual NSI).
- Network Data Analytics Function (NWDAF) – providing network data analytics based on the information collected from NFs; in the context of network slicing, it may span specific NSI(s) and implement analytic algorithms appropriate to NSI-supported service and/or use case

[217] See the scope presented in 3GPP TS 28.530 V15.1.0 (2018-12): *"Concepts, use cases and requirements (Release 15)"*. Available at: https://www.etsi.org/deliver/etsi_ts/128500_128599/128530/15.01.00_60/ts_128530v150100p.pdf

[218] 3GPP TS 23.501 V16.3.0 (2019-12): "*System Architecture for the 5G System (5GS); Stage 2 (Release 16)*". Available at: https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/

specificity, e.g. mechanisms of detection and early warning of possible communication loss due to leaving the slice coverage area by the on-board UE of a drone. In the PLMN CP, there may be deployed multiple, differently specialised NWDAFs with the scope related to supported NFs classes, collection and analytics mechanisms, Tracking (or geographic) Area or management hierarchy level span (global, shared-slice or slice-specific), according to technological constraints and/or MNO policies.

- Network Exposure Function – serving as a CP gateway for non-native or untrusted CP NFs, including also specialised Application Functions (AFs), as well as for exposure of CP services and interaction of the 5G System with external, "business layer" systems, e.g. vertical's environments.
- User Plane Function (UPF) is NSI-specific (its internal architecture is driven by requirements of supported service and additionally by specific use case) and controlled by its individual CP counterpart, Session Management Function (SMF). It is assumed that a UE may be concurrently attached to up to 8 different NSIs of the same PLMN.

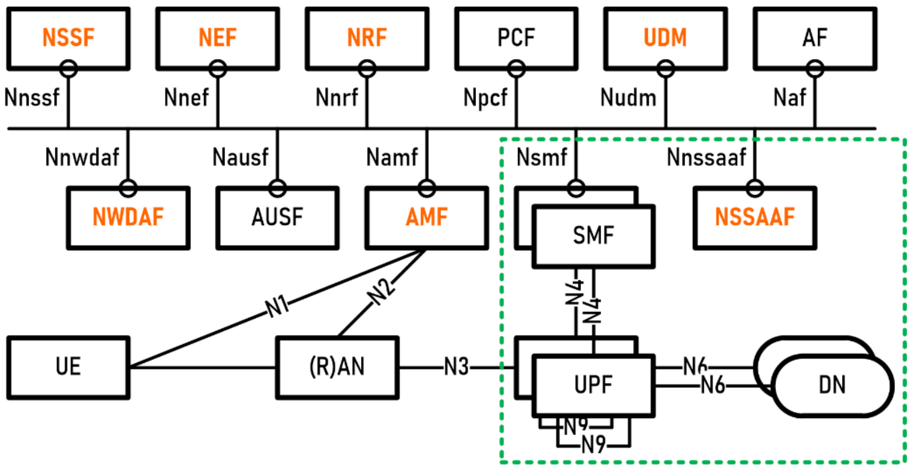


*Figure 12: 5G System basic architecture framework with indication of NFs involved in network slicing (functions inside the green dashed line area are inherently slice-specific)*

The CP SBA mechanisms presented earlier, in particular the authorisation of CP NFs discovery and access at the per-Producer/per-Consumer level, enable logical partitioning of CP, which supports CP network slicing (common slices/dedicated slices). Some NFs may be deployed as globally common, shared or NSI-dedicated, while others will be inherently NSI-specific (cf. Figure 12).

Network slicing support is also envisioned at the level of RAN[219] and includes the following:

- RAN awareness of slices.
- Handling the traffic of different slices by different PDU sessions.
- Implementation of slicing in RAN: scheduling or L1/L2 configurations.
- Slice selection assistance information (S-NSSAI) provided by UE or 5G Core.
- Radio Resources Management (including resources isolation), configuration and QoS/SLA policies on per-NSI level.
- Core Network selection by RAN: UE-assisted or forwarding to default AMF.

[219] See the framework discussed in 3GPP TS 38.300 V16.4.0 (2021-01): *"NR; NR and NG-RAN Overall description; Stage-2"*. Available at: https://www.3gpp.org/ftp/Specs/archive/38_series/38.300/

 

- Support for UE association to multiple slices (up to 8), one common signalling connection for all slices.
- Slice-aware UE admission in RAN (protection against unauthorised access to a slice) and congestion control (if the requested slice is overloaded, the UE will be connected to a default one).

The example of 5G network slicing in CP and UP, with depiction of key mechanisms and essential point-to-point exchange flows, is illustrated in Figure 13.

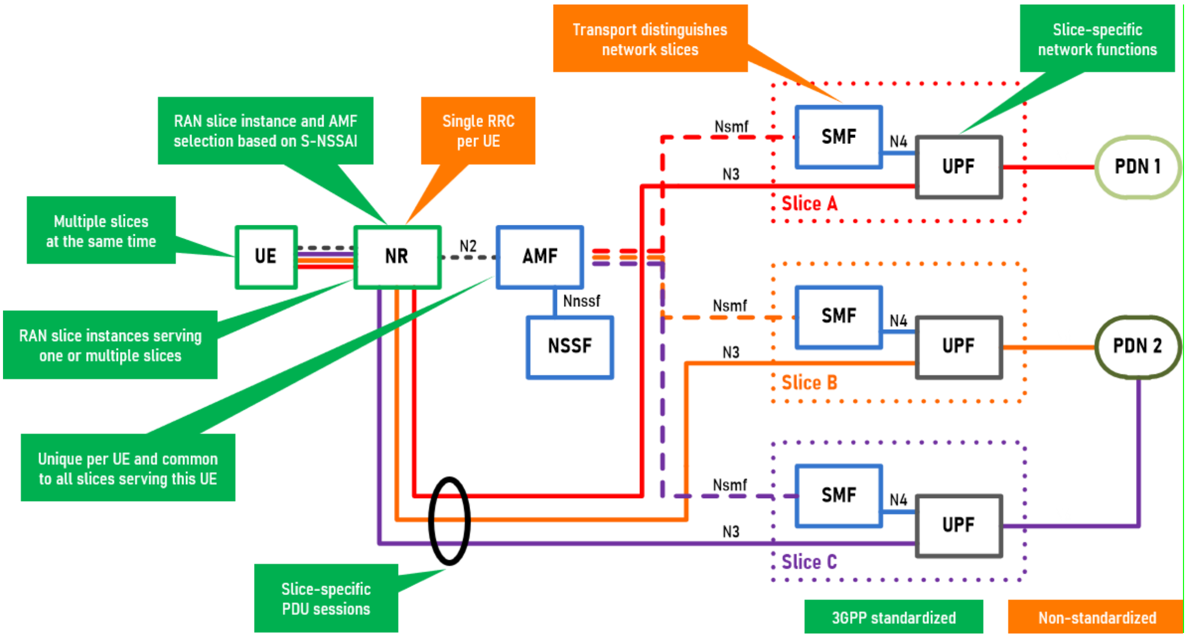


*Figure 13: Example of 5G network slicing*

The vision management of network slicing in the 3GPP 5G System is based on the 4-level hierarchy of end-services deployment: Communication Service Instance (CSI) is located in the Communication Service Provider (CSP) Domain on top of the Network Operator Domain, which is consisted of a stack of Network Slice/Network Slice Subnet/Network Function instances. CSIs may use several NSIs, which are complete, instantiated logical networks that meet certain characteristics as required by these CSIs. NSI can be composed of multiple Network Slice Subnet Instances (NSSIs) that are similar to NSI, but do not have to form a complete logical communication network. They can be considered as NSI building blocks, in general case – recursively formed, which belong to different technological, administrative, geographical or ownership domains. NSSIs will be built of Access or Core NFs (virtual - VNF or physical - PNF) and/or other NSSIs. NSSIs may also be shared by other NSSIs or NSIs. In this concept, CSIs are separate to NSIs, also in terms of decoupling their life cycles. At each of abovementioned levels, the corresponding Management Functions (MFs) are defined (i.e. CSMF, NSMF, NSSMF, and NFMF).

 

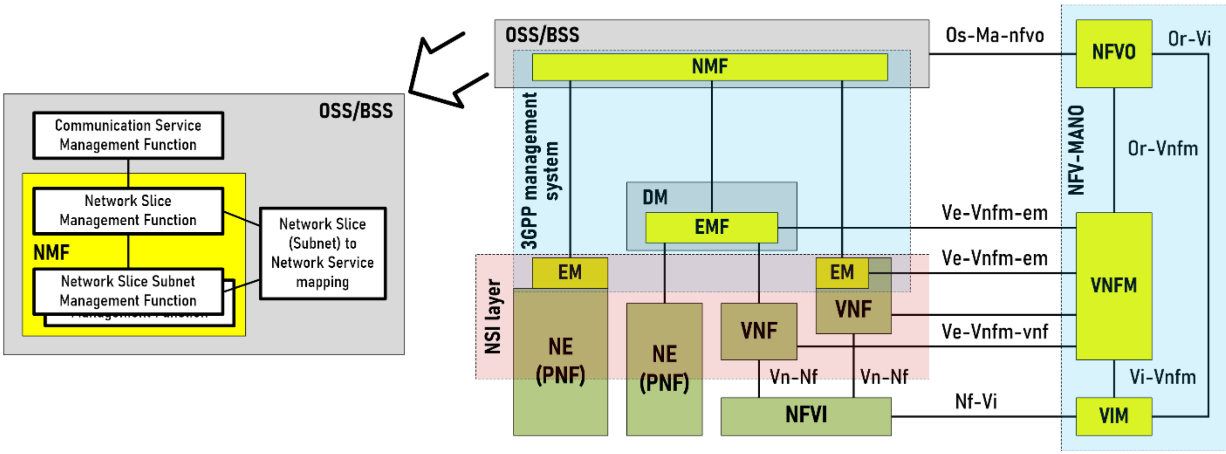


*Figure 14: High-level 5G network management architecture by 3GPP*

The 3GPP 5G System management framework is based on the following architectural assumptions:

- SBA model of management entities' interactions, similarly as in CP (management service Producers/Consumers), including message bus for exchange between management functions.
- Adoption of ETSI NFV MANO framework and mutual complementarity of the 3GPP management layer and ETSI NFV MANO[220]; individual EMs of VNFs or shared EMFs for NF level management of multiple VNFs/PNFs (Domain Managers – DMs) for VNF and PNF management play a role of the 3GPP NFMF, while OSS/BSS contains the 3GPP NSMF and 3GPP NSSMF (cf. Figure 14).
- In addition to aforementioned CSMF, NSMF, NSSMF, and NFMF, two additional management functions are defined: Exposure Governance Management Function (EGMF) and Management Data Analytics Function (MDAF)[221].
- EGMF plays a similar role in the management plane as NEF in CP – acts as a secured gateway for exposure of management services to external or untrusted domains to isolate the PLMN management plane mechanisms, services and data from unauthorised access.
- MDAF plays a similar role in the management plane as NWDAF in CP – provides the Management Data Analytics Service for one or more NFs, NSSIs and/or NSI, and may consume some management services produced by other management plane functional blocks.

Currently, the full inclusion of all network slicing requirements, both generic[222] and implied by specific areas of application, into the 5G System architecture and mechanisms, especially RAN slicing, is still under development (cf. 3GPP Release 17 scope[223]). Network slicing has not been deployed in commercial network, yet. The existing 5G networks still work as general-purpose networks dedicated to meet eMBB characteristics (i.e. as "boosted LTE").

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[220] See the context presented by the Third Generation Partnership Project in 3GPP TS 28.530 V17.0.0 (2020-12): "*Management and orchestration; Concepts, use cases and requirements (Release 17)*". Available at: https://www.3gpp.org/ftp//Specs/archive/28_series/28.530/

[221] 3GPP TS 28.533 V16.6.0 (2020-12): *"Management and orchestration; Architecture framework".* Available at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.533/

[222] See: 3GPP TS 22.261 V17.1.0 (2019-12): "*Service requirements for the 5G system; Stage 1 (Release 17)*". Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/

[223] Available at: https://www.3gpp.org/release-17

It is also worth a mention that the mutual complementarity of ETSI NFV MANO and the 3GPP management vision is also reflected in the incorporation of network slicing support into the ETSI NFV framework. ETSI NFV ISG found the mechanisms of management and isolation between network services in multi-tenant virtualisation platforms generally sufficient to support network slicing. The only additional mechanism of slicing support, included in the NFV specification, is the "priority" attribute of Network Service Deployment Flavour. It is used to specify the priority for the Network Service instance (i.e. NSI). The priority value (integer) is intended for conflict resolution in case of resource shortage, where the "zero" value expresses the highest NSI priority, which means that NSI based on this Deployment Flavour cannot be pre-empted during resource allocation[224].

The intention of a 5G slice is to provide only the traffic treatment that is necessary for the use case, and avoid all other unnecessary functionality. The flexibility behind the slice concept is a key enabler to both expand existing businesses and create new businesses. To enable full automation of network slice management, NFV MANO[225] functions need to be complemented and interwork with the network slice management functions. These management functions can consume the APIs exposed by the NFV Orchestration (NFVO) layer as well as other APIs exposed by other management entities enabling full FCAPS[226] of the network functions involved in the instance of that network slice. Network slice management can be viewed as a functional area that needs to be standardised on top of NFV[227]. Multi-operator inter working will require model harmonisation and this is once such area where a common top down model will be required to serve as an industry business requirement. Network slicing also impacts the NFVI (Network Function Virtualisation Infrastructure) because it places requirements on security, resource usage and fault isolation at the infrastructure layer.

While NSI be defined on top of physical resources, the benefit of using virtualised resources gives the flexibility inherent to NFV, such as sharing resources, allocating resources to a slice dynamically, scaling automatically, self-healing, deploying a slice automatically, etc., while they keep their own network management capabilities. The slicing idea is based on the concept that each slice will be created to cover the demand for one or more services, that is: (i) providing connectivity between endpoints (terminals or network gateways); (ii) processing traffic in between end-point where needed; (iii) providing network and Services management capabilities (OSS[228]) and its own Real Time (RT) network and service management capabilities; and (iv) providing support for the business administration (BSS). Network slices may constitute a set of network functions managed by distinct and possibly different administrative network authorities. Network slices may have dedicated

[224] An interesting and detailed scope has been presented in ETSI GS NFV-IFA 014 V3.3.1 (2019-09): "*Network Functions Virtualisation (NFV) Release 3; Management and Orchestration; VNF Descriptor and Packaging Specification*". Available at: *https://standards.iteh.ai/catalog/standards/etsi/bde92e6c-d4d0-48cc-8a16-1c34ce133675/etsi-gs-nfv-ifa-014-v3.3.1-2019-09*

[225] Management and Orchestration (MANO) has been identified to become a critical component of NFV and an initial framework was defined by ETSI in early 2013. The framework has since evolved significantly and a large set of specifications (interfaces, APIs, data models, etc.) have been published.

For more details see: European Telecommunications Standards Institute (ETSI): ETSI GS NFV-MAN 001 V1.1.1 (2014-12): *"Network Functions Virtualisation (NFV); Management and Orchestration"*. Available at: *https://www.etsi.org/deliver/etsi_gs/NFV-MAN/001_099/001/01.01.01_60/gs_NFV-MAN001v010101p.pdf*

[226] FCAPS is the ISO Telecommunications Management Network model and framework for network management. FCAPS is an acronym for Fault, Configuration, Accounting, Performance and Security which are the management categories into which the ISO model defines network management tasks.

[227] European Telecommunications Standards Institute (ETSI): ETSI GR NFV 001 V1.2.1 (2017-05): *"Network Functions Virtualisation (NFV); Use Cases"*. Available at: *https://www.etsi.org/deliver/etsi_gs/NFV-MAN/001_099/001/01.01.01_60/gs_NFV-MAN001v010101p.pdf*

[228] OSS/BSS include the collection of systems and management applications that service providers use to operate their business. NFV is disruptive to many OSS/BSS functions, as the success of such a technology enabled business transformation is predicated on changes in mind-sets, skillsets and toolsets to support corresponding process re-engineering efforts.

network functions, or multiple network slices can share the same set of network functions and physical resources.

The efforts of 3GPP dedicated to network slicing standardisation are complemented by GSMA. This SDO is working on reference network slice templates development[229]. As a result, the concept of Generic network Slice Template (GST) has been defined. GST is a generic set containing all potential attributes that characterize a type of network slice. When the GST attributes are filled with values based on use case requirements, the Network Slice Template (NEST) is obtained, which may then be used for network slice preparation (cf. Figure 11). The GST attributes may be categorised as character (further split to performance-, function-, and control and management-related) scalability attributes. Currently, there are 36 attributes defined, which are in general one- or more-dimensional variables. Definition of each attribute contains relevant parameters: measurement unit, allowed values, categorisation tags and specifies attribute presence requirement (mandatory/conditional/optional).

The NS concept goes beyond the well-known VPN concept and enables customisation of the control plane operation per slices. Moreover, there exists an option of delegating of some management operations to the vertical, which is using a slice or set of slices. That way the vertical will have a feel of operating of its own virtual network. Such mechanisms were not available in previous generations of mobile networks.

### 2.3.5 Mobile Edge Computing

MEC provides a new ecosystem and value chain and the opportunity for all players within it to collaborate and develop new business models they can each benefit from. Mobile Network Operators (MNOs) can rapidly deploy new services for consumer and enterprise business segments, which can help differentiate their service portfolio.

The definition of the 5GS architecture also enables incorporation of the Mobile Edge Computing (MEC) into the 5GS architecture[230]. MEC enables the implementation of mobile edge applications as software-only entities that run on top of a virtualisation infrastructure, which is located in or close to the network edge[231]. MEC framework shows the general entities involved. These can be grouped into system level, host level and network level entities. With 5G, edge computing is identified as one of the key technologies required to support low latency together with mission critical and future IoT services. The system was designed from the beginning to provide efficient and flexible support for edge computing to enable superior performance and quality of experience.

NSI-specific UPF chaining (especially multi-homed UP sessions), NEF and AF in the CP allow deep integration of AP at the edge of the mobile network (e.g.: location of cloud computing nodes at the gNBs[232]). In this way, the AP-level processing of UP data can be performed as near to the data

[229] GSM Association (GSMA) (11/2020): *Generic Network Slice Template. Version 4.0*. Available at: https://www.gsma.com/newsroom/wp-content/uploads//NG.116-v4.0-2.pdf

[230] For more details see: European Telecommunications Standards Institute (ETSI): ETSI GS MEC 003 001 V1.1.1 (2016-03): *"Mobile Edge Computing (MEC); Framework and Reference Architecture"*. Available at: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/01.01.01_60/gs_MEC003v010101p.pdf

The MEC system as defined in the above specification as well as in the related interface specifications and it is to a large extent self-contained, covering everything from management and orchestration down to interactions with the data plane for steering specific traffic flows.

[231] Also see: European Telecommunications Standards Institute (ETSI): ETSI GS MEC 017 V1.1.1 (2018-02): "*Mobile-Edge Computing (MEC); Deployment of Mobile Edge Computing in an NFV environment*". Available at: https://www.etsi.org/deliver/etsi_gr/MEC/001_099/017/01.01.01_60/gr_MEC017v010101p.pdf

[232] Node B is the radio base station for 3G UMTS (Universal Mobile Telecommunications System), while eNodeB is the radio base station for 4G LTE (Long Term Evolution). The gNB is the logical 5G radio node, the equivalent of what was called NodeB in 3G-UMTS and eNodeB or eNB (i.e., evolved Node B) in 4G-LTE, is now called as the "next generation NodeB".

 

consumer, as it is possible. MEC provides low delay of communication and more efficient data traffic handling, especially in case of streaming services.

Multi-access Edge Computing (MEC), formerly Mobile Edge Computing, is an architectural framework dedicated to provisioning of cloud-computing capabilities at the edge of the mobile network, in the proximity of mobile subscribers. Through placement of IT applications (Layer 4 and above) at the edge of RAN, the Over-the-Top services benefit of low transmission latency, while integration of the MEC framework with RAN and real-time access to RAN information (UE location, radio signal conditions) enables efficient application mobility to follow the customers' mobility. Mobile operator may also benefit of reshaping the traffic distribution and offloading the transport network. The definition of ETSI MEC framework, initially for hardware-based environment, was later extended to accommodate the environments virtualised according to ETSI NFV standard.

The generic MEC architecture[233] is composed of:

- MEC system level entities: OSS, MEC Applications/infrastructure orchestration entities and application life cycle management API proxy.
- MEC host level entities: MEC Platform (MEP) hosting MEC Applications and exposing platform services API to the hosted MEC Applications, MEC Platform Manager (MEPM) responsible for management of platform itself as well as applications rules/requirements/life cycle, Virtualisation Infrastructure and its Manager.
- underlying network – local, external or 3GPP network.

The generic reference architecture of MEC system is shown in Figure 15. The key advantageous features of MEC are:

- Mechanism of seamless MEC Application mobility;
- platform services APIs for radio conditions contexts exposure, users location, and data traffic management;
- mechanisms of underlying data network traffic steering (via Mp2 reference point) for selective redirection of MEC Applications' data;
- mechanisms of MEC Applications implementation and orchestration.

The MEC Platform Radio Network Information Service[234] exposes on per UE or per cell:

- Appropriate radio network information about current radio network conditions;
- UP measurements;
- detailed information – and changes on this information – related to UEs served by the radio node(s) associated with the MEC host (list of served UEs with UE context and associated Radio Access Bearers);
- the MEC Platform Location Service[235] provides the following information about the UEs

[233] See: ETSI GS MEC 003 V2.2.1 (2020-12): *"Multi-access Edge Computing (MEC); Framework and Reference Architecture"*. Available at: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/02.02.01_60/gs_MEC003v020201p.pdf

[234] See: ETSI GS MEC 012 V2.2.1 (2019-12): *"Multi-access Edge Computing (MEC); Location API"*. Available at: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/012/02.01.01_60/gs_mec012v020101p.pdf

[235] See: ETSI GS MEC 003 V2.2.1 (2020-12): *"Multi-access Edge Computing (MEC); Framework and Reference Architecture"*. Available at: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/02.02.01_60/gs_MEC003v020201p.pdf

currently served by the radio node(s) associated with the MEC host:

- location of specific/all/certain category of UEs;
- distance between specified UEs or between a specified location and specific UE;
- list of UEs in a particular location area;
- specific UEs, which move in or out of a particular location area;
- location of all radio nodes currently associated with the MEC host.

A very important MEC Platform service, from the 5G-DRIVE project point of view is V2X Information Service[236], which specifies the API to facilitate V2X interoperability in a multi-vendor, multi-network and multi-access environment.

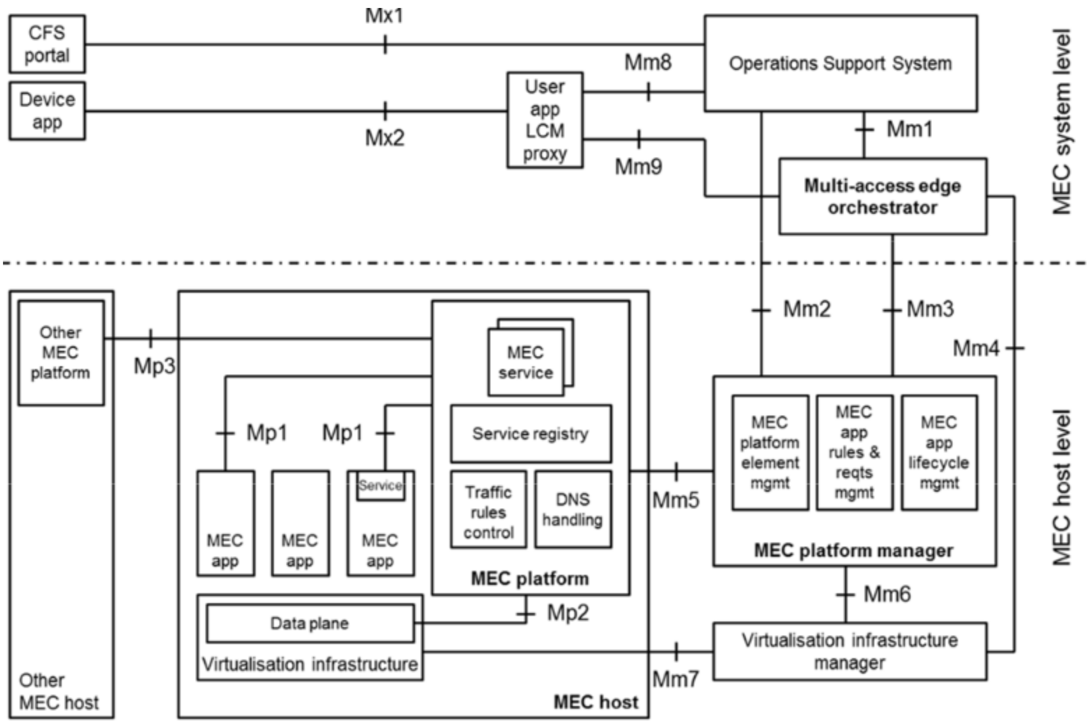


*Figure 15: Multi-access edge system reference architecture [Source: ETSI GS MEC 003 V2.2.1 (2020-12)]*

Alignment of MEC system with ETSI NFV framework slightly changes the generic architecture (cf. Figure 16). MEC Platform and MEC Platform Manager are now implemented as VNFs as well as MEC Applications and the life cycle management is handed over to VNFM. The task of MEC Applications infrastructure orchestration is transferred to NFVO, hence MEC Orchestrator (now renamed to “MEC Application Orchestrator”) plays a role of “service orchestrator”, still remaining in charge of coordination of on-boarding of Application packages and requesting their instantiation, relocation and termination. MEC System also relies on VIM of the NFV platform.

[236] See: ETSI GS MEC 030 V2.2.1 (2020-04): *“Multi-access Edge Computing (MEC); V2X Information Service API”*. Available at: https://www.etsi.org/deliver/etsi_gs/MEC/001_099/030/02.01.01_60/gs_MEC030v020101p.pdf

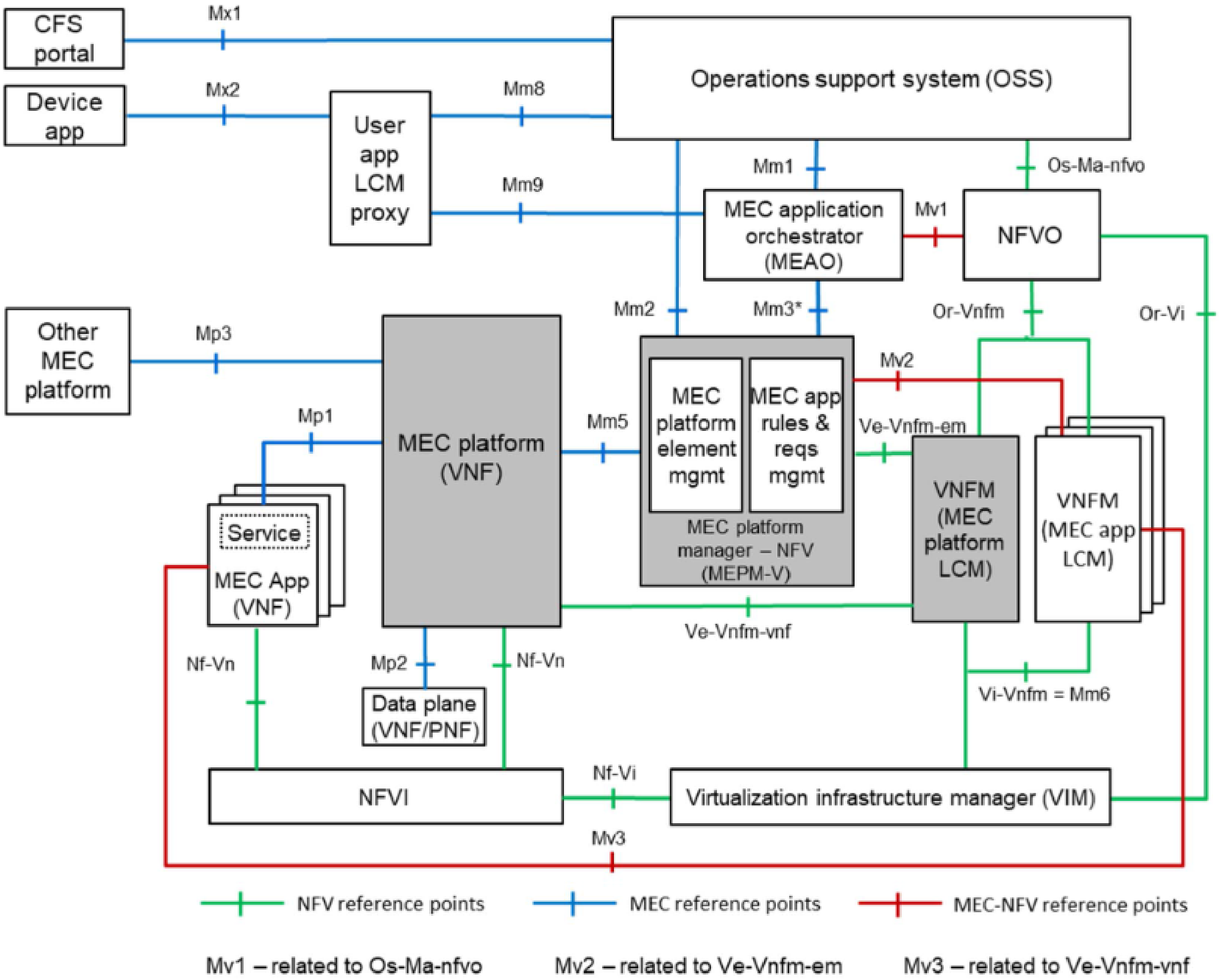


*Figure 16: Multi-access edge system reference architecture variant for MEC in NFV [Source: ETSI GS MEC 003 V2.2.1 (2020-12)]*

Integration of MEC with 5G System is still an open issue:

- It is commonly recognised that MEP will be integrated with the 5G System CP as a special case of AF, where Mp2 = Naf; depending on the NOP policy, MEP may be treated as trusted AF and interact directly with CP NFs or as untrusted and interact through NEF as a secure CP gateway.
- Interactions of MEP with the 5G System CP will be aimed at: influencing the application traffic routing decisions, including UPF (re)selections, to enable local breakout of relevant traffic to MEC Application; accessing NEF for network capabilities; interacting with the policy framework (PCF, cf. TS 23.503[237]) for policy control.
- So far, only the MEC ISG report has been published[238] in which there have been identified 8 key issues and 11 solutions proposed for further evaluation proceeding future normative decision.
- Additional dimension of MEC and 5G System integration is imposed by the question of network slicing; in general, MEC Platform has to be slicing-aware – it has to recognize NSIs,

[237] See: 3GPP TS 23.503 V16.7.0 (2020-12): *"Policy and charging control framework for the 5G System (5GS); Stage 2"*. Available at: https://www.3gpp.org/ftp/Specs/archive/23_series/23.503/

[238] See the work in ETSI GR MEC 031 V2.1.1 (2020-10): *"Multi-access Edge Computing; 5G MEC Integration"*. Available at: https://www.etsi.org/deliver/etsi_gr/MEC/001_099/031/02.01.01_60/gr_MEC031v020101p.pdf

distinguish between them and perform operations on per-NSI level; however, there are various deployment scenarios possible, e.g. MEC Platform inside NSI (dedicated MEC) or NSI inside MEC Platform (shared MEC) – in case of multi-tenant PLMNs or MEC platforms integrated with different PLMNs there is a serious question of isolation of services and information available for a given NSI from other NSIs. There is also the question of who will own the MEC platform, which has access to sensitive data and equally sensitive technological mechanisms. The ETSI MEC ISG report on the issue of network slicing support has already been published[239] with 6 consolidated recommendations addressed to 3 existing ETSI MEC normative documents, but there is no normative follow-up, yet.

The integration visions proposed so far are superficial and create a loose patchwork of essentially unchanged architectures. It should be noted that the effective integration of several architectural frameworks (slicing-enabled 5G System, NFV and MEC) requires thorough analysis and a deep redesign of the final overall architecture. Especially, overlapping functionalities have to be eliminated to avoid competitive behaviour of similar mechanisms, which can make the system instable. The combination of certain functions will lead to a reduction in the number of interactions and reference points in the system.

Moreover, the visions of management architecture proposed by 3GPP and ETSI are centralised, which will create serious problems with scalability of management and orchestration of hundreds or even thousands of concurrently running NSI-based communication networks. Therefore, it is necessary to change the architectural paradigm and move to distributed management architectures; in particular, nesting the management layer within the NSI, using autonomous and cognitive management algorithms with hierarchical Monitor-Analyse-Plan-Execute loops[240] and exposing the intent-based management interface to slice tenant. A proposal of integrated architecture designed in this spirit has defined and published as part of the 5G-DRIVE project[241].

### 2.3.6 Support of demanding QoS

The question of QoS in 5GS may be investigated in four following areas:

- Initial IMT-2020 visions of technology application context and performance targets.
- Service requirements related to use cases specificity.
- Means for providing QoS, defined by the 5GS architecture.
- 5GS performance and QoS measurement standardisation.

The initial definition of QoS targets for radio part of 5GS has been provided by the ITU-R IMT-2020 study[242]. Figure 17, below, shows conceptually the multidimensional 5GS capabilities by ITU-R in comparison with 4G system.

[239] For more details see the framework in ETSI GR MEC 024 V2.1.1 (2019-11): *“Support for network slicing”*. Available at: https://www.etsi.org/deliver/etsi_gr/MEC/001_099/024/02.01.01_60/gr_MEC024v020101p.pdf

[240] IBM, “Autonomic Computing White Paper: An architectural blueprint for autonomic computing”, 3rd edition, 2006.

[241] Tomaszewski, L., Kuklinski, S., and Kołakowski, S. (2020): *A New Approach to 5G and MEC Integration*. In Proceedings of the AIAI-2020 International Conference (I. Maglogiannis, L. Iliadis and E. Pimenidis. (Eds.)), IFIP WG 12.5, AICT, vol. 585, pp.15-24. Springer Nature Switzerland AG.

[242] International Telecommunication Union - Radiocommunications Sector (ITU-R): Recommendation ITU-R M.2083-0 (09-2015): *“IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond”*.

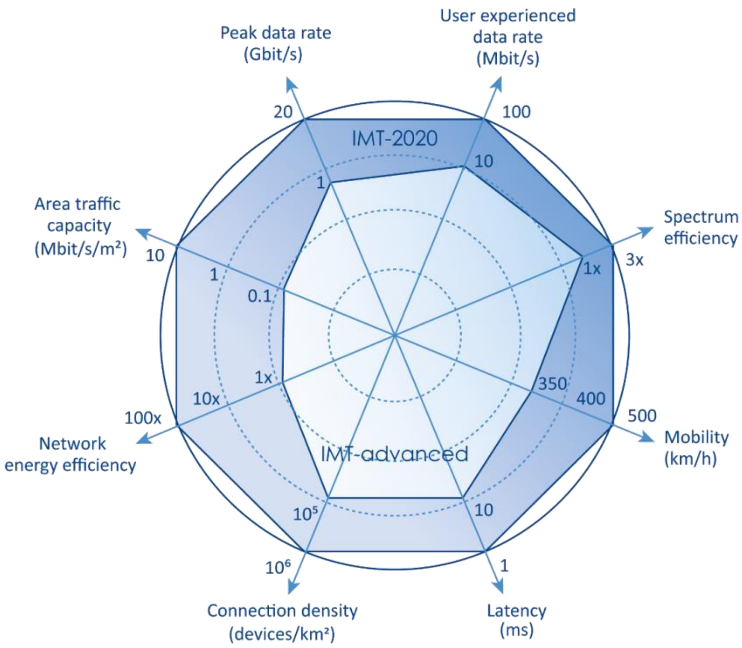


*Figure 17: Comparison of key capabilities of 4G (IMT-Advanced) and 5G (IMT 2020) [Source: ITU-R Recommendation M.2083-0]*

From the 5G-DRIVE project point of view, the most important QoS criteria are:

- **Data rate**: The ITU-R requires the minimum peak data rate of 20 Gbps (DL) and 10 Gbps (UL), while the user experienced rate would be 200 times smaller. These goals will be achieved twofold: by wider transmission bandwidth (up to 100 MHz/1 GHz of total aggregated bandwidth in bands below/above 6 GHz respectively) and by higher efficiency of modulation techniques (peak spectral efficiency 30 bit/s/Hz for DL and 15 bit/s/Hz for UL). It should be noted that the assumed average values of spectral efficiency include different environments (indoor, dense urban or rural), hence the 5GS in 100 MHz bandwidth should be able to deliver data rates of 900/780/330 Mbps DL and 675/540/160 Mbps UL, *respectively*. The assumed values of spectral efficiency consider also terminals' mobility: the target spectral efficiencies for transmission in motion are defined at speeds of 10, 30, 120 and 500 km/h (high-speed trains), providing the targets of 150, 112, 80 and 45 Mbps in 100 MHz bandwidth.
- **Latency**: The ITU-R requirements for maximum UP latency define the target of 4 ms for eMBB services and 1 ms for URLLC services. The defined maximum CP latency (i.e., related to radio layer state transitions) is 20 ms. It should be noted that the radio-layer delay assumptions and promises of ITU-R are commonly confused with the E2E latency perceived by the end-user of the 5GS. This E2E latency is composed of four main contributing factors, as follows:

    1. RAN-related latency, caused by packet transmission between base station (BS) and UE as well as its processing in the Physical layer (PHY) including channel coding, modulation, scrambling and OFDM signal generation in UE and reverse operations in the base station.

    2. Latency related to transmission time between the base station and the Core Network (CN).

    3. CN processing time contributed by CN entities, caused by network procedures related to different network functions (e.g.: mobility aspects or security provision).

    4. Transmission time between the CN and appropriate Data Network (e.g. Internet, Cloud).

 

In order to achieve 1 ms E2E latency in 5GS, several amendments had to be incorporated in comparison to 4G so that to reduce the impact of each one of the above-mentioned components. The first major alteration regards the Physical Interface and modifying possible subcarrier spacing in OFDM. In 5G, subcarrier spacing can be implemented in a range of 15 to 480 kHz (in comparison to fixed 15 kHz in LTE), thus enabling rescaling OFDM symbol duration as well as slot duration within transmitted data frames. Additionally, in order to address sub-1ms latency demand, a scalable Transmission Time Interval (TTI) has been introduced enabling transmission with significantly shortened interval, for example ~140 µs (fixed value of 1 ms for LTE). Other latency reductions in RAN are achieved by implementing solutions such as CodeBlock Group (CBG) retransmissions or new signal reception techniques such as front-loaded Demodulation Reference Signal (DMRS).

Reduction of latency caused by the other components of the network can be efficiently diminished by means of virtualisation and deploying network functions closer to the edge (e.g. by using MEC) and thus minimizing the latency related to the physical transmission between entities. It is worth a mention that the virtualisation technologies due to addition of new layers increase the overall E2E delay; hence the implication of each underlying 5GS technology on the E2E latency has to be carefully and properly analysed.

- **Reliability**: the reliability target according to ITU-R[243] is $1\text{-}10^{-5}$ (i.e. 99,999%), however the specific use case requirements by 3GPP[244,245] set much higher goals (99,9999% for ITS, smart grids, closed-loop control, and even 99,99999% for UHD video in medical imaging). These targets are complemented by the zero mobility interruption time (0 ms) – which is defined as the shortest time duration supported by the 5GS, during which the device cannot exchange packets with any base station due to on-going handover procedure[246].

The vision of 5GS originates from the IMT-2020 initiative of ITU. The fundamental vision assumes a split of a generic, omni-purpose mobile IP access service (LTE and predecessors) into three types of services (also referred to as “usage scenarios”), that is: eMBB, mMTC and URLLC[247].

For each of them there are some dominating aspects: transmission data rate (eMBB), device density (mMTC) and latency combined with transmission continuity and reliability (URLLC).

The commonly agreed targets for IMT-2020 usage scenarios parameters are presented in the following table.

| Parameter | Key Performance Indicator (KPI) | eMBB | mMTC | URLLC |
|---|---|---|---|---|
| Peak data rate | DL 20 Gbps<br>UL 10 Gbps | x | | |
| Peak spectral efficiency[248] | DL 30 bps/Hz | x | | |

243 International Telecommunication Union – Radiocommunications Sector (ITU-R): Recommendation ITU-R M.2083-0 (09-2015): *“IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond”*.

244 3GPP TS 22.261 V17.1.0 (2019-12): *“Service requirements for the 5G system; Stage 1; (Release 17)”*. Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/

245 3GPP TS 22.263, V17.0.0 (2019-12): *“Service requirements for Video, Imaging and Audio for Professional Applications (VIAPA); Stage 1 (Release 17)”*. Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.263/

246 International Telecommunication Union – Radiocommunications Sector (ITU-R): Recommendation ITU-R M.2083-0 (09-2015): *“IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond”*. Available at: https://www.itu.int/rec/R-REC-M.2083-0-201509-I/en

247 Ibid.

| Parameter | Key Performance Indicator (KPI) | eMBB | mMTC | URLLC |
|---|---|---|---|---|
| | UL 15 bps/Hz | | | |
| User Plane latency | 1 ms | | | x |
| | 4 ms | x | | |
| Control Plane latency | 20 ms | x | | x |
| User-experienced data rate | DL: 100 Mbps<br>UL: 50 Mbps | x | | |
| Area traffic capacity | 10 Mbps/m$^2$ | x | | |
| Connection density | 10$^6$ devices/km$^2$ | | x | |
| Energy efficiency | 90% reduction in energy usage | x | x | |
| Reliability (packet loss rate) | 1 ppm | | | x |
| Reliability (transmission success rate)[249] | 99,9999% | | | x |
| Mobility | 500 km/h | x | | |
| Mobility interruption time | 0 ms | x | | x |
| System bandwidth support | Up to 100 MHz (bands <6 GHz)<br>Up to 1 GHz (bands >6 GHz) | x | x | x |
| Radio coverage limit[250] | 164 dB | | x | |
| UE battery life | 15 years | | x | |

*Table 1: KPIs' targets for basic service types251*

The requirements for use cases and applications of 5G services have been defined by the 3GPP in the following documents:

TS 22.261[252]: Service requirements for the 5G system.

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248 Maximum transport capacity of the radio bandwidth used (how much of transmitted data rate can be allocated at each Hz of RF bandwidth).

249 Probability of successful transmission of 32 B within 1 ms.

250 This parameter is used to determine borders of the coverage area in geo-spatial RF signal estimations. It is defined as: *Maximum Coupling Loss (MCL) in UL and DL between device and Base Station site antenna connectors for a data rate of 160 bps, where the data rate is observed at the egress/ingress point of the radio protocol stack in uplink and downlink. The target for coverage should be 164 dB*. For real settings it can be calculated as a difference (result in dB) between the TX output power (in dBm) and RX sensitivity (in dBm). Cf. 3GPP TR 38.913 V16.0.0 (2020-07): "Study on Scenarios and Requirements for Next Generation Access Technologies; (Release 16)" (Available at: https://www.3gpp.org/ftp//Specs/archive/38_series/38.913/ ). For reference also see:

| RAN technology | MCL [dB] |
|---|---|
| E-GPRS | 164 |
| LTE | 144 |
| LTE-M or CAT-M1 | 160 |
| LTE-NB or NB-IoT | 164 |
| LoRa | 157 |

251 Cf. Eiman Mohyeldin (Nokia), Minimum Technical Performance Requirements for IMT-2020 radio interface(s), ITU-R Workshop on IMT-2020 terrestrial radio interfaces, Oct.2017. Available at: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Documents/S01-1_Requirements%20for%20IMT-2020_Rev.pdf. [Also see 3GPP TR 38.913].

TS 22.179[253]: Mission Critical Push to Talk (MCPTT); Stage 1.

TS 22.280[254]: Mission Critical Services Common Requirements (MCCoRe); Stage 1.

TS 22.281[255]: Mission Critical (MC) video.

TS 22.282[256]: Mission Critical (MC) data.

TS 22.186[257]: Service requirements for enhanced V2X scenarios.

TS 22.071[258]: Location Services (LCS); Service description; Stage 1.

TS 22.104[259]: Service requirements for cyber-physical control applications in vertical domains.

TS 22.262[260]: Message service within the 5G System (5GS); Stage 1.

TS 22.125[261]: Unmanned Aerial System (UAS) support in 3GPP.

TS 22.263[262]: Service requirements for Video, Imaging and Audio for Professional Applications (VIAPA).

Apart from functional/behavioural requirements, the KPIs targets have been specified, referring to the ITU-R parameters above and also new ones like payload size or service area square/linear dimension.

The 5G System architecture[263] defines some mechanisms for providing the requested QoS:

- The 5G QoS model is based on QoS Flows, which are identified in the 5G System with their QoS Flow ID (QFI). The flows may be Guaranteed Bit Rate (GBR) type or Non-GBR type. Each QoS flow is characterised at least by its QoS profile (recognised both in the Core Network and Radio Access Network), QoS rules, and Uplink/Downlink (UL/DL) Packet Detection Rules (PDRs), of which UPF is aware to map User Plane traffic to QoS Flows based on packet

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252 See: 3GPP TS 22.261 V17.1.0 (2019-12): "*Service requirements for the 5G system; Stage 1 (Release 17)*". Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/

253 See: 3GPP: TS 22.179 V17.1.0 (2019-02): *"Mission Critical Push To Talk (MCPTT); Stage 1 (Release 17)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.179/

254 See: 3GPP TS 22.280 V17.4.0 (2020-12): *"Mission Critical Services Common Requirements (MCCoRe); Stage 1 (Release 17)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.280/

255 See: 3GPP TS 22.281 V16.0.0 (2018-09): *"Mission Critical Video services Release 16"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.281/

256 See: 3GPP TS 22.281 V16.4.0 (2018-12): *"Mission Critical Data services Release 16"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.282/

257 See: 3GPP TS 22.186 V16.2.0 (2019-06): *"Enhancement of 3GPP support for V2X scenarios; Stage 1 (Release 16)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.186/

258 See: 3GPP TS 22.071 V16.0.0 (2020-07): *"Location Services (LCS); Service Description; Stage 1 (Release 16)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.071/

259 See: 3GPP TS 22.104 V17.4.0 (2020-09): "*Service requirements for cyber-physical control applications in vertical domains; Stage 1 (Release 17)*". Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.104/

260 See: 3GPP TS 22.262 V16.0.0 (2018-12): "*Message Service within the 5G System; Stage 1 (Release 16)*". Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.262/

261 See: 3GPP TS 22.125 V17.2.0 (2020-09): "*Unmanned Aerial System (UAS) support in 3GPP; Stage 1; Release 17*". Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.125/

262 See: 3GPP TS 22.263 V17.3.0 (2020-12): "*Service requirements for video, imaging and audio for professional applications (VIAPA); Stage 1 (Release 17)*". Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.263/

263 For more details also see: 3GPP TS 23.501 V16.3.0 (2019-12): *"System Architecture for the 5G System (5GS); Stage 2 (Release 16)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/23_series/23.501/

 

detection.

