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D3.3: Final Report of eMBB Trials

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Abstract

The focus of this deliverable is to report all the enhanced Mobile Broadband (eMBB) focused trial measurement results and analysis achieved in WP3 trial sites. The eMBB measurement tests have been categorized into two-fold as planned, i.e., radio access technologies and 5G network technologies. Moreover, a number of joint trials have been done with our Chinese twin project. The conducted results have also been reported in this deliverable, together with the joint demos.

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Executive Summary

Deliverable D3.3 reports all results achieved from the eMBB trials conducted in 5G-DRIVE, which targeted on evaluating the performance of enhanced Mobile Broadband (eMBB) over 3.5 GHz by partners in the European trial sites and over 2.6 GHz by our Chinese twin project partners in China's trial sites. WP3 partners conducted the measurements and demonstrated the latest 5G key technologies with respect on eMBB through EU trial sites in UK, Finland, Poland and Greece. Moreover, WP3 joint trials have been done together with our Chinese twin project at both Europe and China.

As originally planned, both radio access technologies as well as network technologies have been measured according to the test plans defined in the previously issued 5G-DRIVE Deliverable D3.1. More specifically, in the radio access technologies part, both outdoor and indoor eMBB non-standalone (NSA) basic performance has been measured in various trial sites based on the KPIs defined in the Deliverable D3.1. In addition, 3D multiple input and multiple output beamforming – as one of the promising techniques considered in 5G – has also been investigated. The beamforming characteristics and the effect of array antenna configuration on 3D beamforming have been studied and evaluated with the field trial measurement for both single and multiple mobile users' scenarios. In the 5G network technologies part, the proposed network slicing KPIs – as in project Deliverable D5.1 – have been tested during the designed experiments. The virtual network functions as well as fronthaul performances have also been measured and corresponding results have been analysed in this deliverable. Moreover, a number of joint trials have been conducted with our Chinese twin project regarding the eMBB basic performance in both NSA and SA 5G. The results have been explained in the present deliverable as well.

More specifically, this report contains the results achieved by WP3 during the project period as well as the performance analysis. The key findings of the eMBB laboratory and field experiments are listed as below:

1. The outdoor eMBB basic performance of Non-standalone (NSA) and standalone (SA) were measured at 5GIC trial site (Surrey, UK), VTT trial site (Espoo, Finland), Orange trial site (Warsaw, Poland) and our Chinese twin project trial site (Hangzhou, China). Both stationary tests and driving tests have been carried several times according to the pre-selected KPIs. It is observed outdoor single user peak data rate limited due to hardware in both NSA and SA architecture during the tests. NSA control plane latency is considerably higher than SA architecture.
2. The indoor eMBB measurements continued the outdoor trials by WP3 partners and the Chinese twin project partners. In Finland, the eMBB indoor measurements were performed at VTT building. The setup contained 4G and 5G picocells, which placed on different floors. It is observed through the results that locations did not have an effect on the RTT, one-way latency or jitter values. Only different network variations are presented. In Hangzhou, first the indoor coverage measurements were performed in a new office building jointly by WP3 partners and our Chinese twin project partners. The network configuration was NSA and the bandwidth for 5G was 100MHz and for LTE-1800 20MHz. The picocells place on the ceiling of an open office space. Then, another set of experiments were focused on SA outdoor gNB supporting indoor coverage. The measurements were carried on a 20-floor shopping mall in the city centre. The gNB was deployed on the top of a building opposite of the measurement area. UEs operated over 2.6 GHz and 4.9 GHz at the preselected points. It is observed that the 4.9GHz could improve the indoor coverage according to the floor layout.
3. WP3 partners and Chinese twin project partners have been jointly work together to investigate the massive MIMO beamforming characteristics and the effect of array antenna configuration on 3D beamforming, especially according to the building height. The field measurements have been tested for both single and multiple users. It is observed, the multilayer beams from 64 transmit/receive antennas at gNB can cover high-rise building with a height of 140 meters with good receive signal quality. For 3D beamforming, in a typical

with medium distance from the gNB good coverage performance can be achieved in all the low, medium and high-rise floors.

4. The network slicing KPIs proposed in Deliverable D5.1, (i.e., slice deployment time, slice deployment time scalability, etc.). have been implemented and measured in WP3, which focused only on parameters that are related to network slicing in an agnostic way. The obtained results show decent scalability of the used platform in the analysed range of numbers of deployed slices - the parallel slice deployment and termination time is considerably lower than in the one-by-one approach.
5. A service level joint demonstration also was setup between WP3 partners, which based the integration of the partner developed services and VNFs, namely the vCache in the trail test bed in Athens, Greece. It is observed that the performance has been significantly improved in terms of the size of cached content per session as well the catching latency.