- QoS profile contains the QoS parameters: 5G QoS Identifier (5QI), Allocation and Retention Priority (ARP), for GBR QoS flows – Guaranteed Flow Bit Rate (GFBR) separately for UL/DL, Maximum Flow Bit Rate (MFBR) also separately for UL/DL, and optionally Maximum Packet Loss Rate separately for UL/DL.

- 5QI is a scalar that is used as QoS flow label with reference to standardised combination of 5G QoS characteristics parameters such as: Resource Type (Non-GBR, GBR, Delay-Critical GBR), Default Priority Level (a priority in scheduling resources among QoS Flows; lower number – higher priority), Packet Delay Budget (in ms), Packet Error Rate, Default Maximum Data Burst Volume (in bytes, for Delay-critical GBR only), and Default Averaging Window (in ms, a period of bit rate calculation). The full table of standardised 5QI with indication of example service relevance is provided in TS 23.501[264].

- ARP contains information about the priority level, the pre-emption capability and the pre-emption vulnerability. It aids decision to accept/reject operations on a QoS Flow and may also be used to pick an existing QoS Flow to pre-empt during resource limitations. The range of the ARP priority level values is 1 to 15 (1 means the highest priority).

In TS 28.552[265] the 3GPP measurement methodology of NFs' KPIs is presented. These include evaluation of several parameters that regard *inter-alia*:

- Data transfer parameters i.e. delay, throughput, packet loss;

- Network function's capability i.e. capacity (e.g. maximum numbers of UDM subscribers);

- Procedural capabilities - successfully conducted procedures, failures and attempts.

So far measurements of the following network functions have been described: gNB, AMF, SMF, UPF, PCF, UDM, N3IWF, NEF, NRF, and NSSF as well as common measurements for NF in general (CPU, memory and disk usage) and mean usage of virtualised resources measurements in single network slice instance.

In TS 28.554[266] the 3GPP measurement methodology of end to end KPIs is presented. Currently, the following categories are included:

- Accessibility:
    - PDU session Establishment Success Rate of one network slice (S-NSSAI).
    - DRB (Dedicated Radio Bearer) Accessibility for UE services.
    - Registration success rate of one single network slice instance.
    - Registered Subscribers of Network and Network Slice Instance through UDM.
    - Registered Subscribers of Network and Network Slice Instance through AMF.
- Integrity:
    - Latency and delay.
    - Upstream/downstream throughput of Network Slice Instance, RAN UE link or at N3 interface.

264 Ibid.

265 3GPP TS 28.552 V16.3.0 (2019-09): *"5G Performance measurements - (Release 16)"*. Accessible at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.552/

266 3GPP TS 28.554 V16.2.0 (2019-09): *"Management and orchestration; 5G end to end Key Performance Indicators (KPI) – (Release 16)"*. Accessible at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.554/

- Utilisation:
    - Mean number of PDU sessions of network and network Slice Instance (also maximum).
    - Virtualised Resource Utilisation of Network Slice Instance.
    - PDU session establishment time of network slice.
    - Mean number of successful periodic registration updates of Single Network Slice.
- Retainability:
    - QoS flow Retainability (a measurement that shows how often an end-user abnormally loses a QoS flow during the time the QoS flow is used).
    - DRB Retainability (a measurement that shows how often an end-user abnormally loses a DRB during the time the DRB is active).
- Mobility:
    - NG-RAN handover success rate.
    - Mean Time of Inter-gNB handover execution of Network Slice.
    - Successful rate of mobility registration updates of Single Network Slice.
- Energy Efficiency (EE) KPI:
    - NG-RAN data energy efficiency.
    - Network slice (eMBB, URLLC, and MIoT) energy efficiency.

In future updates, availability KPI will also be defined.

## 2.4 Scenarios, Use Cases and Trials

### 2.4.1 KPIs as "Servers" of the 5G Deployment

The involvement of vertical customers in the current deployment of 5G networks increases the need for realising tests and measurements, taking into account the strict requirements of the vertical applications and the appearance of new business models[267]. The exploitation of network and computing resource virtualisation and sharing, such as NFV and SDN and the diverse technology sectors involved in the infrastructure substrate (i.e. radio, cloud, transport) implicate that the 5G network becomes somehow increasingly complex to manage, monitor and test.

The business relations between partners in the telecommunications industry are based on Service Level Agreements (SLAs) in which the required and promised QoS is translated into the set of KPIs' targets. As the contracts need to be manageable, the contractual sets of KPIs have to be manageable also, i.e. limited to a few or a dozen. KPIs, as the name suggests, have to reflect legibly the behaviour of the telecommunications network or service at the level of their key symptoms. Each of them provides a dashboard-ready, back-traceable aggregation of multiple Performance Indicators (e.g. even hundreds or thousands), which may be direct readouts of counters or results of some

[267] 5G-PPP - Test, Measurement and KPIs Validation (TMV) Working Group (2016): *Validating 5G Technology Performance Assessing 5G architecture and Application Scenarios - White Paper*. Available at: *https://5g-ppp.eu/5g-ppp-tmv-wp-validating-5g-technlogy-performance-assessing-5g-architecture-and-application-scenarios/*

The Test, Measurement, and KPIs Validation Working Group was founded as part of the 5G PPP effort to promote commonalities across projects that have strong interest in the T&M methodologies needed to provide support to the vertical use cases in the 5G Trial Networks.

processing (e.g. normalised to the maximum value or delta value referred to sampling period). A similar approach is applied to the global management of complex, modularised or distributed systems consisting of autonomous modules, and the correct cooperation between them is based on the exchange of information at the KPI level. The first level of problems solving is local, and when that is not enough, then the globally coordinated resolution process is implemented, based on the E2E observation and interaction of modules' KPIs.

When a vertical customer identifies a breach of a certain SLA, the corresponding actions of trouble-shooting and conflict resolution may implicate for cross-layer coordination of testing and monitoring. Due to the latter, a more generalised conceptual view is proposed to deal with such instances, that particularly incorporates: (i) Roles and expectation of the vertical customers; (ii) definition of testing and monitoring approaches and testing levels (from access network to service); (iii) the need for, and role of Test as a Service (TaaS) to the extent possible; (iv) the need of clearly defined Key Performance Indicators (KPIs) to support the validation of the corresponding 5G technology; (v) the need of a clearly defined KPI Testing and Validation methodology, including KPI monitoring, analysis, verification, and performance diagnosis, and (vii) the need for a common formalisation process for standardizing tests representing different levels of the 5G network. Beyond the acknowledgement and activation of the necessary actors of this initiative, the question remains on the strategy and processes for jointly, safely and efficiently tackling the original testing and validation challenges. And here is where the 5G KPIs come into the picture, constituting a formal liaison, all along the testing and validation process, between the vertical and 5G counterparts. This section discusses the previously introduced viable-predictable and plug-and-play performance assurance aspects.

The envisaged landscape of pervasive 5G services calls for solid and extensive trials, validation tests and measurements that innovative vertical firms strongly need to carry out for extracting reliable conclusions related to 5G performance. The trial environments should reflect the conditions and configuration that the vertical applications will "face" on their launch in production networks, to verify whether the vertical application can be considered as "5G-ready". And, even more importantly, by early testing their innovative use cases over a standards-based full-chain 5G facility, and following a systematic approach, a wide range of vertical industries may timely make well-informed business decisions on launching their services with guaranteed performance levels and, consequently, with higher chances of business success. To support such an effort, the 5G ecosystem needs to accommodate for frameworks that easily test, measure and demonstrate – for the wide range of new use cases and foreseeable conditions of deployments and scenarios – suitable KPIs of the related 5G network environments. New approaches and types of testing shall allow the fastest upgrade and deployment steps. Test and Measurements (T&M) procedures, tools, and methodologies (i.e. testing, monitoring, analytics, and diagnostics) need to be agreed upon, to ensure a proper functioning of the deployed networks. The goal is to provide a commonly agreed framework for T&M across the 5G PPP ecosystem that will allow both vertical customers and operators to verify and validate SLA for the different 5G Services.

A set of standard and well-defined 5G KPIs must be considered for carefully assessing, prior to any development and testing activities, the potential feasibility of every distinct use case over a standard 5G network. More than often, in 5G literature listed 5G KPIs are associated to their values for maximum theoretically achievable and viable performance.

A very detailed and reliable approach has been already been proposed by 3GPP in TS 28.554[268], where a great variety of E2E KPIs have been discussed. This Technical Specification has also examined several use cases of practical interest. The following KPI categories have been discussed:

[268] See: 3GPP TS 28.554 V16.2.0 (2019-09): *"Management and orchestration; 5G end to end Key Performance Indicators (KPI) – (Release 16)"*. Accessible at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.554/

- Accessibility[269].
- Integrity[270].
- Utilisation.
- Retainability[271].
- Mobility.
- Energy Efficiency.

The variety of standard 5G slice service types (eMBB, URLLC, mMTC, V2X), architectural options and alternative configurations have to be taken into account too, since they condition the actual feasibility for a standard 5G environment to support the specific set of 5G KPIs demanded by the application or specific QoS targets. The key success factor is the collaboration in the actual testing activities with a decisive focus on KPI monitoring and assessment, considering a variety of application scenarios and a selection of 5G network configurations and conditions. Following that approach, the involved market actors/verticals not only can benefit from assessing – and hopefully proving – the technical viability (performance-wise) of the related service, but also deriving a model for predicting its service performance in operations for a wide range of foreseeable conditions. That will provide a solid basis for making a well-informed business decision on whether, when, and how they may attempt successfully launching new services.

The 5G-DRIVE project falls within the context of the ICT-22-2018 Call ("EU China 5G Collaboration"). The project aims to perform a "close" collaboration between EU and China to synchronise 5G technologies and spectrum issues before the final rollout of 5G.

### 2.4.2 Formalisation Process and Methodology

Testing (or Active Testing) provides a greater observability due to the active control over the type and intensity of traffic that is pushed through the network and through subsets of the network elements. This provides more degrees of freedom in selecting what can be tested and measured (e.g. scalability or security resilience). Monitoring is instead a generally passive process to provide metrics from various components/layers of the 5G network. For this reason, the testing-measurable KPIs are substantially different than through monitoring alone. An example of these differences can be seen in two similar documents coming from NGMN[272] and 3GPP[273]. The former is focused on testing aspects, while the latter provides an overview of KPIs to be measured during normal network operations.

As the experimentation on top of the 5G networks is ongoing, owners of 5G infrastructures need to selectively expose the network capabilities to experimenters, and allow for configurations, tailored to the needs of the related vertical industries. An initial response to this request is a modular form that includes a formalisation of the information needed to configure a 5G infrastructure for an experiment. Meant to serve as a standardised template for bridging vertical-oriented requirements

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269 The definition of this KPI is provided in: ITU-T Recommendation E.800: *"Definitions of terms related to quality of service"*.

270 Ibid.

271 Ibid.

272 Next Generation Mobile Networks (NGMN) Alliance (01/2019): *"Definition of the Testing Framework for the NGMN 5G Pre-commercial Networks Trials"*. The study is available at: https://www.ngmn.org/wp-content/uploads/Publications/2019/190802_NGMN-PreCommTrials_Framework_definition_v3.0.pdf

273 See the scope discussed in 3GPP TS 28.552 V17.1.0 (2020-12): *"5G Performance measurements"*. Available at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.552/

 

with network configurations, this form can be used for both technical and SLA validations. At its initial state it includes at least the following interlinked fields:

- Experiment description.
- Test case description.
- Scenario identification.

These are briefly discussed as in the flowing sub-clauses:

**Experiment description:** Information required to uniquely identifying an experiment. Each experiment shall include combinations of at least the two mandatory fields for the experiment, namely, the test cases and the scenarios.

**Test case description:** The test case includes information, which is related to the configurations of the experimentation infrastructure needed for receiving the measurement(s). The KPI definition, the measurements methodology, and the information for the equipment preparation are added in this field. More precisely, a test case provides the following info:

- *Target KPI:* Each test case targets a single KPI. Secondary/complementary KPIs could also be defined as complementary measurements. The definition of the main KPI declares at least the reference points from which the measurement(s) will be performed, the underlay system, and the reference protocol stack level[274].
- *Complementary measurements:* A secondary list of KPIs useful to interpret the values of the target KPI. Getting these measurements is not mandatory for the test case. However, allows for test cases that, besides the target measurement, provide an additional set of results useful for analysis and interpretation of the relation between different KPIs.
- *Pre-conditions:* A list of test-specific information about equipment configuration and traffic description. Also, precise description of the initial state of the system under test, required to start executing a test case sequence.
- *Test case sequence:* It specifies the set of processes needed for executing the experiment in the selected underlay system.
- *Methodology, calculation process and expected output:* The experimenter shall provide the acceptable values for variables that affect the testing procedure, as the monitoring time, the iterations required, the monitoring frequency, etc. In addition, the units that shall be used in the measurements and, potentially, a request for first order statistics (Min, Max, etc.) of the target KPI measurement.
- *Applicability:* A list of features and capabilities which are required by the system in order to guarantee the feasibility of the test.

**Scenario identification:** The scenario includes information, which is related to network, service and environment configurations and it is specific to the selected technologies and the target system. From the performance perspective[275] the scenario quantifies the parameters that affect the values of the KPIs to be measured. More precisely, a test case that targets a specific measurement can be set for different scenarios that declare parameters such as the network slice characteristics, network configuration parameters (e.g. the level of the transmission power in a base station), mobility aspects (e.g. the mobility of the end devices), the network status (e.g. the traffic load in the system), etc.

[274] The physical formula, the unit, and the type of the KPI as defined in 3GPP TS 28.554 can be included here. See: 3GPP TS 28.554 V16.2.0 (2019-09*): "Management and orchestration; 5G end to end Key Performance Indicators (KPI) – (Release 16)"*. Accessible at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.554/

[275] See, *for example*: 3GPP TS 28.552 V16.3.0 (2019-09): *"5G Performance measurements – (Release 16)"*. Accessible at: https://www.3gpp.org/ftp/Specs/archive/28_series/28.552/

### 2.4.3 The 5G-DRIVE Scope

The 5G-DRIVE project falls within the context of the ICT-22-2018 Call (“EU China 5G Collaboration”). The main scope is to conduct 5G trials addressing two dedicated scenarios as discussed in the continuity of the present section. The overall goal is to evaluate in real setup innovative end-to-end 5G systems built on the outcomes of the previous phases of the 5G R&I. In particular, 5G-DRIVE’s main scope is to conduct 5G trials addressing two specific scenarios:

(i) ***Scenario no 1*** – enhanced Mobile Broadband (eMBB) on the 3.5 GHz band, which is a priority band in the two regions for early introduction of very high rate services. The applications used to test and validate the use of eMBB in the 3.5 GHz band are typical mobile broadband services as well as Augmented Reality (AR). This is demonstrated in the Surrey and Espoo trial sites, *and;*

(ii) ***Scenario no 2 –*** Internet of Vehicles (IoV) based on LTE-V2X using the 5.9 GHz band for Vehicle-to-Vehicle (V2V) and the 3.5 GHz band for Vehicle-to-Network (V2N). The overall goal is to carry out V2V and V2N service demonstrations in a real-life setup. Trials are conducted in the Espoo site by VTT, Dynniq and Vedia, and in the JRC Ispra site.

Both scenarios are being implemented in both regions (EU and China) through test-beds forming the core of the R&I work. The core objective of the 5G-DRIVE framework is to build engagement between current 5G developments in the European Union and China through joint trials and research activities so that to ease technology convergence, spectrum harmonisation and business innovation in advance of potential large-scale market 5G deployment.

The consensus in 5G-DRIVE is that each project scenario (eMBB and V2X) is illustrated by one or more use cases (as proposed in WP3 and WP4, *respectively*), that a subset of these use cases is demonstrated in the project trials, and that each trial features its own physical and logical architecture.

The ongoing 5G-DRIVE use cases illustrate specific situations in which the technologies and services developed in the context of the project could potentially be used. The various use cases presented in this deliverable cover the eMBB and IoV scenarios described in the ICT-22-2018 Call[276].

Each 5G-DRIVE use case is demonstrated by a specific trial in one or more sites in the project consortium. To do so, each trial is underpinned by a specific architectural design comprising the software/hardware components, network infrastructure and services needed to support the experimental activities in the trial. The underpinning architecture for the eMBB and V2X trials in 5G-DRIVE, follows the description of each separate use case. In addition, as part of the collaboration between the EU and Chinese projects foreseen in 5G-DRIVE we also present the various architectures of the trials to be conducted in the Chinese consortium.

Both eMBB and V2X services are delivered using communication technologies deployed in different frequency bands. Since radio spectrum allocation is a competence of national authorities, the radio spectrum plan for eMBB and V2X services in the EU and China can easily differ.

As of the proposed eMBB use cases it has been assessed that within the context of WP3 the following two are to be deployed and assessed: (i) cloud-assisted AR; and (ii) indoor positioning. In addition, it is expected that other mobile broadband services can be examined in the course of the 5G-DRIVE effort.

As of the proposed V2X use cases it has been assessed that within the context of WP4 the following two are to be deployed and assessed: (i) Green Light Optimal Speed Advisory (GLOSA); and (ii)

[276] For more details also see: *https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ict-22-2018*

intelligent intersection. In addition, it is expected that other autonomous driving or V2X applications can also be studied in the course of the 5G-DRIVE effort.

In the following, we briefly discuss and identify qualitative features of the respective use cases, being at a more generic level of description.

# 3 eMBB Use Cases

## 3.1 General Framework and Implementation Status of WP3

Many mobile broadband operators aim at providing multiple services (Internet, voice and video) across their packet-switched access networks. These services will share the radio and core network resources with best effort services such as Internet browsing and e-mail download, and they all have different QoS requirements in terms of required bit rates as well as acceptable packet delays and packet loss rates. The operator may provide differentiated treatment of the IP traffic for the same service depending on the type of subscription the user has. These subscriber groups can be defined in any way suitable to the operator. There is a need to standardize simple and effective QoS mechanisms for multi-vendor mobile broadband deployments. Such QoS mechanisms should allow the operator to enable service and subscriber differentiation and to control the performance experienced by the packet traffic of a certain service and subscriber group.

MBB is the key use case today and it is expected to continue to be one of the key use cases driving the requirements for 5G. It goes far beyond basic mobile Internet access and covers rich interactive work, media and entertainment applications in the cloud or reality augmentations (both centralised and distributed). Data will be one of the key drivers for 5G and in new parts of this system we may for the first time see no dedicated voice service – in 5G, voice is expected to be handled as an application, simply using the data connectivity provided by the communication system. Data is growing at a rate between 25% and 50% annually and is expected to continue towards 2030[277].

The main drivers for the increased traffic volume are the increase in size of content and the number and proliferation of applications requiring high data rates (e.g. expected boom of eMBB services for drones). Factors include increases in camera resolution, the rise in screen resolution with the recent introduction of 4K (8K is already expected beyond 2020) and the developments in 3D video. Streaming services (audio and video), interactive video and mobile Internet connectivity will continue to be used more broadly as more devices connect to the Internet. Many of these applications require always-on connectivity to push real-time information and notifications to the users. Cloud storage and applications are rapidly increasing for mobile communication platforms. This is applicable for both work and entertainment. Cloud storage is one particular use case driving the growth of uplink data rates; in the past, content was mostly downloaded. 5G will also be used for remote work in the cloud, which (when done with tactile interfaces) requires much lower end-to-end latencies in order to maintain a good user experience. Entertainment, for example cloud gaming (including "serious games") and video streaming, is another key driver for the increasing need for mobile broadband capacity. Entertainment will be very essential on smart phones and tablets everywhere, including high mobility environments such as trains, cars and airplanes. Another very interesting but also very demanding use case is AR for entertainment and information retrieval, which requires very low latencies and significant instant data volumes.

The eMBB is the most obvious extension of LTE capability, providing higher throughputs for applications such as streaming, Web access, video conferencing, and VR. The highest throughput demand concentrations will occur in small cells with limited movement speed of end users, such as pedestrians. This is the emphasis of the first phase of 5G, specified in Release 15 of 3GPP specifications. Providing significant benefits to consumers, eMBB is assessed as an extension to existing 4G network and so it is amongst the first wave of the 5G services. These benefits include significant improvement of download speeds and more cost-efficient data, up to 10 times cheaper compared to 4G. The eMBB will transform user-experience, revolutionize the gaming industry with

[277] Nokia (2014): *5G Use Cases and Requirements, White Paper*.

 

AR/VR cloud gaming and drive 4K video streaming as the new norm, However, the full potential of 5G's commercial benefits are yet to be discovered.

5G's use of higher spectrum waves (such as mmWaves[278]) will enable higher capacity in densely populated areas, greater scalability, higher user mobility for services in moving vehicles and enhanced connectivity everywhere. 5G eMBB is seen as the first of the three broad categories to bring the benefits of 5G to the wider public, as it can deliver high QoS Internet access in previously challenging or prohibitive conditions.

One of the significant ways 5G will deploy across large areas is through fixed wireless access (FWA), which will leverage 5G technologies like beamforming and higher-spectrum bands to deliver wireless broadband to previously unreached coverage areas. In 2019, FWA was part of an initial 5G launch in more than 30 networks and is now gaining ground in Europe, the Middle East and the Asia-Pacific region. Globally, the FWA market is expected to grow exponentially from 2018-2025 at a CAGR of 99.5%[279]. FWA will make a significant impact on global markets, both developing and developed, such as in the US, where sparsely populated, rural areas currently lag far behind cities in broadband access. FWA can deliver speeds comparable to or exceeding those of current fibre-based networks, thus creating a platform for eMBB over vast coverage areas using spectrum bands unavailable to 4G. As 5G eMBB becomes widely available, it can deliver several sub-use cases, such as:

- *Hot spots:* eMBB can enhance broadband access in densely populated areas (such as high-rise building complexes, urban city centres, crowded areas, etc.), boosting indoor and outdoor coverage in high-rise buildings and crowded city centres. Moderate mobility and high data rates are required.

- *Broadband everywhere*: This use case relates to providing a consistent user experience, guaranteeing user speeds of 50+ Mbps everywhere towards a mobile and a connected society; this can be offered by using technologies like FWA, and high mobility will be required.

- *Public transportation:* This use case is about providing broadband access in public transport systems such as high-speed trains and other modes of public transport. The use case consists of providing robust communication link and high-quality Internet for information, entertainment, interaction or work with a high mobility component.

- *Smart offices:* eMBB can deliver high-bandwidth connections to hundreds of users in environments with heavy data traffic. This use case is characterised by heavy data use in an indoor environment that will require low mobility. This is a use case scenario where hundreds of users require ultra-high bandwidth to serve intense bandwidth applications.

- *Large-scale events:* Concerts and sporting events may be served by eMBB, enabling high data rates where tens or hundreds of thousands of people are gathered. This use case requires providing very high connection density in scenarios such as stadiums, concerts and large gatherings where several hundred thousand users are served at high data rate and low latency.

- *Enhanced multimedia:* The related applications require higher data rates to provide high resolution multimedia content to an increasing number of simultaneous and connected users with very high QoS

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278 For more details also see, *among others*: Rappaport, T.S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., *et al.* (2013): Millimeter wave mobile communications for 5G cellular: It will work! *IEEE Access,* **1**, 335-349.

279 For more details also see: https://www.telit.com/blog/5g-embb-use-cases-advantages/

 

requirements. With more devices capable of recording and capturing people's daily experiences, there has been a dramatic increase in user-generated content. The eMBB can provide seamless, high-definition video streaming, mobile TV and real-time content over broad coverage areas. This category of use cases targets providing a high-quality media experience everywhere to meet the growing demands of consumer media consumption. The targeted users are the end-viewers, pay TV operators, broadcasters, new content owners, content aggregators and OTT providers. Recent developments of 4K and 8K video resolution, 3D video, expanded use of HD TV, streaming audio and video services and interactive video on the go over a growing number of video-capable devices are key driving factors for this family of use cases. The higher data capacity, faster data rates, and enhanced broadcast/multicast features will serve these use cases and realize the media vision for a seamless mobile TV experience. Some of the use cases include: (i) broadcast services; (ii) on-demand and live TV services and; (iii) mobile TV services. These are briefly discussed as follows:

- *Broadcast Services:* These services distribute content in both real time and non-real time across a wide distribution area and are typically dominated by the downlink with the uplink providing a feedback channel for interactive services. Sub-use cases consist of: (i) Delivering news and information in audio and video to customers in specific geographic areas; (ii) delivering local services within 1 to 20 km that include scenarios such stadium events, advertisements, fairs, conventions and emergency notifications; (iii) delivering services in a larger distribution within 1 to 100 kms that includes scenarios such as communicating traffic jams, disaster emergency warnings, etc.; and (iv) delivering services at a national level as a complement to broadcast radio or television with additional benefits for the automotive industry.
- *On Demand and Live TV:* This use case is based on scaled up delivery of high-resolution content via live TV or on demand video using enhanced data capacity and data rates.
- *Mobile TV:* Defined by delivery of video streaming and entertainment media to smart phones, tablets and other devices in high mobility environments such as trains, cars and buses.

The above group of use cases is characterised by broadband data access across a wide coverage area in crowded locations, office areas, and high-speed public transport systems. The basic target is to provide maximum user experience by providing connectivity both indoors and outdoors while delivering high QoS broadband even in challenging network conditions. Multi-user interaction, AR and Context Recognition are essential features for this category of use cases.

5G eMBB will be driven by the growth in user-generated content and consumers' expectations of being able to stream what they want, where they want and when they want without needing to log onto a Wi-Fi network. Multimedia streaming and entertainment, however, constitute only some of the needs eMBB could meet. Important business use cases include mobile cloud computing and connected remote smart offices. In addition, the demand and excitement for the latest next generation mobile technology is growing as users now demand increased data throughput on their devices, enhanced signal reliability, and better coverage. Enhanced Mobile Broadband enables 5G to do this by focusing on data-driven use cases that require high rates of data across a large coverage area mainly through mobile devices, including smartphones, tablets, laptops, Mi-Fi[280] and wearables[281].

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[280] Mi-Fi is a brand name used to describe a wireless router that acts as mobile Wi-Fi spot. For more details see, for example: *https://en.wikipedia.org/wiki/MiFi*

[281] ABI Research, a global tech market advisory firm, forecasts that shipments of eMBB-enabled mobile devices will increase from 15 million in 2019 to 1 billion in 2024, at a CAGR of 132.4%. For further information also see, among others: *https://www.bloomberg.com/press-releases/2019-11-21/embb-the-data-and-advanced-connectivity-driver-of-*

The distinctive feature of 5G is its intrinsic flexibility, which allows it to support several use cases in an optimised way, either using low-band spectrum below 1 GHz, mid-band frequencies from 1 GHz to 6 GHz or high-band spectrum above 6 GHz. The low-band spectrum is deemed essential for use cases that require seamless coverage and high mobility, as is the case with URLLC and mMTC. The mid-band spectrum is going to be utilised by the first 5G networks to support eMBB, which is vital to demonstrate the 5G business case and promote investment in 5G networks. When 5G networks become mature, eMBB will have to offer peak data rates of 20 Gbps and experienced user data rates of 100 Mbps to a very high number of involved end-users. With the feasible spectral efficiencies, such transmission speeds can only be delivered using channels with bandwidths in the order of several hundred MHz, which are available only in the high band at mmWave frequencies[282],[283].

Following to the fast technological evolution, it is worth to mention that eMBB-Plus[284], in 6G, will replace its 5G counterpart of eMBB and provide a high quality of experience (QoE) in data utilisation and standards. Notably, other integral components of the wireless communication of network optimisation, handover, and interference should be able to exploit the concepts of big data to facilitate these operations. It should also be more capable of optimizing the cellular networks in terms of interference, hand-over, as well as big data transmission and processing. Providing other add-ons such as accurate indoor positioning and a globally compatible connection among diverse mobile operating networks is expected, at an affordable rate for network subscribers (e.g. accurate indoor positioning and globally compatible connection among diverse mobile operating networks). A strategy should be designed for eMBB-Plus communication services without compromising the security, secrecy, and privacy of network subscribers.

With the agreed scope defined and it encompassing the performance of 5G NR, including indoor performance and mMIMO performance, as well as technologies such as E2E network slicing, SDN and transport networks virtualisation and slicing, the trials for the WP3-related uses cases have been designed and then followed a dedicated schedule.

The focus of the 5G-DRIVE ongoing activities around WP3 is at first on the performance of the 5G NR in different scenarios. The eMBB joint trials enable the comparison of pre-commercial trial results from Europe, undertaken within the 5G-DRIVE project, with those obtained from the 5G Large Scale Trials project led by China Mobile. The specifications for the trials enable a preview of the similarities, differences and complementarity of the trial setups, identifying which results may be directly comparable, and which may provide alternative or additional performance data. The main thrust aims to examine – or confirm – eMBB performance and capabilities, in relation, *for example*, to expected performance defined by the European Telecommunications Standards Institute (ETSI) and the 3GPP, following example test procedures and expected results detailed by the Next Generation Mobile Networks (NGMN) Alliance[285].

An important point of comparison, for example, might be the differences observed in operation due to the spectrum allocation of 3.5 GHz common in Europe, and the specific spectrum at 2.6 GHz

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[5g-will-be-in-over-1-billion-mobile-devices-by-2024](5g-will-be-in-over-1-billion-mobile-devices-by-2024)

[282] While spectrum has become scarce at microwave frequencies, it is plentiful in the mmWave realm. Such spectrum availability has led to a mmWave "gold rush" in which researchers with diverse backgrounds are studying different aspects of mmWave transmission. Although far from fully understood, mmWave technologies have already been standardised for short-range services (IEEE 802.11ad) and deployed for niche applications such as small-cell backhaul.

[283] Also see, *inter-alia*: Pi, Z., and Khan, F. (2011, June): An introduction to millimeter-wave mobile broadband systems. *IEEE Communications Magazine*, **49**(6), 101-107.

[284] Gui, G., Liu, M., Kato, N., Adachi, F., and Tang, F. (2000): 6G: Opening New Horizons for Integration of Comfort, Security and Intelligence. *IEEE Wireless Communications*, **27**(5), 126-132.

[285] Next Generation Mobile Networks (NGMN) Alliance (2019, January): "*Definition of the Testing Framework for the NGMN 5G Pre-commercial Networks Trials".* The study is available at: https://www.ngmn.org/wp-content/uploads/Publications/2019/190802_NGMN-PreCommTrials_Framework_definition_v3.0.pdf

allocated to China Mobile. The aim is not to report on specific vendor device capabilities as that would involve commercially sensitive information: in fact, the vendors of the devices/equipment used will be hidden in the reporting.

The scope of the trials for eMBB on the European and Chinese sides cover:

- Basic performance of the 5G NR in SA[286] and NSA modes, that is with the 5G RAN[287] equipment attached to a 5G CN or a 4G (LTE) CN, respectively.
- Indoor coverage performance tests, for example, using small/pico-cells and/or distributed antenna systems, and examining localisation techniques.
- Multi-antenna or mMIMO array antenna subsystem tests, to examine the enhanced performance possible from such beamforming systems, and different beamforming operational methodologies.

As planned, the implementation of WP3 are progressing as described below:

- Basic performance of the 5G NR in NSA mode have been measured in both Surrey site and Espoo site. Single UE peak data rate has been measured for both uplink and downlink with TCP and UDP protocols. Control plane latency measurement is also under progressing and initial results have been achieved. More measurements will be carried upon achieving stable measurement performance.
- Indoor coverage provided by outdoor gNB measurements are progressing. A 3D model is also under investigating to be employed to compare the measurement results.
- MIMO beamforming techniques have been tested and studied and, *moreover*, results are progressing to collaborate with the SA trial data provided by the Chinese "twin" project.
- Joint AR demo has been tested with the Chinese "twin" project. However, measured performance cannot achieve the requirement of the use case due to the network firewall security issue in China. Therefore, a joint AR demo has been conducted between Surrey trial site and Espoo trial site. The partners from the Chinese "twin" project also participate to this joint demo from the Surrey site.
- Joint trials have been conducted in both China and UK four times, and joint publications are either under review or preparing to be submitted.

## 3.2 Use Case 1: Cloud-Assisted AR

### 3.2.1 Conceptual Description

The synergistic relationship between upcoming technologies in the connectivity and computing space often leads to a revolution across markets. With applications and use cases morphing to take full advantage of new technologies, such as 5G, cloud, and edge computing, the industry is investigating new business opportunities, otherwise not possible before the introduction of these technologies.

5G will reinvent digital media, by enabling us to step into a high-resolution 3D world, where we will experience a new sense of wonder. 5G breathes life into Extended Reality (XR) technologies, such as VR[288] and AR[289,290]. Leveraging recent advances in storage/memory, communication/connectivity,

[286] The EU side will not have the SA mode, at least during 5G-DRIVE project period, due to the delayed progress from vendors. On the contrary, the China side will have both SA and NSA modes.

[287] A Radio Access Network (RAN) connects individual devices to other parts of a network through radio connections.

[288] A very interesting and innovative approach is presented in 3GPP TR 26.918 V16.0.0 (2018-12): *"Virtual Reality (VR) media services over 3GPP"*. Available at: https://www.3gpp.org/ftp/Specs/archive/26_series/26.918/

computing, big data analytics, artificial intelligence (AI), machine vision and other adjunct areas will enable the fruition of immersive technologies such as AR/VR[291]. These technologies will enable the transportation of ultra-high-resolution light and sound in real-time to another world through the relay of its various sights, sounds and emotions. As we use these technologies, information, objects and people will be all around us, instead of just in front of us, creating an intense emotional engagement.

Virtual reality (or VR) is now at a tipping point, poised to revolutionise how we interact with digital media and with each other. The use of VR will go beyond early adopters such as gaming to enhancing cyber-physical and social experiences such as conversing with family, acquaintances, business meeting, or disabled person. Ultimately VR will provide the most personal experience with the closest screen, providing the most connected, most immersive experience witness thus far[292],[293]. Higher resolutions will make our virtual worlds more life-like, and faster networks will enable us to build shared 3D virtual spaces, where we can socialise, play, and study together. Service providers can generate new revenues by offering a platform for compelling 3D VR experiences, being beneficial to various actors such as: (i) Companies that can provide enhanced training environments for employees; (ii) gamers that can enjoy more exciting, realistic experiences; and (iii) friends and family that can be brought closer together, creating a new chapter in our modern social history.

AR adds a digital layer to the camera image, so people can understand the physical world better and can see the surrounding world differently. Whether it is simplifying furniture assembly instructions or helping to troubleshoot a faulty car, augmented reality gives users an expert's eye, with the ability to easily see what they should do next. Service providers can have financial benefits by offering a platform that enables innovative AR applications in several indicative domains such as, *among others*: (i) Assisted guidance that can help to speed-up repairs, increase quality in manual production tasks, and cut training time with on-the-job real-time tuition; (ii) holiday makers can point their phone at tourist attractions for a visual commentary; (iii) shoppers can see products in action by pointing their phone at the box on the shelf.

More specifically, edge computing is the technology to move the execution applications closer to the users. This will enable latency sensitive applications such as AR/VR or mission critical (MC) use cases. This is done by having cloud platforms distributed further out in the radio network. In this scope, both virtual reality and augmented reality are considered as among the most attractive use cases for 5G. These technologies are promising to transform the way content is consumed and communicated

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[289] For more details also see, *among other sources*: Nokia (2014): *5G Use Cases and Requirements, White Paper*. Also see the detailed context presented in: https://www.nokia.com/networks/5g/use-cases/immersive-experiences/?did=d000000004if&gclid=EAIaIQobChMIh6fS9s2s7gIVibbtCh2rfAlaEAAYASABEgKAoPD_BwE#augmented-reality-ar

[290] Qiao, X, Ren, P., Nan, G., Liu, L., et *al.* (2019): Mobile web augmented reality in 5Gand beyond; Challenges, opportunities and future directions. *China Communications*, **16**(9), 141-154.

[291] Immersion enhances everyday experiences, making them more realistic, engaging, and satisfying. In particular, VR can provide the ultimate level of immersion, creating a sense of physical presence in real or imagined worlds. VR will bring a new paradigm for how we can interact with the world, offering unprecedented experiences and unlimited possibilities that will enhance our lives in many ways. To stimulate our human senses with realistic feedback, truly immersive VR places extreme requirements on several dimensions of the three pillars of immersion that is: visual quality, sound quality and intuitive interactions. Adding to the complexity, mobile VR requires full immersion at low power and thermals so that the headset is sleek, lightweight, and stylish while remaining cool.

[292] Rosedale, P. (2017, January): Virtual reality: The next disruptor: A new kind of worldwide communication. *IEEE Consumer Electronics Magazine*, **6**(1), 48-50.

[293] Bastug, E., Bennis, M., Médard, M., and Debbah, M. (2016): Towards interconnected virtual reality: Opportunities, challenges and enablers. *IEEE Communications Magazine*, **55**(6), 110-117.

and help a wide variety of industries increase productivity and change the way they do business[294]. Both VR and AR have the potential to become the next big computing platform. All around us are examples of where VR (which immerses the user in a virtual world) and AR (which overlays digital information onto the physical world) can reshape existing ways of doing things. AR and VR have similar underlying technologies, but distinct experiences[295]. Both AR and VR applications can be very sensitive to network performance, as any associated hiccup can penalize the overall user experience. The already existing 4G networks cannot always support AR and VR applications, but impose several restrictions such as latency and capacity, which can negate some use cases entirely. Although present 4G networks are appropriate for some early adopter AR and VR experiences, the introduction of 5G, which signifies a significant rise over 4G, will "strengthen" experiences, enable new ones, and make them available for mass adoption. Providing increased capacity, lower latency and a sort of a more uniform experience, 5G will not only advance but will also be a requirement for some of the most exciting AR and VR use cases (such as, *for example*, automotive content streaming, social sharing from event venues, next-generation video and tactile Internet). By default, AR and VR offer an immense number of promising applications and affect a variety of market sectors, allowing the creation of much promising use cases and applications. In fact, within enterprise verticals[296] both AR and VR offer promising ROI, improved safety and novel workforce capabilities, while in the consumer space, users are promised immersive content and new social experiences[297],[298].

**Virtual Reality (VR)** is the term used to describe a three-dimensional, computer-generated environment that can be explored and interacted with by a person[299].

That person becomes part of this virtual world or is immersed within this environment and whilst there, is able to manipulate objects or perform a series of actions. The overarching goal of VR is to generate a digital real-time experience which mimics the full resolution of human perception. This entails recreating every photon our eyes see, every small vibration our ears hear and other cognitive aspects (e.g., touch, smell, etc.).

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[294] ABI Research estimates the total AR market will reach US$114 billion by 2021, and the total VR market will reach US$65 billion within the same time-frame. See: https://www.abiresearch.com/press/abi-research-shows-augmented-reality-rise-total-ma/

[295] Perkins Coie LLP and Upload. (09/2016): *2016 Augmented and Virtual Reality Survey Report*. [Online]. Available at: https://dpntax5jbd3l.cloudfront.net/images/content/1/5/v2/158662/2016-VR-AR-Survey.pdf.

[296] The enterprise domain seeks to find new approaches to increase workplace efficiency and productivity through applications such as virtual training systems, augmentation of manufacturing and enhanced remote collaboration. In addition, the professional services sector is embracing virtual reality for applications ranging from real estate to psychological counselling. Business models within the enterprise market are highly sensitive to the ownership of assets, especially those with a relatively high rate of depreciation.

[297] Use of virtual and augmented reality in the consumer domain has an emphasis on entertainment, where gaming and 360° panoramic video have driven adoption. Social aspects are beginning to emerge within this domain to alleviate the sensation of isolation inherent in the general principles of virtual reality. Interoperable end-to-end ecosystems for immersive content production and delivery to end-users is essential to establishing virtual reality as a mass market service and also change the content storage pattern from the local device to a cloud-based thin client.

[298] Goldman Sachs (01/2016): *Virtual and Augmented Reality Industry Report.* Goldman Sachs Group, Inc. Also see: https://www.goldmansachs.com/insights/pages/technology-driving-innovation-folder/virtual-and-augmented-reality/report.pdf

[299] Many interesting studies have been proposed about VR issues, since almost three decades ago. See, *for example*: Pimentel, K., and Teixeira, K. (1993): *Virtual Reality: Through the New Looking Glass*. Intel Windcrest.

Also see: Sherman, W.R., and Craig, A.B. (2003): *Understanding Virtual Reality: Interface, Application, and Design (First edition)*. Morgan Kaufmann Publishers.

Another interesting approach has been proposed by: Zhao, Q.P. (2009): A survey on virtual reality. *Science in China, Series F: Information. Sciences*, **52**(3), 348-400.

 

VR is a rendered version of a delivered visual and audio scene. The rendering is designed to "mimic" the visual and audio sensory stimuli of the real world as naturally as possible to an observer or user as they move within the limits defined by the application. VR usually, but not necessarily, requires a user to wear a head-mounted display (HMD), to completely replace the user's field of view with a simulated visual component, and to wear headphones, to provide the user with the accompanying audio. Some form of head and motion tracking of the user in VR is usually also necessary to allow the simulated visual and audio components to be updated in order to ensure that, from the user's perspective, items and sound sources remain consistent with the user's movements. Additional means to interact with the VR simulation may be provided but are not strictly necessary.

Thus, VR[300] is the technology to construct a virtual environment, which may be based on the real environment within which people could have real-time interaction[301]. VR immerses a user in an imagined or replicated world (such as, *among others*: video games, movie or flight simulation) or simulates presence in the real world (like watching sport event live. One of the major developments in VR is CAVE (Cave Automatic Virtual Environment[302]), in which the person is fully immersed within it. CAVE takes the form of a cube-like space in which images are displayed by a series of projectors[303]. Some systems enable the person to experience additional sensory input, such as sound or video, which contributes to the overall experience. A main feature of the CAVE system is interaction. The combination of interaction and total immersion is known as "telepresence", in which a person can literally lose themselves within the virtual environment. Interaction takes place using a variety of input devices, such as a joystick, a wand or, more commonly, a haptics (touch) device (e.g. data glove). This enables the person to interact with objects, for example, by pulling, twisting, or gripping by means of touch. The ability to do this is known as haptics. VR engineering includes the use of 3D modelling tools and visualisation techniques as part of the design process. This technology enables engineers to view their project in 3D and gain a greater understanding of how it works. Plus, they can spot flaws or potential risks before implementation. This also allows the design team to observe their project within a safe environment and make changes as necessary. What is important is the ability of VR to depict fine-grained details of an engineering product to maintain the illusion. This means high-end graphics, video with a fast refresh rate, and realistic sound and movement.

VR technologies have been employed by researchers to achieve an immersive and interactive environment[304],[305]. Various VR-based visualisation and interaction techniques have been developed[306]. VR applications using numerical simulation began in the 90s. The promise of VR has excited us for decades, but it is happening now due to the alignment of ecosystem drivers and

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300 Bastug, E., Bennis, M., Médard, M., and Debbah, M. (2017): Toward interconnected virtual reality: opportunities, challenges, and enablers. *IEEE Communications Magazine*, **55**(6)**,** 11-17.

301 There are a number of key technologies used together to enable VR, that is: 360 degree panorama video, Freeview-point, computer graphics, light field, etc. Many applications are derived from VR, *for instance*, VR gaming, VR broadcasting, VR simulated environment for education, healthcare, military training, etc. Moreover, the mutuality of the Cloud capability (e.g. rendering in cloud, edge computing) as well as pervasive network infrastructure deployment will bring VR applications to a new dimension.

302 The CAVE has been being increasingly used and explored in many projects and application domains. It can be seen used in military and training applications, education, medicine, scientific visualisations, and many other areas of human activities. For more details see, *inter-alia*: *https://en.wikipedia.org/wiki/Cave_automatic_virtual_environment*. Also see the original approach discussed in: Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., Kenyon, R.V., and Hart. J.C. (06/1992): The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*, **35**(6), 64-72.

303 Muhanna, M.A. (2015): Virtual Reality and the CAVE. *Journal of King Saud University – Computer and Information Sciences*, **27**(3), 344-361. Available at: *https://www.sciencedirect.com/science/article/pii/S1319157815000439*.

304 Cline, M.S. (2005): *Power, Madness & Immortality – The Future of Virtual Reality*. University Village Press.

305 Nagata, H., Mikami, D., Miyashita, H., Wakayama, K. and Takada, H. (2017): Virtual reality technologies in telecommunication services. *Journal of Information Processing*, **25**, 142-152.

306 Macedonia, M.R., and Zyda, M.J. (1997): A taxonomy for networked virtual environments. *IEEE Multimedia*, **4**(1), 48-56.

technology advancements. In fact, it is mobile technologies that are accelerating VR adoption[307]. To stimulate our human senses with realistic feedback, truly immersive VR places extreme requirements on several dimensions of the three pillars of immersion (i.e. visual quality, sound quality and intuitive interactions). For creating truly immersive experiences, VR places high emphasis on these three pillars of immersion to stimulate our senses with realistic feedback, providing: (i) Visuals so vibrant that they are eventually indistinguishable from the real world; (ii) sounds so accurate that they are true to life, and (iii) interactions so intuitive that they become second nature and the users forget there is even an interface.

Several researchers[308],[309] focused on using the VR environment for finite element analysis (FEA) result visualisation. Scherer and Wabner[310] proposed a system for structural and thermal analysis. Their method visualizes FEA results with a three-dimensional glyph. Another glyph-based simulation result visualisation system was proposed by Neugebauer et *al.*[311], in which stresses can be displayed using 3D glyphs. Buchau[312] introduced a VR-*based* numerical simulation system, which integrates a COMSOL Multiphysics solver for efficient computation. The post processing of simulation data plays a vital role, as accurate visualisation of simulation data could improve user experience in the VR environment. By using the Visualisation Toolkit[313], the computation results can be visualised with the interaction function provided[314]. In addition, deformation simulation has been conducted by several researchers[315]. Some of the studies use artificial neural network (ANN) and other approximation methods to achieve real-time solutions. Interaction methods have been studied to utilize the simulation results provided in a VR environment so as to improve the efficiency of the analysis and the design process[316]. Even though VR systems can provide visualisation of the engineering analysis and simulation results in an intuitive and efficient way, there are still limitations. First, establishing a virtual environment with all the information involved is difficult as the detailed physical models and properties of the surrounding objects should be defined precisely. Secondly, there is no physical relationship between a user and the virtual content, such that the user has no influence on the environment. This reduces the immersion feelings experienced by the user. Furthermore, the

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[307] The mobile ecosystem has characteristics that make the proliferation of new technologies very feasible, such as: (i) Innovation at scale, which brings both cutting edge technology and cost advantages. Over a billion smartphones are shipping globally per year, which brings tremendous scale and innovation to mobile; (ii) rapid design cycles, which bring fast adoption of those cutting edge technologies; (iii) mass adoption, which means that smartphone usage has created a broad appeal for mainstream consumers. Smartphone users are adventurous and willing to try new things, such as downloading new apps from an app store.

[308] Yagawa, G., Kawai, H., Yoshimura, S., and Yoshioka, A. (1996): Mesh-invisible finite element analysis system in a virtual reality environment. *Computer Modeling and Simulation in Engineering,* **1**(2), 289-314.

[309] Yeh, T.P., and Vance, J.M. (1997): Combining MSC/NASTRAN, sensitivity methods, and virtual reality to facilitate interactive design. *Finite Elements in Analysis and Design*, **26**(2), 161-169.

[310] Scherer, S., and Wabner, M. (2008): Advanced visualization for finite elements analysis in virtual reality environments. *International Journal for Interactive Design and Manufacturing*, **2**(3), 169-173.

[311] Neugebauer, R., Weidlich, D., Scherer, S., and Wabner, M. (2008): Glyph based representation of principal stress tensors in virtual reality environments. *Production Engineering*, **2**(2), 179-183.

[312] Buchau, A., and Rucker, W.M. (2011): *Analysis of a Three-Phase Transformer using COMSOL Multiphysics and a Virtual Reality Environment*. In Proceedings of the 2011 COMSOL Conference, pp.1-6. Stuttgart, Germany, October 26-28, 2011.

[313] Avila, L.S., Barre, S., Blue, R., Geveci, B., et *al.* (2010): *The VTK User's Guide, 5th edition*. Kitware: New York, NY, US.

[314] Schoning, M., and Hameyer, K. (2008): Applying virtual reality techniques to finite element solutions. *IEEE Transactions on Magnetics*, **44**(6), 1422-1425.

[315] Tzong-Ming, C., and Tu, T.H. (2009): A fast parametric deformation mechanism for virtual reality applications. *Computers & Industrial Engineering*, **57**(2), 520-538.

[316] Ingrassia, T., and Cappello, F. (2009): VirDe: a new virtual reality design approach. *International Journal of Interactive Design and Manufacturing*, **3**(1), 1-11.

equipment for an immersive VR-based system is not cost-effective and can cause ergonomic problems, such as nausea during use.

**Augmented Reality (AR)** is an interactive experience of a real-world environment where the objects that reside in the real-world are "augmented" by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory[317],[318][319]. AR is a technique where the real-world view is augmented, or assisted, by a computer-generated views, this can be in single or multi-sensory modes including, auditory, visual, and haptic. AR is when a user is provided with additional information or artificially generated items or content overlaid upon their current environment. Such additional information or content will usually be visual and/or audible and their observation of their current environment may be direct, with no intermediate sensing, processing and rendering, or indirect, where their perception of their environment is relayed via sensors and may be enhanced or processed. An example of AR application is a field technician who receives explanatory captions and markings added to the attended equipment he sees, as a form of deep contextual integration with the equipment documentation.

Thus, AR overlays digital imagery onto the real world. The overlaid sensory information can be constructive (i.e. additive to the natural environment) or destructive (i.e. masking of the natural environment) and is seamlessly interwoven with the physical world such that it is perceived as an immersive aspect of the real environment. In this way, AR alters one's ongoing perception of a real-world environment, whereas VR completely replaces the user's real-world environment with a simulated one. An AR system has the following essential features[320]: (i) combines real and virtual objects in a real environment; (II) registers (aligns) real and virtual objects with each other; and (III) Runs interactively, in three dimensions, and in real time. Three aspects of this definition are important to mention. Firstly, it is not restricted to particular display technologies such as a head-mounted display (HMD). Nor is the definition limited to the sense of sight, as AR can and potentially applies to all senses, including hearing, touch, and smell. Finally, removing real objects by overlaying virtual ones, approaches known as mediated or diminished reality, is also considered AR.

AR is related to two largely synonymous terms: mixed reality and computer-mediated reality. The primary value of AR is that it brings components of the digital world into a person's perception of the real world, and does so not as a simple display of data, but through the integration of immersive sensations that are perceived as natural parts of an environment. The first commercial AR experiences were used largely in the entertainment and gaming businesses, but now other industries are also getting interested about AR's possibilities (for example in knowledge sharing, educating, managing the information flood and organizing distant meetings). Augmented reality is also transforming the world of education, where content may be accessed by scanning or viewing an image with a mobile device or by bringing immersive, marker-less AR experiences to the classroom. AR is used to enhance natural environments or situations and offer perceptually enriched experiences. With the help of advanced AR technologies (e.g. adding computer vision and object recognition) the information about the surrounding real world of the user becomes interactive and digitally manipulable. Information about the environment and its objects is overlaid on the real world. This information can be virtual or real, for example seeing other real sensed or measured information such as electromagnetic radio waves overlaid in exact alignment with where they

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[317] Huffington Post. (May 15, 2016): *The Length History of Augmented Reality.* [Available at: *http://images.huffingtonpost.com/2016-05-13-1463155843-8474094-AR_history_timeline.jpg*]. For further information also consider: *https://en.wikipedia.org/wiki/Augmented_reality*

[318] Also see, *among others*: Li, W., Nee, A.Y.C., and Ong, S.K. (2017): A State-of-the-Art Review of Augmented Reality in Engineering Analysis and Simulation. *Multimodal Technologies and Interaction,* **1**(3), 17-39.

[319] Jacob, R.J.K. (2006): *What is the next generation of human-computer interaction?* In Proceedings of the 2006 Conference on Human Factors in Computing Systems (CHI'06), pp.1707-1710. ACM Press, April 23, 2006.

[320] Azuma, R.T. (08/1997): A survey of augmented reality. *Presence,* **6**(4), 355-385.

actually are in space. AR also has a lot of potential in the gathering and sharing of tacit knowledge[321]. Augmentation techniques are typically performed in real time and in semantic context with environmental elements. Immersive perceptual information is sometimes combined with supplemental information like scores over a live video feed of a sporting event. This combines the benefits of both AR technology and heads up display technology.

AR transforms the way we live and interact with the world by offering unprecedented experiences and increased productivity[322]. AR has been studied for several decades and can be combined with human abilities as an efficient and complementary tool to enhance the quality of engineering analysis[323]. An AR system can overlay computer-generated contents on views of the physical scene, augmenting a user's perception and cognition of the world[324]. AR allows the users to continue interacting with both the virtual and real objects around them. A near real-time interaction with these virtual and real objects enables a user to judge multiple parameters simultaneously and analyse the problem efficiently. A complete AR system should include three main elements (i.e. tracking, registration, and visualisation). Development of AR technology with precise information augmentation in real-time is a foreseeable reality that can be used in almost any domain. Over the past decade, AR has undergone a transition from desktop to mobile computing. The portability and propagation of mobile platforms has provided engineers with convenient access to relevant information *in situ*. Integrating AR with engineering problems is a concept that has appeared in recent years. The improvement of equipment performance makes data processing and near real-time display possible. AR is capable of providing an immersive and intuitive environment for the user to achieve near real-time simulation results for problem analysis. Many review works have been conducted to summarize the systems in this field, and at least six classes of potential AR applications have been explored: medical visualisation, maintenance and repair, annotation, robot path planning, entertainment, and military aircraft navigation and targeting.

5G would allow for higher flexibility in a great variety of relevant use cases. AR is commonly used on smartphones or tablets in museums to present additional content for exhibits, or for interior design, allowing shoppers to virtually place furniture in a room to see how it matches. Thus, AR serves distinct business cases while VR serves both consumer and business applications[325]. There are certain areas where both AR and VR overlap[326]. With 5G, the ability to use AR in live, outdoor environments away from reliable Wi-Fi signals can influence the types of interactions and integrations that developers can build. In conclusion, AR is a combination of the real scene viewed by a user and a virtual scene generated by a computer that augments the scene with additional information. The

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321 For example, see the scope discussed in: Krevelen, D.W.F., and Poleman, A. (2010): A survey of augmented reality technologies, applications, and limitations. *International Journal of Virtual Reality*, **9**(2), 1-20.

322 Schreiber, W., Alt, T., Edelmann, M., and Malzkorn-Edling, S. (2002): *Augmented Reality for Industrial Applications – A New Approach to Increase Productivity?* In Proceedings of the WWDU Conference. May 22-25, 2002, Berchtesgaden, Germany.

Also see: Abraham, M., and Annunziata, M. (03/2017): Augmented Reality is Improving Worker Performance. *Harvard Business Review*, 1-5.

Also see: Wild, F., Klemke, R., Lefrere, P., Fominykh, M., and Kuula, T. (2017): Technology Acceptance of Augmented Reality and Wearable Technologies. In: Beck, D. et *al.* (Eds.), Proceedings of the Immersive Learning Research Network (iLRN 2017) Conference. Communications in Computer and Information Science, vol.725, pp.129-141. Springer, Cham.

323 The European Telecommunications Standards Institute (ETSI) has launched an Industry Specification Group called as Augmented Reality Framework (ISG ARF) with the purpose of defining a framework for the interoperability of AR applications and services, thereby thwarting market fragmentation and allowing players to provide part of an overall AR solution.

324 Azuma, R.T. (1997): A survey of augmented reality. *Presence: Tele-operators and Virtual Environments*, **6**(4), 355-385.

325 Consumer Technology Association (10/2016): *Augmented reality and virtual reality: Consumer sentiments*.

326 Pan, Z., Zhigeng, A.D., Yang, H., Zhu, J., and Shi., J. (02/2006): Virtual reality and mixed reality for virtual learning environments. *Computers & Graphics*, **30**(1), 20-28.

virtual content can be interacted with in real time, while virtual objects appear fixed in space. The AR improves our perception of the real world as well as our performance in it.

AR refers to a crucial technology which promotes a major paradigm shift in the way that users interact with data. This has just been known as a feasible solution to different critical needs recently. Moreover, AR technology can be utilised to visualize data from hundreds of sensors concurrently, overlaying related and actionable information over your environment via a headset. With much more data flow, 5G helps AR technology to be much faster. Featured with easier and more reachable use, it is more likely to be widely applied in various different functions (including video gaming).

The AR is a variation of Virtual Environments (VEs) or VR as it is more commonly called. VE technologies completely immerse a user inside a synthetic environment. While immersed, the user cannot see the real world around him. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it[327]. We can summarise by providing the following essential features of VR *vs.* AR, which indicatively implicate for the depiction of Table 2, as follows:

| VR essential features | AR essential features |
|---|---|
| ▪ Computer-generated simulation of a 3D environment;<br>▪ Lack of real elements;<br>▪ Totally immersive environment;<br>▪ Visual senses are under control of system (sometimes aural (sound) and proprioceptive sense too). | ▪ An AR system adds virtual computer-generated objects, audio and other sense enhancements to a real-world environment in real time;<br>▪ System augments the real-world scene;<br>▪ User maintains a sense of presence in real world;<br>▪ Needs a mechanism to a combined virtual and real world. |

*Table 2: VR vs. AR (essential features)*

AR and VR represent two ends of the spectrum. One the one hand AR bases reality as the main focus and the virtual information is presented over the reality, whereas VR bases virtual data as the main focus, having the user immerse into the middle of the synthetic reality virtual environment. One can also imagine a mixed reality where AR meets VR, by merging the physical and virtual information seamlessly.

VR/AR technologies have a number of potential use cases in both entertainment (e.g. gaming) and also more practical scenarios such as manufacturing or medicine and could extend to many wearable technologies[328]. For example, an operation could be performed by a robot that is remotely controlled by a surgeon on the other side of the world. This type of application would require both high bandwidth and low latency beyond the capabilities of LTE, and therefore has the potential to be a key business model for 5G networks. The following Figure 18 depicts the evolution of user experience from VR to AR. This figure also introduces the notion of “Extended Reality” (XR)[329] which refers to all real-and-virtual combined environments and human-machine interactions generated by computer

[327] An easy way to “differentiate” between the two technologies is that VR uses an opaque headset (which prevents the user from seeing through) to completely immerse the user in a virtual world, whereas AR uses a clear headset so the user can see the real world and overlay information and imagery onto it.

[328] Also see the scope discussed in Li, J., and Barmaki, R.: Trends in Virtual and Augmented Reality Research: A Review of Latest Eye Tracking Research Papers and Beyond. *Preprints* **2019**, 2019090019 ([doi: 10.20944/preprints201909.0019.v1](doi:10.20944/preprints201909.0019.v1)).

[329] An interesting framework has been provided in 3GPP TR 26.928 V16.1.0 (2020-12): *“Extended Reality (XR) in 5G”*. Available at: https://www.3gpp.org/ftp//Specs/archive/26_series/26.928/

 

technology and wearables. It includes representative forms such as AR, Mixed Reality[330] (MR) and VR and the areas within the continuum among them. The levels of virtuality range from partially sensory inputs to fully immersive VR. A key aspect of XR is the extension of human experiences especially relating to the senses of existence (represented by VR) and the acquisition of cognition (represented by AR). In the scope of XR provision, the terms "Presence" and "Immersion"[331].

Presence is the feeling of being physically and spatially located in an environment. VR allows us, for the first time, to feel Presence in another realm, in a virtual realm. It is one of the most important yet indescribable factors of VR. Presence can be divided into 2 types: Cognitive Presence and Perceptive Presence. Cognitive Presence is the presence of your mind. It can be achieved by watching a compelling film or reading an engaging book. Cognitive Presence is important to an immersive experience of any kind. Perceptive Presence is the presence of our senses. To accomplish Perceptive Presence, your senses, sights, sound, touch and smell, have to be tricked. Perceptive Presence can only be achieved by VR and AR.

Immersion is different from Presence. The former means that someone can feel surrounded by or the virtual world while the latter means that someone feel he/she is within the virtual world. Presence is achieved when the involuntary aspects of our reptilian corners of our brains are activated. When the user reaches out to grab the virtual apple, becomes unwilling to step off a plank or feel nervous when walking on rooftops.

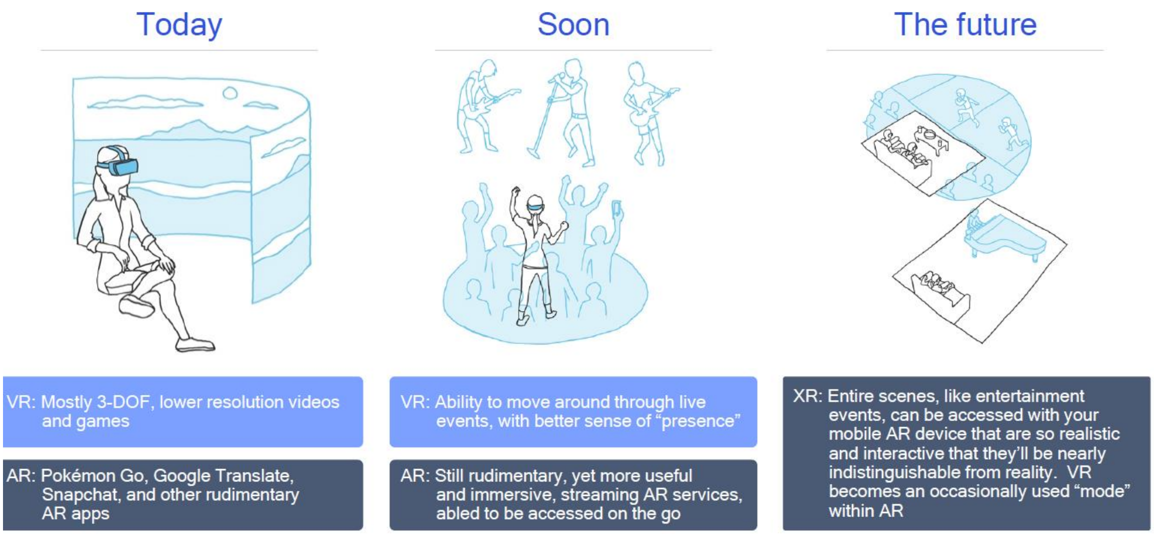


*Figure 18: Evolution of user experience from VR to AR332*

However, it should be pointed out that VR/AR systems are still in their infancy and their development will be largely dependent on advances in a host of other technologies such as motion sensors and heads up display[333] (HUD). It remains to be seen whether these applications could become profitable businesses for operators in the future[334],[335].

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[330] Mixed reality (MR) is an advanced form of AR where some virtual elements are inserted into the physical scene with the intent to provide the illusion that these elements are part of the real scene.

[331] For more details also see, *among others*: https://xinreality.com/wiki/Presence

[332] Qualcomm Technologies Inc. (10/2018): *The mobile future of augmented reality*. Available at: https://www.qualcomm.com/media/documents/files/the-mobile-future-of-augmented-reality.pdf

[333] HUD is any transparent display that presents data without requiring users to look away from their usual viewpoints. The origin of the name stems from a pilot being able to view information with the head positioned "up" and looking forward, instead of angled down looking at lower instruments. A HUD also has the advantage that the pilot's eyes do not need to refocus to view the outside after looking at the optically nearer instruments. Although they were initially

Audio-visual interaction is characterised by a human being interacting with the environment or people, or controlling a UE (User Equipment), and relying on audio-visual feedback. In the use cases like VR[336] and interactive conversation the latency requirements include the latencies at the application layer (e.g. codecs), which could be specified outside of 3GPP.

To support VR environments with low motion-to-photon capabilities, the 5G system shall support: (i) motion-to-photon latency[337] in the range of 7-15 ms while maintaining the required user data rate of 1 Gbps; and (ii) motion-to-sound delay of <20 ms.

To support interactive task completion during voice conversations, the 5G system shall support low-delay speech coding for interactive conversational services (100 ms, one-way mouth-to-ear).

Due to the separate handling of the audio and video component, the 5G system will have to cater for the VR audio-video synchronisation in order to avoid having a negative impact on the user experience (i.e. viewers detecting lack of synchronisation).

While the VR market is still relatively emerging, there is strong potential for this breakthrough technology, which will likely have multiple applications for both consumers and enterprises. To enable an immersive user experience, VR practically delivers the following:

- *Spatiality*: Users can access massive information from spatial virtual environment data.
- *Interaction*: Users can interact with spatial data in virtual environments and with other users, forming connections and flows between users.
- *Real-time experience*: Users can interact in virtual environments in real-time, which requires real-time connections
- However, the huge increase in bandwidth generated by VR services will put *considerable pressure on networks*. Delivering a seamless, high-quality and immersive VR experience will require high bandwidth, low latency, and on-demand capabilities.

### 3.2.2 Definition and Status of Implementation

5G networks are heterogeneous by default, offering different types of connectivity optimised for different types of services[338]. They will offer enhanced mobile broadband connections, but will also

developed for military aviation, HUDs are now used in commercial aircraft, automobiles, and other (mostly professional) applications. A typical HUD contains three primary components: a *projector unit*, a *combiner*, and a *video generation computer*. For more details also see, *among others*: https://en.wikipedia.org/wiki/Head-up_display

334 To this aim, the VR/AR Association (VRARA) is an international organisation designed to foster collaboration between innovative companies and people in the virtual reality and augmented reality ecosystem that accelerates growth, fosters research and education, helps develop industry standards, connects member organisations and promotes the services of member companies. Also see: https://www.thevrara.com/blog2/tag/ETSI

335 For more details also see the context presented in GSM Association (GSMA) (2020): *Cloud AR/VR Whitepaper*. Available at: https://www.gsma.com/futurenetworks/wiki/cloud-ar-vr-whitepaper/

336 In principle, video-based services (e.g. live streaming, VR) and personal data storage applications have been instrumental for the massive growth in mobile broadband traffic. Subject to service agreement between the operator and the content provider, the information of content and content itself can be aware by operator. In-network content caching provided by the operator, a 3rd party or both, can improve user experience, reduce backhaul resource usage and utilize radio resource efficiently.

337 The motion-to-photon latency is defined as the latency between the physical movement of a user's head and the updated picture in the VR headset. The motion-to-sound latency is the latency between the physical movement of a user's head and updated sound waves from a head mounted speaker reaching their ears.

338 Also see: 5G-PPP IA, 5G PPP Architecture Working Group (2016): *View on 5G Architecture*. Available at: https://5g-ppp.eu/wp-content/ uploads/2014/02/5G-PPP-5G-Architecture-WP-For-public-consultation.pdf.

 

support low latency and high reliability mission-critical services, which are necessary requirements for immersive AR and VR experiences. The usefulness of AR and VR going forward is heavily dependent on three primary network components, that is: high capacity, low latency and a uniform experience. Some applications rely on one component more than another, but supporting all three simultaneously is critical to enabling all AR and VR use cases under the same network.

5G is expected to bring enhanced mobile broadband speeds to mobile networks and increase network capacity many times compared to previous generations. Capacity need is a result of two primary drivers: bandwidth per application and simultaneous usage of those applications; although there are numerous compelling AR and VR applications, video is the most important and unique in its high bandwidth requirements. VR and AR technology holds the promise to fundamentally transform how people interact with and experience the physical world, how they are entertained, and how services are delivered to them.

As of latency, it plays an important role for AR and VR experiences, but it is important to understand when low latency is crucial and what type of latency is under consideration. Latency is critical for interactive AR and VR users' experiences. Moving content and network functionality to the edge of the network can reduce latency and so edge computing can support towards achieving the appropriate level of network performance. Enabling ultra-fast connections is relatively straight forward, but making sure that users get a consistent experience with ultra-fast connectivity is not. Reliably delivering bandwidth to a significant portion of mobile users is equally important and cannot be understated for AR and VR use cases.

The key to make forward use of AR technology in praxis is sensitivity to latency and capacity for data volume. Performance is also expected in the case of cloud distributed application and online data processing. Nowadays Google is coming with game-streaming service Google Stadia. According to Google, the success of game streaming all comes down to codecs, encoders, and decoders capable of minimising delay – along with ruthlessly striking the correct balance between quality and latency. In Figure 19 we see a depiction of per-packet feedback signals for Cloud Gaming.

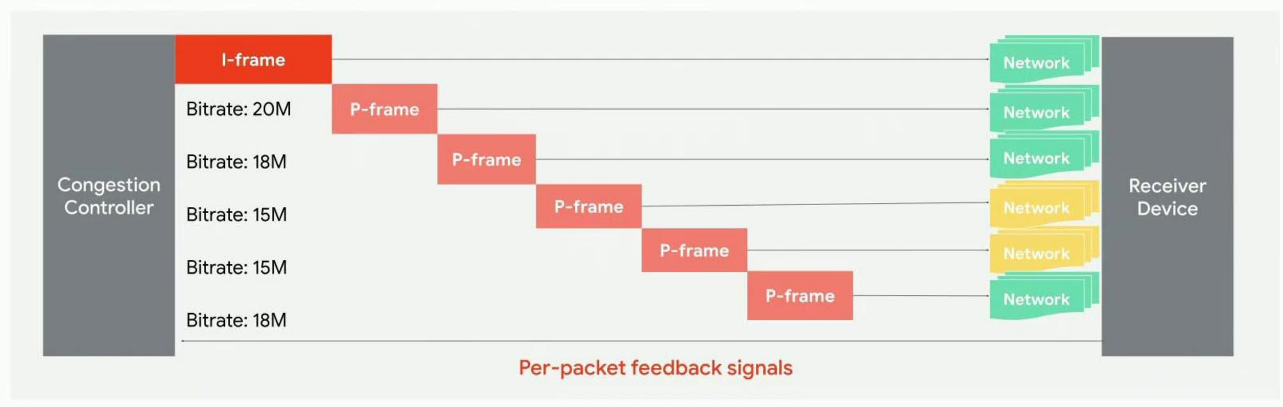


*Figure 19: Google Stadia Streamer*

Such technology as Google Stadia is promising for cloud services performance handle AR application in the near future. Still there is need for wide data channel in the chain of using such streaming technology by the user. Figure 20 shows Network congestion control by Google Stadia.

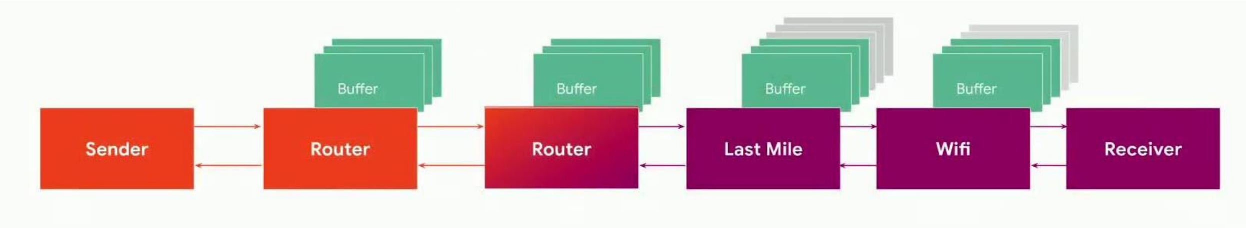


*Figure 20: Google Stadia congestion control*

In this chain is the part where can 5G technology play key role. In our use case is cloud assisted 3D AR described as:

- Cloud-assisted 3D AR: As opposed to conventional gaming consoles or personal computers.
- Both AR and VR applications can be very sensitive to network performance. The already existing 4G networks cannot always support AR and VR applications, but impose several restrictions such as latency and capacity, which can negate some use cases entirely.
- Reference is also made in the direction of performance to the corresponding KPIs, on a per use case basis, as these have been identified and considered for the intended evaluation/assessment of the project technical progress.

Cloud VR/AR brings together significant advances in cloud computing and interactive quality networking to provide high-quality experiences to those who were previously priced out of immersive technologies. “Mixed Reality” (MR) environments merge elements of physical and virtual worlds into a single immersive experience that is generally depicted as an AR experience. The Cloud is a computing architecture whereby resources can be called upon an as-needed basis. Those resources include general and specific computing functions as well as persistent storage but may also include software functions. The key advantage of a cloud computing architecture is that it can accommodate any compute and storage requests made by an application. Early cloud deployments built out all resources into large data centres with high capacity networking for access, however recent demands for low latency interactions with cloud-based applications have seen resources move closer to the edge of the network.

Cloud-assisted 3D AR is a 5G-DRIVE use case in the eMBB scenario. As opposed to conventional gaming consoles or personal computers (which are highly dependent on the signal processing capabilities of the GPU), cloud-assisted AR enables users to stream video games or virtual contents from cloud servers like other streaming media. This new type of services offers an opportunity for more varied and interactive contents and makes user devices lighter and cheaper as well as software development/upgrade mechanisms easier and cheaper due to its more centralised and better serviceable placement. While some new technologies, such as eye tracking and foveated[339] rendering are essential ingredients for high-resolution head-mounted displays (HMDs), bandwidth and latency requirements have pushed the expectations for 5G networks. As it is known, display resolutions and high immersive content play a key role to push users to seek out more robust data service and plans. FOV could range from 1080×1200 per eye to retina AR display (6600×600) per sys and require data rates at the low end (30 fps) between 100 Mbps to 9.4 Gbps at the high end (120 fps). For the eMBB it is required to reach tens of Gbps to support the speed requirement of AR application, providing a more uniform experience for users of AR given the ultra-high data volume requirements that can be handled more effectively.

During the project life time AR/VR use case development was defined minimum technical requirements:

- FOV could range from 1080×1200 per eye to retina AR display (6600×600) per sys.
- Data rates at the low end (30 fps) between 100 Mbps to 9.4 Gbps at the high end (120 fps).
- For the eMBB it is required to reach tens of Gbps to support the speed requirement of AR application, providing a more uniform experience for users of AR given the ultra-high data volume requirements that can be handled more effectively.

339 The fovea is a small portion of the retina in the eye and is responsible for sharp vision.

To maintain the QoE levels required in real-time, cloud-assisted 3D AR, the related KPIs have been measured during our tests and demos in this use case[340],[341]:

The joint AR demo has been tested between Surrey site and China Mobile site in December 2019. However, due to the network firewall security issues, the tested network performance (i.e. data rate and E2E latency) cannot meet the requirement as expected for this type of services. A replaced joint AR demo was then setup between Surrey site and Espoo site, and partners from the Chinese "twin" project participated this just demo at Surrey site as well.

The joint AR demo has been tested several times between Surrey trial site and China Mobile trial site in November 2019. However, due to the network firewall security issues, the network performance (i.e., data rate and E2E latency) cannot meet the requirement as expected for this type of services. The average frame rate is below 20 Mbps at 20 FPS. To overcome this practical situation, another joint AR demo was then setup between Surrey site and Espoo site in December 2019 as shown in Figure 21. EU partners from 5G DRIVE project and China "twin" project partners participated to this demo at Surrey site, as shown in Figure 22. Finally, Figure 23 depicts a screen-shot of the real-time 3D video as shown at VTT site, transmitted from Surrey site.

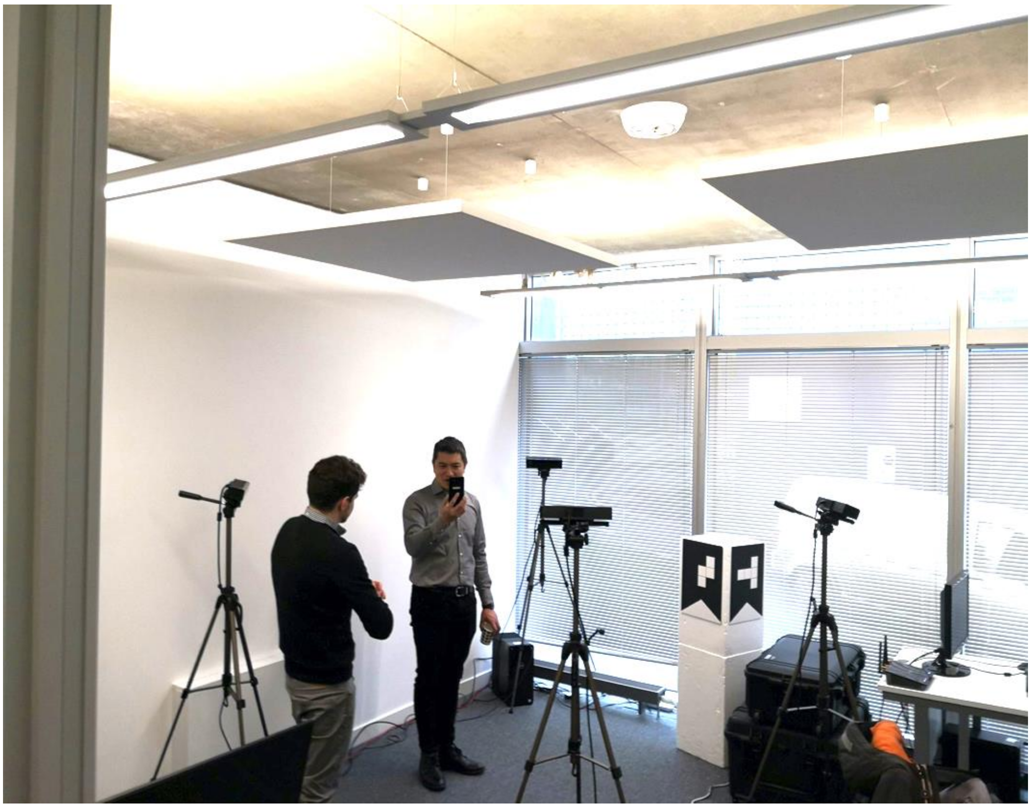

*Figure 21: UoS and VTT partners are setting up joint AR demo between Surrey and Espoo trial in December 2019*

[340] Also see: 5G-DRIVE Project (01/2019): Deliverable 3.1: *"eMBB Development and Test Plan"*. Available at: *https://5g-drive.eu/resources-and-results/project-deliverables/*

[341] Also see: 5G-DRIVE Project (06/2019): Deliverable 3.2: *"Joint Specification for eMBB Trials"*. Available at: *https://5g-drive.eu/resources-and-results/project-deliverables/*

*Figure 22: 5G-DRIVE project coordinator and China twin project partners participated to the joint AR demo at Surrey site*

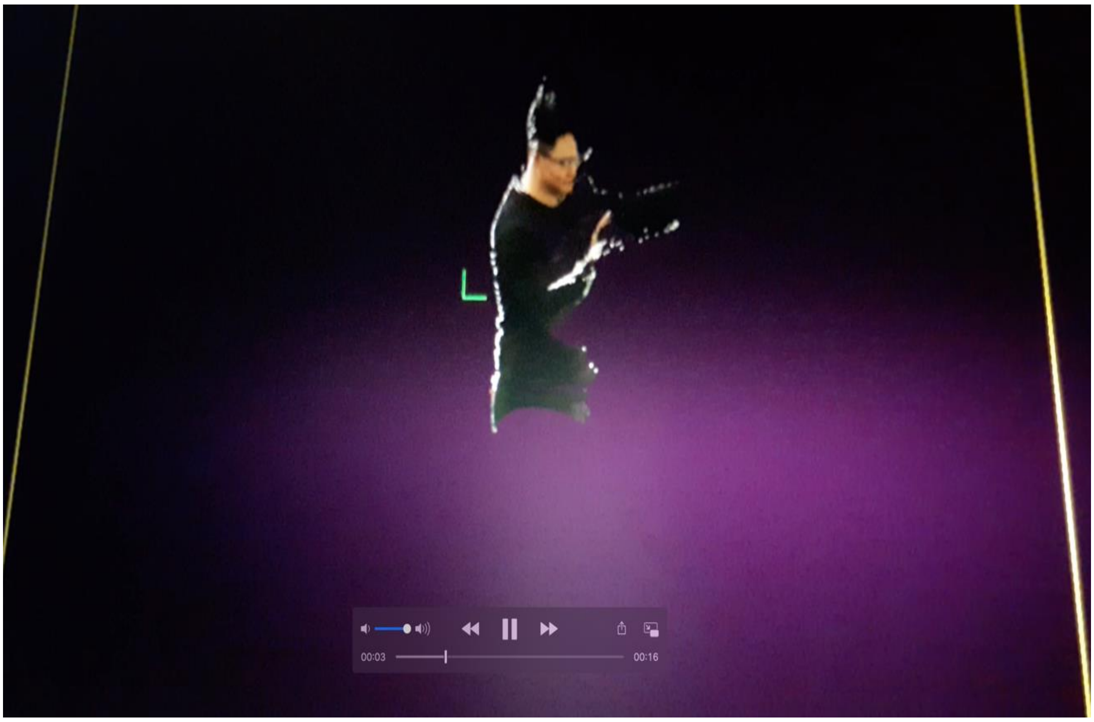


*Figure 23: Screen-shot of the real-time 3D video as shown at VTT site transmitted from Surrey site*

**Measured KPIs for this use case during tests:**

Aim of demo was to take screen-shot of the real-time 3D video as seen transmitted between partners placed in different countries. The performance of use case was tested and demonstrated 2 times with respected results.

To maintain the QoE levels required in real-time, cloud-assisted 3D AR, the following KPIs have been measured during our tests and demo in this use case:

| KPIs | Tests with CMRI in November | Demo with VTT in December |
|---|---|---|
| Peak data rate | 18-22 Mbps | 45-50 Mbps |
| fps | 20 fps | 30 fps |

*Table 3: KPIs for the cloud-assisted AR use case*

In the following part, we briefly discuss the proposed development notice. This part should be devoted to ETSI Architecture document with the aim to give a basis for developers in AR solutions:

- *DGS/ARF-003[342] – AR framework Architecture*

  An AR system is based on a set of hardware and software components as well as data describing the real world and virtual content. Figure 24 presents a global overview of an AR system architecture. The architecture diagram is structured in three layers, in the upper part the hardware, in the middle the software, and in the lower part the data.

- *Hardware layer:*

  **Tracking Sensors:** These sensors aim to localize (position and orientation) the AR system in real-time in order to register virtual contents with the real environment. Most of AR systems such as smartphones, tablets or see-through glasses embed at least one or several vision sensors (generally monochrome or RGB cameras) as well as an inertial measurement unit and a GPS™. However, specific and/or recent systems use complementary sensors such as dedicated vision sensors (e.g. depth sensors and event cameras), or exteroceptive sensors (e.g. Infrared/laser tracking, Li-Fi™ and Wi-Fi™).

  **Processing Units:** Computer vision, machine learning-based inference as well as 3D rendering are processing operations requiring significant computing resources optimised thanks to dedicated processor architectures (e.g. GPU, VPU and TPU). These processing units can be embedded in the device, can be remote and/or distributed.

  **Rendering Interfaces:** Virtual content requires interfaces to be rendered to the user so that he or she can perceive them as part of the real world. As each rendering device has its own characteristics, the signals generated by the rendering software generally need to be transformed in order to adapt them to specific rendering hardware.

- *Software layer:*

  **Vision Engine:** This software aims to mix the virtual content with the real world. It consists of localizing (position and orientation) the AR device relative to the real-world reference, localizing specific real objects relatively to the AR device, reconstructing a 3D representation of the real world or analysing the real world (e.g. objects detection, segmentation, classification and tracking). This software component essentially uses vision sensors signals as input, but not only (e.g. fusion of visual information with inertial measurements or

[342] Also see the detailed contents in European Telecommunications Standards Institute (ETSI): ETSI GS ARF 003 V1.1.1 (2020-03): *"Augmented Reality Framework (ARF); AR framework architecture"*. Available at: https://www.etsi.org/deliver/etsi_gs/ARF/001_099/003/01.01.01_60/gs_ARF003v010101p.pdf

initialisation with a GPS), it benefits from the hardware optimisation offered by the various dedicated processors embedded in the device or remote, and will deliver to the rendering engine all information required to adapt the rendering for a consistent combination of virtual content with the real world.

**3D Rendering Engine:** This software maintains an up-to-date internal 3D representation of the virtual scene augmenting the real world. This internal representation is updated in real-time according to various inputs such as user's interactions, virtual objects behaviour, the last user viewpoint estimated by the Vision Engine, an update of the World Knowledge to manage for example occlusions between real and virtual elements, etc. This internal representation of the virtual content is accessible by the renderer (e.g. video, audio or haptic), which produces thanks to dedicated hardware (e.g. Graphic Processing unit) data (e.g. 2D images, sounds or forces) ready to be played by the Rendering Interfaces (e.g. screens, headphones or a force-feedback arm).

- *Data layer:*

**World Knowledge:** This World Knowledge represents the information either generated by the Vision Engine or imported from external tools to provide information about the real world or a part of this world (CAD model, markers, etc.). This World Knowledge corresponds to the digital representation of the real space used for different usages such as localisation, world analysis, 3D reconstruction, etc.

**Interactive Contents:** These Interactive Contents represent the virtual content mixed to the perception of the real world. These contents can be interactive or dynamic, meaning that they include both 3D contents, their animations, their behaviour regarding input events such as user's interactions. These Interactive Contents could be extracted from external authoring tools requiring adapting original content to AR application (e.g. 3D model simplification, fusion, and instruction guidelines conversion).

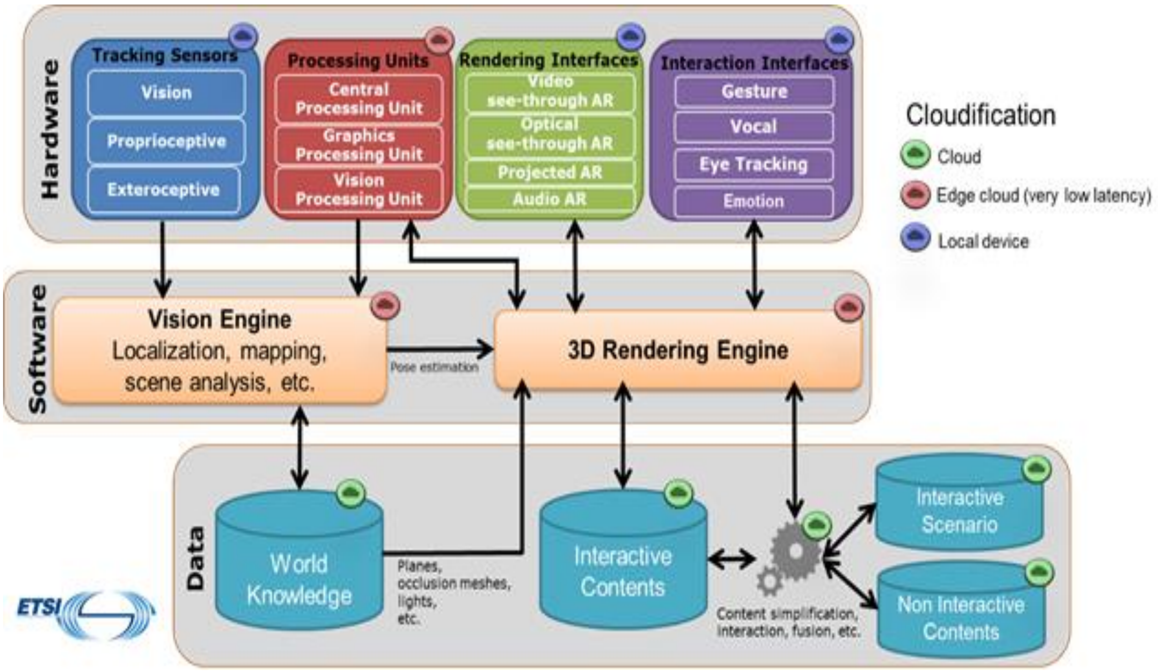


*Figure 24: Global overview of the architecture of an AR system*

Figure 25 shows the functional architecture specified by the present document addressing both fully embedded AR systems and implementations spread over IP networks in a scalable manner. Logical functions are shown as named boxes that may be nested in cases where a high-level function is composed of several sub-functions. The logical functions are connected by reference points. A reference point in a functional architecture is located at the conjunction of two non-overlapping functions and represents the interrelated interactions between those functions.

A reference point allows a framework to aggregate those abilities that one function provides towards another function. In a practical deployment each of these reference points can be realised by a physical interface that conveys information between the connected sub-functions in a unidirectional or bidirectional way using a specified protocol. Depending on the deployment scenario and the applications that need to be supported, multiple logical sub-functions can also be combined in one deployable unit. All of these sub-functions can either be deployed on the device that also presents the AR implementation or they can be provided via cloud technology.

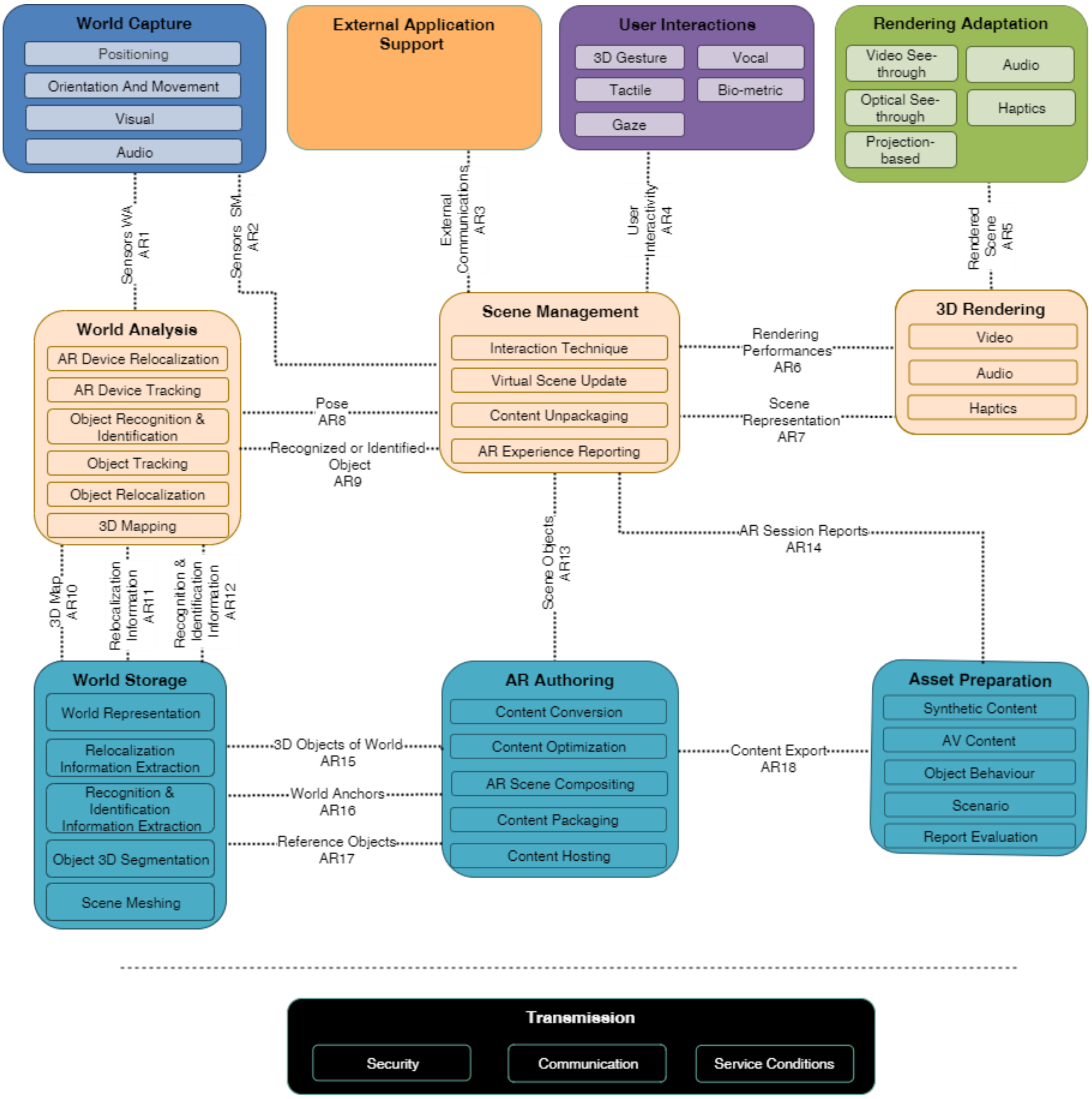


*Figure 25: Diagram of the reference functional architecture*

Presented architectural concept was developed as part of European standardisation organisation ETSI, in the Industry Specification Group of AR. We strongly encourage developers in the field of AR/VR to start development of its own application with the respect of proposed architecture.

The eMBB Use case Cloud-Assisted AR in the 5G-DRIVE project clearly showed near future potential of use case with respecting and reached KPIs defined in the beginning of the project.

In the following, we briefly identify several issues affecting training, industrial options, service development and manufacturing processes.

***Training***

At present, law enforcement and rescue agencies train their staff for radiological incidents using three distinct modalities:

- physical simulations (using live sources, simple mock-ups or simulants);
- multimedia simulations;
- desktop-based simulations.

Physical simulations provide a level of training, which is the closest to real conditions, and can be used as mission rehearsal exercises and to improve readiness. Using real resources, physical simulations are expensive, mobilizing resources that could be spent elsewhere for the time of the training, and may put these resources at risk. Multimedia and desktop-based simulations do not have these drawbacks but instead lack fidelity, in particular equipment fidelity. This kind of training (e.g. Command Post Exercises, Tactical Exercises without troops, etc.) can be well suited for strategic and tactical-level operator training but clearly lacks simulation fidelity for operational-level operators.

***Industrial***

In the industry, but also at home, wireless networks are backbones that support numerous devices and objects from the Internet of Things.

The deployment of that kind of infrastructure in factories or at home is sometimes complex due to the intangible nature of wave propagation. An interesting challenge is how to place emitters and repeaters to optimize the wireless coverage.

Once the coverage is well tailored and established, the installation of the connected objects is another interesting challenge. The objects have to be identified, integrated safely in the network, but also stored their position and orientation in the real world. Indeed, this location information is highly valuable to provide smart contextual services to the end-user.

A typical use of the position of the object is to provide access to information or to an interface on the objects that are in the field of user’s view. It can also be used to ease the construction of home automation scenarios involving different objects; making a switch command different sets of lamps or of blinds for example.

AR can greatly facilitate the wireless network deployment, the installation of objects and, afterwards, it could also help providing rich contextual services to use them or to service them.

***Service***

In the competitive working environment of today cost and time pressure are business-relevant issues for service and maintenance and in a world of more and more connected work flows there are rising demands on availability and service quality. Additionally, the technical complexity of solutions is increasing as well as the amount of data that needs to be processed and evaluated as part of the work process.

The transfer of knowledge is essential for guaranteeing a certain level of service quality and experience and skills need to be transferred fast and efficiently to employees and subcontractors. The well-known paper-based documentation is upgradable in an extensive way but there are no feedback functions foreseen and its usage can become impractical, especially for outdoor activities. Documentation has to be kept up-to-date and it should be centrally provided without any media disruption. The level of detail of such documentation needs to be adaptable to the problem that needs to be solved and to the knowledge of the employee. Newcomers may get a “step-by-step” description whereas experts only have to check items provisioned by a check list.

***Manufacturing***

The manufacturing and training processes have been optimised so much over the last decade that new technologies like AR, cloud computing, artificial intelligence, internet of things and others are beginning to be taken into consideration in the attempt of further improving the Key Performance Indicators of production plants. This is one reason why Industry 4.0 is increasingly used as a new trend in industry and research. The AR is actually considered as one of the 10 strategic technologies of Industry 4.0. Research shows that AR can reduce assembly errors, assembly time and training requirements and can increase the recall of work instructions, among other positive effects.

## 3.3 Use Case 2: Indoor Positioning System (IPS)

### 3.3.1 Conceptual Description

Positioning systems can be categorised depending on the target environment as either indoor, outdoor, or mixed type. Indoor Positioning Systems (IPSs) locate objects in closed structures such as office buildings, hospitals, stores, factories and warehouses, airport, a subway and university campuses, where Global Positioning System (GPS) devices generally do not work[343]. Most available systems apply wireless concepts, optical tracking, and/or ultrasonic techniques. Object detection and tracking is the basis of many applications in surveillance and activity recognition. There are many solutions developed for position estimation of indoor or outdoor objects[344]. Most of these solutions are based on triangulation and multi-lateration methods using light, ultrasound or radio signals and they provide positional information. There are also other techniques, which provide relative positioning such as, inertial methods; unfortunately, they accumulate errors in time and require periodic recalibration.

In addition to the indoor positioning technologies, there are several indoor positioning techniques that can be applied at different indoor positioning technologies. One or more techniques can be applied together to compensate for the limitations of a single positioning technique[345]. Indoor positioning techniques were classified[346] into four classes: (i) triangulation[347]; (ii) fingerprinting[348]; (iii) proximity[349]; and (iv) vision analysis[350].

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343 For more details see, *inter-alia*: D. Zhang, D., Xia, F., Yang, Z., Yao, L., and Zhao, W. (2010): *Localization technologies for indoor human tracking*. In Proceedings of the 5th International Conference on Future Information Technology (FutureTech'10), pp.1-6. Busan, South Korea, May 21-23, 2010.

344 Lee, B.-G., Lee, Y.-S., and Chung, W.-Y. (2008): 3D Navigation Real Time RSSI-based Indoor Tracking Application. *Journal of Ubiquitous Convergence Technology*, **2**(2), 67-77.

345 Gu, Y., Lo, A., and Niemegeers, I. (2009): A survey of indoor positioning systems for wireless personal networks. *IEEE Communications Surveys & Tutorials*, **11**(1), 13-32.

346 Ibid.

347 The triangulation location sensing technique uses the geometric properties of triangles to compute object locations. Triangulation is divisible into the subcategories of lateration and angulation. Lateration, which is sometime called range measurement, computes the position of an object by measuring its distance from multiple reference points. Angulation uses angles to determine the position of an object as well as distances.

348 Instead of determining the distances between an object and reference points and triangulating the object's location, location fingerprinting matches the fingerprint of some characteristic of a signal such as RSS (Received Signal Strength) which is location-dependent. There are two stages for location fingerprinting: offline stage and online stage.

Also see, *among others*: Yassin A., Nasser, Y., Awad, M., Al-Dubai. A., Yuen, C., Raulefs, R., and Aboutanios, E., (2017): Recent advances in indoor localization: A survey on theoretical approaches and applications. *IEEE Communications Surveys & Tutorials*, **19**(2), 1327-1346.

349 A proximity location sensing technique examines the location of a target object with respect to a known position or an area. Proximity techniques estimate the position of a mobile target when it is close to an antenna or a sensor. The object's presence is sensed using a physical phenomenon with a limited range. The proximity location technique needs

Various wireless technologies are used for wireless indoor location[351],[352]. These may be classified based on: (i) The location positioning algorithm, that is the method of determining location, making use of various types of measurement of the signal such as Time Of Flight (TOF), angle, and signal strength; and (ii) the physical layer or location sensor infrastructure, that is the wireless technology used to communicate with the mobile devices or static devices. In general, measurement involves the transmission and reception of signals between hardware components of the system. An indoor wireless positioning system consists of at least two separate hardware components, that is a signal transmitter and a measuring unit. The latter usually carries the major part of the system "intelligence".

An indoor positioning system (IPS) is a system that continuously and in real-time determine the position of a person or an object in an indoor environment[353] which has various applications[354],[355]. Such systems can be used for different private home applications that can range from detection and tracking of items, providing assistance for elderly and disable people in their daily activities, and medical monitoring for vital signs and emergencies. Public building (e.g., malls and museums) can be target for different useful applications of IPSs including indoor navigation systems for blind and visually impaired people, aiding tourists in museums, and tracking kids in crowded places. Medical care in hospitals is also an important application area for IPSs where they can be used for patient tracking, tracking expensive equipment to prevent them from thefts, and precise positioning for robotic assistance during surgeries. Furthermore, IPSs can be used by police and fire-fighters for rescue operations.

There are many characteristics that make indoor positioning different from outdoor positioning[356]. In comparison with outdoor environments, indoor environments are more complex as there are various objects (such as walls, equipment, and people) that reflect signals and lead to multipath and delay problems. Also, due to existence of various objects, indoor environments typically rely on Non-Line-of-Sight (NLoS) propagation where signal cannot travel directly in straight path from an emitter to a receiver, which causes inconsistent time delays at the receiver. Furthermore, the existence of objects and obstacles leads to high attenuation and signal scattering. Typically, indoor positioning applications require a higher precision and accuracy in comparison with outdoor positioning applications in order to deal with relatively small areas and existing obstacles. On the other hand,

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to fix a number of detectors at the known positions. When a tracked target is detected by a detector, the position of the target is considered to be in the proximity area marked by the detector.

Also see: Hightower, J., and Borriello, G. (2001): Location sensing techniques. Technical report. IEEE Computer.

350 The vision analysis method estimates a location from the images received at one or multiple points. Usually, one or multiple cameras are fixed in the tracking area of an IPS to cover the whole place and take real time images. From the images, the tracked targets are identified.

351 Brena, R.F., García-Vázquez, J.P., Galván-Tejada, C.E., Muñoz-Rodriguez, D., Vargas-Rosales, C., and Fangmeyer, J. Jr. (2017): Evolution of Indoor Positioning Technologies: A Survey. *Hindawi, Journal of Sensors*, 1-21.

352 Al-Ammar, M.A., Alhadhrami, S., -Salman, A., Alarifi, A., Al-Khalifa, H.S., Alnafessah, A. and Alsaleh, M. (2014): *Comparative Survey of Indoor Positioning Technologies, Techniques, and Algorithms*. In Proceedings of the 2014 International Conference on Cyberworlds, pp.245-252. MDPI, Santander, Spain, October 06-08, 2014.

353 Gu, Y., Lo, A., and Niemegeers, I. (2009): A survey of indoor positioning systems for wireless personal networks. *IEEE Communications Surveys & Tutorials*, **11**(1), 13-32.

354 Al Nuaimi, K., and Kamel, H. (2011): *A survey of indoor positioning systems and algorithms*. In Proceedings of the 2011 IEEE International Conference on Innovations in Information Technology (IIT), pp.185-190. IEEE, Abu Dhabi, April 25-27, 2011.

355 Mautz. R. (2012): *Indoor positioning technologies. PhD Habilitation Thesis*. ETH, Zurich, Switzerland. Available at: *https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/54888/eth-5659-01.pdf*

356 Ibid.

 

there are some characteristics of indoor environments that facilitate positioning[357]. For example, small coverage area makes it relatively under control in terms of predetermined infrastructure, corridors, entries and exits, small temperature and humidity gradients, and slow air circulation. Also, indoor environment is less dynamic due to a slower moving speed within.

Thus, an IPS is a system used to locate objects or people inside a building using lights, radio waves, magnetic fields, acoustic signal, or other sensory information[358],[359]. There are several commercial systems on the market, but there is no specific standard for an IPS system. By the complex nature of indoor environments, the development of an indoor localisation technique is always associated with a set of challenges like smaller dimensions, high none line of sight (NLOS), influence of obstacles like walls, equipment, movement of human beings, doors, and other factors[360]. Multipath effect signals are reflected and attenuated by walls and furniture and noise interference. These challenges result mainly from the influence of obstacles on the propagation of electromagnetic waves. For instance, the mobility of people incurs changes in physical conditions of the environment, which might significantly affect the behavior of wireless radio propagation. Although these negative effects cannot be eliminated completely, in recent years researches are constantly going on to improve the performance of indoor (human/object) tracking. For getting good and accurate results, a positioning system must be able to handle these problems. Beside this, higher accuracy is also required indoors to locate a user at least in the right room. One of the important aspects indoors is indoor signal property characteristics.

IPSs use numerous positioning approaches that vary greatly in terms of accuracy, responsiveness, coverage, adaptiveness, availability, scalability, capacity, cost and complexity, privacy, security and topology. Some applications may require less cost IPS while others may require high accuracy IPS such as medical tracking, industrial environmental tracking, indoor navigation system for blind.

The performance criteria associated with localisation systems can be classified into the following areas:

(i) *Accuracy* (or location error) of a system is the important user requirement of positioning systems. Accuracy can be reported as an error distance between the estimated location and the actual mobile location. Sometimes, accuracy is also called the area of uncertainty; that is, the higher the accuracy is, the better the system is. However, there is always a trade-off between accuracy and other characteristics and some compromise between “suitable” accuracy and the other characteristics is needed.

(ii) *Responsiveness*, which determines how quickly the location estimate of a moving target is updated.

(iii) *Coverage*: The problem of determining the network coverage for a designated area is important when evaluating the effectiveness of a positioning system. Coverage is closely related to accuracy and can be categorised as local coverage, scalable coverage, and global coverage[361]. Coverage area is the area that is covered by the IPS. Each IPS works in a different range. The most effective systems are the ones that cover the widest range. Generally, for

357 Ibid.

358 Liu, H., Darabi, H., Banerjee, P., Liu, J., et *al.* (2007, November): Survey of Wireless Indoor Positioning Techniques and Systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, **37**(6), 1067-1080.

359 Curran, K., Furey, E., Lunney, T., Santos, J., Woods, D., and McCaughey, A. (2011): An Evaluation of Indoor Location Determination Technologies. *Journal of Location Based Services,* **5**(2), 61-78.

360 See, *among others*: Yiming, J. (2010): *Indoor Location Determination, in Location-Based Services Handbook.* CRC Press.

361 Local coverage is a small well-defined, limited area which is not extendable (e.g. a single room or building). In this case, the coverage size is specified (e.g. (m), (m2), or (m3)). Scalable coverage means systems with the ability to increase the area by adding hardware, and global coverage means system performance worldwide or within the desired/specified area.

 

positioning systems, there are three levels of coverage, that is: local, scalable, and global. Local coverage refers to a well-defined, limited area, which is not extendible such as a single room or building, while scalable coverage refers to ability of a system to increase the area by adding hardware. On the other hand, global coverage refers to a system that has a worldwide area such as GPS. Nowadays, ranges of existing IPSs go from 5 meters to 50 meters. Therefore, providing a system that has coverage of more than 60 meters is challenging.

(i) *Adaptiveness*: Environmental influence changes may affect the localisation system performance. The ability of the localisation system to cope with these changes is called its adaptiveness[362].

(ii) Availability: It is the percentage of time during which the positioning service is available for use with the required accuracy and integrity. An IPS Integrity is the confidence which can be placed in the output of the IPS. The availability could be limited by random factors such as communications congestion and by scheduled factors such as routine maintenance. Generally, availability can be seen as three levels; low availability (< 95%), regular availability (> 99%), and high availability (> 99.9%)[363].

(iii) *Scalability:* A positioning system may be able to locate objects worldwide, within a metropolitan area, throughout a campus, in a particular building, or within a single room. Also, the number of objects the system can position with a certain amount of infrastructure or over a given time may be limited. Scalability of an IPS means the system ensures the normal positioning function when it scales in one of the two dimensions: geography and number of users. The number of users' scale means that the number of units located per geographic area per time period increases[364]. Scalability is a desirable property in almost any system that suggests how well the system performs when it operates with a larger number of location requests and a larger coverage. The scalability character of a system ensures the normal positioning function when the positioning scope gets large. Usually, the positioning performance degrades when the distance between the transmitter and receiver increases. Poor scalability can result in poor system performance, necessitating the reengineering or duplication of systems. A scalable positioning system should be able to handle large numbers of tags without unnecessary strain. A location system may need to scale on two axes: geography and density. Geographic scale means that the area or volume is covered. Density means the number of units located per unit geographic area/space per time period. As more area/space is covered or units are crowded in an area/space, wireless signal channels may become congested, more calculation may be needed to perform location positioning, or more communication infrastructure may be required. Another measure of scalability is the dimensional space of the system. The current system can locate the objects in 2-D or 3-D space. Some systems can support both 2-D and 3-D space.

(iv) *Capacity:* For communication systems designed specifically to transmit indoor location data, capacity is essential and fundamental since simple processes can be interrupted due to the overflow of the transmission capacity, thus generating a defective QoS.

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362 A system that is able to adapt to environmental changes can provide better localisation accuracy than systems that cannot adapt. An adaptive system can also prevent the need for repeated calibration.

363 Al Nuaimi, K., and Kamel, H. (2011): *A survey of indoor positioning systems and algorithms*. In Proceedings of the 2011 IEEE International Conference on Innovations in Information Technology (IIT), pp.185-190. IEEE, Abu Dhabi, April 25-27, 2011.

364 Liu, H., Darabi, H., Banerjee, P., and Liu, J. (2007): Survey of wireless indoor positioning techniques and systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews,* **37**(6), 1067-1080.

(v) *Cost and Complexity:* The cost of a positioning system may depend on many factors. The cost gained from a positioning system can arise from the cost of extra infrastructure, additional bandwidth, money, lifetime, weight, energy, and nature of the deployed technology. This can be caused at different levels of the system: system installation and maintenance, infrastructure components, and positioning devices. The time factor is related to installation and maintenance. Mobile units may have tight space and weight constraints. Mobile units may have tight space and weight constraints. Measuring unit density is considered to be a space cost. The cost may include installation and survey time during the deployment period. The cost for system installation and maintenance includes cost required for installation, and any expenses required to keep the system functional, while the cost for infrastructure components and positioning devices may include cost for buying components and preparing them, space, and energy to run those components. If a positioning system can reuse an existing communication infrastructure, some part of infrastructure, equipment, and bandwidth can be saved. The complexity of the signal processing and algorithms used to estimate the location is another issue that needs to be balanced with the performance of positioning systems. Trade-offs between the system complexity and the accuracy affect the overall cost of the system.

(vi) *Privacy:* Privacy is extremely important to individuals using IPSs, where a strong access control over how users' personal information is collected and used is crucial[365]. In order to improve users' privacy, security mechanisms should be implemented and maintained to protect data from intrusion, theft, and misuse. Unfortunately, the security aspect of IPSs has not been a major concern in most of the undertaken research in the field of indoor positioning.

(vii) *Security:* The security and privacy of the users must be guaranteed when using any technology, and even more so when exchanging information among millions of interconnected objects. Security mechanisms must be implemented and maintained to protect data against intruders, theft and misuse. Information about the user's location is sensitive data that may present a problem.

(viii) *Topology:* The network topology refers to how the devices are connected, both active and passive, and the form of communication. The topology directly affects the performance and capacity of the connected devices within the network and therefore a correct topology will optimize costs on the system.

IPS can be used to locate people or objects inside buildings, typically via a mobile device such as a smart phone or tablet[366]. Although the technology is newer than GPS, services that leverage IPS are quickly gaining traction in places like shopping malls, hospitals, airports and other indoor venues where navigation and other location-based services (LBS) can prove to be indispensable[367].

Indoor positioning systems use different technologies, including distance measurement to nearby anchor nodes (nodes with known fixed positions, e.g. WiFi/LiFi[368] access points or Bluetooth

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365 See, *among others*: Gu, Y., Lo, A., and Niemegeers, I. (2009): A survey of indoor positioning systems for wireless personal networks. *IEEE Communications Surveys & Tutorials*, **11**(1), 13-32.

366 Mier, J., Razamillo-Alcázar, A., and Freire, J.J. (2019): *At a Glance: Indoor Positioning Systems Technologies and Their Applications Areas*". In Information Technology and Systems, pp.483-493. Springer.

367 Also see: Linde, H. (08/2006): *On Aspects of Indoor Localization. Thesis*. University of Dortmund, Germany. Available at: *https://eldorado.tu-dortmund.de/bitstream/2003/22854/1/dissertation_linde.pdf*

**368** Li-Fi (light fidelity) is wireless communication technology, which utilizes light to transmit data and position between devices. In technical terms, Li-Fi is a light communication system that is capable of transmitting data at high speeds over beacons), magnetic positioning and dead reckoning[369]. They either actively locate mobile devices and tags or provide ambient location or environmental context for devices to get sensed. The localised nature of an IPS has resulted in design fragmentation, with systems making use of various optical, radio or even acoustic technologies. Different indoor positioning technologies can be used concurrently to gain the advantages of each one. The appropriate indoor positioning technology should be selected carefully in order to make the right trade-off between the performance and the complexity of IPSs.[370]

For smoothing to compensate for stochastic (unpredictable) errors there must be a sound method for reducing the error budget significantly. The system might include information from other systems to cope for physical ambiguity and to enable error compensation. Detecting the device's orientation (often referred to as the compass direction in order to disambiguate it from smartphone vertical orientation) can be achieved either by detecting landmarks inside images taken in real time, or by using trilateration[371] with beacons. There also exist technologies for detecting magnetometric information inside buildings or locations with steel structures or in iron ore mines.

Due to the signal attenuation caused by construction materials, the satellite based Global Positioning System (GPS) loses significant power indoors affecting the required coverage for receivers by at least four satellites. In addition, the multiple reflections at surfaces cause multi-path propagation serving for uncontrollable errors. These very same effects are degrading all known solutions for indoor location which uses electromagnetic waves from indoor transmitters to indoor receivers. A bundle of physical and mathematical methods is applied to compensate for these problems. Promising direction radiofrequency positioning error correction opened by the use of alternative sources of navigational information, such as Inertial Measurement Unit[372] (IMU), monocular camera

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the visible light, ultraviolet, and infrared spectrums. In terms of its end use, the technology is similar to Wi-Fi with the latter using radio frequency to transmit data. Using light to transmit data allows Li-Fi to offer several advantages, most notably a wider bandwidth channel, the ability to safely function in areas otherwise susceptible to electromagnetic interference (e.g. aircraft cabins, hospitals, military), and offering higher transmission speeds. The technology is actively being developed by several organisations across the globe.

For more details also see, *among others*: LiFi Research: Comprehensible Summary of Modulation Techniques for LiFi. [www.lifi.eng.ed.ac.uk].

369 Qiu, C., and Mutka, M. (2016): CRISP: Cooperation among smartphones to improve indoor position information. *Wireless Networks (Springer),* **24**(3), 867-884.

370 According to the need for hardware, IPS can be classified into two classes, that is technologies requiring special hardware in the building and the self-contained technologies. Other potential criterion for classification can be based on IPSs' need for existence of networks, which results to network-based and non-network-based technologies. If we consider a criterion the system architecture, then we can distinguish three classes: (i) Self-positioning architecture where objects calculate their positions by themselves; (ii) infrastructure positioning architecture which estimates the positions of the targets using the infrastructure to find if the target is in the coverage areas and track them, and; (iii) self-oriented infrastructure-assisted architecture which depends on the system that calculates positions then sends them to the tracked target in response to its request. In addition, IPSs can also be classified into six classes based on the main medium used to determine positions: (i) Infrared (IR) technologies; (ii) ultrasound technologies; (iii) radio frequency (RF) technologies; (iv) magnetic technologies; (v) vision-based technologies; and (vi) audible sound technologies.

371 Trilateration is the measurement of the lengths of the three sides of a series of touching or overlapping triangles on the earth's surface for the determination of the relative position of points by geometrical means (as in geodesy, map making and surveying).

372 An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers. IMUs are typically used to maneuver aircraft (an attitude and heading reference system), including unmanned aerial vehicles (UAVs), among many others, and spacecraft, including satellites and landers. Recent developments allow for the production of IMU-enabled GPS devices. An IMU allows a GPS receiver to work when GPS-signals are unavailable, such as in tunnels, inside buildings, or when electronic interference is present. A wireless IMU is known as a WIMU. Also see, *for example*: https://en.wikipedia.org/wiki/Inertial_measurement_unit.

Simultaneous Localisation and Mapping[373] (SLAM) and WiFi SLAM[374]. Integration of data from various navigation systems with different physical principles can increase the accuracy and robustness of the overall solution.

In the past decades, wireless localisation technologies have undergone considerable progress. They gradually play an important role in all aspects of people's daily lives[375], including e.g. living assistant, navigation, emergency detection, surveillance/tracking of target-of-interest, and many other location-based services. Reliable, accurate, and real-time indoor tracking services are required by people even more strongly than ever. For example, with the severely increasing number of elder people, the aging population has become a burning issue for all modern societies around the world. It has consequently become an urgent problem how to monitor those old people effectively when they are at home or inside other buildings[376]. In addition, more and more attention has been paid to context-aware applications, which can make our life easier and convenient[377]. The realisation of these applications is essentially based on location information.

Indoor positioning systems are used to locate people or required objects in large buildings and in closed areas. For example, locating patients in the hospital, finding people trapped in a burning building or finding workers in a large office block are a few applications of indoor positioning systems. The IPS allow to develop diverse applications, among others with the control of accesses, the security in networks, the management of information, and optimisation of the services of emergency. Obtaining data in real time provides an important advantage over what clients or administrators need. This advantage can be well exploited in indoor environments[378]. The correct choice of a connection technology for IPS offers innovative solutions to needs of users to improve their quality of life and provide an opportunity to use daily applications.

With the help of the Global Positioning System (GPS), outdoor positioning becomes full-fledged and can be regarded as accurate in most application scenarios now. However, indoor positioning is still far from maturity, because of the complex indoor electromagnetic propagation environment[379]. Accurate and reliable indoor positioning services will radically change the living habits of mobile

[373] In navigation, robotic mapping and odometry for virtual reality or augmented reality, simultaneous localisation and mapping (SLAM) is the computational problem of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent's location within it. There are several algorithms known for solving it, at least approximately, in tractable time for certain environments. Popular approximate solution methods include the particle filter, extended Kalman filter, Covariance intersection, and Graph SLAM. Existing SLAM algorithms are tailored to the available resources, hence not aimed at perfection, but at operational compliance. Published approaches are employed in self-driving cars, unmanned aerial vehicles, autonomous underwater vehicles, planetary rovers, newer domestic robots and even inside the human body.

For more details also see, *for example*: Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., Reid, I., and Leonard, J.J. (2016): Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics,* **32**(6), 1309-1332.

[374] See, *for example*, the context proposed in: Herranz, F., Llamazares, A., Molinos, E., Ocaña, M., and Sotelo, M.A. (04/2016): WiFi SLAM algorithms: an experimental comparison. *Cambridge University Press,* **34**(4), 837-858.

[375] See the interesting context proposed in: Gu, Y., Lo, A., and Niemegeers, I. (2009): A Survey of Indoor Positioning Systems for Wireless Personal Networks. *IEEE Communications Surveys & Tutorials*, **11**(1), 13-32.

[376] Ng, J.W.P. (2005): *Ubiquitous Healthcare Localisation Schemes*. In Proceedings of the 7th International Workshop on Enterprise networking and Computing in Healthcare Industry, (HEALTHCOM, 2005), pp.156-161. Busan, South Korea, June 23-25, 2005.

[377] Amundson, I., and Koutsoukos, X.D. (2009): *A Survey on Localization for Mobile Wireless Sensor Networks*. In "Mobile Entity Localization and Tracking in GPS-less Environments", LNCS 5801, pp.235-254. Springer.

[378] Svalastog, M.S. (2007): *Indoor Positioning-Technologies, Services and Architectures. Thesis*. University of Oslo, Norway. Available at: https://www.duo.uio.no/bitstream/handle/10852/9742/Svalastog.pdf?sequence=1

[379] Oh, J., Thiel, M., and Sarabandi, K. (2014): Wave-propagation management in indoor environments using micro-radio-repeater systems. *IEEE Antennas and Propagation Magazine*, **56**(2), 76-88.

users and open up new niches for economic prosperity. On the other hand, there is a growing consensus that accurate indoor positioning might not be viable by sole utilizing RF communications[380]. Such a crucial and impactful application is highly expected to be realised in the era of 6G with more advanced non-RF communication technologies.

We can summarize in brief, by identifying several beneficial opportunities for IPS adoption in the market sector, as follows:

- In the retail market, the IPSs are a great opportunity for retailers to increase their incomes by providing an exciting experience to their customers. Thus, retail companies are looking for cutting-edge IPSs to attract customer impressions and complementing them with the online experience. Choose goods and just go away is one example of business models that are recently emerging in the world of rails where both customers and retailers will benefit from IPSs saving their time and money respectively.
- Within the manufacturing framework, IPSs will be one of the pillars of Industry 4.0 helping to cost reduction, improving business efficiency, and decreasing risks to workers' lives and health. Indeed, IPSs allow the manufacturer real-time monitoring and recording of workers' movements within the working space, which allows a reactive control of the work and ensures an efficient execution of work protocols and procedures.
- IPSs are also a great opportunity for Healthcare systems to make life easier and to enhance financial efficiency and to reduce waiting time for patients. Indeed, IPSs can efficiently address the serious management and optimisation challenges imposed by large spaces of hospitals and clinics and crowded floors of thousands of people, both personnel and patients (especially in exceptional situations like as COVID19).
- As of logistics, IPSs will help to increase the efficiency of logistics operational processes. Indeed, With IPSs, employees will spend less time to find finding every item, collecting all of them, and putting them into a box. IPSs are also an opportunity for logistic companies to facilitate searching for employees and controlling their working load, as well as to analyse people's and vehicles' routes and to provide data for an informed management decision.

### 3.3.2 Definition and Status of Implementation

Indoor position information obviously supports navigating within building premises. However, this location information is also a valuable asset for providing and maintaining high quality eMBB services to end user devices. Positioning offers means to utilize location information to improve network communication reliability, to reduce latency and to balance data loads.

Although the literature on positioning approaches is vast, there is little reference about a comprehensive integration of different technologies, positioning methods, and visualisation tools. In particular, implementations supporting 5G location-based services are rare. Previous work on indoor positioning platforms focuses mainly on Wi-Fi and sensors technologies. To the best of our knowledge, only few of the test-beds for indoor positioning include cellular technologies. As an initial reference for cellular systems, the work proposed by Liu et *al.*[381] describes the evolution of positioning technologies in 3GPP standards, and Positioning Architecture in LTE networks. In a

[380] Dang, S., Ma, G., Shihada, B., and Alouini, M.-S. (2019): Enabling smart buildings by indoor visible light communications and machine learning. Available at: https://repository.kaust.edu.sa/handle/10754/660495

[381] Liu, Q., Qiu, J., and Chen, Y. (2016): Research and development of indoor positioning. *China Communications*, **13**(Supplement2), 67-79.

 

further approach[382] the requirements for an open platform providing Location Based Services (LBS) is discussed.

Since most of the network control components are fixed at specific locations, eMBB services to mobile end user devices require also support for mobility. First the mobile terminal receives the eMBB service signal from one base station and then gradually moves to the coverage area of another base station, so a handover in the indoor network is executed.

Mobility comes at a cost in terms of extra signalling messages, processing resources and delay in set-up and data message transactions. Due to the nature of network control and monitoring, additional signalling overhead gets created from sending infrequently small packets. From the mobile network side, this requires re-allocation and scheduling of radio resources with increased latency. Location information can be used by the network and devices to optimise communication and to save energy by reducing signalling. Combining location information with other forthcoming functionalities, it may be possible to dynamically adjust data loads and routing and to control the latency and its deviation. The shared location information is therefore a valuable asset for both mobile end users and eMBB service providers to maintain and operate their devices.

The latency trials can be carried out at three levels: E2E latency between UE and application server, RAN latency, and core network latency. The 3GPP "target" latency and bandwidth for each of the deployment scenarios are[383] as follows:

- E2E Latency for the eMBB use case is less than 15 ms.
- RAN Latency is less than or equal to 8 ms.
- The expected data rate bandwidth for wide area deployment at carrier frequency in below 6 GHz with Channel bandwidth of 100 MHz is 3 Gbps/1.5 Gbps for DL/UL.

The latency trials include testing to validate different mobility state transitions (control plane) and their transition times (i.e. these tests aim to quantify "Idle to Connected"/"Connected to Idle", and "Inactive to Connected"/"Connected to Inactive" state transition times), as well as to verify the associated process for each type of state transition.

On the UE side, at least the following metrics are available for performance assessment: (i) RSRP (Reference Signal Received Power); (ii) RSRQ (Reference Signal Received Quality); (iii) RAN Latency (when possible); (iv) E2E Latency; (v) Ping Success Rate; and (vi) Packet Loss Rate. As of the gNB side we consider latency from gNB to EPC/NGC.

The 3D model of Otaniemi (as in Figure 26(a), below) allows to take the shadowing effects of buildings and terrain into account[384]. Figure 26(b) "depicts" the expected measurement route for providing reference location and indoor maps.

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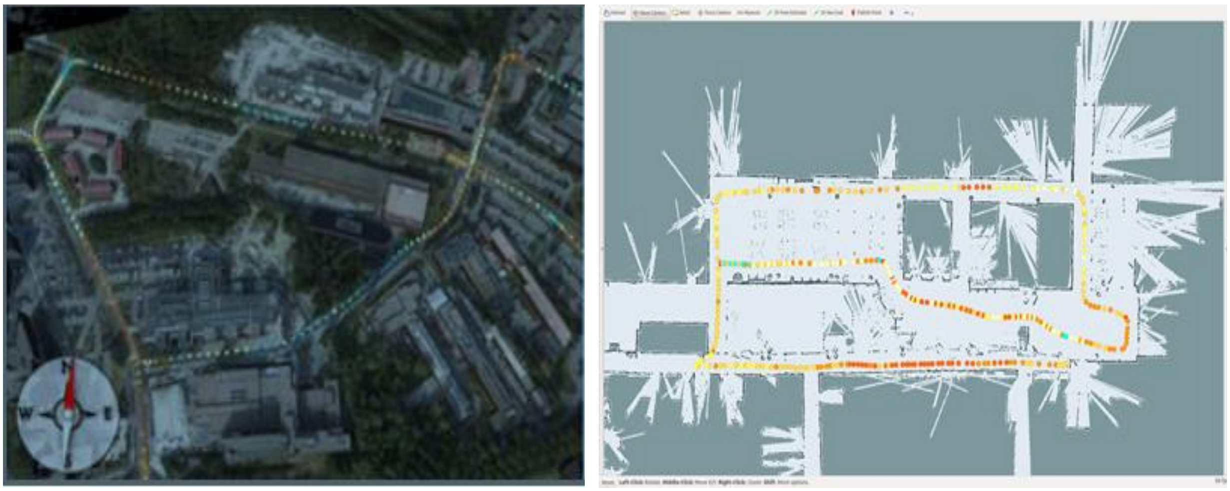
[382] Cho, E. Park, S., Rew, J., Park, C., Lee, S., and Park, Y. (2018): *Towards a sustainable open platform for location intelligence and convergence*. In Proceedings of the 2018 International Conference on Information and Communication Technology Convergence (ICTC), pp. 1411-1413. Jeju, 2018.

[383] Also see, *for example*, 3GPP TS 22.261 V17.1.0 (2019-12): *"Service requirements for the 5G system; Stage 1 (Release 17)"*. Also see the wider context included in: https://www.3gpp.org/news-events/1831-sa1_5g.

[384] Horsmanheimo, S., Lembo, S., Tuomimäki, L., Huilla, S., Honkamaa, P., Laukkanen, M., and Kemppi, P. (2019): *Indoor positioning platform to support 5G location based services*. In Proceedings of the 2019 IEEE International Conference on Communications Workshops (ICC Workshops), pp.1-6. IEEE, Shanghai, China, May 20-24, 2019.



(a) (b)

*Figure 26: (a) 3D Model of Otaniemi, Finland (VTT) and; (b) floor map including the measured signal strength values*

Research on indoor communication quality and positioning is supported by a mobile robot shown in the left-hand side of the picture below (Figure 27). The robot has two main tasks. It simultaneously constructs a map from its surroundings and localizes itself within it. This mobile robot is used to carry multiple measurement devices and to provide a reference location and timestamp for each measurement sample.

In a typical setup, the robot is equipped with NEMO Outdoor laptop and six to nine terminals measuring different radio access technologies and different mobile operators. The picture on the right-hand side of Figure 27 simply "depicts" positioning network performance measurement and tools.

*Figure 27: Measurement devices used for indoor and outdoor measurements*

The floor maps generated by the robot and existing 3D Otaniemi[385] model are used for developing

[385] For the latency measurements, specific measurement sites have been selected based on signal strength measurements. Currently, there are already three buildings in Espoo Otaniemi where the latency measurements are performed. The reason for having different measurement sites is to perform measurements in good, medium, and bad propagation conditions.

highly localised propagation models and positioning algorithms to capture the effects of LoS and NLoS regions shown in Figure 26(b). The indoor positioning focuses on network-based positioning techniques covering signal strength based, time-based Uplink-Time Difference of Arrival (UTDOA) and Observed Time Difference of Arrival (OTDOA), and learning / data correlation-based algorithms. The location information is used in several use cases e.g. for remote control and monitoring in industrial spaces, for location-aware traffic offloading using SDN, and location-aware access-control and network services in enterprise and public Wi-Fi deployments. The configuration has been used also for testing movable Wi-Fi APs, Wirepas sensors[386], and Raspberry beacons[387] in ad-hoc networks.

Measurements can be real-time or offline network performance measurements. Measurements are used for: (i) optimisation of indoor LTE-WiFi pico-cell installations for positioning and latency reduction, and (ii) fine-tuning indoor or outdoor coverage prediction models. Coverage predictions can be used for: (i) estimating the coverage of licensed and unlicensed wireless networks, and (ii) planning locations for new base stations to improve coverage and/or increase positioning accuracy.

For the trials, tests are being carried out to measure user throughput including peak throughput, throughput at interference limited cell edge, cell edge coverage throughput, and throughput in different interference/coverage conditions. Peak user throughput is the maximum DL/UL data rate achievable for a single user located at the best location within a cell. On UE side, the following metrics and the derived link budget are available for performance assessment:

- DL throughput;
- UL throughput;
- RSRP (Reference Signal Received Power);
- RSRQ (Reference Signal Received Quality);
- SINR;
- DL BLER (at first retransmission);
- MIMO mode used (incl. MIMO rank);
- UE & gNB Tx power;
- Channel utilisation or scheduling/activity factor.

To support overall performance assessment, all above KPI measurement results can be recorded with location stamps by utilizing VTT's positioning platform as described above.

This subsection describes the test set-up and procedure for single/multiple pRRU UL/DL throughput and coverage, while the actual execution may be modified during the test subject to resource availability[388]. The KPIs test methodology follows the NGMN trial framework document. The main objectives include to test the coverage of single/multiple pRRUs under NR frequency band as well as to test the service capabilities of the single/multiple pRRUs.

The following are some example test conditions and example procedural steps to describe the testing. The base station (BS) configurations include single/multiple distributed pRRU coverage (3.5 GHz) without external antennas. The trial site also has single/multiple FD-LTE pRRU coverage (2.5 GHz). The BBU connects 1 RHUB, and the RHUB connects to the pRRU. A single cell configuration provides 100 MHz bandwidth connectivity, which is supported by the UE. The pRRU coverage is tested with TCP/UDP traffic service following a path from the cell centre to the edge.

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386 Also see, *among others*: https://wirepas.com/wirepas-connectivity-for-sensors/

387 For further details also consider: https://learn.adafruit.com/pibeacon-ibeacon-with-a-raspberry-pi

388 Broader details are provided within the scope of the 5G-DRIVE Deliverable D3.2: *"Joint Specification for eMBB Trials"*.

 

The first step is that the test UE (using e.g. the NEMO tool from Keysight[389]) connects to the pRRU cell. In case of a single pRRU condition, the NEMO test software is used to perform cell locking of the terminal. The test UE then runs FTP downlink service. An indoor robot is utilised to move the test UE along the predefined path to the edge of the cell (i.e. until throughput drops to near zero or until there is no ping to the network). For verification, this procedure step is carried out twice.

All data parameters are recorded including timestamps, location (x and y coordinates in a building's coordinate system), RSRP, SINR/RSRQ, CQI, UL and DL data rates with UDP and TCP/IP traffic (small packet size), and RTT (ping). As far as indoor coverage tests are concerned, the most important test parameters are throughput and RTT. The recorded data includes also the constellation and distance of the pRRUs.

The indoor positioning platform has been further enhanced and tested for support of autonomous systems connectivity and navigation. The following photo (Figure 28) shows the pre-test setup of the network measurement equipment including the PC for KPI data collection and analysis, the UE devices, and power units.

*Figure 28: Pre-test set-up of the network equipment (including the PC for KPI data collection and analysis, the UE devices, and power units) in Espoo VTT site*

In the actual measurement setup, we have equipped the mobile robot with four UE devices as shown in the following photo (Figure 29) of the indoor positioning platform. Four identical UE devices have been used to increase the sampling rate; that is, a fourfold amount of data samples is collected as training and testing data for positioning and handover algorithms. The mobile robot uses SLAM algorithm to provide a reference location for each measurement sample, and the timestamp for each measurement sample is taken from the robot's central clock.

389 For further details also see, *inter-alia*: https://www.keysight.com/us/en/assets/7018-05622/brochures/5992-2114.pdf

*Figure 29: Mobile robot used for the indoor positioning platform at Espoo site*

The following Figure 30 shows the coloured route of the indoor positioning platform on the VTT premises floorplan when conducting the network measurements. In this particular case, a total of 100,000 measurement samples have been gathered while the mobile robot moved along the route for a period of 5 hours.

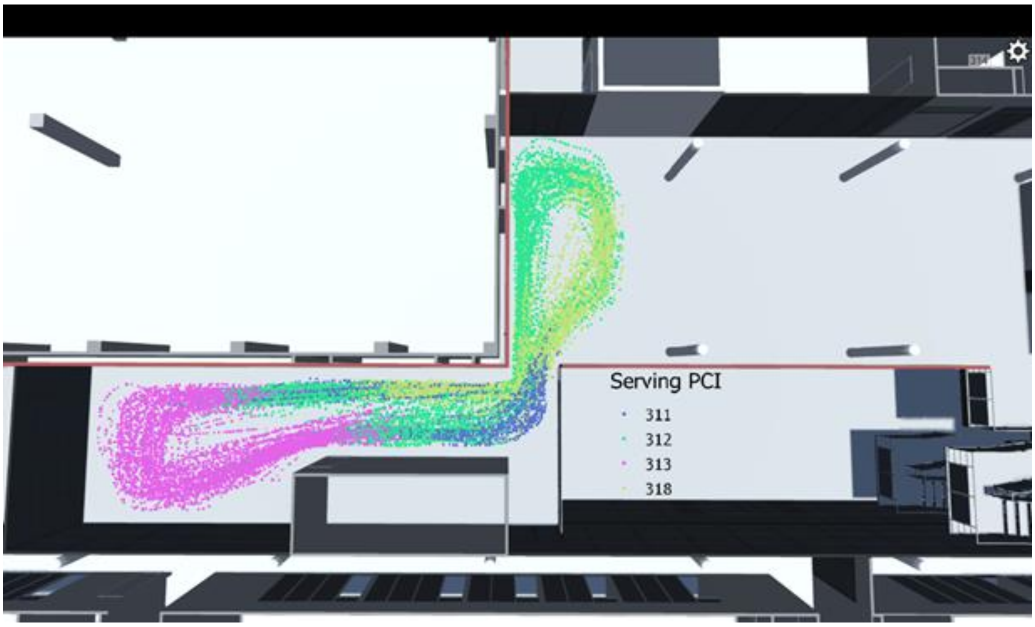


*Figure 30: Coloured route of the indoor positioning platform on the VTT premises floorplan*

Four picocells are serving the indoor positioning platform in the above indoor environment (i.e., the changes of the four colours show where handovers occur along the route of the mobile robot). The RSRP and RSRQ levels of serving and detected picocells can be utilised by AI/ML algorithms to support cellular network-based positioning and handover parametrisation.

The positioning platform enables recording of measurements conducted in different occasions. These measurements can later be played in parallel to see how well the positioning platform performs in case of multiple users. Moreover, the same information from terminals can be used to assess pros and cons of different positioning algorithms. The applied visualisation application shows each user's location accuracy, positioning method, and network performance values like received signal strength and received signal quality of different technologies.

**Relevant KPIs for this use case:**

- **Peak data rate:** this metric denotes the maximum physical-layer throughput achievable between the 5G gNB and the UE, in Gbps.
- **Jitter:** this KPI denotes the variation in the delay experienced by received packets (in ms).
- **Latency:** radio latency is the radio access network contribution to the total delay between the transmitter and the receiver, expressed in ms.

## 3.4 KPIs relevant to eMBB Trials

The KPIs relevant to the 5G-DRIVE use scenarios have been identified in the previous Sections 3.2 – 3.3. In the scope of the Deliverable D3.1 we have listed list the relevant 5G KPIs related to the radio access network (RAN) and used them as a reference for different trial sites to conduct trials under the same baseline. The sources of the KPI definitions come from ITU-R M.2410-0[390], NGMN 5G Trial and Testing Initiative Pre-commercial Network Trials Framework Definition[391], 5G-PPP Phase-II KPI definitions[392], and 3GPP[393]. Note that the KPIs defined in these documents are used to provide a throughout performance evaluation of 5G systems. However, considering the capability and availability of the trial facilities in the project, only a selected set of KPIs are evaluated in the project. For this reason, we only list the KPIs relevant to the project trials and provide the test procedure.

By following the common test procedure, the trial results from different trial sites can be compared. A selected set of KPIs are to be measured in both the 5G-DRIVE and the Chinese twin project and results are reported in the joint trial reports. In the following, we first provide the definition of the selected KPIs, and describe the test setup, test procedure, evaluation criteria and reporting process of each of the KPIs listed as follows:

- **Data rate**: It is the number of bits transmitted through the system per unit of time. (There are different terms to represent the data rate. Some documents use the term “data rate”, while others use the term “throughput”).
  - *Peak data rate* in bit/s is the maximum achievable data rate under ideal conditions to a single mobile station, to which all assignable radio resources for the corresponding link direction are assigned, except the radio resources used for PHY layer synchronisation, reference and pilot signals, guard bands and guard times. In some documents, it is referred to the peak user throughput.
  - *User experienced data rate* is the 5% point of the cumulative distribution function (CDF) of the user throughput. User throughput is defined as the number of correctly received bits, i.e. the number of bits contained in the service data units (SDUs) delivered to Layer 3, over a certain period of time.

[390] International Telecommunications Union – Radiocommunications Sector (ITU-R): *“Report M2410-0 (2017-11) – Minimum requirements related to technical performance for IMT-2020 radio interface(s)”*. Available online at: https://www.itu.int/pub/R-REP-M.2410-2017.

[391] Next Generation Mobile Networks (NGMN) Alliance (2019): *“5G trial and testing initiative pre-commercial network trials framework definition v2.0”*. Available at: https://www.ngmn.org/fileadmin/ngmn/content/downloads/Technical/2019/190111_NGMN_PreCommTrials_Framework_definition_v2_small.pdf.

[392] 5G-PPP Infrastructure Association (5G-IA) (01/2019): *“5G-PPP Phase-II KPIs”, Report*. [https://5g-ppp.eu/kpis/]

[393] See, *for example*: http://www.3gpp.org/ftp//Specs/archive/28_series/28.554/

  - *Cell edge user data rate:* In 3GPP, the cell edge user data rate is defined as the 5% point of the CDF of user's average data rate. The user's average data rate is linked to the average spectral efficiency, used bandwidth, and the number of TRxP used in the system.

- **Latency:** In communications, the latency is the time interval for a bit of data, usually a data packet, to travel across the network from one node or endpoint to another. According to the purpose of evaluation, there are two types of latencies: user plane latency and control plane latency.
  - *User plane latency*: At the application level, the most important latency is the end-to-end latency, which is the maximum tolerable elapsed time from the instant a data packet is generated at the source application to the instant it is received by the destination application. If direct mode is used, this is essentially the maximum tolerable air interface latency. If infrastructure mode is used, this includes the time needed for uplink, any necessary routing in the infrastructure, and downlink.
  - *Control plane latency* refers to the transition time at the UE side from the idle or inactive RRC state to the start of continuous data transfer (e.g. Active state).

- **Cell capacity** is the KPI to evaluate the aggregate capacity of multiple users served by a cell. It can be measured by the cell peak throughput and cell average throughput. In the measurement, multiple UEs are placed in the different locations to represent different propagation environments. The results of cell capacity can be explained as the spectrum efficiency.

- **Spectral efficiency**: Spectrum efficiency refers to the data rate that can be transmitted over a given bandwidth in a communication system. In the 5G-DRIVE project, it is the data rate per UE at given condition divided by the bandwidth used by UE for corresponding data rate. It is an important performance KPI of 5G system. The spectrum efficiency is also a good indicator to show the performance difference between 4G and 5G systems.

- **Coverage:** The coverage area of a mobile system is the geographic area where the base station and the user device can communicate. The coverage is evaluated by the communication availability, in which the signal strength of a cell needs to exceed a defined minimum threshold and the achieved service quality, in which a minimum data rate in case of mobile data services or a minimum speech quality in case of voice services is required. The coverage depends on several factors, including the environment, buildings, technology, and radio frequency and most importantly for two-way telecommunications the sensitivity and transmit efficiency including maximum output power of the base station and the end-user device.

- **Mobility** is the maximum mobile station speed at which a defined QoS can be achieved (in km/h). There are several classes of mobility: (i) Stationary: 0 km/h; (ii) Pedestrian: 0 km/h to 10 km/h; (iii) Vehicular: 10 km/h to 120 km/h; and (iv) High speed vehicular: 120 km/h to 500 km/h.

- **Reliability** relates to the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability. Reliability is the success probability of transmitting a layer 2/3 packet within a required maximum time, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface at a certain channel quality.

- **Area traffic capacity** is the total traffic throughput served per geographic area (in Mbit/s/m2). The throughput is the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time.

Within the context of the 5G-DRIVE Deliverable D3.1 ("*eMBB development and test plan*"), the consortium has analytically described the corresponding test procedure(s) together with the evaluation criteria for the KPIs that have been presented above.

In the context of the performed trials, as the reference test methodology it has been selected the KPI test methodology from the NGMN trial framework document (i.e. "*5G trial and testing initiative pre-commercial network trials framework definition v2.0*"). This is an important methodology approach for 5G pre-commercial trials[394].

According to the 5G-DRIVE Deliverable D3.1, an initial trial plan has been composed to describe "how the network performance is tested, together with the evaluation KPIs covered by the partners" setup. The selected KPIs subject to various trial sites availability are described as shown below in Table 3[395].

| KPIs | Trial sites(s) | Involved Partner(s) |
|---|---|---|
| **Latency** | Surrey site, Espoo site | UoS, VTT |
| **Coverage** | Espoo site | VTT |
| **Mobility** | Espoo site | VTT |
| **Reliability** | Espoo site | VTT |
| **Peak Data Rate** | Surrey site, Espoo site | VTT, UKent (*for transport arch.*) |
| **User-experienced Data Rate** | Surrey site, Espoo site | VTT, UKent (*for transport arch.*) |

*Table 4: KPI evaluation per trial site and per involved 5G-DRIVE partner*

## 3.5 Architecture for the WP3 Test Cases

### 3.5.1 Architecture for the Cloud-Assisted AR Use Case

The test-bed for the 5G-DRIVE cloud-assisted AR trial is located across various locations in the Surrey County (UK) with its headquarters at University of Surrey (UoS) campus in Guildford. The 5GIC (5G Innovation Centre) can connect to remote sites throughout the UK and Europe. In the UK it has been enhanced providing 5G mobile coverage at industrial locations in Worcestershire, as well as amongst moving vehicles between Millbrook and the 5GIC. In addition, it connects remote islands with LTE and 5G mobile coverage to the mainland, and to the 5GIC test-bed via a multi-core gateway for domestic and IoT services targeted at local farming. The test-bed features a 3GPP Release 15 SA architecture and supports multi-RAT technologies, as described below:

**Outdoor:**

- Ultra-dense LTE-A-DD C-RAN – 44 sites;

[394] Depending on the trial settings in the project, which may be potentially limited by the availability of network equipment and the deployment scenario, *per case*, the test setup and procedure may be modified during the trials, *if and when necessary*. The actual test setup and procedure will be reported in the trial result report.

[395] Actual measured KPIs also need to subject to availability of various trial sites.

- 5G eMBB C-RAN 3.5 GHz – TDD – 7 outdoor sites, 8 cells;
- 5G URLLC RAN: 3.5 GHz – 1 site;
- 5G RAN 700 MHz – 1 site.

**Indoor:**

- C-RAN – 6 cells in the same building (2 floors);
- WiFi – 6 APs;
- LTE-A-TDD – 6 pico-cells;
- 5G RAN 26 GHz – 1 site.

The overall test-bed and its interconnections are shown as in the figure below:

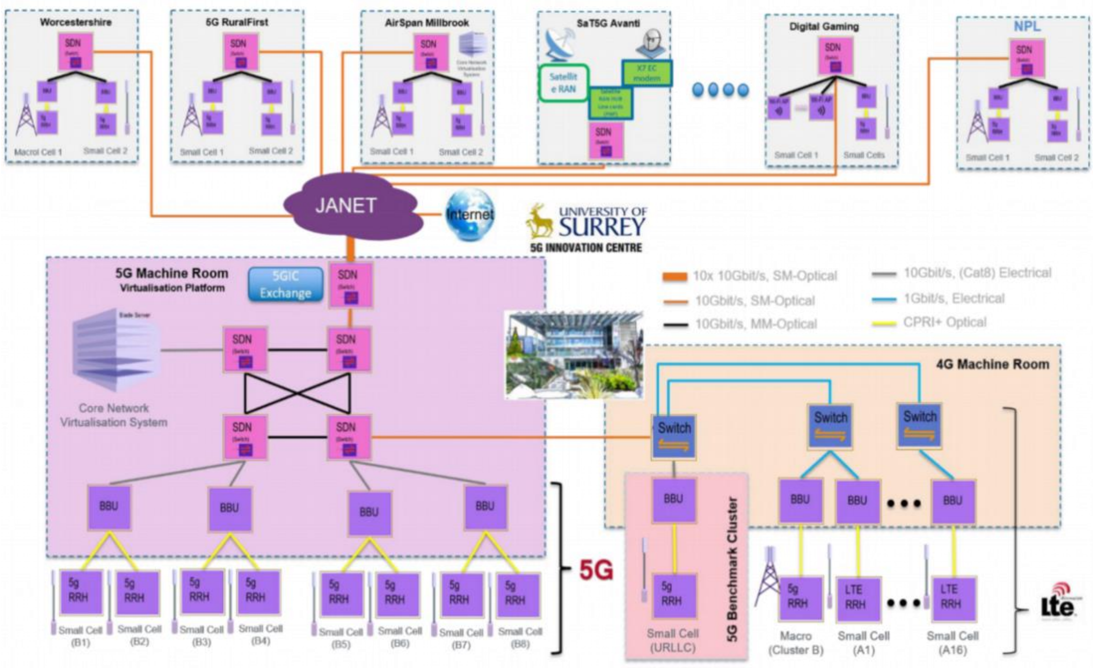


*Figure 31: 5GIC test-bed overall architecture*

The main part of the 5GIC test-bed is installed in University of Surrey (UoS) campus at Guildford. The multi-RAT (6 WiFi and 50 LTE-A) base stations at the UoS campus (as of 2017) are shown in the following figure.


*Figure 32: Locations of multi-RAT base stations at UoS campus (2018)*

In 2018 the 5GIC was enhanced by 5G-eMBB (7 sites), one 5G-URLLC site (both according to Release 15 with CUPS) and one LTE-A (700 MHz site). The locations of the sites at the UoS campus are shown in Figure 33.


*Figure 33: Locations of new base stations at UoS campus (2018)*

The network infrastructure uses NFV & SDN technologies. 5GIC uses a special approach to virtualisation called *Flat Distributed Cloud* (FDC) and new *Meta-Data Protocol* (MDP) that provides a context-aware user plane control.

- The test-bed uses NFV-based EPC. It can collect data from all network devices and make a visual presentation of collected live and historical analytics concerning network devices and data flows. It is built for experimentation purposes; for example, a mobile core dynamic network slicing mechanism has been implemented (the demonstrated slice rollout time was about 2 minutes). In addition, there is work in progress on AI-driven autonomous slicing. Finally, the 5GIC test-bed has been tested with 1 million emulated users, achieving a peak per-cell throughput of 8 Gbps in some tests.

Protocol data contained in the user-plane and control-plane messages exchanged between the 5G gNB and the UE can later be extracted by post-processing the IQ data[396] encapsulated in the CPRI frames. In addition, since IQ data is just a digitised version of an analogue 5G NR waveform, both the uplink and downlink 5G NR waveforms from probed 5G gNBs, could also be synthesised and played back in the anechoic chambers of the JRC Ispra site using a vector signal generator or a Universal Software Radio Peripheral (USRP). This procedure enables a detailed RF characterisation and performance evaluation of 5G gNBs without the logistics complexity of conducting an exhaustive over-the-air RF measurements campaign at the Surrey trial site.

To support the eMBB trials, UKent uses a measurement platform (shown in Figure 34) that combines Ethernet devices that include 10GbE connectivity and can act as precision-time protocol (PTP) transparent clocks (TCs), boundary clocks (BCs) and slave or master clocks. The platform includes hardware Ethernet probes that, according to appropriately defined filters (which instruct a probe to “capture” packets of a given traffic flow), generate filter result packets (FRPs, these carry timestamps, sequence numbers and other metadata fields for the monitored packets) and forward them to a probing server. The platform can be used for performance analysis in a number of “use cases”, that is for: (i) fronthaul/xhaul/backhaul links for eMBB; (ii) Coordinated Multipoint (CoMP); (iii) localisation; and (vi) Mobile Edge Computing (MEC) use cases. For all these use-cases, UKent contributes to the measurement of latency metrics for adherence to the latency KPIs definitions.

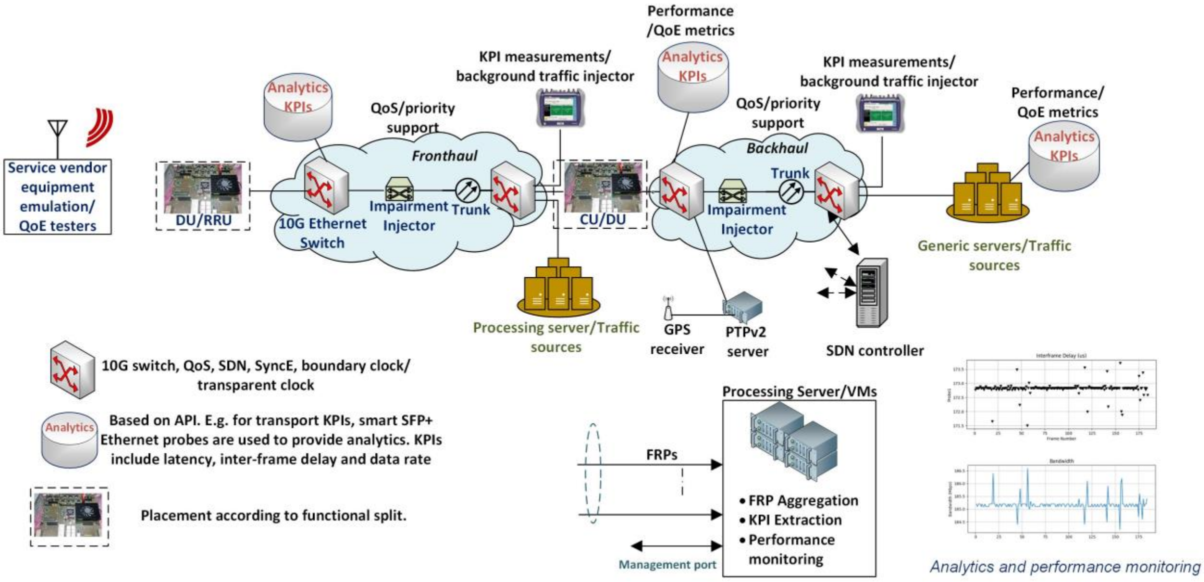


*Figure 34: High-level view of UKent test network*

### 3.5.2 Architecture for the Indoor Positioning Use Case

The indoor positioning setup is designed to support both terminal and network side positioning. It is planned to be integrated into VTT’s 5G test-bed, which is part of the 5GTNF (*www.5gtnf.fi)* infrastructure. Since the network side positioning sets stringent requirements for the response time

396 In general, I/Q data describes a complex baseband signal b(t) which can be transformed to or can be derived from a corresponding real valued RF signal x(t). The “in-phase” component or real part of b(t) is called i(t). The “out-of-phase” component or imaginary part of b(t) is called q(t).

 

and scalability, also MEC technology is planned to be exploited to offer positioning services at building level.

The MEC based positioning platform concept is presented in Figure 35, in case of two buildings (BLD1 and BLD2). The MEC has two main tasks, that is to: (i) run building specific distributed positioning services; and (ii) provide status information from pico-cells that are connected to it.

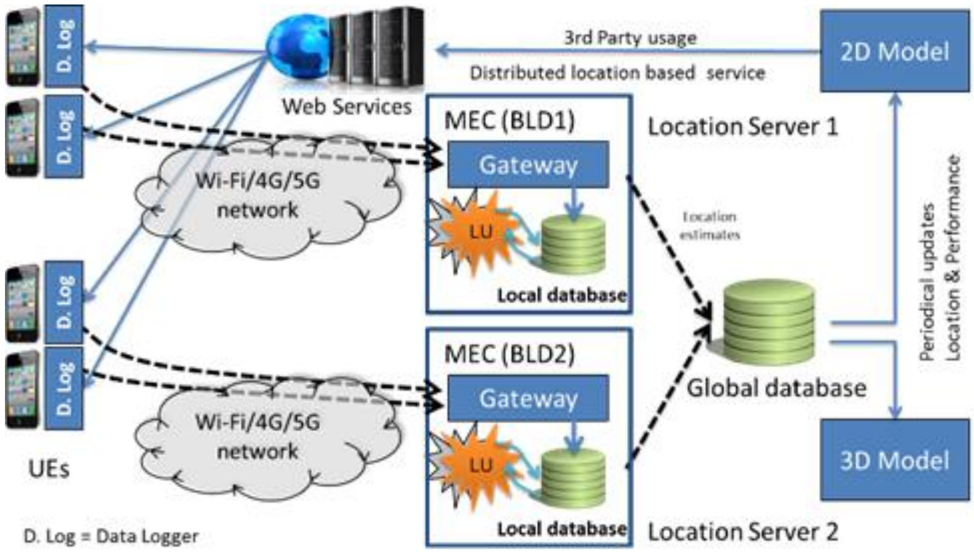


*Figure 35: MEC based positioning system using 4G pico-cells*

The main processing is done on a Location Unit (LU) running on the MEC. The information needed for positioning is sent e.g. from mobile devices to a location server framed in blue in the above Figure 35 over Wi-Fi, 4G, or (later) 5G connection, using User Datagram Protocol (UDP). The incoming information contains end-users' payload data, which is then extended with location information. Loss of some samples is not considered critical, since the positioning rate is designed to be around 2 Hz. In addition to mobile phones, the information can also be retrieved directly from eNodeBs via MEC platform or from a so-called sink node in the ad-hoc Wi-Fi network. Information from the Wi-Fi FTM network is also sent via smartphone.

The MEC gateway shown in the above figure stores incoming information to the local database. Location estimates are computed with the distributed LUs. In our implementation, one MEC instance is serving one building. Only samples coming from building's indoor base stations connected to the MEC are processed and stored to the database. This low-level filtering reduces the amount of data being processed and improves the scalability of the overall system.

The local database contains information about registered devices' recent locations, network structure information for multilateration, recorded measurement samples for training and actual localisation using different positioning algorithms, and images for image-based positioning.

The global database is used for sharing location and network performance information about registered users with 3rd party applications. 2D models are used for presenting the real-time positioning data on mobile applications, whereas 2D and 3D models are used with laptop and desk computers.

Registered users' location and network performance information is periodically retrieved from the database using Message Queuing Telemetry Transport (MQTT) protocol. MQTT is an ISO standard (ISO/IEC PRF 20922) publish-subscribe-based messaging protocol. It works on top of the TCP/IP protocol and is designed for connections with remote locations where a "small code footprint" is required e.g. due to the limited network bandwidth.

An MQTT broker component is running next to the global database. According to the publish/subscribe messaging pattern, the component periodically publishes location and network performance related topics, which are then received by registered MQTT clients of 2D and 3D visualisation applications.

# 4 V2X Communications Use Cases

## 4.1 General Framework and Implementation Status of WP4

Advances in wireless communications and in particular vehicular communications have led to the advent of cooperative Intelligent Transportation Systems[397],[398] (ITS). These systems are a global phenomenon attracting worldwide interest from transportation professionals, automotive industry and political decision makers. They apply advanced communications, information and electronics technology to solve various problems such as traffic congestion, safety, transport efficiency and environmental conservation. The ITS objective is to provide an improved system by informing users about traffic situations and by making mobility coordination safer and smarter. In recent years, ITS has been widely applied along with the development of IT technologies such as robotics, signal and image processing, computing, sensing, and communications[399]. By using V2V, V2I, and I2V communication and Autonomous Vehicle (AV) technologies, a sort of autonomous intersection management can improve the efficiency of existing intersections[400],[401].

ITS systems for inter-vehicle cooperative (active) safety have been the subject of intense research worldwide in government and industry consortia, such as the Crash Avoidance Metrics Partnership and Vehicle Infrastructure Integration Consortium in the United States[402], the Car2Car Communications Consortium[403] in Europe, and the Advanced Safety Vehicle project[404] in Japan. ITS' objective is to leverage real-time data and communications to make transportation safer, more efficient, and more environmentally sustainable. To achieve these objectives, both the automobile industry and the government agencies are proactively adopting new technologies at various levels (either at individual vehicle or at infrastructure level). ITS can be applied to the vast transportation infrastructure of highways, streets, bridges, tunnels, railways, port and airport infrastructures, as well as to a growing number of vehicles, including cars, buses, lorries and trains, as well as aircraft and waterborne vessels. They can be used for both passenger and freight transport. Moreover, ITS apply to all transport modes and can facilitate their interlinking or multimodality[405]. Regarding the

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[397] European Telecommunications Standards Institute (ETSI): TR 102 638 V1.1.1 (2009-06): *"Intelligent Transport Systems; Vehicular Communications; Basic set of Applications; Definitions"*. Available at: https://www.etsi.org/deliver/etsi_tr/102600_102699/102638/01.01.01_60/tr_102638v010101p.pdf

[398] Figueiredo, L., Jesus, I., Machado, J.A.T., Ferreira, J.R., and Martins de Carvalho, J.L. (2001): *Towards the development of intelligent transportation systems*. In Proceedings of the IEEE ITS 2001 Conference, pp. 1206-1211. IEEE, Oakland, CA, US, August 25-29, 2001.

[399] Qu, F., Wang, F.-Y., and Yang, L. (2010): Intelligent transportation spaces: Vehicles, traffic, communications, and beyond. *IEEE Communications Magazine,* **48**(11), 136-142.

[400] Wuthishuwong, C., and Traechtler, A. (2017, March): Consensus-based local information coordination for the networked control of the autonomous intersection management. *Complex Intelligent Systems,* **3**(1), 17-32.

[401] For instance, Austroads analyzed the potential benefits of C-ITS in Australia and found that V2V communication can reduce serious road collisions by up to 35%.

Also see: Asselin-Miller, N., Biedka, M., Gibson, G., Kirsch, F., Hill, N., White, B., and Uddin, K. (2016): Study on the deployment of C-ITS in Europe: Final report," Report for DG MOVE MOVE/C.3, No.2014-794. European Commission. Available at: https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[402] For more details see, *inter-alia*: https://www.its.dot.gov/research_archives/cicas/index.htm

[403] For more details see: https://www.car-2-car.org/

[404] For more details see, for example: https://www.mlit.go.jp/jidosha/asv_english/asv3.htm

[405] ITS vary in the technologies they apply, from basic management systems such as car navigation, traffic signal control systems, container management systems, variable message signs, enforcement systems for monitoring applications (security CCTV systems), through to more advanced applications that integrate live data and incorporate feedback from other sources, such as parking guidance and information systems or weather information.

 

European framework, the ITS Directive 2010/40/EU[406] adopted in August 2010, and its subsequent already adopted Delegated Regulations, for instance on road safety, real-time-traffic and multimodal travel information, provides the necessary legal and technical framework to steer and ensure the interoperability of deployed ITS services[407],[408].

A typical example of a foreseen evolution strategy towards 5G is the case of "connected vehicles" application. For this, it is not envisaged that 5G would simply supersede earlier investments in ITS-G5[409] technology, as currently deployed in Europe and in other regions of the world. This technology is based on an evolution of the WiFi standard (IEEE 802.11.p[410]). The main scenario contemplated for the introduction of 5G functionalities is for the provision of additional services compared to the earlier rolled out technologies, following a hybrid communication approach. The inclusion of communication technologies into vehicles and along the roads has already been extremely successful in delivering benefits to the drivers, the automakers and other stakeholders in the transportation and emergency service ecosystems. In Europe, Basic System Profiles (BSPs) have been developed by the Car-2-Car Communication Consortium (C2C-CC)[411] and the EU funded C-Roads Platform project[412], assuming ITS-G5 with IEEE specifications as radio access technology for V2V and V2I communication. Over recent years, the emphasis in intelligent vehicle research has turned to Cooperative ITS[413] (C-ITS) in which the vehicles communicate with each other and/or with the infrastructure[414]. C-ITS can

[406] European Parliament and Council (2010): Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 *on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport*. Official Journal (OJ) L207, 06.08.2010, pp.1-13. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32010L0040

The ITS Directive 2010/40/EU may be used as the basis to adopt a coherent set of rules at EU level in order to create a single market for cooperative, connected and automated vehicles .

[407] Also see: European Commission (2016): Communication on "*A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility*", COM(2016) 766 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2016%3A766%3AFIN

[408] See the scope discussed in European Telecommunications Standards Institute (ETSI): ETSI TS 103 723 V1.2.1 (2020-11): *"Intelligent Transport Systems (ITS); Profile for LTE-V2X Direct Communication"*. Available at: https://www.etsi.org/deliver/etsi_ts/103700_103799/103723/01.02.01_60/ts_103723v010201p.pdf

[409] "ITS" is the acronym for Intelligent Transport System. The "G5" is a standard for car-to-car communications and should not be confused with "5G". ITS-G5 is an extension of IEEE 802.11p, modified and optimised for operation in a dynamic automotive environment. ITS-G5 was originally defined in 2004 and has undergone a thorough standardisation process.

[410] The IEEE 802.11p is an approved sequential amendment to the original IEEE 802.11 standard (for the 802.11 standard "as a whole" see, *for example*: http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm) intending to add wireless access in vehicular environments (WAVE), a vehicular communication system. It defines enhancements to 802.11 (the basis of products marketed as Wi-Fi) required to support Intelligent Transport Systems (ITS) applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure, so called V2X communication, in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz).

The IEEE 1609 is a higher layer standard based on the IEEE 802.11p (See: United States Department of Transportation – ITS Standards Program: "IEEE 1609 – Family of Standards for Wireless Access in Vehicular Environments (WAVE)". Accessible at: https://www.standards.its.dot.gov/Factsheets/Factsheet/80). It is also the basis of a European standard for vehicular communication known as "ETSI ITS-G5". The detailed presentation of "ETSI ITS-G5" is as follows: European Telecommunications Standards Institute (ETSI): EN 302 663 V1.2.1 (2013-05): *"Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band"*. For more details also see, *among others*: https://en.wikipedia.org/wiki/IEEE_802.11p

[411] C2C-CC (2020): Basic System Profile, Release 1.5.0. Available at: https://www.car-2-car.org/fileadmin/documents/Basic_System_Profile/Release_1.5.0/C2CCC_RS_2037_Profile.pdf.

[412] C-Roads Platform: https://www.c-roads.eu.

[413] EIP (European ITS Platform) + White Paper on Cooperative ITS Services (2016, March): Deliverable 1 of EIP+ Sub-Activity 4.1. Version 1.0. Available at: file:///C:/Users/ICHOCH~1/AppData/Local/Temp/EIP+C-ITS%20White%20Paper-Final-1.pdf

[414] Festag, A. (2015): Cooperative Intelligent Transport Systems in Europe. *IEEE Communications Magazine*, **53**(12), 64-70.

greatly increase the quality and reliability of information available about the vehicles, their location and the road environment. It improves existing services and will lead to new ones for the road users, which, in turn, bring major social and economic benefits and lead to greater transport efficiency and increased safety[415].

The Cooperative Intelligent Transport Systems (C-ITS) use technologies that allow road vehicles to communicate with other vehicles, with traffic signals and roadside infrastructure as well as with other road users[416]. The systems are also known as V2V communications or V2I communications. With alerts generated from the increased information available, these systems have a strong potential to improve road safety and the efficiency of the road transport. Because of these expected benefits and considering the overall relatively moderated costs linked to deployment, there is a strong interest in enabling a fast move at European scale that can be "translated" into market production and early deployment.

Vehicles are getting safer, cleaner, and more intelligent. Various sensors and assistant systems enable vehicles to monitor their environment. By means of information exchange among vehicles, as well as between vehicles and the roadside infrastructure, vehicles transform from autonomous systems into cooperative systems. Inter-vehicle communication is a cornerstone of ITS, commonly referred to as cooperative ITS (C-ITS) or Car-2-X communication. The development of C-ITS is primarily driven by applications for active road safety and traffic efficiency, which help drivers to be aware of other vehicles, disseminate warnings about road hazards, and provide real-time information about traffic conditions for speed management and navigation. Typically, these C-ITS applications rely on always-on connectivity among the vehicles in the vicinity, including the roadside infrastructure, and frequent data exchange. Additionally, Internet access and location-based services, such as for point-of-interest notification, road access control, and parking management, improve the driving convenience. Among the various possible communication technologies for ITS, a dedicated variant of IEEE 802.11, an allocated frequency band at 5.9 GHz for road safety and traffic efficiency applications, ad hoc networking, and C-ITS specific message sets have emerged as the current state-of-the-art.

In order to reduce the number of road accidents and improve road safety, vehicles should be able to detect what is happening around them, predict what will happen next, and take protective actions, accordingly. This implicates that that vehicles shall have the ability to exchange messages with each other. V2X[417] is one sort of solution which can be assessed as a wireless sensor system that allows vehicles to share information with each other via a dedicated communication channel. Compared with standard sensors (such as radar, LIDAR, lasers, ultrasonic detectors, etc.) the utilisation of a V2X system can get information out of sight, testing hidden threats, expanding the scope of the driver's perception, and as a result improve driving safety, efficiency and comfort as a result of driving automation[418]. Automation in road transport is expected to contribute to the key objectives of the EU transport policy, namely to increase safety, improve traffic efficiency and minimize pollutant emissions. It is also expected to maximise the comfort of the end users considering also societal aspects e.g. the needs of elderly and impaired people. Automation in this context is envisaged as automated and autonomous driving applications actively interacting with intelligent environment.

415 International Organization for Standardization (ISO) / European Electrotechnical Committee (CEN): "*Cooperative Intelligent Transport Systems (C-ITS). Guidelines on the usage of standards, Edition 26, June 2020*". Available at: https://www.itsstandards.eu/app/uploads/sites/14/2020/10/C-ITS-Brochure-2020-FINAL.pdf

416 Lu, M., Blokpoel, R.J. (2016): *A Sophisticated Intelligent Urban Road-Transport Network and Cooperative Systems Infrastructure for Highly Automated Vehicles*. In Proceedings of the 2016 World Congress on Intelligent Transport Systems, pp.1-8. Montreal, Canada.

417 Storck, C.R., and Duarte-Figueiredo, F. (2020): A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated With Vehicle-to-Everything Communications by Internet of Vehicles. *IEEE Access*, **8**, 117593-117614.

418 Next Generation Mobile Networks (NGMN) Alliance Ltd. (07/2018): *V2X White Paper – V1.0*. Available at: https://www.ngmn.org/wp-content/uploads/V2X_white_paper_v1_0-1.pdf

For this to happen, intelligence and automated applications should reside on all actors of the transportation network, the driver, traveller, vehicles, infrastructure, road/Public Transport (PT) operators, Traffic Management Centres (TMCs), etc. All major automotive manufacturers and tier-1 suppliers are investing a lot in research and development in automation and several highly and fully automated technological advancements are being demonstrated in numerous events. It is commonly accepted that automation will become a reality sooner or later and that it will play a key role in future transport systems.

Big tech firms such as Alphabet, IBM and Amazon have already believed in autonomous driving technology. Also, Nvidia, Intel, and the giants of the car industry are joining in with Ford, Tesla, Nissan, and others. Even Uber and Lyft ride-hailing firms are going all-out. The advances in autonomous driving technology are only going to get better over time. Furthermore, autonomous driving technology is expected to save the time of passengers since AVs can take the wheel completely. During this time, passengers can be interested in performing various activities such as social and physical activities, online shopping, and consuming various forms of content. This could be a real opportunity to build an ecosystem of services by partnering with technology and content providers exploiting AI-enabled AV capabilities to give recommendations, to provide customised services, and to connect to external systems like smart homes. Autonomous driving can be a significant shift for logistic companies providing much cheaper delivery services. Indeed, self-driving delivery vehicles will cost less compared to deliveries that have to pay human drivers an hourly wage. AV can also serve as mobile hotels offering the same comfort and amenities an airplane or train ride has, but with more space and infotainment.

5G-based Connected and Automated Mobility services along roads comprise a broad range of digital services in and around vehicles including safety-related, transport efficiency-related and other commercial services provided, enabled, or supported by 5G multi-service networks[419]. The rollout and evolution of the next generation of mobile technologies (5G) is expected to become a “game changer”. For the first time, mobile networks can offer a broad range of connectivity performances including gigabit speeds and mission critical reliability. Most importantly, the prospect that 5G will be a unified multi-service platform, serving not only the traditional mobile broadband market but also enabling digital transformation in several so-called “vertical industries”, is expected to result in the creation of unprecedented opportunities for innovation and economic growth. Communication between vehicles, infrastructure and with other road users is crucial also to increase the safety of automated vehicles[420] and their full integration into the overall transport system. Cooperation, connectivity, and automation are not only complementary technologies as they reinforce each other and will over time merge.

The V2X technology is the next big feature to evolve further the automotive and transportation industry[421]. The V2X concept uses the latest generation of information and communication technology to realize omnidirectional V2V, V2I, V2P and V2N/V2C network connection[422]. The above types of V2X applications can use “co-operative awareness” to provide more intelligent services for

[419] 5G Public Private Partnership (5G-PPP) (10/2020): *5G Strategic Deployment Agenda for Connected and Automated Mobility in Europe*.

[420] AVs can gather information about the surrounding environment by using the camera, radar, LiDAR, laser, ultrasonic sensors, and GPS. Therefore, from a transportation engineering perspective, AVs are expected to enhance the safety, efficiency, ecology, and passenger comfort of the transportation system.

[421] Global System for Mobile Communications Association (GSMA) (2019): *Connecting Vehicles – Today and In the 5G Era with C-V2X – White Paper 2019*. Available at: https://www.gsma.com/iot/wp-content/uploads/2019/08/Connecting-Vehicles-Today-and-in-the-5G-Era-with-C-V2X.pdf

[422] See the context of the study in 5G Americas (03/2018): *Cellular V2X Communications Towards 5G*. Available at: http://www.5gamericas.org/en/resources/white-papers/

 

end-users[423]. This means that entities, such as vehicles, roadside infrastructure, application server and pedestrians, can collect knowledge of their local environment (e.g., information received from other vehicles or sensor equipment in proximity) to process and share that knowledge in order to provide more intelligent services, such as cooperative collision warning or autonomous driving[424]. In the following Figure 36 we provide an indicative illustration of the various V2X communications. Here, apart from the well-known notations of V2V, V2N, V2P, V2I we also consider the cases of V2S[425] ("Vehicle-to-Sensors") and V2R[426] when the 5G Wireless Access Technology[427] (WAT) is incorporated into the vehicles.

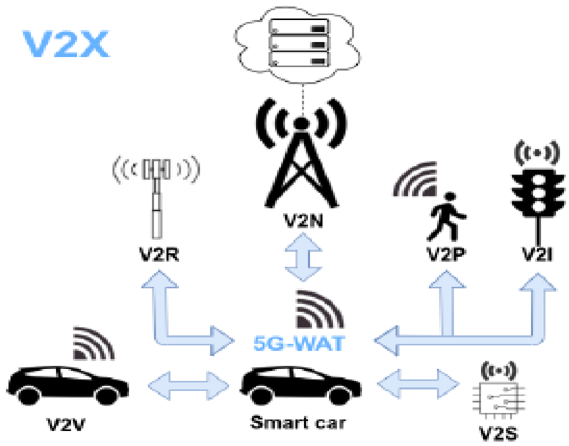


*Figure 36: Depiction of V2X conceptual illustration[428]*

V2V applications expect UEs that are in proximity of each other to exchange V2V application information. 3GPP transport of messages containing V2V application information requires the UE to have a valid subscription and authorisation from a network operator. Transport for a valid subscriber is provided whether the UE is served or not served by E-UTRAN. The UE supporting V2V applications transmits messages containing V2V application information (e.g. location, dynamics, and attributes). The message payloads may be flexible in order to accommodate varying amount of information. 3GPP transport of message containing V2V application information is predominantly broadcast-based. Such 3GPP transport includes the transport between UEs directly and/or, due to the limited direct communication range, the transport between UEs via infrastructure supporting V2X communication, e.g., RSU, application server, etc.

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[423] European Telecommunications Standards Institute (ETSI): ETSI TS 122 185 V14.3.0 (2017-03): *"LTE; Service requirements for V2X services (3GPP TS 22.185 version 14.3.0 Release 14)"*. Available at: https://www.etsi.org/deliver/etsi_ts/122100_122199/122185/14.03.00_60/ts_122185v140300p.pdf

[424] European Telecommunications Standards Institute (ETSI): ETSI TR 102 638 V1.1.1 (2009-06): *"Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions"*.

[425] For further information also see, among others: Kaiwartya, O., Abdullah, A.H., Cao, Y., Altameem, A., Prasad, M., Lin, C.-T., and Liu, X. (2016): Internet of vehicles: Motivation, layered architecture, network model, challenges, and future aspects. *IEEE Access*, **4**, 5356-5373.

[426] For more informative details see, *for example*: Shrivastava, P., Ashai, S., Jaroli, A., and Gohil, S. (2012): Vehicle-to-Road-Side-Unit Communication Using WiMAX. *International Journal of Engineering Research and Applications (IJERA)*, **2**(4), 1653-1655.

[427] In the IoV heterogeneous network environment, a WAT range is going to be available for connections with several applications on smart devices and the cloud based servers. The WAT is divided into vehicular, cellular mobile and small range static communications; and since these technologies have been developed for different types of communication networks, their characteristics are different.

[428] Source: Storck, C.R., and Duarte-Figueiredo, F. (2020): A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated With Vehicle-to-Everything Communications by Internet of Vehicles. *IEEE Access*, **8**, 117593-117614.

 

V2P applications expect UEs that are in proximity of each other to exchange V2P application information. 3GPP transport of messages containing V2P application information requires the UE to have a valid subscription and authorisation from a network operator. Transport for a valid subscriber is provided whether the UE is served or not served by E-UTRAN[429]. The UE supporting V2P applications transmits messages containing V2P application information. It is expected that V2P application information can be transmitted either by a UE supporting V2X application in a vehicle (e.g., warning to pedestrian), or by a UE supporting V2X application associated with a vulnerable road user (e.g., warning to vehicle). 3GPP transport of messages containing V2P application information includes the transport between UEs directly and/or, due to the limited direct communication range, the transport between UEs via infrastructure supporting V2X communication, e.g., RSU, application server, etc.

The main difference between 3GPP transport of messages with V2P and V2V application information is due to the properties of the UE. A UE supporting V2P applications used by pedestrian might, for example, have lower battery capacity, the radio sensitivity might be limited, e.g. due to antenna design, and therefore it may not be able to send messages with the same periodicity as UEs supporting V2V application, and/or receive messages. V2V and V2P communications are essentially between vehicles or between vehicles and vulnerable road users (for example, pedestrian, cyclist) to provide information about location, velocity and direction to avoid accidents. V2I transmission is between a vehicle and a road side unit[430] (RSU). An RSU is used to extend the range of a message received from a vehicle by acting as a forwarding node.

V2I includes communications between vehicles and traffic control devices in the road vicinity. It is a short range communication where one endpoint is a vehicle and the other endpoint is a roadside infrastructure with an RSU. Messages may be transmitted in both directions between the end-points. The UE supporting V2I applications transmits messages containing V2I application information to an RSU or locally relevant application server. The RSU and/or the locally relevant application server transmit messages containing V2I application information to one or more UEs supporting V2I applications. A locally relevant application server serves a particular geographic area. There can be multiple application servers serving overlapping areas, providing the same or different applications.

V2N transmission is between a vehicle and a V2X application server to provide connected services to a vehicle[431]. This technology links the various elements of transportation, such as pedestrians, vehicles, roads, and cloud environments. The UE supporting V2N applications communicates with an application server supporting V2N applications. Both parties communicate with each other via Evolved Packet Switching (EPS).

V2X not only can support vehicles to help them obtain more information and promote the innovation and application of automated driving technology, but also can contribute to building an intelligent transport system and promote the development of new modes and new forms of automobiles and

429 For more details see, *for example*: European Telecommunications Standards Institute (ETSI): ETSI TS 136 300 V11.5.0. (2013-04): *"LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (3GPP TS 36.300 version 11.5.0 Release 11)*". Available at: https://www.etsi.org/deliver/etsi_ts/136300_136399/136300/11.05.00_60/ts_136300v110500p.pdf

430 In general, an RSU is a communication unit, often connected to roadside infrastructure. It can supports V2I communication and communicate with vehicles using short range communication (e.g. C-V2X PC5 or 802.11p). RSUs may be connected to the network through wired or wireless long-range backhaul. Thus, the RSU is a logical entity that combines V2X application logic with the functionality of an eNB (referred to as eNB-type RSU) or UE (referred to as UE-type RSU).

431 V2I Services should not be confused with V2N (Vehicle-to-Network) Services such as telematics, software/maps download and update, etc., which are typically delivered based on dedicated agreements between the MNO, the OEM, the service provider, and the vehicle owner where applicable.

transportation services[432]. It is of great significance for improving traffic efficiency, reducing pollution[433], saving resources, reducing the incidence of accidents, and improving traffic management[434].

The basic categories of V2X services for V2X originally described in the TR 22.885[435] can be grouped into the following main categories based on ITS definition of basic set of services:

- Road Safety Requirements (e.g. Queue warning use case related requirements).
- Mutual Vehicle Awareness – Information only (e.g. forward collision warning requirements).
- Vehicle Related Application Requirements (e.g. automated parking system requirement).

Related service requirements can be categorised as follows:

***Latency/Reliability Requirements:*** Maximum tolerable elapsed time from the instant a data packet is generated at the source application to the instant it is received by the destination application. Low Latency values are provided to support services in the case of mutual awareness of vehicle or to send warning messages as defined in some use cases in TR 22.885.

***Reliability***: Maximum tolerable packet loss rate at the application layer, a packet is considered lost if it is not received by the destination application within the maximum tolerable end-to-end latency for that application.

***Message Size Requirements:*** Messages sizes are important when multicast or broadcast messages are being sent to vehicles within range to either warn them for collision prevention or when an event occurs to inform other vehicle about an accident.

***Frequency Requirements:*** Minimum required bit rate for the application to function correctly. The sending rates i.e. frequency of messages is relatively important especially for critical vehicular safety application.

***Range Requirements***: Maximum distance between source and destination(s) of a radio transmission within which the application should achieve the specified reliability

***Speed Requirements:*** Maximum relative and absolute speed under which the specified reliability should be achieved.

Through various communication technologies, V2X allows a vehicle linking to other vehicles, pedestrians, road infrastructure, the Internet, and other entities in the transportation ecosystem. V2X provides the infotainment experiences, and eventually "key enablers" towards autonomous driving. It is predicted that by 2022, there will be more than 125 million vehicles connected by various V2X technologies[436] potential to offer unprecedented safety, novel transportation services as well as other novelties[437],[438].

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432 IMT-2020 (5G) Promotion Group (06/2018): *C-V2X Security White Paper*. Available at: http://www.imt2020.org.cn/zh/documents/download/82

433 U.S. Department of Transportation (USDOT). *How Connected Vehicles Work*. Study available at: https://www.its.dot.gov/factsheets/pdf/connected_vehicles_work.pdf

434 A very interesting study has been proposed in 5GAmericas (10/2016): *V2X Cellular Solutions.* Available at: http://www.5gamericas.org/files/2914/7769/1296/5GA_V2X_Report_FINAL_for_upload.pdf

435 3GPP TR 22.885 V14.0.0 (2015-12): *"Study on LTE Support for Vehicle to Everything (V2X) Services Architecture Enhancements for V2X Services (Release 14)".* Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.885/

436 Counterpoint (2018): *Global Connected Car Tracker 2018, Market Research Report*. Available at: https://www.counterpointresearch.com/125-million-connected-cars-shipments-2022-5g-cars-2020/

437 3GPP TR 36.885 V14.0.0 (2016-06): *"Study on LTE-based V2X Services; (Release 14)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/36_series/36.885/

 

In recent years, different regions in the world have conducted intensively V2X trials. There are two V2X technical paths followed by the automotive industry. One is the ETSI ITS-G5 based on 802.11p technologies; the other is the 3GPP LTE-V2X rooted from the 3GPP standards[439]. The LTE-V2X is a wireless communication technology for V2X with high data rate and controlled QoS[440] which is based on the evolution of LTE mobile communication technology defined by 3GPP, including two kinds of working modes of cellular communication (Uu) and direct communication (PC5)[441],[442]. The Uu mode uses the existing LTE cellular network to implement V2V communication by forwarding and the PC5 mode is similar to the DSRC[443], enabling direct communication between vehicles[444]. Additionally, the PC5 interface has been enhanced in many aspects to accommodate exchanges of rapidly changing dynamic information (position, speed, driving direction, etc.) and future advanced V2X services (automatic driving, vehicle platooning, sensor sharing, etc.)[445].

3GPP Releases 15 and 16 have defined both a traditional Base Station-User Equipment (BS-UE) Uu interface and a peer-to-peer PC5 interface for V2X communication. Those 5G systems are designed to support 10 ms end-to-end (E2E) latency, 1 ms physical (PHY) layer latency and 99.999% reliability.

As new use cases like autonomous driving and smart transportation increase over the next decade, the speed of vehicles may increase well beyond today's limit that is designed for human drivers, such as going beyond 100 miles per hour. The general rule of thumb for inter-vehicle distance (for instance, two seconds to impact), could also be largely reduced - thereby further improving traffic efficiency. Collaborative communication and computing among nearby vehicles and mobile edge computing nodes would also boost new location based, latency sensitive services that could bring

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[438] Chen, S., Hu, J., Shi, Y., Peng, Y., et *al.* (2017, July): Vehicle-to-Everything (V2X) Services Supported by LTE-Based Systems and 5G. *IEEE Communications Standards Magazine,* **1**(2), 70-76.

[439] Also see, *among others*: Roux, P., Sesia, S., Mannoni, V., and Perraud, E. (2019): System Level Analysis for ITS-G5 and LTE-V2X Performance Comparison. In Proceedings of the 2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS-2019), pp.1-9. IEEE, Monterey, CA, USA, November 04-07, 2019.

Also see: Molina-Masegosa, R., Gozalvez, J., and Sepulcre, M. (2020): Comparison of IEEE 802.11p and LTE-V2X: An Evaluation With Periodic and Aperiodic Messages of Constant and Variable Size. *IEEE Access*, **8**, 121526-121548.

[440] Araniti, G., Campolo, C., Condoluci, M., Iera, A., and Molinaro, A. (2013): LTE for vehicular networking: A survey. *IEEE Communications Magazine*, **51**(5), 148-157.

[441] 3GPP TS 23.285 V14.9.0 (2019-12): *"Architecture Enhancements for V2X Services (Release 14)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/23_series/23.285/

[442] Uhlemann, E. (2017): Initial steps toward a cellular vehicle-to-everything standard [connected vehicles]. *IEEE Vehicular Technology Magazine*, **12**(1), 14-19.

[443] The DSRC (Dedicated Short Range Communications) system consists of a series of IEEE and SAE standards (for more details see, *for example*: Kenney, J.B. (2011): Dedicated short-range communications (DSRC) standards in the United States. *Proceedings of the IEEE*, 99, 1162–1182).

Also see: European Electrotechnical Committee (CEN (2004, July): EN 12253: Road transport and traffic telematics - Dedicated Short Range, Communication (DSRC) -Physical layer using microwave at 5,8 GHz.

At the physical layer and the medium access control (MAC) layer, the DSRC uses the 802.11p protocol, which simplifies authentication, associated processes, and data transmission before sending data, enabling vehicles to broadcast relevant security information directly to neighboring vehicles and pedestrians. The network architecture and security protocols are defined in the IEEE 1609WAVE.

For further reading also see, *among others*: Abboud, K., Omar, H.A., and Zhuang, W. (12/2016): Interworking of dsrc and cellular network technologies for v2x communications: A survey. *IEEE Transactions on Vehicular Technology*, **65**(12), 9457-9470.

[444] Chen, S., Hu, J., Shi, Y., Peng, Y., Fang, J., Zhao, R., and Zhao, L. (2017): Vehicle-to-everything (v2x) services supported by LTE-based systems and 5G. *IEEE Communications Standards Magazine*, **1**(2), 70-76.

[445] 5G And Autonomous Driving (5GAA) (December 2017): An Assessment of LTE-V2X (PC5) and 802.11p Direct Communications Technologies for Improved Road Safety in the EU. Available at: http://5gaa.org/wp-content/uploads/2017/12/5GAARoad-safety-FINAL2017-12-05.pdf

intelligence to the transportation system. Under these new scenarios, the coordination among autonomous vehicles, human-driving vehicles, pedestrians, transportation infrastructure like traffic lights, roadside units, and mobile edge computing nodes will require even lower latency. For instance, we may see requirements such as up to 1 ms E2E latency, or 1/10 ms for the PHY layer, with 99.99999% reliability in ultra-high density environments of tens of thousands of mobile or stationary nodes squeezed within a square mile area - with or without cellular network infrastructure support. Even today's sophisticated 5G V2X solutions are probably unlikely to deliver the required latency, reliability and vehicle density needed for such use cases, and hence a new network evolution will be needed.

The application of V2X involves many aspects, such as intelligent transportation, intelligent connected vehicles, and automated driving[446]. Different applications have different requirements for latency, reliability, throughput, user density, and safety of the V2X environment[447]. Safety applications and automated driving require extremely low latency and a secure network environment[448]. For example, vehicles usually spend most of their time moving at high speed and malicious attackers could cause serious traffic accidents by broadcasting false messages. Malicious attackers may also obtain a vehicle owner's identity information, vehicle location information, driving trajectory, and so on by interception of data packets[449]. This violates user privacy. The V2X data includes information about roads and geography, which relates to national security.

Different regions show their own preference on the technologies. China selects C-V2X (LTE-V2X) as the national standard. In Europe, the debate is ongoing on how to adopt the technologies. The 5G Automotive Association[450] (5GAA), the international association with the mission to promote C-V2X technologies, expects that the first commercial deployments of V2X will occur in China and Europe, while deployments in the US and other parts of Asia will follow closely. Considering the life cycle of road infrastructure is normally 30 years, and the life cycle of a car is 10-15 years, the selection the V2X technology will be critical for the future evolution of technologies. For compatibility reasons it is crucial that the various regions cooperate to ensure harmonisation of technologies.

Under this consideration, Europe and China have established a way of cooperation on C-V2X technology validation through joint research and trials. Car manufacturers, road authorities, telecom vendors, and mobile operators team up to trial C-V2X key technologies and use cases.

The Cellular in association with V2X (C-V2X) is a communicating base that offers enhanced road safety and autonomous driving[451]. It uses a transmission mode called direct C-V2X, which provides longer communication range and higher reliability to connect "vehicles", "things" and "human". The

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[446] Rebbeck, T., Steward, J., Lacour, H.A., Killeen, A., McClure, D., and Dunoyer, A. (2017): *Final Report for 5GAA Socio-Economic Benefits of Cellular V2X. 5GAA.* Available at: [5gaa.org/wp-content/uploads/2017/12/Final-report-for-5GAA-on-cellular-V2X-socio-economic-benefits-051217_FINAL.pdf](5gaa.org/wp-content/uploads/2017/12/Final-report-for-5GAA-on-cellular-V2X-socio-economic-benefits-051217_FINAL.pdf)

[447] See, *for example,* the work in 3GPP TR 22.885 V14.0.0 (2015-12): *"Study on LTE Support for Vehicle to Everything (V2X) Services Architecture Enhancements for V2X Services (Release 14)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.885/

[448] 3GPP TS 22.185 v16.0.0 (2020-07): *"Service requirements for V2X services; Stage 1 (Release 16)"*. Available at: https://www.3gpp.org/ftp//Specs/archive/22_series/22.185/

[449] Dolev, S., Krzywiecki, Ł., Panwar, N., and Segal, M. (2017): Dynamic attribute based vehicle authentication. *Wireless Networks*, **23**, 1045-1062.

[450] The 5G Automotive Association (5GAA) is an international, global, cross-industry organisation of companies from the automotive, technology, and telecommunications industries. Its goal is, to develop end-to-end solutions for future mobility and transportation services, so avoiding incompatibility problems from the beginning. For more details also see: https://5gaa.org/

[451] Kutila, M., Pyykonen, P., Huang, O., Deng, W., Lei, W., and Pollakis, E. (2019): *C-V2X supported automated driving*. In Proceedings of the IEEE 2019 International Conference on Communications, Workshops (ICC Workshops 2019), pp.1-5. Shanghai, China, May 20-24, 2019, IEEE.

C-V2X chipset solution is going to be compatible with 5G and with the Advanced Driver Assistance Systems (ADAS) sensors as part of a specific platform for the C-V2X direct communication mode. It was designed to offer IoV connections with or without cellular network for V2I, V2V and V2P[452], as shown in Figure 37.

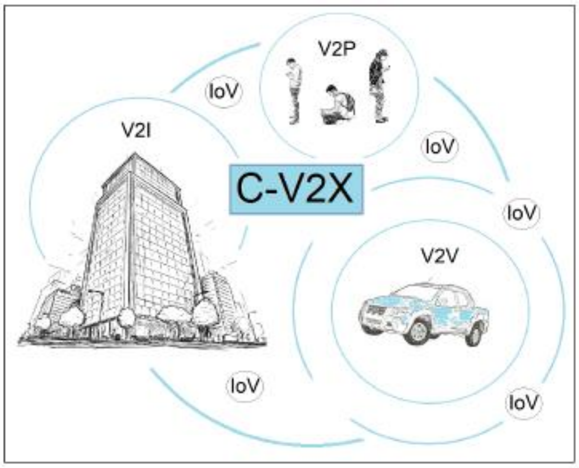


*Figure 37: Internet of Vehicles (IoV) on C-V2X453*

The 5G-DRIVE EU-funded project is one of the projects that work on C-V2X trials with China. The aim is to compare the performance in joint V2X use cases, and identify any potential interoperability problems.

In Europe, V2X deployment is underpinned by the European Commission's Cooperative Intelligent Transport Systems (C-ITS) Framework Directive (2010/40/EU). In Europe, the standardisation efforts are driven by the European Car-2-Car Communication Consortium (C2C-CC)[454], an industry consortium of automobile manufacturers, suppliers and research organisations, ERTICO, a European organisation of stakeholders with public and private partners, as well as by ETSI's Centre for Testing and Interoperability, ETSI CTI. The C-ITS standards follow a general architecture, specified in ETSI EN 302 665[455] and ISO 21217[456], with the ITS station as the core element, representing vehicle, personal (mobile personal devices), roadside (infrastructure), and central (backend systems and traffic management centres) subsystems[457]. For C-ITS, the ISO OSI reference model was adapted to cover horizontal layers for access technologies, networking and transport, facilities and applications, and vertical entities for management and security. On the policy and regulatory level, the Commission coordinates the V2X development in different Member states of the EU. In November 2016, the European Commission approved the C-ITS strategy for the EU. It provides the legal framework to facilitate the convergence of investments and regulatory frameworks across the EU. The V2X pilots

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452 Qualcomm Technologies Inc. (2019). *Cellular Vehicle-to-Everything*. Available at: [https://www.qualcomm.com/invention/5g/cellular-v2x](https://www.qualcomm.com/invention/5g/cellular-v2x)

453 Source: Storck, C.R., and Duarte-Figueiredo, F. (2020): A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated With Vehicle-to-Everything Communications by Internet of Vehicles. *IEEE Access*, **8**, 117593-117614.

454 Car-2-Car Communication Consortium, [http://www.car-2-car.org](http://www.car-2-car.org).

455 European Telecommunications Standards Institute (ETSI): EN 302 665 V1.1.1 (2010-09): *"Intelligent Transport Systems (ITS); Communication Architecture"*.

456 International Organization for Standardization (ISO): *ISO 21217:2014 (Intelligent transport systems - Communications access for land mobiles (CALM) - Architecture)*, [https://www.iso.org/standard/61570.html](https://www.iso.org/standard/61570.html)

457 Kosch, T., Kulp, I., Bechler M., et *al.* (2009): Communication Architecture for Cooperative Systems in Europe. *IEEE Communications Magazine*, **47**(5), 116-125.

 

are done under the C-Roads Platform[458]. This platform is a joint initiative of European Member States and road operators for testing and implementing C-ITS services for cross-border harmonisation and interoperability. It targets to cover 43 European cities, 6000 km of C-ITS equipped road sections by end of 2019. Currently there are three large Europe projects working on C-ITS corridor trials cross-border[459,460,461].

It is worth mentioning C-ITS services. In Europe C-ITS services will be implemented in phases based on their priority[462]. There are two priority groups called *Day 1* and *Day 1.5* services[463]. *Day 1* services will be deployed starting from 2019. These services are used for hazardous location notifications and signage. The former includes road works warning, weather conditions, emergency break light, etc. The later includes in-vehicle signage, green light optimal speed advisory (GLOSA), traffic signal priority request, etc. The specifications and standards of the second phase *Day 1.5* C-ITS services are still under development[464]. Those services include vulnerable road user (VRU) protection, on/off street parking information, traffic information, etc.

In China, the V2X development is regulated by the Ministry of Industry and Information Technology (MIIT), Ministry of Public Security (MPS), and Ministry of Transport (MOT). The MIIT specifies the spectrum for V2V and V2I operation, and coordinates the C-V2X trial activities in China. The MPS takes charge of the standard revision on traffic light and regulations on traffic information access. The MOT is responsible for regulating the road infrastructure for V2X services. Three ministries have defined the V2X test specification. So far, the LTE-V2X trials have been done in Wuxi, Shanghai, and other pilot areas. The V2X services defined match the Day-1 C-ITS services defined by Europe. However, in China some Day-1.5 services, like VRU protection have also been tested. The trials are expected to conclude in early 2020.

The C-V2X roadmap in Europe and China is shown in the following Figure 38. Other regions and countries follow a similar roadmap. Currently, C-V2X has been standardised by 3GPP in Release 14. Both Europe and China have adopted 5.9 GHz spectrum for the V2V, V2I, and V2P services. Qualcomm, Huawei, and Datang have released LTE-V2X chipsets and modules. The C-V2X standard continued in 3GPP release 15 for performance improvement. The 5G V2X, known as NR-V2X, will be standardised in 3GPP Release 16 and introduce the 5G New Radio features and low latency services into C-V2X.

458 C-Roads Platform: https://www.c-roads.eu.

459 5G-MOBIX project, https://www.5g-mobix.com

460 5GCARMEN project, http://5gcarmen.eu

461 5GCroCo project, http://5gcroco.eu

462 European Commission (01/2016): "C-*ITS Platform", Technical Report*. Available online at: https://ec.europa.eu/transport/sites/transport/files/themes/its/doc/c-its-platform-final-report-january-2016.pdf

463 Mellegård, N., and Reichenberg, F. (2020): The Day 1 C-ITS Application Green Light Optimised Speed Advisory - A Mapping Study. *Elsevier Transportation Research Procedia*, **49**, 170-182.

464 C-ITS Platform (2017): *Platform for the Deployment of Cooperative Intelligent Transport Systems in the EU (C-ITS Platform) Phase II Final Report, DG MOVE - DG Mobility and Transport, September 2017, Brussels*. Available at: https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf

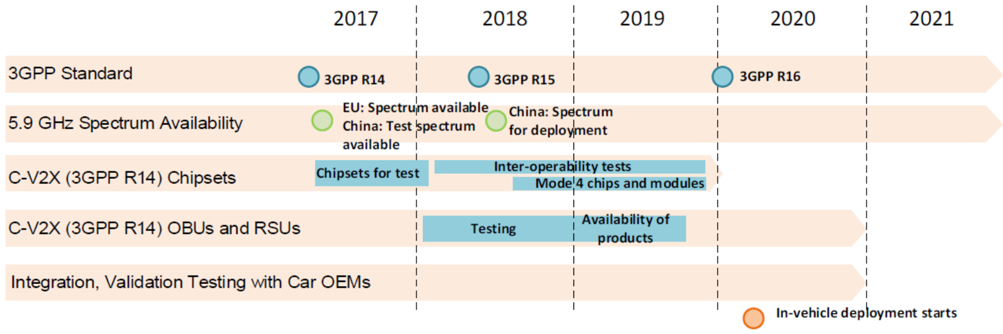


*Figure 38: C-V2X roadmap in Europe and China*

A primary goal of C-ITS is to ensure users of the same service can interoperate with each other, to maximize the safety effect[465]. However, automotive and transport ecosystems involve different stakeholders such as car OEMs, regional roads and transport authorities, and third-party service providers, who may adopt different implementation solutions when offering the same services. This makes interoperability of C-ITS services a challenge. Even both Europe and China have considered C-V2X technologies, when comparing the different flavours of V2X standards, there are differences in terms of both message types and available functional capabilities. For example, while China uses Basic Safety Message (BSM) for both status information and event notifications, Europe has split these into Cooperative Awareness Message (CAM) and Decentralised Environmental Notification Message[466],[467] (DENM). The CAM protocol conveys critical vehicle state information in support of safety and traffic efficiency application, with which receiving vehicles can track other vehicles positions and movement. The DENM protocol disseminates event-driven safety information in a geographical region.

The EU-China collaborative projects such as the 5G-DRIVE, aim to investigate these inter-operability problems.

Since vehicles usually spend most of their time moving at high speed, it may have serious consequences when an accident happens and even threaten the safety of the driver and passengers. Safety always has the highest priority, so how to ensure vehicle safety has always been a serious topic. In the field of traditional automobiles, various testing and evaluation systems have been established in all world countries. Testing is an indispensable part of the Internet of Vehicles which is a new thing for us. If a vehicle receives erroneous data in a specific environment such as a highway or a crowded area, it may cause false triggering of a safety application, resulting in a serious traffic accident. Testing can ensure the reliability of the communication, thus ensuring the safety of the entire V2X environment. Because of the high requirements for security of the V2X, the priority of V2X testing is also high, Internet of Vehicles is a new cross-industry thing involving many industries such as automotive, communications, transportation, etc. As the name implies, V2X needs to connect all

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[465] Lu, M., Türetken, O., Adali, O.E., Castells, J., Blokpoel, R., and Grefen, P. (2018): *C-ITS (Cooperative Intelligent Transport Systems) deployment in Europe - challenges and key findings*. In Proceedings of the 25th ITS World Congress, pp.1-10. Copenhagen, Denmark, 17-21 September 2018.

[466] The Decentralised Environmental Notification Message (DENM) is another Facilities layer message. More details are also given in ETSI EN 302 637-3 V1.2.2 (2014-11): *"ITS Vehicular Communications: Basic Set of Applications; Part 3: Specification of Decentralized Environmental Notification Basic Service".*

DENM contains information related to a road hazard or abnormal traffic conditions such as the type of event and its position. It is employed to alert other road users about the occurrence of an unexpected event that has potential impact on road safety or traffic condition. The DENM is also considered for *Day-1* deployment. The management of a DENM transmission depends on whether the vehicle is the generator of the message or a forwarder

[467] Santa, J., Pereniguez-Garcia, F., Moragón, A., and Skarmeta, A.F. (2014): Experimental evaluation of CAM and DENM messaging services in vehicular communications. *Transportation Research Part C: Emerging Technologies*, **46**, 98-120.

 

vehicles together, so the interconnection and interoperability are important attributes[468]. In the Internet of Vehicles, if a vehicle cannot understand the data sent by another vehicle with different brand, it will cause the lack of the information, and greatly reduce the meaning of V2X. Besides it may also lead to serious accidents resulting in unnecessary loss. At present, countries in which the V2X is growing up have been developing communication standards to help vehicles and other transportation participants to communicate unimpeded. These standards can also achieve understanding between different brands of vehicles and different intelligent transportation infrastructures, to ensure interconnection and interoperability of the V2X.

Testing aims to ensuring safe and effective use of the Internet of Vehicles[469]. Different testing methods are adopted for different needs. Communication standards, as a common language among vehicles, infrastructures, clouds, etc., can help vehicles communicate with other traffic participants accessibly, enabling the interconnection and interoperability. Interoperability testing can ensure information exchange and coordination between devices. The protocol conformance testing aims to verify the conformity of each manufacturer's terminals with standards[470]. They lay a foundation for the interconnection and interoperability between different manufacturers' devices. Different V2X applications have different communication performance requirements, such as automatic driving needing extremely low latency, and video entertainment applications requiring larger bandwidth. The performance testing is mainly used to test the performance of the V2X network in different scenarios, including latency, communication range, packet loss rate, etc., to ensure that communication can meet the needs of the applications. Ensuring the safety, effectiveness and reliability of V2X applications is also an important goal of testing. The function testing can determine whether an application is valid, whether it can be triggered correctly in a specific scenario, and whether it can ensure vehicles safety. Malicious applications will be removed after function testing. In general, we need to test functionality, performance, interoperability and consistency of the V2X terminal. Function testing, performance testing, and communication protocol conformance testing are mainly used to meet the testing requirements for latency and reliability. Security protocol consistency, gateway testing, penetration testing, and accelerated testing can find vulnerabilities and potential risks and its applications to ensure its security. After laboratory testing, V2X applications must undergo field testing before they can be used commercially. Field testing is mainly used to evaluate the performance of V2X applications in a real environment and to meet the performance function requirements in a large-scale environment.

***EU China V2X joint trials***

The purposes of the V2X trial collaboration between EU and China is to evaluate similar use cases, identify the inter-operability problems On the EU level, there are two research projects working on joint C-V2X trials between Europe and China[471]. 5G-DRIVE is an EU H2020 project working under EU-China collaboration agreement. It cooperates with the 5G Large-scale Trial project led by China Mobile. 5G-DRIVE aims to trial 5G eMBB services operating at 3.5 GHz, and V2X services operating at

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468 Gravina, R., Palau, C.E., Manso, M., Liotta, A., and Fortino, G. (2018): *Integration, Interconnection, and Interoperability of IoT Systems*. Springer International Publishing, New York, NY, USA.

469 See the following paper and references therein: Wang, J., Shao, Y., Ge, Y., and Yu, R. (2019): A Survey of Vehicle to Everything (V2X) Testing. *Sensors 2019*, **19**, 334, 1-20.

470 See, *for example*: Aho, A.V., Dahbura, A.T., Lee, D., and Uyar, M.U. (1991): An optimisation technique for protocol conformance test generation based on UIO sequences and rural Chinese postman tours. *IEEE Transactions on Communications*, **39**(11), 1604-1615.

471 Kostopoulos, A., Chochliouros, I.P., Dardamanis, A., Segou, O., Kafetzakis, E., Soua, R., Zhang, K., Kuklinski, S., Tomaszewski, L., Yi, N., Herzog, U., Chen, T., Kutila, M., and Ferragut, J. (2019): *5G trial cooperation between EU and China*. In Proceedings of the IEEE 2019 International Conference on Communications, Workshops (ICC Workshops 2019), pp.1-6. IEEE, Shanghai, China, May 20-24, 2019.

 

3.5 GHz for V2N[472] and 5.9 GHz for V2V and V2I. The key objective of 5G-DRIVE is to promote research and innovation cooperation on 5G and V2X between EU and China through joint trials and research activities. The project has 17 partners from 10 European countries. The partners ERTICO, BMW, VTT, European Commission – Joint Research Centre, Dynniq, Orange, University of Luxemburg, and Vedia work on V2X topics in the project. The project works on trials in V2N, V2V and V2I scenarios. The V2N scenario tests the performance of cellular network to support V2N services, in which DENM, IVI[473], SPAT[474] and MAP[475] messages[476],[477],[478] are evaluated. The MEC server is deployed

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[472] V2N communications such as sending video, sound feed information and other diagnostics from the vehicle, along with environmental information, to the remote driver and reliably transmitting control commands from the remote driver to the vehicle to maneuver the vehicle in real-time, can be enabled with 5G. The requirements to support these communications consist of meeting strict constraints on latency, reliability and security in a wide coverage area.

[473] The In-Vehicle Information message (IVI) is an I2V message format conveying information about infrastructure-*based* traffic services needed for the implementation of use cases focusing on road safety and traffic efficiency. For the first phase of C-ITS deployment in Europe, C-Roads and the C2C-CC have agreed on adopting IVI profiling examples based on the IVI message format standardised in ISO/TS 19321 (See: ISO/TS 19321 (2015): *Intelligent transport systems - Cooperative ITS-Dictionary of in-vehicle information (IVI) data structures*. Available at: https://www.iso.org/standard/64606.html).

In turn, this standard refers to the sign catalogue established by ISO/TS 14823, which presents standardised codes for existing signs and pictograms used to deliver Traffic and Traveller Information (TTI). The IVI message transmission is operated in accordance to the standard ETSI TS 103 301, which describes facilities layer protocols and communication requirements for infrastructure-based services. Similar to other ETSI C-ITS messages, an IVI PDU is encapsulated in the *ItsPDUHeader* and transmitted as IVI through the lower layer of the communication stack.

C-Roads uses the IVIM to transmit static as well as dynamic road sign and message sign information on highways. Static road signs are actual sign plates placed on the side of the road. On the contrary, dynamic road signs are signs that indicate variable information.

[474] A SPaT (Signal Phase and Timing) message describes the current phase at a signalised intersection, together with the residual time of the phase, for every lane (hence every approach and movement) of the intersection. The SPaT is an I2V message primarily used to communicate the intersection status to vehicles approaching an intersection. It usually contains dynamic information about the state of a signalised intersection. It can contain the traffic light state, future state predictions, speed advice, queue state information and whether a priority request is active. The corresponding estimate is periodically broadcast by the intersection, say once per 100ms. For a fixed-time controller the SPaT information is definitive; the challenge is for an actuated controller for which only an estimate of the residual time can be given, and for which the SPaT message data elements include StartTime of the phase, its MinEndTime, MaxEndTime, LikelyTime, Confidence (in the LikelyTime) and NextTime (when this phase will next occur). A SPaT message is used together with a MAP message, which describes the physical geometry of one or more intersections. A vehicle approaching or leaving the intersection, with knowledge of its own position and speed and MAP information, can take the residual time of the current phase from the SPaT message to calculate a speed profile that reduces stop-and-go driving and idling.

The SPaT message is used to convey the current status of one or more signalised intersections. Along with the MAP message (which describes a full geometric layout of an intersection) the receiver of this message can determine the state of the signal phasing and when the next expected phase will occur.

[475] The Map Message (MAP) is an I2V message used by the RSI to convey many types of geographic road information. At the moment, MAP is used to convey one or more intersection lane geometry information within a single message. The message content includes items such as complex intersection descriptions, road segment descriptions, high speed curve outlines (used in curve safety messages), and segments of roadway (used in some safety applications). The contents of this message define the details of indexing systems that are in turn used by other messages to relate additional information about events at specific geographic locations on the roadway.

MAP is the effective result of the Road and Lane Topology (RLT) infrastructure service which manages the generation, transmission and reception of a digital topological map. This service along with its operational parameters is defined in ETSI TS 103 301 (ETSI TS 103 301 V1.1.1 (2016-11): *"Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements"*. Available at: *https://www.etsi.org/deliver/etsi_ts/103300_103399/103301/01.01.01_60/ts_103301v010101p.pdf*), which in turn refers to the SAE J2735 data dictionary [For more details about the matter also see: *https://www.sae.org/standards/content/j2735_201603/*]. Being part of the *Day-1* deployment in Europe, data elements, data frames and service parameters of the MAPEM (MAP Extended Message) shall be used according to the definitions provided by the C-ITS Infrastructure Functions and Specifications of the C-Roads Platform.

 

in 5G network to process vehicle sensing data. The V2V and V2I scenarios are realised using LTE-V2X modules. The new V2V message set will be defined to enable collaborative sensing and manoeuvring between two vehicles. The trial use cases are jointly identified with the Chinese twin project. Both projects work on the similar trial cases and compare the performance.

5G-DRIVE project has two V2X trial sites. The Espoo trial site is located in Karaportti area at Espoo, Finland, which is equipped with 3.5 GHz base-stations, LTE-V2X equipment and mobile traffic light. The length of the roads available in site is about 2.6 km including intersections and parking areas. The trial use cases in the Espoo trial site include GLOSA and intersection safety.

The JRC site at Ispra, Italy, features 36 km of internal roads under real-life driving conditions, as well as 9 vehicle emissions laboratories for calibration and electromagnetic compatibility and interference testing, amongst other. The JRC Ispra site evaluates GLOSA, and tests the co-existence of LTE-V2X and ITS-G5 in the 5.9 GHz band.

5G-MOBIX is the other EU project cooperating with China on joint V2X trials. 5G-MOBIX develops and tests automated vehicle functionalities using 5G technologies along multiple cross-border corridors in Europe, China and South Korea. The project focuses on evaluating benefits of Cooperative, Connected, Automated and Autonomous Mobility (CCAM) technologies. The use cases in 5G-MOBIX include cooperative overtake, highway lane merging, truck platooning, road user detection, vehicle remote control, see through, HD map update, etc.

In China, 5G MOBIX will evaluate CCAM scenario at the Jinan trial site. The trial site has two main road equipped with 5G V2X communication infrastructure by CATT and LTE-V2X infrastructure supported by China Unicom. The trial use cases include: automated driving (automated overtake and cooperative collision avoidance); road safety and traffic efficiency services; digitalisation of transport and V2X in areas outside network coverage.

One of the 5G-DRIVE project main objectives is to develop key 5G technologies at pre-commercial test-beds V2X services and then demonstrate IoV services using V2I and V2V communications. The 5G benefits over the other communication options like ITS G5[479] is going to be estimated for the existing GLOSA and intelligent intersection use cases. Special attention is paid for automated driving challenges[480].

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[476] Also see: *https://smartmobilitycommunity.eu/talking-traffic-dutch-profiles-and-itf*

[477] Amelink, M. (2015, September): *Signal phase and time (SPAT) and map data (MAP)*. Amsterdam Group. Available at: *https://amsterdamgroup.mett.nl/downloads/handlerdownloadfiles.ashx?idnv=500795*.

[478] International Organization for Standardization: ISO/TS 19091:2017 *("Intelligent transport systems — Cooperative ITS — Using V2I and I2V communications for applications related to signalized intersections")*. Available at: *https://www.iso.org/standard/69897.html*

The ISO/TS 19091:2017 document defines the message, data structures, and data elements to support exchanges between the roadside equipment and vehicles to address applications to improve safety, mobility and environmental efficiency. In order to verify that the defined messages will satisfy these applications, a systems' engineering process has been employed that traces use cases to requirements and requirements to messages and data concepts.

[479] Also see: Lin, L., and Misener, J.A. (2015): *Message sets for vehicular communications*. In Proceedings of the Vehicular ad hoc Networks, pp.123-163. Springer.

[480] Also see the scope presented in the 5G-DRIVE Project Deliverable D4.2 (08/2019): *"Joint specification for V2X trials"*. This deliverable provides scenarios and KPIs for latencies and network availability. The selected use cases and trials have been planned in collaboration between the 5G-DRIVE and the Chinese 5G related project (5G Product R&D Large-Scale Trial). [Available at: *https://5g-drive.eu/resources-and-results/project-deliverables/*].

## 4.2 Radio Frequency Spectrum for Cooperative Intelligent Transport Services (C-ITS)

Radio spectrum availability is a key factor for the successful deployment of C-ITS services worldwide. This is particularly relevant in the EU, where harmonised spectrum (i.e., the same portions of the radio spectrum in the same frequency bands) must be made available across EU Member States to avoid fragmentation.

This section discusses the state of play of radio spectrum availability for C-ITS services in the EU, China and the United States, taking into account any relevant recent development, compared to previous approaches that have been discussed in the scope of the prior 5G-DRIVE Deliverable D2.2[481]. Special emphasis is put on the 5.9 GHz band for safety-related C-ITS services in the EU, where coexistence mechanisms between competing C-ITS technologies such as ITS-G5 and LTE-V2X is currently being studied.

### 4.2.1 European Union

#### 4.2.1.1 The Radio Spectrum Committee

The Radio Spectrum Committee[482] (RSC) is a complementary advisory body to the European Commission established by the Radio Spectrum Decision (2002/676/EC)[483]. The RSC assists the Commission in the development of technical implementing decisions to ensure harmonised conditions across Europe for the availability and efficient use of the radio spectrum. The RSC is composed by representatives of each EU Member States and is chaired by the European Commission.

As part of its responsibilities under the Radio Spectrum Decision, the European Commission (via the RSC) may issue mandates to the European Conference of Postal and Telecommunications Administrations (CEPT) for the development of technical implementing measures that can ensure harmonised conditions for the availability and efficient use of radio spectrum. These mandates specify the concrete tasks to be undertaken, as well as the timeframe in which they should be achieved.

#### 4.2.1.2 The C-ITS Radio Spectrum Band

The deployment of C-ITS services in the 5.9 GHz radio frequency band can be analysed from two different perspectives:

- From the **EU policy perspective**, Commission Implementing Decision (EU) 2020/1426 of 7 October 2020[484] (repealing Commission Decision 2008/671 of 5 August 2008) harmonises the conditions for the availability and efficient use of the frequency band 5875-5935 MHz (also known as “the safety-related ITS band” or “the 5.9 GHz band”) for safety-related applications

[481] See 5G-DRIVE Project (04/2019): Deliverable 2.2: *“Joint Architecture, Use Cases and Spectrum Plan”*. Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

[482] For more details see: https://ec.europa.eu/digital-single-market/en/radio-spectrum-committee-rsc

[483] European Parliament and Council (2002): Decision No 676/2002/EC of the European Parliament and of the Council of 7 March 2002 *on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision)*. Official Journal (OJ) L108, 24.04.2002, pp.1-6. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32002D0676

[484] European Commission (2020): Commission Implementing Decision (EU) 2020/1426 of 07.10.2020 *on the harmonised use of radio spectrum in the 5875-5935 MHz frequency band for safety-related applications of intelligent transport systems (ITS) and repealing Decision 2008/671/EC*. Official Journal (OJ) L328, 09.10.2020, pp.19-23. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020D1426

 

of Intelligent Transport Systems in the European Union. As shown in Figure 39, the Implementing Decision provides non-exclusive access for all safety related ITS applications in the 5875-5925 MHz band. In particular, road ITS applications shall have priority below 5915 MHz, whilst urban rail ITS shall have priority above 5915 MHz. By contrast, the 5925-5935 MHz band is harmonised for safety-related urban rail ITS applications on an exclusive-access basis. The deadline for frequency band designation by EU Member States is June 30, 2021.

- From the **standardisation perspective**, Harmonised European Standard ETSI EN 302 571[485] provides the normative framework for radiocommunications equipment operating in the 5.9 GHz band to comply with the essential requirements in article 3.2 of EU Directive 2014/53/EU (also known as "the Radio Equipment Directive"[486] or RED, in short). This article of the RED establishes the regulatory conditions for placing radio equipment on the EU single market. Manufacturers of radiocommunications devices can use Harmonised European Standards (such as EN 302 571) to provide presumption of conformity with the essential requirements of article 3.2 of the RED.

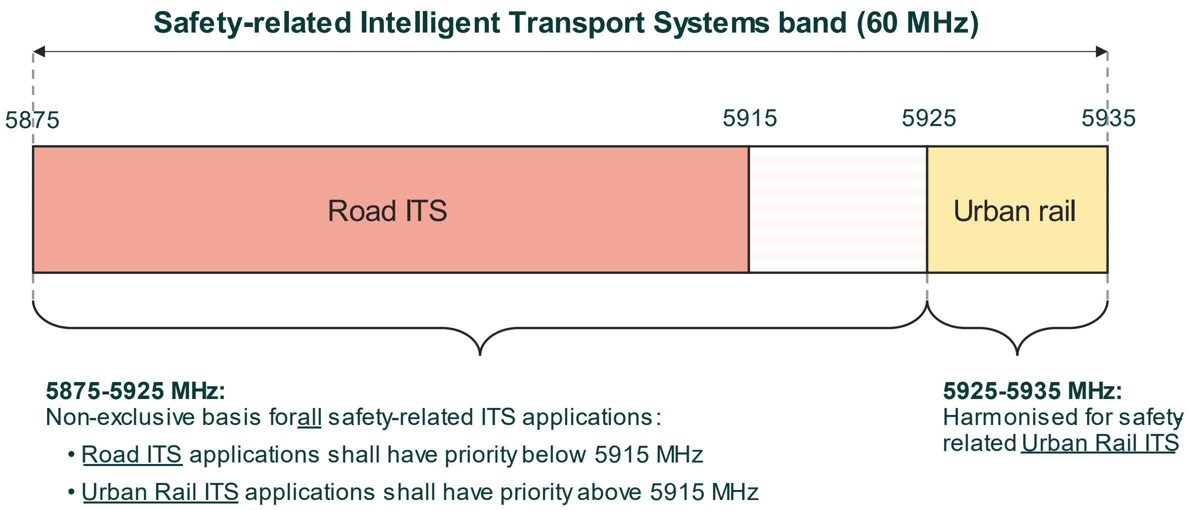


*Figure 39: Harmonised safety related ITS Band in the EU (Commission implementing Decision (EU) 2020/1426)*

At the time of writing, the main C-ITS technologies in the EU are ITS-G5 and LTE-V2X. Both technologies aim at providing Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) services in the 5.9 GHz band. In addition, LTE-V2X also provides Vehicle-to-Network (V2N) services over conventional LTE frequency bands (e.g., 1.8 GHz, 2.1 GHz, 2.6 GHz, etc.).

Despite providing the same user services, ITS-G5 and LTE-V2X differ significantly in their physical and access layers of the communications protocol stack. ITS-G5 is a fully distributed **asynchronous** technology based on a CSMA/CA channel access mechanism similar to that of Wi-Fi networks. By contrast, LTE-V2X is a fully distributed **synchronous** technology that uses semi-persistent scheduling of radio resources to enable shared user access to the wireless medium. At the time of writing, ITS-

[485] European Telecommunications Standards Institute (ETSI): ETSI EN 302 571 (V2.1.1) (2017-02): "*Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive*". Available at: https://www.etsi.org/deliver/etsi_en/302500_302599/302571/02.01.01_60/en_302571v020101p.pdf

[486] European Parliament and of the Council (2014): Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 *on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC*. Official Journal (OJ) L153, 22.05.2014, pp.62-106. Available at: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32014L0053

G5 and LTE-V2X are not designed to coexist with each other and might create harmful interference when operating in proximity using the same frequency and time.

#### 4.2.1.3 Challenges

One of the main challenges for a technology-neutral deployment of C-ITS services is the coexistence and interoperability of ITS-G5 and LTE-V2X systems in the 5.9 GHz band. Two communications technologies can coexist if their simultaneous operation in the same frequency band does not create harmful interference to each other. By contrast, interoperability refers to the ability of two different communications technologies to seamlessly communicate with each other.

Coexistence of road ITS technologies (such as ITS-G5 and LTE-V2X) in the 5.9 GHz band is a major challenge from both the technical and EU policy points of view. This is also applicable to the coexistence between road and urban rail ITS technologies, as well as to road/urban rail ITS technologies and short-range electronic toll collection systems (such as CEN DSRC[487] and HDR DSRC[488]). In February 2019, the Technical Group 37 of the ETSI Technical Committee on Electromagnetic Compatibility and Radio Spectrum Matters (ETSI TC ERM TG37[489]) launched two work items (WIs) aimed at studying coexistence mechanisms to avoid harmful interference between ITS-G5 and LTE-V2X systems in the 5.9 GHz band, namely:

- Work item **DTR/ERM-TG37-273**: This WI focuses on conducting studies on the feasibility of **co-channel** co-existence between ITS-G5 and LTE-V2X technologies based on solutions presented to CEPT. In addition, this work item also aims at defining methodologies and metrics required for performing the studies and evaluating the performance of the solutions being analysed. Additional tasks are finding co-channel co-existence methods which enable both technologies to use the same frequency channel in the same geographical area while meeting the metrics defined, as well as to classify co-channel co-existence methods depending on the observed metrics. The output of this WI will be published in ETSI TR 103 766 (expected release date: mid-May 2021).
- Work item **DTR/ERM-TG37-274**, which is tasked with proposing an overall framework based on combinations of **co-channel** and/or **non-co-channel** operation (as presented to CEPT) to address spectrum sharing between ITS-G5 and LTE-V2X ITS technologies enabling both technologies to use the same spectrum in the same geographical area. The overall framework may consist of several options for such combined operation. The output of this WI will be published in ETSI TR 103 667 (expected release date: mid-May 2021).

Similarly to the issue of coexistence, interoperability of ITS-G5 and LTE-V2X systems is a major challenge for a fully technology-neutral C-ITS deployment scenario. Although upper layers of the protocol stack (facilities, transport, network, security) are common to both technologies, the access and physical layers feature significant differences. ETSI Technical Report TR 103 576-2[490] discusses

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[487] The CEN Dedicated Short-Range Communication (DSRC) technology has been developed specifically to provide a reliable and effective communication means for traffic and transport applications in single lane and high speed multilane free flow environments. For further details also see: https://www.itsstandards.eu/25-2/wp-1/cen-dsrc/

[488] For relevant information also see, *among others*: European Telecommunications Standards Institute (ETSI): ETSI TR 103 403 V1.1.1 (2017-06): *"Intelligent Transport Systems (ITS); Mitigation techniques to avoid harmful interference between equipment compliant with ES 200 674-1 and ITS operating in the 5 GHz frequency range; Evaluation of mitigation methods and techniques"*.

Available at: https://www.etsi.org/deliver/etsi_tr/103400_103499/103403/01.01.01_60/tr_103403v010101p.pdf

[489] For more details about the TG37 also see: https://portal.etsi.org/TB-SiteMap/ERM/ERM-ToR/ERMtg37-ToR

[490] European Telecommunications Standards Institute (ETSI): ETSI Technical Report TR 103 576-2 v1.1.1 (2020-02): *"Intelligent Transport Systems (ITS); Pre-standardization study on ITS architecture; Part 2: Interoperability among heterogeneous ITS systems and backward compatibility"*. Available at: https://www.etsi.org/deliver/etsi_tr/103500_103599/10357602/01.01.01_60/tr_10357602v010101p.pdf

the topic of interoperability and backwards compatibility of C-ITS technologies.

### 4.2.2 China

#### 4.2.2.1 V2X Frequency Bands

In contrast with the technology-neutral spectrum decision in the EU, in 2016 the Chinese government designated C-V2X as its technology of choice for the large-scale deployment of C-ITS services across the country. Concretely, in November 2016 the Chinese Ministry of Industry and Information Technology (MIIT) designated the 5905-5925 MHz frequency band as experimental radio spectrum for C-V2X development in six major cities (Beijing, Shanghai, Chongqing, Changchun, Wuhan and Hangzhou). This frequency band will be used to provide short-range, device-to-device communication services between vehicles using exclusively LTE-V2X and its future evolution (NR-V2X).

#### 4.2.2.2 Challenges

Designating a single C-ITS technology of choice in the 5.9 GHz band solves the issue of coexistence and interoperability in the Chinese V2X ecosystem and simplifies the deployment and adoption of C-ITS throughout the country. Nevertheless, coexistence and interoperability with ITS-G5 might still remain a technical issue for Chinese car exports. Likewise, coexistence and interoperability with LTE-V2X might also remain a technical issue for vehicle imports featuring ITS-G5 into the Chinese market.

### 4.2.3 United States

#### 4.2.3.1 V2X Frequency Bands

In November 2020, The Federal Communication Commission (FCC) adopted new rules for the 5.9 GHz band (5.850-5.925 GHz) to make new spectrum available for unlicensed uses, such as Wi-Fi, and to improve automotive safety[491]. Specifically, the approved band plan designated the lower 45 MHz of the 5.9 GHz band (5.850-5.895 GHz) for unlicensed uses, and the upper 30 MHz (5.895-5.925 GHz) for enhancing road transport safety using Cellular Vehicle-to-Everything (C-V2X).

By adopting these rules, the FCC designated C-V2X as the technology standard for safety-related transportation and vehicular communications in the US in detriment of the former designated standard – the IEEE 802.11p-based Dedicated Short-Range Communications (DSRC).

The FCC justified its decision on the lack of DSRC deployment in the US over the last 20 years and the need to allocate additional spectrum for unlicensed operations and demanding services to rural and underserved areas.

#### 4.2.3.2 Challenges

The FCC decision from November 2020 faced strong opposition from several C-ITS stakeholders in the US, most prominently from the US Department of Transportation (DOT). In a letter from the US DOT's General Counsel addressed to FCC Chairman Ajit Pai[492], the US DOT formally asked the FCC to revisit its approach to the proposed 5.9 GHz band allocation in light of the concerns below (verbatim):

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491 Federal Communication Commission (FCC) (11/2020): *Use of the 5.850-5.925 GHz Band; First Report and Order, Further Notice of Proposed Rulemaking, and Order of Proposed Modification; 20 November 2020*. Available at: https://docs.fcc.gov/public/attachments/DOC-360940A1.pdf

492 See: https://www.fcc.gov/ecfs/filing/1109637413744

- *"FCC's reallocation of the 5.9 GHz band is unworkable and undermines innovation in transportation safety";*
- *"FCC has prematurely chosen an unproven technology winner (C-V2X)";*
- *"FCC undervalues the transportation safety benefits of the 5.9 GHz Band and underestimates the cost and disruption that will result here."*

## 4.3 Use Case 1: Green Light Optimised Speed Advisory (GLOSA)

### 4.3.1 Conceptual Description

The highest fuel consumption on urban arteries is associated with driving in congested traffic, characterised by higher speed fluctuations and frequent stops at intersections. The best flow of traffic on arterial streets, in terms of fuel consumption and emissions, is the one with fewest stops, shortest delays, and moderate speeds maintained throughout a commute.

Traffic lights control as one of the traffic management methods is an important and effective way to improve urban road capacity, ease traffic congestion and reduce vehicle delay time. The rationality and efficiency of traffic signal control strategy are directly related to the effectiveness of urban traffic management. Therefore, extensive research has been ongoing to develop traffic signal control algorithms[493]. Traffic control strategies have been evolved with the aim of minimizing the total time spent by vehicles[494] In general, traffic control can be primarily divided into two elementary categorisations: (i) the fixed time/Pre-timed control; and (ii) the traffic responsive control. The fixed time control works well within closely spaced intersections with consistent traffic volumes and patterns through the defined times of a day but it cannot respond to traffic changes in real time since cycle length, phase plan, and phase times are pre-determined. To solve this drawback, researchers proposed the traffic responsive control which embraces both actuated and adaptive traffic control. Firstly, the actuated traffic control uses detector measurements such as inductive loops or pattern recognition cameras to cope with the traffic volume. Based on detection data, green time for each phase is extended.

Traffic light forecast is a service that improves safety and convenience for drivers by assisting them at intersections. This includes services like Time-To-Green (TTG), which provides real time information about the traffic light cycles, and Green Light Optimised Speed Advisory[495] (GLOSA), which calculates the optimum approach speed to get a green light at the upcoming intersection (cf. Figure 40). These services that act as "cooperative" green light functions, implicate for several benefits as: (i) they save fuel and reduce pollution; (ii) the bring comfort and "wow" to drivers; (iii) they increase throughput; (iv) they enhance safety as relaxed drivers can behave in a more secure way. The GLOSA systems seem to be an interesting first step in ADAS systems[496] based on V2X communication with infrastructure, before the use of information by autonomous vehicles to handle intersections.

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[493] Yang, K., Guler, S.I., & Menendez, M. (2016): Isolated intersection control for various levels of vehicle technology: Conventional, connected, and automated vehicles. *Transportation Research Part C: Emerging Technologies,* **72**, 109-129.

[494] Ibid.

[495] GLOSA systems date back to as early as 1983 when Volkswagen introduced the Wolfsburger Welle, a driver assistance system that informed approaching drivers about the signals of infrared communication enabled traffic lights.

Also see: Zimdahl, W. (1984): *Guidelines and some Developments for a new Modular Driver Information System*. In Proceedings of the 34th IEEE Vehicular Technology Conference (VTC1984), pp.178-182. IEEE, Pittsburgh, PA, USA: IEEE, May 1984.

[496] Advanced driver-assistance systems, or ADAS, are systems to help the driver in the driving process. When designed with a safe human-machine interface, they should increase car safety and, more generally, the road safety. Most road accidents occurred due to the human error. Advanced driver-assistance systems are systems developed to automate,

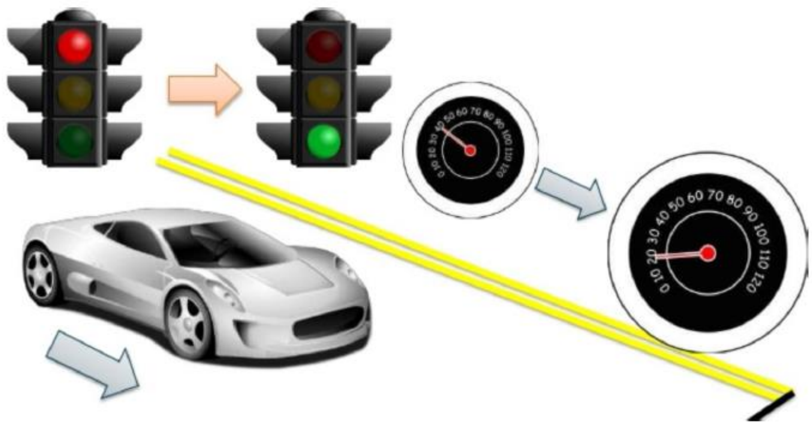

*Figure 40: Conceptual Approach of the GLOSA use case*

The GLOSA business model aims to provide *car drivers* an optimised driving experience through real-time optimised speed advice. A service provider offers a software application (or on-board unit) to car drivers, which can track their speed and location. Through integrating user and traffic data, the service provider can offer real-time advice with regards to the (expected) state of upcoming traffic lights, allowing *car drivers* to alter their speed accordingly. The business model is completed by a sponsor, which ensures the financial feasibility of the model, as well as a road operator and data provider, which take care of both streams of data.

One way to reduce excessive stop-and-go driving on urban streets is to optimize signal timings. Historically, signal timing optimisation tools were developed to reduce delays and stops experienced by urban drivers. More recently, new methods in traffic signal optimisation have incorporated changes in drivers' behaviour to achieve optimum performance at signalised intersections. Today, vehicles are equipped with a range of sensors, driver assistance and safety related systems. Safety and comfort have been further improved by adding cellular communication capabilities to millions of cars and this is growing rapidly. Many of the use cases described in the ETSI ITS specifications and other documents are already implemented using existing cellular network connections. For example, cellular networks already enable features like slow or stationary vehicles in traffic ahead warnings, road works warnings, weather conditions, hazard warnings, in-vehicle signage and speed-limits. Connected vehicles technology provides a two-way wireless communication environment enabling vehicle-to-vehicle and vehicle-to-infrastructure communications, which can be used for a variety of mobility and safety applications. One such application is called as the Green Light Optimised Speed Advisory (GLOSA)[497],[498]. This system uses timely and accurate information about traffic signal timing

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adapt and enhance vehicle systems for safety and better driving. The automated system which is provided by ADAS to the vehicle is proven to reduce road fatalities, by minimizing the human error. Safety features are designed to avoid collisions and accidents by offering technologies that alert the driver to potential problems, or to avoid collisions by implementing safeguards and taking over control of the vehicle. Adaptive features may automate lighting, provide adaptive cruise control and collision avoidance, pedestrian crash avoidance mitigation (PCAM), incorporate satnav/traffic warnings, connect to smartphones, alert driver to other cars or dangers, lane departure warning system, automatic lane centering, or show what is in blind spots.

Also see, *among others*: Shaout, A., Colella, D., and Awad, S. (2011): *Advanced driver assistance systems-past, present and future*. In Proceedings of the 7th International Computer Engineering Conference (ICENCO-2011), pp. 72-82, IEEE and;

Lu, M., Wevers, K., and Heidjen, Van der (2005): Technical feasibility for advanced driver assistant systems (ADAS) for road traffic safety. *Transportation Planning and Technology*, **28**(3), 167-187.

497 See, *for example*: Stevanovic, A., Stevanovic, J., and Kergaye, C. (2013): Green Light Optimized Speed Advisory Systems: Impact of Signal Phasing Information Accuracy. *Journal of the Transportation Research Board*, **2390**(1), 53-59.

and traffic signal locations to guide drivers (through infrastructure-to-vehicle communication) with speed advice for a more uniform commute with less stopping time through traffic signals[499]. A GLOSA implementation can potentially be evaluated for two types of traffic signal timing: predictable fixed-time signal timing and unpredictable actuated-coordinated signal timing[500]. GLOSA systems provide drivers with speed advices that allow them to pass traffic lights during green interval.

The objective of GLOSA systems is to provide to the driver the optimal speed to cross the next intersection with a green phase[501],[502]. The intersection needs to be equipped with a communication device and be interfaced with the intersection controller[503]. This way, the intersection sends data to the approaching vehicles such as the intersection topology, the location, the traffic lights current phases and their duration. The on-board system processes these data to calculate the optimal approaching speed of the vehicle to reach the intersection with a green light. GLOSA systems improve traffic efficiency by: (i) reducing stop times; (ii) bettering the fluidity of the traffic; (iii) giving anticipating data which improve the safety; and (iv) reducing $CO_2$ emissions, fuel consumption and reducing waiting time and travel time. This kind of system also helps the vehicles reaching the Green Wave if several traffic lights are coordinated, for example with wireless sensor networks. This ensures a continuous flow of vehicles. Moreover, this system can be useful for emergency vehicles to request a right of way if traffic lights are able to communicate.

In fact, GLOSA systems have been shown to be able to reduce both $CO_2$ emissions and fuel consumption[504] by giving drivers speed recommendations when approaching a traffic light[505]. For the system to reach its maximum potential, it is necessary to properly predict all different types of traffic lights, that is, also adaptive traffic lights where signals may change with lead times as short as 1 s[506].

GLOSA requires a definition of the intersection topology (including ingressing and egressing lanes' geographic coordinates) that is transmitted as a V2X I2V MAP message. This is used by receiving vehicles to compute the relevance of the received information with respect to their position. The dynamic information is disseminated using the Signal Phase and Timing (SPaT) V2X I2V message and

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498 Radivojevic, D., Stevanovic, J., and Stevanovic, A. (2016): Impact of green light optimized speed advisory on unsignalised side-street traffic. *Transportation Research Record: Journal of the Transportation Research Board*, **2557**, 24-32.

499 Katsaros, K., Kernchen, R., Dianati, M., and Rieck, D. (2011): *Performance study of a green light optimized speed advisory (GLOSA) application using an integrated cooperative ITS simulation platform*. In Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC), pp. 918-923. Istanbul, Turkey, July 04-08, 2011.

500 Relevant informative data can also be found at: Koonce, P. (2008): *Traffic signal timing manual*. US Department of Transportation, Tech. Rep. FHWA-HOP-08-024, 2008.

501 Lebre, M.A., Le Mouël, F., Ménard, E., Garnault, A., Bradaï, B., and Picron, V. (2015): *Real scenario and simulations on GLOSA traffic light system for reduced $CO_2$ emissions, waiting time and travel time*. In Proceedings of the 22nd ITS World Congress, pp.1-12. Bordeaux, France, October 05-09, 2015.

502 Wan, N., Luckow, A., and Vahidi, A. (2016). Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. *Transportation Research Part C: Emerging Technologies,* **69**, 548-563.

503 Eckhoff, D., Halmos, B., and German, R. (2013): *Potentials and Limitations of Green Light Optimal Speed Advisory Systems*. In Proceedings of the 5th IEEE Vehicular Networking Conference (VNC 2013), pp.103-110. IEEE, Boston, MA, USA, December 2013, pp. 103-110.

504 See: Tielert, T., Killat, M., Hartenstein, H., Luz, R., Hausberger, S., and Benz, T. (2010): *The Impact of Traffic-Light-to-Vehicle Communication on Fuel Consumption and Emissions*. In Proceedings of the Internet of Things 2010 Conference (IoT2010), pp. 1-8. Tokyo, Japan, November 29 – December 02, 2010.

505 Bradaï, B., Garnault, A., Picron, V., and Gougeon, P. (2014). *A green light optimal speed advisor for reduced $CO_2$ emissions*. Springer International Publishing.

506 Bodenheimer, R., Brauery, A., Eckhoffz, D., and German, R. (2014): *Enabling GLOSA for Adaptive Traffic Lights*. In Proceedings of the IEEE 2014 Vehicular Networking Conference (VNC), pp.167-174. IEEE.

contains the traffic lights' time to change and speed advice information that apply to group of ingressing lanes[507],[508].

There are a number of challenges in realizing GLOSA. Firstly, it requires standardised communication infrastructure (e.g. short range such as ETSI ITS-G5[509], cellular communication such as 5G[510] or a hybrid approach) and protocols (e.g. SPAT and MAP[511]). Secondly, there are challenges for the on-board functionality, such as: how to reliably handle possibly inaccurate predictions of time-to-green and time-to-red for dynamic traffic lights (that adapts to current traffic and pedestrians); how to predict the route to be able to plan optimal speed across multiple road segments; how safety and fellow road users are affected,

The GLOSA algorithm reduces the number of stops at traffic signals, decreases delay and fuel consumption, by recommending a speed advisory based on signal control information and the current position of the vehicle. GLOSA calculates such advisory speeds based on the distance between approaching vehicles and traffic signals, while taking into account the current state of traffic signals and whether a vehicle should stop or go through the next intersection. GLOSA also estimates the length of queues in front of signals by considering the positions and speeds of arriving vehicles, as well as discharging rates of the queues. Hence, GLOSA improves mobility and environmental performance of traffic on arterials by encouraging uninterrupted traffic flows. When determining advisory speeds, GLOSA uses the speed limit as an upper boundary while the lower limit is set arbitrarily (e.g. 5 km/h). GLOSA and similar methods have been evaluated in terms of mobility and energy efficiency in previous studies[512]. By its design, GLOSA is intended to reduce the number of stops and improve traffic flow progression on major streets. The impact of GLOSA on side-street traffic could have two major components – mobility (increased waiting time for side-street vehicles) and safety (shorter gaps may cause some riskier movements).

The GLOSA application provides the advantage of timely and accurate information about traffic lights cycles and traffic lights position information through infrastructure-to-vehicle (I2V) communication, and provides drivers with speed advice guiding them with a more constant speed and with less stopping time through traffic lights[513],[514]. The main challenges in achieving this include the modelling of the vehicle traffic, the communications between traffic lights and vehicles and finally the driver's behavior. Individual research has been performed for each one of these areas, but complete simulations by taking into account the dynamics of all parameters are scarce.

The main goal of the GLOSA service is to predict the green phases of the traffic lights as well as to provide the drivers the information, if they can pass the traffic light within the present green phase.

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507 MAVEN Project (02/2018): Deliverable D5.1: *"V2X communications for infrastructure-assisted automated driving"*.

508 MAVEN Project (01/2018): Deliverable 4.1: *"Cooperative adaptive traffic light with automated vehicles (Initial version)*".

509 European Telecommunications Standards Institute (ETSI): EN 302 663 V1.2.1 (2013-05): *"Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band"*.

510 See, *for example*: [https://www.etsi.org/technologies/5g](https://www.etsi.org/technologies/5g).

511 Society of Automotive Engineers (SAE) (03/2016): *SAE J2735_201603, Dedicated Short Range Communications (DSRC) Message Set Dictionary*.

512 Suramardhana, T.A., and Jeong, H.Y. (2014): *A driver-centric green light optimal speed advisory (DC-GLOSA) for improving road traffic congestion at urban intersections*. In Proceedings of the2014 IEEE Asia Pacific Wireless and Mobile Conference, pp.304-309. IEEE, Bali, Indonesia, August 28-30, 2014.

513 Chao-Qun, M., Hai-Jun, H., and Tie-Qia, T. (2008): *Improving urban traffic by velocity guidance*. In Proceedings of the International Conference on Intelligent Computation and Automation (ICICTA-2008), vol.2, pp.383-387. Hunan, China, October 20-22, 2008.

514 Wan, N., Luckow, A., and Vahidi, A. (2016): Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. *Transportation Research Part C: Emerging Technologies*, **69**, 548-563.

 

The two main applications are the Green-Wave Assistant and the Deceleration Assistant[515]. The Green-Wave-Assistant shows information enabling to reach the green phase at the next signal-controlled junction; thus, unnecessary stopping and acceleration procedures can be prevented. The Deceleration Assistant works so that the driver will be informed that he cannot reach the green phase at the next signal-controlled junction. He can roll out the vehicle to prevent unnecessary brake and acceleration procedures. With help of these two applications, the driver can adapt his driving behavior according to the information and thereby the efficiency and driving comfort can be increased.

GLOSA yields substantial better utilisation of infrastructure capacity and it can reduce vehicles' delay and emissions; consequently, it implicates for significantly influence the quality of life, which is a major goal of smart city initiatives[516],[517]. Related works[518] have demonstrated that full market penetration of connected conventional vehicles managed by the GLOSA technique results in achieving waiting time reduction of 66%, compared to having conventional vehicles without GLOSA connectivity.

### 4.3.2 Definition and Implementation Status

GLOSA is a Day-1 signage C-ITS service aimed at informing end users about the speed that needs to be sustained (within legal limits) to reach an upcoming traffic light in green status. The drivers approaching the traffic lights are provided with a speed advice and information about the phases, based on which they can accelerate to cross the intersection or decelerate to wait less for the upcoming green. This use case leads to a reduced number of stops at the red light and a faster restart when the light turns green. The level of congestion at the intersections chosen should be low or medium, to not hinder GLOSA's functions and resulting impacts. The aim of implementing GLOSA is to avoid the stop-and-go traffic and to increase the throughput.

Although specific UI features are manufacturer-specific, end-user GLOSA notifications usually follow the structure below:

- *"The upcoming traffic light will switch status in 20 seconds (countdown)".*
- *"Keep speed at 35 km/h to reach the upcoming traffic light in green status".*
- *"As per applicable legal speed limits in this area, you will reach the upcoming traffic light in red status".*

GLOSA provides end-users with short-term information on upcoming traffic light status to optimise traffic flows, helps prevent speed limits violations, improves fuel efficiency and reduces pollution[519]. It requires a definition of the intersection topology (including ingressing and egressing lanes' geographic coordinates) that is transmitted as a V2X I2V MAP message. This is used by receiving vehicles to compute the relevance of the received information with respect to their position.

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515 In the C-Roads Platform, there are two ways to get the GLOSA service into the vehicles, that is: (i) via ETSI G5 directly into the on-board computer of the vehicle, *and* (ii) via mobile network into a smartphone application.

516 Pereira, A.M., Anany, H., Přibyl, O., and Přikryl, J. (2017): *Automated vehicles in smart urban environment: A review*. In Proceedings of the 2017 Smart City Symposium Prague (SCSP), pp.1-8. Prague, Czech Republic, 2017.

517 Anany, H. (2019): *Effectiveness of a speed advisory traffic signal system for Conventional and Automated vehicles in a smart city - PhD Thesis*. Department of Science and Technology, Linköping University, Sweden. Available at: *http://www.diva-portal.org/smash/get/diva2:1315167/FULLTEXT01.pdf*

518 Ibid.

519 Asadi, B., and Vahidi, A., (2010): Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time, *IEEE Transactions on Control Systems Technology*, **19**(3), 707-714.

In order to evaluate the related use case, the following parameters/data can be collected: (i) Speed of the vehicle; (ii) acceleration/deceleration of the vehicle; (iii) braking power, moment of braking; (iv) time between the reception of the C-ITS message and the arrival at the intersection; (v) position; (vi) C-ITS message data log (content, timing and position of the reception, etc.), (vii) vehicle ITS station and HMI data log; and (viii) fuel consumption.

Such data may help in order to assess how safety, traffic efficiency and the environment are affected by the specific C-ITS service serving the GLOSA use case. In addition, this can provide feedback for response to several questions dealing with: (i) the instant -or not- change of speed immediately after message reception; (ii) compliance of driver's speed with the suggested speed; (iii) driver's time response after the traffic light turn to green; and (v) the way how the instant speed fluctuations change.

According to the received information from existing reports, the driver can accelerate to reach the crossing before the red light or decelerate to wait less for the green. The abruptness of the manoeuvre can perturb the upstream traffic flow. Higher compliance with speed suggestions leads to less vehicles waiting to cross the intersection, reducing the number of acceleration and deceleration, queue's length and improving the crossing efficiency. Furthermore, knowing when the light is becoming green leads to faster restart of the vehicles and quicker acceleration, impacting the traffic flow across the intersection.

Based on prior approaches[520], the following Key Performance Indicators of the field tests can potentially be calculated: (i) Speed adaptation (difference between the average speed of the vehicle and the speed limit) - from the reception of the C-ITS message until the stop line; (ii) speed standard deviation; (iii) speed adaptation (difference between the average speed of the vehicle and the speed limit) - from the reception of the C-ITS message until the position of traffic light; (iv) instantaneous accelerations and decelerations; (v) percentage of test vehicles able to cross the intersection without stopping (with and without GLOSA) and this evaluation can take advantages if combined with data describing congestion at traffic lights (magnetic loops or other sensors); (vi) time between the instant when the light turns green and the departure of the test vehicle (if it is the leading vehicle, that is the first vehicle stopped at the traffic light) and this evaluation can take advantages if combined with traffic lights stop line position to know the first vehicle in lane; (vii) travel time/delay (for intersection crossing time); (viii) travel time / average speed - from the reception of the C-ITS message until the position of traffic light; (ix) fuel consumption; and (x) noise.

In a GLOSA use case, an RSU co-located with a traffic light (and having access to its internal finite state machine), broadcasts timing information about the traffic light's "red", "amber" and "green" status via Signal Phase and Timing messages (SPAT). Neighbouring vehicles can receive these messages and process them locally along with their own positioning, speed and direction data (amongst others). By doing so, on-board V2X modules can notify drivers about the optimal speed to reach an upcoming traffic light in green status or, alternatively, to be aware that the traffic light will nevertheless transition to red imminently. The dynamic information is disseminated using the Signal Phase and Timing (SPaT) V2X I2V message and contains the traffic lights' time to change and speed advice information that apply to group of ingressing lanes. The MAP and SPaT messages are already standardised[521] and profiled[522]. However, the interpretation of their content at the receiving side (cooperative vehicles), and the relation between this content and the actual current status of the

520 C-Roads Platform (06/2019): *Evaluation and Assessment Plan. Working Group 3 - Evaluation and Assessment. V1.1*. Available online at: https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/C-Roads_WG3_Evaluation_and_Assessment_Plan_version_June19_adopted_by_Countries_Final.pdf

521 Society of Automotive Engineers (SAE) (03/2016): *SAE J2735_201603, Dedicated Short Range Communications (DSRC) Message Set Dictionary*. Available at: https://www.sae.org/standards/content/j2735_201603/

522 Talking Traffic consortium, Dutch profiles and ITF (2019): *Smart Mobility Community for Standards and Practices*. Available at: http://www.smartmobilitycommunity.eu/talking-traffic-dutch-profiles-and-itf.

 

traffic light controller can still lead to confusion. Knowing how to interpret the SPaT content at the receiving side is particularly critical in the case of Connected Automated Vehicles[523],[524] (CAVs). In fact, the automated behavior of CAVs when approaching a Cooperative Intersection[525] (CI) will strongly depend on the information communicated in this message. Based on the correct interpretation of the SPaT content, and together with other environmental information achieved via on board sensors, CAVs will decide whether adapting the speed to the suggested one or prepare for stopping.

For the 5G-DRIVE project, GLOSA is an attractive V2X use case to improve the traffic flow in the urban area. It provides drivers an optimal speed advice when they approach to a signalised intersection. The advice, which is normally shown on the dashboard of the car, instructs the driver to maintain actual speed, slow down, or adapt a specific speed. GLOSA may also provide time-to-green information when the vehicle is stopped in the stop bar. Application of GLOSA takes advantage of real-time traffic sensing and infrastructure information, which can then be communicated to a vehicle aiming to reduce fuel consumption and emissions.

The GLOSA-related demo can be as illustrated in Figure 41. The detailed framework for the GLOSA test plan and the performance test procedures have been presented in detail in the context of the previously submitted 5G-DRIVE Deliverable D4.3[526]. This document has also identified and described the related hardware and software tools.

[523] A Cooperative Automated Vehicle (CAV) is assumed to be an ETSI ITS G5 (ETSI EN 302 663) equipped vehicle with automated driving capabilities. In this sense, it is an improved version of a cooperative vehicle. It uses vehicle sensors and V2X receptions to monitor the surroundings of the vehicle, and V2X communications to interact with other cooperative vehicles, CAVs and with CIs. It uses the acquired flow of information for trajectory and maneuver planning, platoon organisation and implementation of improved ADAS functions. A CAV can be any type of vehicle, for example a car, bus or truck and any vehicle class, for example a regular passenger vehicle, priority vehicle or emergency vehicle. Multiple CAVs may form a platoon and assume one out of two roles: platoon leader or follower. The platoon leader interacts with the environment on behalf of the platoon, whereas the followers primarily interact with the platoon leader.

[524] Englund, C., Chen, L., Ploeg, J., et *al.*, (08/2016): The grand cooperative driving challenge 2016: Boosting the introduction of cooperative automated vehicles. *IEEE Wireless Communications*, **23**(4), 146-152.

[525] A Cooperative Intersection (CI) is assumed to be an ETSI ITS G5 equipped traffic light controller at a signalised intersection. Besides infrastructure sensors such as inductive loops and cameras to detect any type of road user, it uses V2I communication to exchange data with cooperative vehicles and CAVs. The CI uses the flow of information for the adaptive optimisation of the timing of traffic lights while taking into account policy parameters (including priorities) and traffic demand (including vulnerable road users). In addition, it uses V2I communication to interact with cooperative vehicles, for example to provide advisory information like speed advice and lane advice. Multiple CIs may be connected to enable traffic light coordination along a specific traffic corridor.

[526] 5G-DRIVE Project: Deliverable D4.3 (10/2019): *"Report on Potential Vulnerabilities of V2X Communications"*. Available at: *https://5g-drive.eu/resources-and-results/project-deliverables/*


*Figure 41: An LTE-V2X GLOSA demonstration by China Mobile, Huawei and ASTRI (EU-China Joint Kick-Off, Wuxi (China), November 2018)*

**Relevant KPIs for this use case:**

Since the project aims to compare and benchmark the 5G benefits between Europe and China, the common test scenarios are planned so they can be realised both in China and the European trial sites. The common KPIs are defined to measure the same things and compare the results. The Chinese KPIs are more exhaustive since the focus is more in network optimisation whereas 5G-DRIVE is application driven.

Due to the small volume of information being transmitted in GLOSA (essentially, traffic light state machine timing data), KPIs such as peak/user-perceived data rate are not a major concern in this particular use case. Instead, the most relevant service-level performance indicators for GLOSA are:

- **Packet Error Rate (PER)**: ratio of unsuccessfully received packets in the OBU *vs.* total number of packets sent by the RSU (in percentage).
- **Latency:** the radio access network contribution to the total elapsed time, measured from the instant the RSU sends a packet to the moment when the OBU receives it (in ms).

Within the scope of the respective 5G-DRIVE Deliverable D4.2[527] ("Joint specifications for V2X trials") a more detailed analysis has taken place for the selected KPIs, also following to the progress of corresponding trials.

According to the scope discussed in the 5G-DRIVE Deliverable D4.3 ("Report on Potential Vulnerabilities of V2X Communications"), the aim is to realize a performance test and, therefore, there are no pass/fail success criteria. The goal of the test is to evaluate the resilience of ITS-G5 and LTE-V2X units against external harmful interference. To evaluate this, a non-corrupted [.pcap] file must successfully be retrieved from the victim OBU's internal storage after each test run.

From this packet capture, the following KPIs are evaluated:

- Channel Busy Ratio[528] (CBR)

[527] 5G-DRIVE Project: Deliverable D4.2 (08/2019): *"Joint Specifications for V2X Trials"*. Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

- Duty cycle[529]
- Packet Error Rate (PER)
- Co-channel and adjacent-channel interference[530],[531] level (in dBm).

For the purpose of conducting the GLOSA trial, the JRC has deployed a commercial C-ITS roadside unit covering a section of its internal road infrastructure. The RSU sits at the junction of two suburban-type roads of 420 m and 220 m, respectively, at a height of approximately 10 m. In addition, the RSU is connected to the internal JRC network infrastructure to allow remote configuration, management and traffic monitoring. The commercial RSU runs an Automotive Grade Linux operating system, thus allowing the execution of custom user space applications (such as a virtual traffic light for the GLOSA service). This setup is described in Figure 42 and Figure 43.

[528] CBR (Channel Busy Ratio) or CBT (Channel Busy Time) is defined as ratio between the time the channel is sensed as busy and the total observation time (e.g., 100 ms). It is a measure for the channel load perceived by a vehicle, and depends on the number of vehicles in its transmission range and their individual message generation rates. Many congestion control algorithms, such as periodically updated load sensitive adaptive rate control (PULSAR), random transmit power control (RTPC), distributed fair transmit power adjustment (D-FPAV), distributed network utility maximisation (D-NUM), packet-count based decentralised data-rate congestion control algorithm (PDR-DCC) use CBR/CBT as one of the metrics to analyze the communication benefit of the algorithms. CBR has been shown to be a suitable metric to increase packet delivery performance. For analytical research about CBR, see the following paper that give a mathematical model in terms of CBR for channel load at a single position, load contribution from a single transmitter and channel load distribution on road respectively: Chen, Q., Jiang, D., Tielert, T., and Delgrossi, L. (2011): *Mathematical modeling of channel load in vehicle safety communications*. In Proceedings of the 2011 IEEE Vehicular Technology Conference (VTC Fall), pp.1-5. San Francisco, CA, USA, September 05-08, 2011, IEEE.

[529] Duty cycle is the cycle of operation of a machine or other device which operates intermittently rather than continuously. It corresponds to the time occupied by the cycle of operation of a machine or other device, especially as a percentage of available time. Sometimes it is called as duty factor.

[530] Co-channel interference or CCI is crosstalk from two different radio transmitters using the same channel. Co-channel interference can be caused by many factors from weather conditions to administrative and design issues. Co-channel interference may be controlled by various radio resource management schemes. For more informative details also see, *among others*: https://en.wikipedia.org/wiki/Co-channel_interference

[531] Adjacent-channel interference (ACI) is interference caused by extraneous power from a signal in an adjacent channel. ACI may be caused by inadequate filtering (such as incomplete filtering of unwanted modulation products in FM systems), improper tuning or poor frequency control (in the reference channel, the interfering channel or both). For more informative data also see, *among others*: https://en.wikipedia.org/wiki/Adjacent-channel_interference

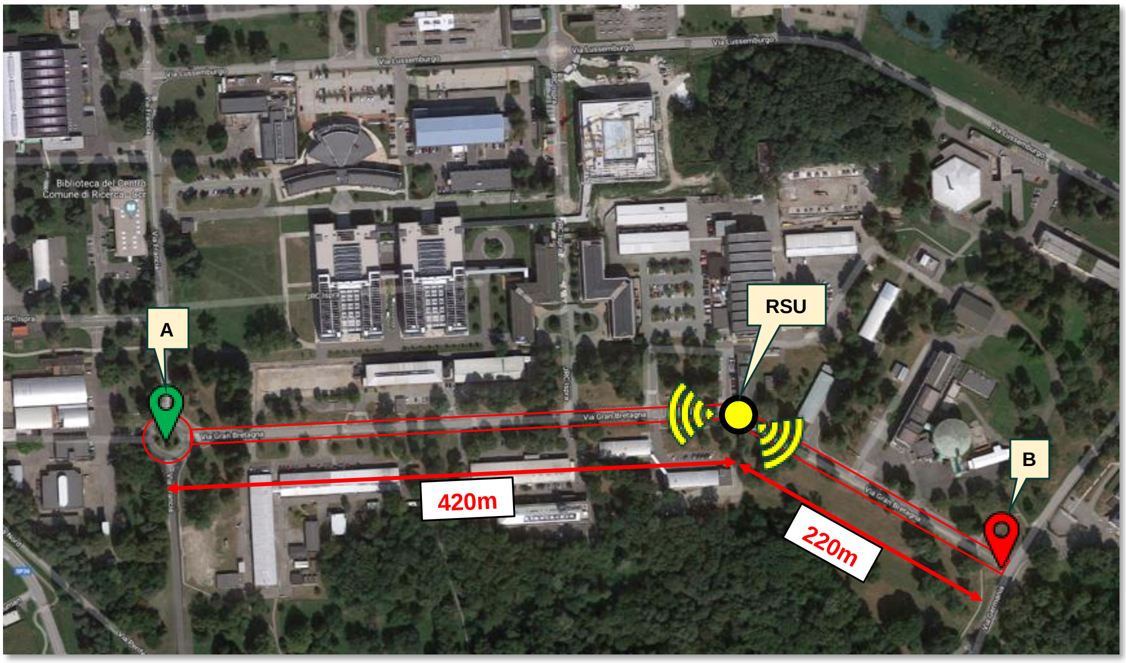


*Figure 42: Location of the RSU providing the GLOSA service at the JRC Ispra campus*

*Figure 43: ITS-G5 RSU deployed in the JRC Ispra campus*

The GLOSA setup described above is to be extended by deploying an LTE-V2X unit co-located with the ITS-G5 RSU. The LTE-V2X unit is also connected to the JRC internal network for remote configuration, management and traffic monitoring purposes.

In the context of the GLOSA trial, both technologies are tested in a mutually-exclusive fashion to avoid harmful interference between them.

This road C-ITS infrastructure is complemented by two OBUs (one ITS-G5, one LTE-V2X) co-located in a test vehicle to conduct the GLOSA trials. These OBUs are connected to a laptop for experiment configuration and traffic monitoring purposes.

## 4.4 Use Case 2: Intelligent Intersection

### 4.4.1 Conceptual Description

Intersections are hazardous places. The intersection plays an important role in the traffic network, which is also one of the main causes of traffic accidents. Based on the statistical data, about 40% of the crashes that occurred in the United States in 2008 were intersection-related[532],[533]. Crashes near intersections might also lead to serious traffic jams on multiple roads, which apparently waste time and money of drivers and also cause unnecessary air pollution. It is also reported that about 96% of the intersection-related crashes had critical reasons attributed to drivers, such as inadequate surveillance, false assumption of other's action, and turned with obstructed view.

Threats arise from interactions among pedestrians, bicycles and vehicles, more complicated vehicle trajectories in the absence of lane markings, phases that prevent knowing who has the right of way, invisible vehicle approaches, vehicle obstructions, and illegal movements. These challenges are not fully addressed by the "road diet" and road redesign prescribed in "Vision Zero"[534] plans. Nor will they be completely overcome by autonomous vehicles[535] with their many on-board sensors and tireless attention to sensor readings[536]. Accidents can also occur because drivers, bicyclists and pedestrians do not have the information they need to avoid wrong decisions[537],[538]. In these cases, the

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[532] Choi, E. (09/2010): *Crash factors in intersection-related crashes: An on-scene perspective. NHTSA Technical Report. Report no. DOTHS811366*.

[533] Also see, *for example*: *Vehicle safety and fuel economy rulemaking and research priority plan 2011-2013*, Washington, DC, USA, Mar. 2011. Available at: *https://www.federalregister.gov/articles/2011/03/31/2011-7433/finalvehicle-safety-rulemaking-and-research-priority-plan-2011-2013*

[534] "Vision Zero" (VZ) is a multi-national road traffic safety project that aims to achieve a highway system with no fatalities or serious injuries involving road traffic. It started in Sweden in October 1997. A core principle of the vision is that "Life and health can never be exchanged for other benefits within the society" rather than the more conventional comparison between costs and benefits, where a monetary value is placed on life and health, and then that value is used to decide how much money to spend on a road network towards the benefit of decreasing how much risk. Vision Zero has been variously adopted in different countries or smaller jurisdictions, although its description varies significantly. For more details also see, *for example*: *https://en.wikipedia.org/wiki/Vision_Zero*

VZ plans seek to lower the accident rate through physical redesign of intersections to protect cyclists by separating them from vehicles making turns, by pedestrian-friendly signal timing such as leading pedestrian intervals, by reducing the number of lanes, and lower speed limits for vehicles.

[535] Data from several studies prove that human error plays a crucial role in traffic congestion and accidents. Recent studies indicate that driver error contributes to up to 75% of all roadway crashes (See, *for example*: Stanton, N.A., and Salmon, P.M. (2009): Human error taxonomies applied to driving: A generic driver error taxonomy and its implications for intelligent transport systems. *Safety Science*, **47**(2), 227-237.) However, developments in computer science, sensing technology, artificial intelligence (AI), and communication technology have highlighted the possibility of introducing autonomous vehicles (AVs). The major concepts that must be improved by the development of AVs, namely sensing environments, data collection and analysis, planning, decision making, and vehicle control, have the potential to solve current problems with traffic management systems.

[536] Some interesting concerns of broader applicability have been discussed in: Chen, L., and Englund, C. (02/2016): Cooperative intersection management: A survey. *IEEE Transactions on Intelligent Transportation Systems*, **17**(2), 570-586.

[537] For more information see, *inter-alia*: Ahn, H., and Del Vecchio, D. (2018): Safety verification and control for collision avoidance at road intersections. *IEEE Transactions on Automatic Control Systems*, **63**(3), 630-642.

[538] Ahn, H., Rizzi, A., Colombo, A., and Del Vecchio, D. (2015): *Experimental testing of a semi-autonomous multi-vehicle collision avoidance algorithm at an intersection testbed*. In Proceedings of the IEEE/RSJ International conference on Intelligent Robots Systems (IROS), pp. 4834-4839. IEEE, September 28 – October 02, 2015.

 

missing information can be calculated and communicated by an intelligent intersection[539,540] so that to enhance security[541]. The information gives the current full signal phase, an estimate of the time when the phase will change, the occupancy of the blind spots of the driver or autonomous vehicle, and detection of red-light violators. Intersection management is one of the most challenging problems within the transport system for keeping traffic safety[542] and smoothing traffic flow. Although intersections take a relatively small part of the entire road system, it accounts for a significant part of traffic accidents. In the near future, intersections will have the ability to control signal phase and autonomous speed vehicle approaching the intersection.

Intersections are common bottlenecks in roadway systems and applying intelligent systems for controlling traffic congestion in urban roadways has been inevitable[543]. Traffic control makes the current roadway system operate more efficiently without building new roads or widening the existing ones, which is often impossible due to scarce land availability. Examples of intelligent management systems include machine learning methods, fuzzy systems, and multi agents, as well as enhancing vehicle-to- infrastructure connectivity as in GLOSA systems.

Intersection management is one of the most challenging problems within the transport system[544,545]. Traffic light-based methods have been efficient but are not able to deal with the growing mobility and social challenges. On the other hand, the advancements of automation and communications have enabled cooperative intersection management[546], where road users, infrastructure, and traffic control centres are able to communicate and coordinate the traffic safely and efficiently[547]. Major techniques and solutions for cooperative intersections have been proposed for both signalised and non-signalised intersections[548]. In this scope, several cooperative methods, including time slots and space reservation, trajectory planning, and virtual traffic lights have also been proposed[549,550].

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539 Grembek, O., Kurzhanskiy, A., Medury, A., Varaiya, P., and Yu, M. (03/2018): An Intelligent Intersection, *Computer Science*. Available at: https://www.semanticscholar.org/paper/An-Intelligent-Intersection-Grembek-Kurzhanskiy/c25c7bcef969ec9101a147f50377fc91b1fe803e

540 Guler, S.I., Menendez, M., and Meier, L. (2014): Using connected vehicle technology to improve the efficiency of intersections. *Transportation Research Part C: Emerging Technologies*, **46**, 121-131.

541 Kurzhanskiy, A., and Varaiya, P. (2019): *Safety and Sustainability with Intelligent Intersections*. University of California, Berkeley, US. Available at: https://www.sacog.org/sites/main/files/file-attachments/item_2_a__b_1.pdf

542 Kowshik, H., Caveney, D. and Kumar, P. (2011): Provable system wide safety in intelligent intersections. *IEEE Transactions on Vehicular Technology*, **60**(3), 804-818.

543 Koonce, P. (2008). *Traffic signal timing manual. U.S. Department of Transportation, Tech. Rep. FHWAHOP-08-024*. Available at: http://www.signaltiming.com/The_Signal_Timing_Manual_08082008.pdf

544 Chen, L., and Englund, C. (2016): Cooperative intersection management: A survey. *IEEE Transactions on Intelligent Transportation Systems*, **17**(2), 570-586.

545 Rios-Torres, J., and Malikopoulos, A.A. (2016): A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps. *IEEE Transactions on Intelligent Transportation Systems,* **18**(5), 1066-1077.

546 Chouhan, A.P., and Banda, G. (2018): Autonomous intersection management: A heuristic approach. *IEEE Access*, **6**, 53287-53295.

547 Hausknecht, M., Chiu Au, T., and Stone, P. (2011). *Autonomous intersection management: multi intersection optimization*. In Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.4581-4586. IEEE, San Francisco, CA, September 25-30, 2011.

548 Namazi, F., Li., J., and Lu, C. (2019): Intelligent Intersection Management Systems Considering Autonomous Vehicles: A Systematic Literature Review. *IEEE Access*, **7**, 91946-91965.

549 See, *for example*: Clement, S.J., Taylor, M.A., and Yue, W.L. (2004): Simple platoon advancement: a model of automated vehicle movement at signalised intersections. *Transportation Research Part C: Emerging Technologies*, **12**(3), 293-320.

550 Parent, M. (2013). *Automated Vehicles: Autonomous or Connected?* In Proceedings of the 2013 IEEE 14th International Conference on Mobile Data Management, pp.2-2. IEEE Computer Society, Milan, Italy, June 03-06, 2013.

An intersection could be signalised -or un-signalised- and regulated by V2V and V2I communication. In the scope of the existing international literature, several works have investigated different aspects of AVs, such as adaptive cruise control (ACC) systems[551], cooperative adaptive cruise control (CACC) systems[552], decision-making and control approaches[553], the impact of AVs on traffic[554], techniques related to AV localisation[555], communication between AVs and road users[556], and vehicular communication for controlling the traffic[557].

It is critical to collect performance measures at an intersection to determine how well that intersection operates and serves the public[558]. Reviewing and updating the intersection-specific timing and operational aspects of individual signalised intersections on a regular basis is extremely important, especially where changes in traffic volumes and/or adjacent land uses have occurred.

Unlike streets with well-defined lane dividers, intersections do not have markers in the pavement that separate users and movements. The paths of vehicles, bicyclists and pedestrians cross each other within intersections, creating "conflict zones" and the potential for crashes. So, avoidance of crashes[559] requires the movements of different agents to be separated in time or space. Collisions between two vehicles can be prevented by controlling the longitudinal velocity and displacement of each vehicle along its path, never controlling vehicle steering[560],[561]. We can assume that each vehicle is equipped with sensors for state measurement (absolute position, heading, velocity, acceleration, brake torque, and pedal position), V2V communication and the ability to automatically actuate the throttle and brake. We can also assume that a related collision avoidance system is active well before the vehicles approach the intersection, preventing initial vehicle configurations generating unavoidable collision[562],[563]. It is impossible to fully achieve this separation and so the risk of

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551 Xiao, L., and Gao, F. (201): A comprehensive review of the development of adaptive cruise control systems. *Vehicle Systems Dynamics*, **48**(10), 1167-1192.

552 Dey, K.C., Yan, L., Wang, X., Wang, Y., Shen, H., Chowdhury, M., Yu, L., Qiu, C., and Soundararaj, V. (2016): A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (CACC). *IEEE Transactions on Intelligent Transportation systems,* **17**(2), 491-509.

553 Veres, S.M., Molnar, L., Lincoln, N.K., and Morice, C.P. (2011): Autonomous vehicle control systems—a review of decision making. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, **225**(2), 155-195.

554 Hounsell, N., Shrestha, B., Piao, J., and McDonald, M. (2009): Review of urban traffic management and the impacts of new vehicle technologies, *IET Intelligent Transport Systems,* **3**(4), 419-428.

555 Kuutti, S., Fallah, S., Katsaros, k. Dianati, M., McCullough, F., and Mouzakitis, A. (2018): A survey of the state-of-the-art localization techniques and their potentials for autonomous vehicle applications. *IEEE IoT Journal*, **5**(2), 82-846.

556 Onishi, H. (2018*): A survey: Why and how automated vehicles should communicate to other road-users*. In Proceedings of the 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), pp. 1-6. IEEE.

557 Li, L., Wen, D., and Yao, D. (2013): A survey of traffic control with vehicular communications. *IEEE Transactions on Intelligent Transportation Systems*, **15**(1), 425-432.

558 Muralidharan, A., Coogan, S., Flores, C., and Varaiya, P. (2016): Management of intersections with multi-modal high-resolution data. *Transportation Research, Part C*, **68**, 101-112.

559 Hafner, M. Cunningham, D., Caminiti, L., and Del Vecchio, D. (2013): Cooperative collision avoidance at intersections: Algorithms and experiments. IEEE Transactions on Intelligent Transportation Systems, **14**(3), 1162-1175.

560 Colombo, A., and Del Vecchio, D. (2012): *Efficient algorithms for collision avoidance at intersections*. In Proceedings of the 15th ACM International Conference on Hybrid Systems: Computation and Control, pp.145-154, April 2012.

561 European Telecommunications Standards Institute: TS 101 539-2 V1.1.1 (2018-06): *"Intelligent Transport Systems (ITS); V2X Applications; Part 2: Intersection Collision Risk Warning (ICRW); Application Requirements Specification"*. Available at: *https://www.etsi.org/deliver/etsi_ts/101500_101599/10153902/01.01.01_60/ts_10153902v010101p.pdf*

562 Azimi, S., Bhatia, G., Rajkumar, R., and Mudalige, P. (2011): Vehicular networks for collision avoidance at intersections. *SAE International Journal of Passenger Cars-Mechanical Systems*, **4**(1), 406-416.

563 Azimi, R., Bhatia, G., Rajkumar, R., and Mudalige, P. (04/2012): *Intersection management using vehicular networks. SAE Tech. Papers 2012-01-0292*.

 

intersection crashes remains. Traffic signal control provides limited separation because it does not simultaneously give the right-of-way (green light) to two conflicting movements. Although critical to safety, its effectiveness is often compromised. A driver (or autonomous vehicle) planning a certain movement (say a left turn) can see from the signal light whether his/her own planned left turn is permitted, but he/she may be unable to figure out whether another conflicting movement (say a through movement or a right turn by another vehicle or bicycle, or a pedestrian crossing) is also permitted; that is, the signal light visible to the driver does not provide the complete phase information. Similarly, a pedestrian or bicyclist undertaking a movement may be unaware of a permitted conflicting vehicle movement. This spatial uncertainty about rights-of-way is eliminated by an intelligent intersection that provides the complete phase information. Furthermore, road users do not rely solely on their current view of the traffic signal. They also (implicitly) predict how the signal will change in the next few seconds. An accurate prediction of the duration of the current phase and the upcoming phase can be supplied by the intersection, thus reducing temporal uncertainty about rights-of-way. This information can be provided by processing signal phase data accumulated at the intersection. Intersections present a challenging environment both to urban road users and to AV designers. An intelligent intersection can broadcast two crucial information messages. A SPAT (Signal Phase and Timing) I2V message[564] that the SAE[565] has standardised, gives the full signal phase (not just the partial view of the signal that a user or AV has) and an estimate of the time when the signal phase will change. Together with what road users and AV sensors can see, SPaT eliminates most possible conflicts. Intelligent intersections would broadcast SPAT messages[566]. The second message informs an AV[567] what its blind spots are and which of them (if any) is occupied by another user. Computation of the SPaT message requires real time access to the intersection phase. Calculation of blind spot occupancy requires real time sensing of well-defined regions of the intersection. These two messages can resolve all conflicts within the intersection.

Even when the driver (bicyclist or pedestrian or an autonomous vehicle) knows the complete phase, his/her knowledge of the intersection state will be limited by the extent to which his/her view of the intersection is obscured by other users. If the driver cannot fully see a conflict zone, he/she must guess whether there is a hidden user undertaking a movement in the conflict zone. This dilemma can lead either to slow driving that is overly cautious (when there is no hidden user), or to driving optimistically at a normal speed with greater risk of a crash (because there is a hidden user). The intelligent intersection can process sensor measurements to determine the presence or absence of a hidden user and communicate that to the driver, thereby eliminating the risk of an overly pessimistic or optimistic assessment[568]. Lastly, even when no conflicting movement is present, a crash may occur

[564] A SPaT (Signal Phase and Timing) message describes for each lane the current phase at a signalised intersection together with an estimate of the residual time of that phase. Accurate SPaT messages can be used to construct a speed profile for a vehicle that reduces its fuel consumption as it approaches or leaves an intersection.

Also see: National Operations Center of Excellence (2016): Implementation Guide: SPAT Challenge. Available at: https://www.transportationops.org/spatchallenge/resources/Implementation-Guide

[565] SAE (Society of Automotive Engineers) is a non-profit educational and scientific organisation dedicated to advancing mobility technology to better serve humanity. Over 90,000 engineers and scientists, who are SAE members, develop technical information on all forms of self-propelled vehicles including automobiles, trucks and buses, off-highway equipment, aircraft, aerospace vehicles, marine, rail, and transit systems. SAE disseminates this information through its meetings, books, technical papers, magazines, standards, reports, professional development programs, and electronic databases. For more details also see: https://www.standardsportal.org/usa_en/sdo/sae.aspx

[566] Ibrahim, S., Kalathil, D., Sanchez, R.O., and Varaiya, P. (2017): *Estimating phase duration for SPaT messages*. Cornell University, US. Available at: https://arxiv.org/pdf/1710.05394v2.pdf.

[567] Rios-Torres, J., and Malikopoulos, A.A. (2016): A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps. *IEEE Transactions on Intelligent Transportation Systems*, **18**(5), 1066-1077.

[568] Medury, A., Yu, M., Grembek, O., Kurzhanskiy, A.A., Flores, C., and Varaiya, P. (2017): The disengagement dilemma of automated vehicles. In Proceedings of the ITS World Congress 2017, pp.1-18. Montreal, Canada, October 29 - November 02, 2017.

from the illegal movement of another car, bicycle or pedestrian. A common example is a car or bicycle running a red light or a pedestrian crossing against a "don't walk" signal. If appropriate sensor measurements (similar to that collected by a red-light camera system) can be acquired and processed rapidly, the driver at risk could be warned to take evasive action.

In summary, the acquisition and processing[569] of appropriate sensor data at an intelligent intersection can generate I2V messages that give complete phase information, predict the signal phase and timing in the next cycle, accurately assess the occupancy of blind zones, and warn of the danger from traffic signal violators.

Extended sensors refer to the ability of vehicles to obtain information about objects around them located beyond the view of their own on-board sensors[570] Other nearby vehicles that can detect these objects process them, then broadcast them out to aid other vehicles around in building up a more complete picture of the road world. Overall, this provides vehicles in an area a more complete picture of the traffic environment. Current work on this aspect is taking place in ETSI ITS and 5GAA. Sensors enable the sharing of raw and processed sensor data (for example, cameras, radar, Lidar) among vehicles, RSUs, pedestrians and V2X application servers. The sensor data that a vehicle can share ranges from a photo of a perceived object to its real-time video stream. The availability of sensor data from multiple disparate sources enhances situation awareness of the vehicles and pedestrians, and thus improves road safety. Extended sensors also enable new features and capabilities such as cooperative driving[571] and precise positioning, which is necessary for autonomous driving[572]. Autonomous cars use a combination of technologies to detect their surroundings including wireless communication technologies, laser and radar sensing, GPS, odometers, computer vision, and advanced control systems. All this data is analysed, processed with artificial intelligence and deep learning computer systems to distinguish between different cars on the road and identify appropriate navigation paths given obstacles and considering the rules of the road. The 5G technologies enable these cooperative automatic driving use cases in an enhanced fashion, where sensor information will be exchanged in real time between thousands of cars connected in the same area. Thus, the 5G features are expected to provide communications with increased coverage, reliability and performance levels with higher orders of magnitude compared to existing technologies today.

Active monitoring of intersections provides the driver and/or intelligent vehicle system a very important time advantage to take action, even before a problem would have otherwise become visible[573]. This means the technology potentially allows drivers to take preventative action and avoid critical situations. Sensors including Lidar, radar and cameras can be used in accordance with this technology to detect pedestrians and vehicles in a 360-degree perimeter of the intersection. This

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[569] For further reading also see: Muralidharan, A., Coogan, S., Flores, C., and Varaiya, P. (2016): Management of intersections with multi-modal high-resolution data. *Transportation Research, Part C*, **68**, 101-112.

[570] Also see: 3GPP TS 22.186 V16.2.0 (2019-06): *"Enhancement of 3GPP support for V2X scenarios; Stage 1 (Release 16)"*. Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.186/

[571] Cooperative driving systems enable vehicles to adapt their motion to the surrounding traffic situation, by utilizing information communicated by other vehicles and infrastructure in the vicinity. Some benefits of cooperative driving include improvements on the efficiency and safety of traffic flow, reduction of traffic congestion, reduction of fuel consumption and associated positive environmental and economic impacts.

For more details also see, *among others*: Behere, S., Törngren, M. and Chen, D.-J. (2013): A reference architecture for cooperative driving. *Journal of Systems Architecture*, **59**(10), Part C, 1095-1112.

[572] As a conceptual extension, the "fully autonomous driving" involves the capability of a vehicle to sense its environment and navigate without human input under all scenarios and conditions. This is an evolving development area, but it is anticipated that by 2020 and further on will be fully developed.

[573] For more details also see: https://www.continental-corporation.com/en/press/press-releases/ces2018-116936

 

information is then combined by sensor-fusion algorithms and can be sent to approaching vehicles where on-board units receive and process it, warning drivers if a collision is imminent.

Intersection Collision Warning (ICW) is a system that alerts drivers of potentially dangerous traffic situations when they approach an intersection[574]. It does so by providing reliable and timely warnings to other vehicles that are approaching the intersection and therefore prevents collisions. Early results showed that collision warning systems could significantly reduce crash fatality and property damage. When multiple vehicles are approaching an intersection at about the same time, ICW could help avoid potential collisions if the drivers know the information of all the vehicles in the vicinity, including locations, velocity, and moving directions. Based on the location, moving direction and velocity in the information, such a system estimates the time a potential collision would occur and warns the drivers to avoid the collision[575],[576].

Specifically, the collision avoidance problem[577] can be "addressed" by computing the set of states, which are called the backward reachable set or the capture set, that lead to an unsafe configuration (a collision) independently of the input choice[578]. Then, according to the usual approach, a feedback map is computed that restricts the control inputs when necessary to prevent entrance in the capture set. While this approach is theoretically appealing because it ensures safety by construction and applies overrides only when necessary, its practical applicability is often limited by the complexity associated with the computation of the capture set[579],[580]. Researchers have been tackling computational issues by, among other approaches, focusing on restricted classes of systems[581],[582].

In order to make an intersection safer[583] via the inclusion of an I2V information system, a four-step approach can be proposed[584]. In the scope of the step 1, trajectories[585] of users (cars, bicycles,

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[574] Also see the scope proposed in: U.S. Department of Transportation (USDOT): Cooperative Intersection Collision Avoidance Systems (CICAS). Available at: https://www.its.dot.gov/research_archives/cicas/index.htm

[575] Basma, F., Tachwali, Y., and Refai, H.H (2011): *Intersection collision avoidance system using infrastructure communication*. In Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems (ITSC-2011), pp.422-427. IEEE, Washington, DC, US, October 05-07, 2011.

[576] Ahn, H., and Del Vecchio, D. (2018): Safety verification and control for collision avoidance at road intersections. *IEEE Transactions on Automatic Control Systems*, **63**(3), 630-642.

[577] A collision may occur for a number of reasons, including a distracted driver not seeing the incoming vehicle, underestimating the vehicle speed, and violating red lights or stop signs.

[578] Tomlin, C.J., Lygeros, J., and Sastry, S. (2000): A game theoretic approach to controller design for hybrid systems. *Proceedings of the IEEE*, **88**(7), 949-970.

[579] Henzinger, T.A., Horowitz, B. Majumdar, R. and Wong-Toi, H. (2000): *Beyond HyTech: Hybrid systems analysis using interval numerical methods*. In *Hybrid Systems: Computation and Control, B. Krogh and N. Lynch (Eds.)*, New York, Springer-Verlag. (Lecture Notes in Computer Science, pp.130-144).

[580] Tomlin, C.J., Mitchell, I., Bayen, A.M., and Oishi, M. (07/2003): Computational techniques for the verification of hybrid systems. *Proceedings of the IEEE*, **91**(7), 986-1001.

[581] Althoff, M. (2010): *Reachability analysis and its application to the safety assessment of autonomous cars, Ph.D. dissertation*. Lehrstuhl für Steuerungs-und Regelungstechnik, Tech. Univ. München, München, Germany.

[582] Le Guernic, C. (2009): *Reachability analysis of hybrid systems with linear continuous dynamics, Ph.D. dissertation*. Ecole Doctorale Mathématiques, Sciences et Technologies de l'Informatique, Inf., Université Joseph Fourier, Grenoble, France, 2009.

[583] Grembek, O., Kurzhanskiy, A., Medury, A., Varaiya, P., and Yu, M. (05/2019): Making intersections safer with I2V communications. *Elsevier, Transportation Research, Part C,* **102**, 396-410.

[584] Federal Highway Administration (2008): *Traffic signal timing manual. Technical Report FHWA-HOP-08-024, U.S. Department of Transportation*. [http://www.ops.fhwa.dot.gov/publications/fhwahop08024/fhwa_hop_08_024.pdf].

[585] A trajectory is a path traced out by a vehicle as it moves through the intersection. Only legal or permissible trajectories are considered. A guideway is the bundle of vehicle trajectories that make the same movement. A guideway starts from a single lane entering the intersection and ends in a single outgoing lane.

pedestrians) are grouped into "guideways" corresponding to their movements within an intersection. In step 2, "conflict zones" are identified as regions where two guideways intersect, creating the potential for an accident. In step 3, a procedure is used to determine if a planned movement can be safely executed with the information made available to the user. This information consists in what users themselves can sense of the other users in the intersection, together with the SPaT message from the intersection. The message gives the full current phase and an estimate of the time when the phase will change. Most conflicts are resolved by step 3. The conflicts that remain are due to blind zones. In step 4, sensor information provided by the intersection tells whether these blind zones are occupied by other users or not. Note that steps 1 and 2 are conducted offline, where steps 3 and 4 require real time information. The approach is described for a standard four-leg intersection. Upon entering any leg, a vehicle may turn left, turn right, or go straight, giving in all 12 vehicle movements or phases.

*Figure 44: Conceptual Approach of the Intelligent Intersection use case*

An intelligent intersection implements the four-step approach described above. It has a map of the intersection that includes guideways, movements, conflict zones and blind zones; and sensors that detect the occupancy of these blind zones. The map is constructed offline. The map may be downloaded by connected vehicles and other users. The intersection software records the signal phase in order to calculate SPaT messages in real time. The intersection broadcasts in real time the SPaT message and the occupancy of the blind zones. These broadcasts are received by connected users of the intersection. An intelligent intersection can also detect red-light violators via the inclusion of a video camera which is triggered by the detection of the intruding vehicle at a high speed traveling into the intersection during a red signal. The detection takes place before the vehicle entered the intersection and can warn the vehicle with right-of-way (ROW).

The intelligent intersection also functions as a limited but flexible protected intersection. Protected intersections[586] refer to physical modifications designed to improve the passage of cyclists through an intersection. Its key features are: (i) Insertion of "refuge islands" to sharpen turning radius of cars, forcing them to slow down when turning right; (ii) special bike lane setback as they cross the intersection; (iii) forward stop bar for cyclists, far ahead of waiting cars; (iv) special cyclist-activated traffic lights; (v) advance green traffic signals for cyclists; and (vi) turn restrictions for cars, while all turns allowed for cyclists.

An intelligent intersection can be enhanced to provide several safety benefits. Bicyclists or pedestrians could put apps in their smartphones that alert the intersection controller of their location and direction thereby serving as a mobile bicycle or pedestrian sensor. Knowing how many bicycles there are and their desired turn movements, the controller could adaptively set the duration

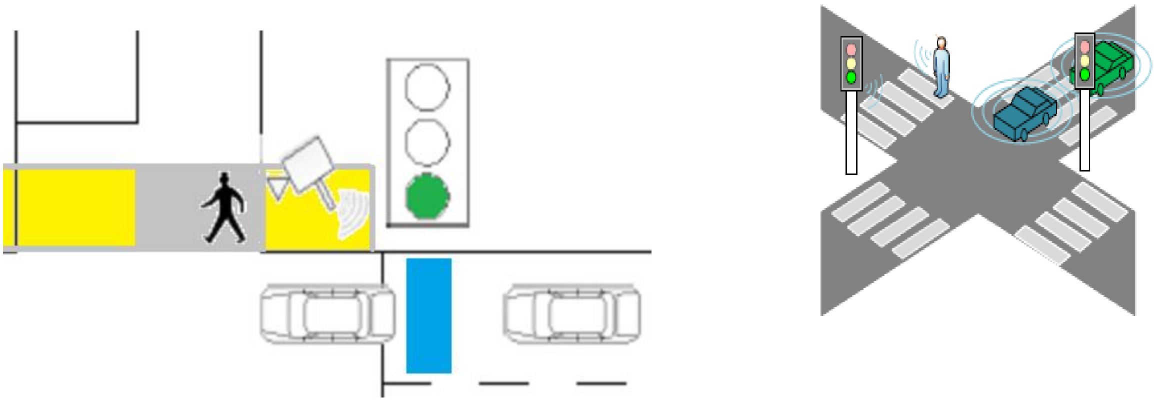
586 Falbo, N. (02/2014): *Protected Intersections for Bicyclists*. Vimeo, Inc. Available at: https://vimeo.com/86721046

of the bicycle signal to reduce backups. The SPaT calculation could be used to signal to cyclists that they should speed up or slow down to avoid stopping.

An intelligent intersection has four capabilities. First, it has a GIS map that describes all the lanes, stop bar locations, and permissible movements. An algorithm can then construct the guideways, conflict zones, possible queue obstructions at stop bars and blind spots. Second, it has historical and real time signal phase data that record the time of each phase change. The phase data and the signal timing plan are used to construct the distribution of the remaining duration of the current phase. This information is needed to compute the SPaT message. (The phase data itself can be obtained from the controller or its conflict monitor[587]. Third, sensors must be installed at strategic locations along guideways upstream of conflict zones to detect whether a blind zone is occupied. Fourth, the intersection must be able to transmit the SPaT and blind zone occupancy messages to users and AVs. The easiest way to communicate would be via a smartphone app. Such an app would be automatically triggered by crossing a geo-fence around the intersection; it would inform the intersections of the smartphone of a pedestrian or cyclist; the intelligent intersection would return information or use the presence of the phone to set signal timing. The safety benefits of an intersection upgrade depend on the traffic demand. From the map of the intersection one can calculate the conflict zones and roughly estimate queues to see how frequently blind zones will occur.

### 4.4.2 Definition and Implementation Status

The 5G-DRIVE intelligent intersection use case deals with safety on intersections, by focusing on infrastructure detection situations that are difficult to perceive by vehicles themselves. A good example is the situation where a vehicle wants to make a right turn while parallel VRUs also have a green phase and right of way (permissive green for motorised traffic). This situation is depicted in Figure 45.



a) (b)

*Figure 45 (a) and (b): Perception areas of the intelligent intersection*

When a pedestrian is detected on the crosswalk (as in the grey area of Figure 45(a)) a Decentralised Environmental Notification Message[588] (DENM) should be broadcasted by the RSU, while the back-

[587] Also see, *among others*: Ibrahim, S., Kalathil, D., Sanchez, R.O., and Varaiya, P. (2017): *Estimating phase duration for SPaT messages*. Cornell University, US. Available at: https://arxiv.org/pdf/1710.05394v2.pdf.

[588] A DENM is structured as a code for a specific warning event together with a small map of the relevance area and the approach towards it. The approach is similar to the principle of the MAP, so that vehicles should check whether they are close to the approach and driving in the same direction; if this may be the case, then the warning message should be displayed on the Human-Machine Interface (HMI). In our approach, DENM itself contains a pedestrian on the road warning and is 60 bytes, but the lower level headers take another 92 bytes, bringing the total at 152 bytes. This is the

office should geocast[589] this to all vehicles in the vicinity. This is to warn vehicles further upstream that a potential conflict may occur in the future and to prevent future hard braking. In the yellow areas of Figure 45(a), given a movement direction of the pedestrian towards the intersection, the infrastructure should send out Collective Perception Messages[590] (CPM). This is to warn vehicles further upstream that a potential conflict may occur in the future and to prevent future hard braking.

This use case deals with safety on intersections, focusing on infrastructure detection of situations that are difficult to perceive by vehicles themselves. The example of the collision avoidance is shown in Figure 45. In this example, a vehicle wants to make a right turn, while parallel VRUs also have a green phase and right of way (permissive green for motorised traffic).

Other DENMs can also be tested within 5G-DRIVE, as the message supports various warnings. Depending on the complexity of the warning, the message can have a different length, which can result in different results with regards to communication performance.

It should be noted that the focus of the use case is not on the human-machine interface, but on the V2X performance and that situations on the test tracks are mostly emulated not to put real pedestrians at risk and ease requirements on timing the approach of the vehicle.

Since this use case is about safety, latency of V2X communications and delivery guarantee are very critical. Latency on older 3G networks was found to have outliers up to 25 seconds, which is unacceptable for these applications. Instead, 100 ms is the absolute maximum for the intersection safety DENM and 1000 ms for the CPM as it is more of a preventive message.

The use case development is done parallel with the GLOSA use case. GLOSA is dedicated for sending CAM messages but intelligent intersection is dedicated for using SPAT messages to improve vehicle situation awareness. Currently, the vehicle and interfaces exist in the software level and first implementation exists but with ITS G5. Now the communication devices are changed to C-V2X but this should not influence to messages minimally.

**Relevant KPIs for this use case:**

The KPIs for this use case are similar to GLOSA, but due to the safety critical element and the variability in previous work, some more contextual KPIs are required to get a more predictable latency:

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simplest warning possible without accuracy confidence indications and only two points to indicate the curvature of the approach towards the event.

589 *GeoCast* messages rely on connected vehicles knowing their own location, and uses this information to create a “neighbourhood” table for all connected vehicles and their locations, trajectories, and transmission reliability. This allows routing based on position, so messages may address a particular vehicle. These messages use beaconing for neighbour discovery and location collection. This protocol relies on honesty in vehicles reporting their own location.

590 The Collective Perception (CP) service (CPS) uses CP Messages (CPMs) to transmit data about locally detected objects (i.e. non-cooperative traffic participants, obstacles and alike) to improve situational awareness. By exploiting the increasing sensing and communication capabilities of future vehicles, CP is considered by the car industry as a natural key enabler for cooperative automated driving applications. For this reason, CP standardisation has been started at ETSI ITS (as in ETSI TS 103 324 and ETSI TR 103 562) at later stages of deployment (*Day-2* and beyond). ETSI CPMs foster sustainability and interoperability by transmitting abstract representations of detected objects instead of type- and vendor-dependent raw sensor data. In addition, CPMs abstract descriptions can derive from detections made by single sensors or by result of local sensor fusion algorithms, which provides implementation flexibility. The CP is designed to allow sharing detections made by both vehicles and RSI. For this purpose, detected object descriptions are shared referred to a coordinates system that is different according to the nature of the CPM originating station.

When receiving a CPM with no object detected in a given direction, a CAV can make a cross-check by analysing the Fields of View (FoW) information; if it says that the originating station has no sensors covering that direction, objects can be actually present in reality.

Also see: ETSI TR 103 562 V0.0.15 (2019-10): *“Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective -Perception Service (CPS)”*.

- **Packet Error Rate (PER)**: ratio of unsuccessfully received packets in the OBU vs. total number of packets sent by the RSU (in percentage).
- **Latency:** the radio access network contribution to the total elapsed time, measured from the instant the RSU sends a packet to the moment when the OBU receives it (in ms).
- **Total active stations:** This KPI tracks how many other stations were active at the same time while in communication range of the test subject.
- **Total channel load in Mbps:** The total load of the channel is an important contextual variable to determine how much interference can be expected.
- **Total messages per seconds on channel:** One other client using a load of 1 Mbps has much less chance of packet collisions than a hundred clients transmitting at 10 kbps.

Within the scope of the respective 5G-DRIVE Deliverable D4.2 ("Joint specifications for V2X trials") a more detailed analysis has taken place for the selected KPIs, also following to the progress of corresponding trials.

According to the scope discussed in the 5G-DRIVE Deliverable D4.3 ("*Report on Potential Vulnerabilities of V2X Communications"*), the aim is to realize a performance test and, therefore, there are no pass/fail success criteria. The goal of the test is to evaluate the resilience of ITS-G5 and LTE-V2X units against external harmful interference. To evaluate this, a non-corrupted .pcap file must successfully be retrieved from the victim OBU's internal storage after each test run.

From this packet capture, the following KPIs are evaluated:

- Transmission range (in m);
- Average data rate (in Mbps);
- Total messages per second on channel;
- Latency (in ms);
- Packet Error Rate (PER, in percentage).

Note that jamming is a malicious attack for which resilience requirements do not exist. Interference should be reported directly and prosecuted by the authorities. Therefore, there is no direct pass/fail criterion for this test.

## 4.5 Joint KPIs for WP4 Use Cases

Aiming to provide some sort of "joint" KPIs for all selected WP4-*based* use cases and taking into account the progress that has already been made as of the performed trials, we can conclude by presenting the following table[591][592].

There, for all possible and ongoing works we have summarised by "depicting" the corresponding trial coming directly from the selected use case, the related operational environment as well as the resulting KPI targets.

591 Also see: 5G-DRIVE Project (02/2019): Deliverable 4.1: "V2X Development and Test Plan". Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

592 Also see: 5G-DRIVE Project (08/2019): Deliverable 4.2: "Joint Specification for V2X Trials". Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

| Trial | Environment | KPI targets |
|---|---|---|
| DENM V2I | 5/10/15/20 DENM stations<br>50/100/150/200 CAM stations | PER < 1%<br>Latency < 100 ms<br>Active stations >=300 |
| GLOSA V2N | 100/200/300/400/500<br>CAM stations | PER < 10%<br>Latency: MAP < 5s, SPaT < 2s |
| CPM V2X | 80/100/120/140 CAM and CPM station | PER < 10%<br>Latency < 100 ms<br>Bandwidth > 1.6 Mbyte/s |
| MCM[593] V2X | 100/200/300/400/500 active CAM and MCM stations | PER < 10%<br>Latency < 100ms<br>Active stations >=300 |

*Table 5: Target KPIs by different trial use cases in 5G-DRIVE project*

## 4.6 Architecture for the WP4 Test Cases

### 4.6.1 The Physical Architecture of the GLOSA Use Case

The next figure depicts the physical architecture of the GLOSA use case, as per its planned implementation at the JRC Ispra site. As shown in Figure 46, the key architectural elements of this use case are as follows:

- A **physical/virtual traffic light** and its associated traffic controller to orchestrate the transitions between the "red", "amber" and "green" states. For the purpose of experimentally evaluating this use case, the traffic light can be either physical (i.e., a commercial product) or virtual (a software running on/communicating with the C-ITS RSU and implementing the transitions described in the FSM).
- A C-ITS **RSU** co-located with the traffic light (if physical) or communicating with the traffic controller (if virtual). The RSU periodically broadcasts Signal Phase and Timing messages (SPAT) (e.g., every 100 ms) to all neighbouring vehicles. Amongst other, DENM messages include the traffic light's current state and FSM timing information.
- **C-ITS OBUs** deployed in the test vehicles. The OBUs receive and process the SPAT messages locally to compute the relevant GLOSA information in various forms (e.g., remaining time until next traffic light state transition, optimal speed to reach traffic light in green state, etc.). Once computed, the GLOSA information is relayed to an on-board laptop (or UI device), where it is displayed both visually and audibly to the driver.
- The **JRC internal communications network** provides connectivity between the C-ITS RSUs and various supporting services running in the JRC data centre (e.g., experiment management console, traffic light controller, log server, etc.)
- **Physical/virtual servers** in the JRC data centre running the above supporting services. For the purpose of implementing and experimentally evaluating this use case, these servers can be

[593] See: ETSI TR 103 578 V0.0.2 (2018-10): *"Intelligent Transport Systems (ITS); Vehicular Communication; Informative Report for the Maneuver Coordination Service"*.

The European Telecommunications Standards Institute (ETSI) is currently defining the Manoeuver Coordination Service (MCS). The standardisation process is based on a purely distributed solution where vehicles coordinate their manoeuvers using V2V communications.

provisioned either physically or virtually (via Virtual Machines (VMs)).

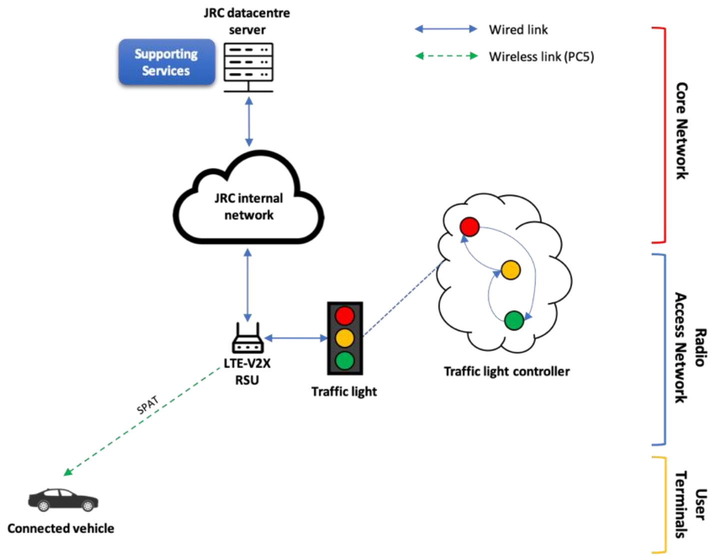


*Figure 46: The GLOSA physical architecture at the JRC Ispra site*

### 4.6.2 The Physical Architecture of the Intelligent Intersection Use Case

The physical architecture for the intelligent intersection is similar to the GLOSA architecture in the previous section, with the exception of not using an internal network, but a VPN instead to connect the back office to the RSU and the omission of the traffic light. A functional view of the architecture is shown in the figure below:

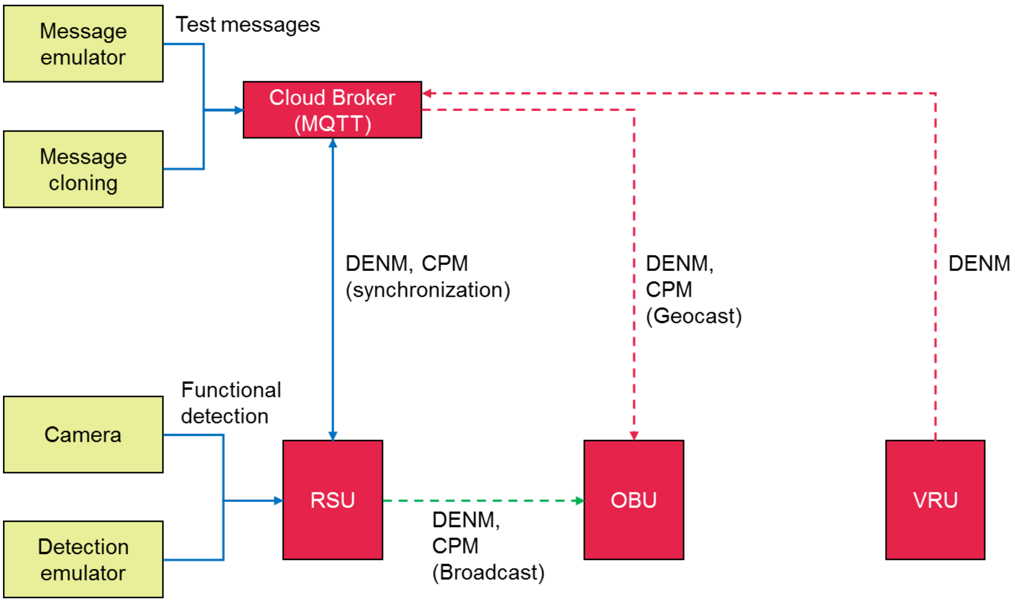


*Figure 47: Functional architecture of the intelligent intersection use case*

The dashed lines are eMBB wireless communication lines, while the green dashed are V2X local communications.

- **RSU:**

  The RSU is responsible for V2X communications and collection of locally available sensor data. In the case of this trial, the possibility of using emulated detections is also added. This data is used to encode the DENM and CPM messages that can be sent directly via V2X, or synchronised with the cloud broker to enable wireless geocasting via eMBB connectivity.

- **OBU:**

  The OBU receives information in a mobile client; in the case of 5G-DRIVE this is a vehicle. It should decode the received messages and display functionally relevant data to the driver or to the automated driving logic. The focus here is on the communication performance and not on the HMI aspects. Therefore, this is kept to either command line output or an app from another project can be used.

- **Cloud Broker:**

  The cloud broker collects all traffic information in an efficient way to allow geocasting with minimal overhead. The IoT Message Queuing Telemetry Transport (MQTT) protocol is used for this and the data is ordered according to tiles that allow geocasting without the need for clients having to share their location. This saves communication bandwidth and ensures privacy. Messages that are generated locally at the RSU need to be uploaded to the broker, while messages from a cloud source can be downloaded to an RSU. The advantage of downloading is that messages can be broadcasted letting all local clients receive it at once, instead of having to set up multiple parallel eMBB links.

- **VRU:**

  The Vulnerable Road User can also upload its own warning messages when it enters a conflict area to the cloud broker. This is an interesting option when infrastructure sensors are not available. It does, however, add an extra (wireless) communication step when compared to infrastructure detection. It is unlikely that VRUs are equipped with more expensive V2X technology in the future, and therefore this option is not considered here.

- **Camera:**

  The camera detects positions and trajectories of VRUs (about) to cross a conflict area. This data is sent to the RSU in a camera-vendor specific format.

- **Detection Emulator:**

  For testing purposes and to avoid having to invest in camera infrastructure, the detection information can also be emulated with a simple application run on a field laptop connected to the RSU. This also allows for detailed timing coordination during the experiment and avoids having to risk an actual VRU entering the conflict area.

- **Message Emulator:**

  The message emulator works at the cloud level and can inject test messages into the cloud system. This gives full control over the message type, length and relevance location.

- **Message cloning:**

  Cloning a message means using data from a live intersection elsewhere and transforming the location so it can be used by vehicles at the test site. For GLOSA this entails a manual edit of the MAP message and an automatic edit of the SPaT to match the IDs in the transformed MAP message.

### 4.6.3 Joint Architecture for the GLOSA and the Intelligent Intersection Use Cases

The trials at the site in Finland are deployed with mobile equipment as described in the 5G-DRIVE Deliverable D4.1[594]. The setup is shown as in the figure below.

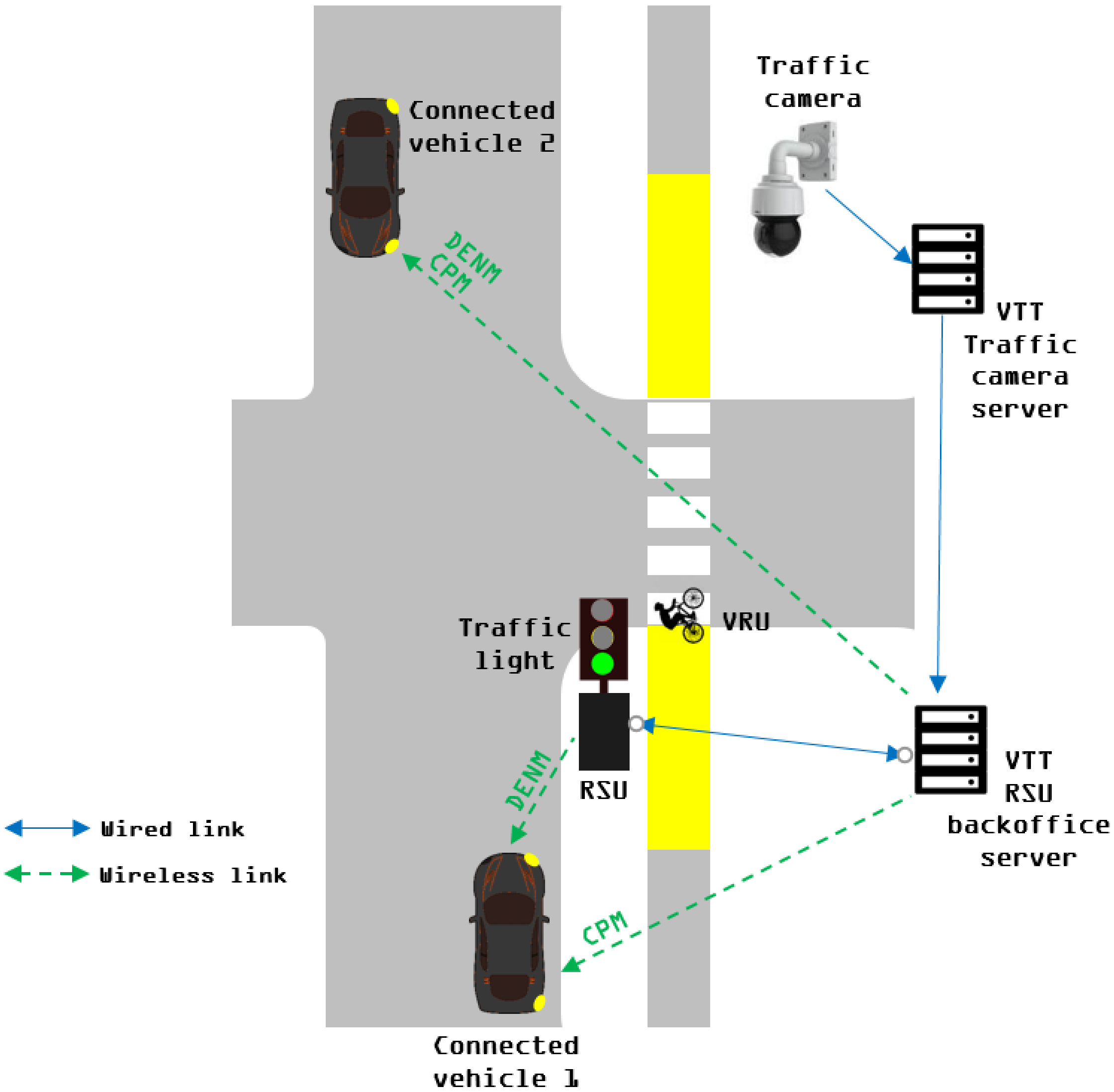


*Figure 48: Architecture of the GLOSA and Intelligent intersection test cases*

The Connected Vehicle 1 (CV1) is warned about the VRU (cyclist) with intelligent intersection service (DENM message).

Note that the messages for GLOSA are not shown in the above figure and that two possible locations of the RSU are shown (with the MEC/back-office server or attached to the traffic light). The key architectural elements of this use case are as follows:

- A **physical/virtual traffic light** in static control mode to implement the transitions between the "red", "amber" and "green" states. For the purpose of experimentally evaluating this use case, the traffic light can be either physical (i.e., a commercial, end-user product, but without loop detectors) or virtual (a software running on/communicating with the RSU). Another

[594] 5G-DRIVE Project, Deliverable D4.1 (04/2019): *"V2X Development and Test Plan"*. Available at: https://5g-drive.eu/resources-and-results/project-deliverables/

variable is the communication channel. Data can be retrieved locally if interfaces are available on-site, or it can be originated from a traffic management centre and distributed through Dynniq's CCSP Cloud that implements IoT protocols to communicate with agents in the field. The traffic light is only required for the GLOSA use case and the content of the SPaT message has to be retrieved from it.

- An **LTE-V2X RSU** co-located with the traffic light (if physical) or running/communicating with the traffic light implementation (if virtual). When a VRU is detected in the zebra crossing, a Decentralised Environmental Notification Message (DENM) should be broadcasted by the RSU, while the back-office should geocast this to all vehicles in the vicinity. In the yellow areas, given a movement direction of the VRU towards the intersection, the infrastructure should send out Collaborative Perception Messages (CPM). For GLOSA it should broadcast both MAP and SPaT messages.
- An **ITS-G5 RSU** co-located with the traffic light (if physical) or running/communicating with the traffic light controller implementation (if virtual). When a VRU is detected in the zebra crossing, a Decentralised Environmental Notification Message (DENM) should be broadcasted by the RSU, while the back-office should geocast this to all vehicles in the vicinity. In the yellow areas, given a movement direction of the VRU towards the intersection, the infrastructure should send out Collaborative Perception Messages (CPM). For GLOSA it should broadcast both MAP and SPaT messages.
- At least **Two OBU**s (one ITS-G5, one LTE-V2X) deployed in the test vehicles. The OBUs receive and process the MAP, SPaT, DENM and CPM messages locally to show GLOSA information or compute the potential conflicts with the VRUs on the zebra crossing and also warn vehicles further upstream that a potential conflict may occur in the future and to prevent future hard braking.
- A **VTT automated vehicle with sensors** to fill CPM messages with real sensor data in V2V scenarios.
- A **VTT Traffic camera** detecting and tracking VRUs in the intersection.
- A **VTT Traffic camera server** can provide connectivity between the RSUs and various supporting services/servers running in the VTT data centre. When a pedestrian is detected in the zebra crossing, a Decentralised Environmental Notification Message (DENM) should be broadcasted by the RSU, while the VTT RSU back-office server should geocast this to all vehicles in the vicinity (Connected vehicle 1, Connected vehicle 2). In the yellow areas, given a movement direction of the VRU towards the intersection, the infrastructure should send out Collaborative Perception Messages (CPM). The length of the yellow area is the same as the length of the zebra area. For more controlled testing it should also be possible to generate messages based on emulated VRU movements.
- **VTT RSU back-office server** in the VTT data centre running all the needed supporting services.

To execute the tests, the following tools are used:

- **Tcpdump**[595] is a Linux tool that enables to log all communications. It also has the option to store communication in log files in .pcap format, which includes a radiotap header[596] indicating the signal strength of the received packets.

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595 For further details also see: https://www.tcpdump.org/manpages/tcpdump.1.html

596 The radiotap header format is a mechanism to supply additional information about frames, from the driver to userspace applications such as libpcap, and from a userspace application to the driver for transmission. For further details also see, *for example*: https://www.radiotap.org/

- **ITS *Day-1* services app**. This app only works in combination with a Dynniq OBU with 802.11p communications. It displays information of the messages to the driver and can assist with qualitative assessment of the use case performance. Note that timestamp logging is not possible in this application and it can therefore only be used for qualitative assessment.
- **ITS *Day-1* facilities layer software**. This is OBU/RSU software running on the Dynniq 802.11p equipment and decodes MAP, SPaT and DENM messages. A special webpage at port 8082 gives a functional overview of all messages received and can be a useful tool for qualitative analysis. Note that timestamp logging is not possible in this application and it can therefore only be used for qualitative assessment.
- **Geonet[597] Daemon software**. This is OBU/RSU software running on the Dynniq 802.11p equipment and enables sending and receiving of raw application layer byte arrays. This can be the basis for using the new message sets. Note that timestamp logging is not possible in this application and therefore tcpdump should always be used in conjunction, while application layer software connecting to it has to log timestamps.
- **Encoding/Decoding software**. The messages used for all test cases are defined using the ASN.1 standard. In case of the MCM and CPM, no default software exists yet and therefore custom encoders/decoders can be implemented for 5G-DRIVE. This software should also indicate timestamps when a message is received and when it is decoded to track the latency in the full system.
- **MCM/CPM visualisation software**. A very basic GUI showing some instructions to the driver in case of MCM and a 2D overview of detected objects for CPM. This software can be implemented for 5G-DRIVE and is intended for qualitative assessment, not for demonstrations.
- **Interfacing with LTE-V2X RSU/OBU**. What the Geonet Daemon will do for 802.11p, this new software that has to be developed for 5G-DRIVE, should do for the LTE-V2X communication units.
- **IoT client software.** V2N messages originating from the cloud are available through the MQTT protocol. The client software should also log timestamps whenever messages are received.

End-to-end latency should be measured by logging time stamps in the following order:

1. Message generation time is usually encoded in the message itself; it is a timestamp at the start of the encoding process.
2. Message transmission by the source: virtual RSU publishing in IoT platform.
3. Reception of message by MEC or RSU.
4. Transmission by MEC or RSU on V2X channel.
5. Reception by OBU.

It should be noted that for V2N step 3 and 4 are skipped and for locally interfaced information sources (traffic controller or VRU cameras) step 2 is skipped. The IoT platform itself also does not have options to log timestamps due to the large amount of data passing through it. Latency would be created by doing that. The latency between step 2 and 3 is therefore transmission from virtual RSU to IoT + IoT processing time + transmission from IoT to MEC/RSU. In case this latency is high it can be more isolated by setting up test clients in the same environment as the IoT to isolate the processing delay.

[597] See, *for example*: https://en.wikipedia.org/wiki/GeoNet

The first test is a very simple range test for V2X communications. Each partner with equipment can carry out these tests and report the setup to the link budget model calculations. Focus should be on reporting altitude of the antenna, vegetation, size and density of objects that are near the communication path. The test should be carried out as follows:

- One communication unit is placed at a stationary location and set to transmit CAM messages and logs all incoming communication in pcap format with radiotap header enabled.
- The other communication unit can do at least 10 approaches going from 1000 to 0 m distance back and forth. This unit can also transmit CAM messages in which the GPS position is important because it can be used for distance calculation in post-processing.
- The objects used in these tests are pedestrians crossing the intersection and vehicle approaching the intersection area. In addition, traffic light status related DENM message is transmitted.

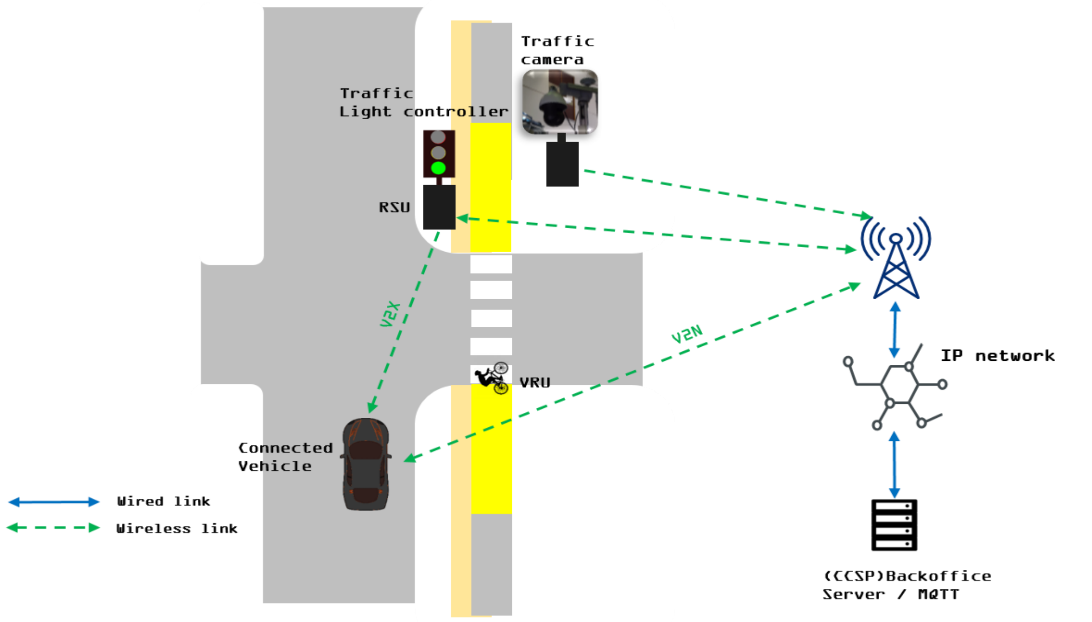
The logs with the .pcap files can be analysed to make plots of signal strength versus distance between the pairs.

Based on the above architectural description which proposed a “joint” framework for GLOSA and Intelligent Intersection, some parallel trials have been performed between the EU and China, as shown in the following Figure 49:

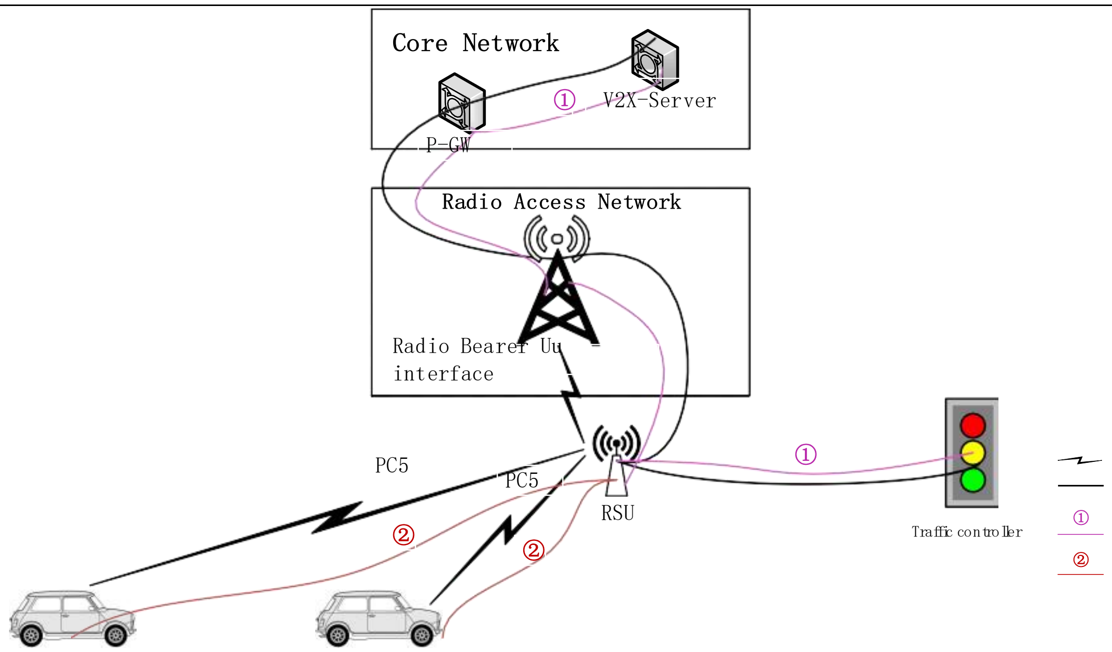

(i) Tampere Test (June 25-26, 2020) (ii) Shanghai Test (July-August 2020)

*Figure 49: Tests in EU and China for the V2X scenario*

Following to the above tests, we also depict the corresponding architectures as appearing in Figure 50, below:




(i) Tampere Test Architecture




(ii) Shanghai Test Architecture

*Figure 50: Architectures of: (i) the 5G-DRIVE and; (ii) the 5G Large-scale Trial project, for the V2X scenario*

The following Figure 51 shows the architecture of the sub-system implemented for the V2X trials in Espoo. The mobile roadside unit is the smart traffic running with intersection (pedestrian detection) support algorithms. The data is sent via LTE/Pre-5G channels to the backend server and the traffic light data is read via the MQTT interface. The virtual traffic light read from the cloud via the LTE communication channels. The local communication channels are C-V2X based representing PC5 based solutions with low latencies. The comparison is conducted to compare PC5 against the LTE/Pre-5G channels.

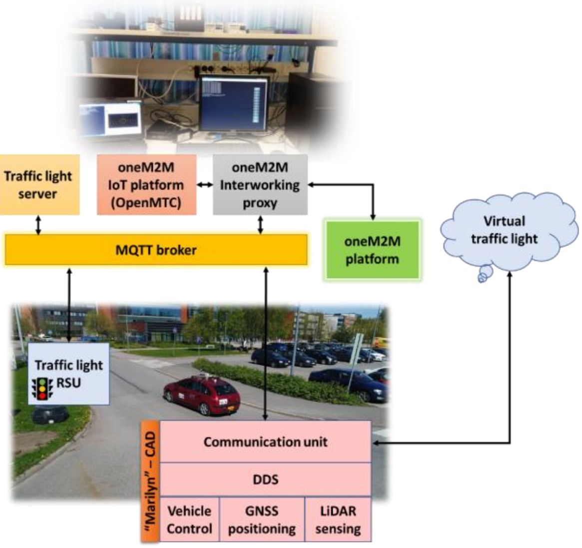



*Figure 51: The system architecture of the modules to support automated driving in intersection warning use case, 5G-Drive V2X team*

C-V2X trials at both sides serve the same purposes for C-V2X communication. Therefore, both sides face the same challenges on the front of C-V2X. C-V2X requires high security, low latency and high reliability while the electromagnetic interference is complex. The featured use cases in both projects are comparable between China and EU. The services and scenarios are categorised differently. On the one hand, C-V2X scenarios in 5G Large-scale Trial categorizes according to V2V (such as Emergent braking warning), V2I (such as traffic light optimisation) and V2N (such as traffic info broadcasting). On the other hand, C-ITS in Europe are categorised according to services: day 1 services, day 1.5 services and day 2 services. From this perspective, the joint trial use cases and trial plans are created and tailored to test the validity of the harmonised methodology, and to ensure comparison in the GLOSA use case and Intersection use case (collision warning of vehicle to Vehicles, VRU[598] or incident warning).

The virtual joint trials between EU and China can be briefly summarised as follows regarding their actual status and their achievements:

- Jointly defined and demonstrated the 5G-based IoV scenarios, and ensured interoperability in Beijing and in Tampere/Hervanta, Finland.
- Performed work (between 5G-Drive V2X team and 5G Large-scale V2X team in China) transferred to online cooperation.
- Joint trials are ongoing, separately being performed in EU and in China: Showcase mandatorily the two joint use cases: GLOSA and intelligent intersection use case.
- In China, the 5G Large-scale V2X team has finished trialling and collected results from July to August 2020.
- In Europe, the 5G-Drive V2X team has been going slow during lockdown but resuming, Intelligent intersection use case is performed and the GLOSA use case has been performed in October 2020.
- Data of Tampere trials has been analysed and shared with China and received acknowledgement. China is cleaning up data and producing report. Comparisons can be made on all aspects.
- EU-China joint trial demonstration is cancelled due to travel restriction. The EU trial demonstration can be held virtually with China twinning project's participants.

598 VRU stands for vulnerable road user. They are "non-motorised road users", such as pedestrian and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation.

- Lessons learnt from the joint trial EU-China and results from above lead to a joint harmonised methodology, hopefully contribute to the interoperability of V2X development in EU and in China.

# 5 Concluding Remarks

The present deliverable is an extended and a more detailed composition of the previously submitted "MS4" ("Milestone 4") report. Our basic aim has been to further discuss, explain, assess and analyze the 5G-DRIVE originally selected use cases that are examined in the frameworks of the respective WP3 and WP4, where trials are performed for their evaluation. In way to provide additional information for the validity of the selected uses cases and for their inclusion, as "5G enablers" in the wider framework for development, we have re-assessed the original 5G framework of reference where our 5G-DRIVE project is carried-out. Thus, especially within Section 1 we have provided up-to-date information emphasizing upon the actual European policy framework for the promotion of 5G and for its inclusion as innovator for market growth. As the 5G-DRIVE project has specifically been focused on trials procedures we have so re-assessed the current European initiative for the promotion of trials, within the on-going 5G-PPP framework.

The next challenge has been about properly identifying the "updated" (i.e. as a result of the trials that have taken place and of the results that have been achieved until today) the 5G-DRIVE perspective and the innovative features of our effort. Thus, in the framework of the dedicated Section 2, we have re-approached the overall 5G-DRIVE concept together with the two fundamental scenarios covering eMBB and V2X communications. For each scenario we have additionally discussed past and/or ongoing EU-funded projects -especially those belonging to the 5G-PPP context- conceptually relevant to our approach (in an explicit and/or implicit way). This has been quite useful in order to "identify" the contributions and the support provided by the 5G-DRIVE effort for the promotion of EU-funded R&I, within the two fundamental scenarios composing the "core" of our project. In order to "better correlate" our work to modern 5G-related technological challenges, we have also discussed the essential technical background for the 5G realisation via dedicated and distinct technologies acting as "enablers", by discussing their basics. We have also discussed a more generalised 5G-based approach for the definition of appropriate KPIs, in a broader scope.

Then our work has been purely emphasised on the detailed description of the selected use cases, each one within the respective scenario. The first scenario has been about eMBB applications on the 3.5 GHz, while the second scenario has been about Internet of Vehicles (IoV) applications based on LTE-V2X using the 5.9 GHz band for Vehicle-to-Vehicle (V2V) and the 3.5 GHz band for Vehicle-to-Network (V2N). In addition, we have also examined potential market relevance and appearing market applicability of the proposed use cases, so that to be able to assess them as real "5G enablers" and promoters of innovation.

Section 3 has been dedicated to the eMBB scenario. We have introduced the two corresponding use cases (i.e.: cloud-assisted AR and indoor positioning) and we have extensively discussed their conceptual background, in parallel with their actual implementation status. For each use case we have identified challenges for growth and their indispensable role for supporting development with the 5G growth. Based on the progress performed we have discussed suitable KPIs for assessment, conformant to the related trials. We have also presented and discussed the related essential architecture, selected to serve each one among the eMBB-related use cases.

Section 4 has followed a "similar" approach, as the previous one. Here, however, our main focus has been about V2X communications as part of the 5G evolution, by emphasising upon two selected use cases (i.e.: GLOSA and intelligent intersection). In this scope we have also provided an update of latest radio frequency spectrum policy issues for C-ITS (as performed in the EU, China and the US) being potentially able to influence our work in the near future. In our approach we have analysed the main concept of each separate use case and we have assessed their actual implementation status. Once again, we have proposed selected KPIs for assessment, for each separate use case, conformant to the related trials. Our work has also provided detailed information for the related essential architectures, on a per use case basis. As an extra step, we have proposed a "joint" architectural approach to serve, simultaneously, both GLOSA and intelligent intersection use case. These are expected to have a strong influence in traffic applications, for a variety of reasons covering technical, business, social and other perspectives.

Further technical results and/or potential updates will be provided in the forthcoming WP3/WP4 deliverables, dealing specifically with the trials' activities.

Our work has been concluded with a selection of appropriate bibliographical references, able to support each separate thematic section of our work, thus creating a supportive framework for each interested future reader.

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