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Abbreviations

3D	Three-Dimensional
3GPP	The 3rd Generation Partnership Project
4G	The 4th Generation of mobile technology
5G	The 5th Generation of mobile technology
5GIC	5G Innovation Centre
ADB	Android Debug Bridge
AGW	Access Gateway
AoD	Angle of Departure
API	Application Programming Interface
AR	Augmented Reality
ASiR	AirScale indoor Radio System
BBU	Baseband Unit
BLER	Block Error Rate
BS	Base Station
BSS	Business Support System
BW	Bandwidth
C-RAN	Cloud Radio Access Network
CLI	Command-Line Interface
CoS	Class of Service
CP	Control Plane
CPE	Customer Premises Equipment
CPU	Central Processing Unit
CQI	Channel Quality Indicator
CSI	Channel State Information
CSI-RS	Channel State Information - Reference Signal
CU	Centralized Unit
CW	Continuous-Wave
DL	Downlink
DP	Data Plane
DRB	Data Radio Bearer
DU	Distributed Unit
E2E	End-to-End
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
eMBB	enhanced Mobile Broadband

eNB	Evolved nodeB (4G)
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
EU	European Union
FDD	Frequency Division Duplex
FPS, fps	frames per second
FR1	Frequency Range 1 including sub-6 GHz frequency bands
FR2	Frequency Range 2 including 24.25 GHz to 52.6 GHz frequency bands
GbE	Gigabit Ethernet
GHz	Giga Hertz
GIS	Geographic Information System
gNB	Next Generation nodeB (5G)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Group Specification
GW	Gateway
HO	Handover
HSS	Home Subscriber Server
HTTP, http	Hyper-Text Transfer Protocol
HTTPS, https	Hyper-Text Transfer Protocol Secure
iBLER	Initial Block Error Rate
ID, id	Identifier
IETF	Internet Engineering Task Force
INS	Inertial Navigation System
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
KPI	Key Performance Indicator
LAN	Local Area Network
LOS	Line-of-Sight
LTE	Long Term Evolution (4G)
MAC	Medium Access Control
MANO	Management and Orchestration

MCS	Modulation and Coding Scheme
MIMO	Multiple Input, Multiple Output
MNO	Mobile Network Operator
MU	Multi-User
NFV	Network Functions Virtualisation
NFVI	Network Functions Virtualisation Infrastructure
NFVO	Network Functions Virtualisation Orchestrator
NLOS	Non-Line-of-Sight
NR	New Radio (5G)
NS	Network Service
NS	Network Slice
NSA	Non-standalone (5G mode)
OAM	Operation, Administration and Maintenance
OCNG	Orthogonal Channel Noise Generation
OFDM	Orthogonal Frequency-Division Multiplexing
OSM	Open Source MANO
OSS	Operational Support System
OWD	One-Way Delay
PBCH	Physical layer Broadcast Channel
PC	Personal Computer
PC	Power Control
PCC	Policy and Charging Control
PCI	Physical Cell Id
PCRF	Policy Control and Charging Rules Function
PDCCH	Physical layer Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PHY	Physical (OSI layer)
PLR	Packet Loss Ratio
PMA	Performance Monitoring Agent
PNF	Physical Network Function
PRB	Physical Resource Block
pRRH	Pico-Remote Radio Head
PTP	Precision Time Protocol
PTPv2	Precision Time Protocol version 2
PUSCH	Physical Uplink Shared Channel

QAM	Quadrature Amplitude Modulation varying from 64 to 1024
QoS	Quality of Service
QGIS	Quantum Geographic Information System (Open Source application)
QPSK	Quadrature Phase Shift Keying
R-HUB	Remote Radio Unit Hub
RAM	Random Access Memory
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RFC	Request for Comments
RI	Rank Indicator
RLC	Radio Link Control
RRH	Remote Radio Head
RRU	Remote Radio Unit
RS	Reference Signal
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTK	Real-Time Kinematic
RTT	Roundtrip Time
RU	Remote Unit
Rx	Reception
SA	Standalone (5G)
SCC	Secondary Component Carrier
SDN	Software Defined Network
SDR	Software-Defined Radio
SDT	Slice Deployment Time
SDTS	Slice Deployment Time Scalability
SINR	Signal-to-Interference-plus Noise Ratio
SN	Secondary Node
SNR	Signal-to-Noise Ratio
SRS	Sounding Reference Signal
SS	Synchronization Signal
SSB	Synchronisation Signal Block
STT	Slice Termination Time
STTS	Slice Termination Time Scalability
SUL	Supplementary UpLink

TCP	Transmission Control Protocol
TDD	Time Division Duplex
TS	Technical Specification
TWAMP	Two-Way Active Measurement Protocol
Tx	Transmission
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UP	User Plane
USB	Universal Serial Bus
UTRAN	Universal Terrestrial Radio Access Network
vEPC	virtualized Evolved Packet Core
VIM	Virtual Infrastructure Manager
VLAN	Virtual Local Area Network
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
vPMA	virtual Performance Monitoring Agent
VPN	Virtual Private Network
WP	Work Package
WWW, www	World Wide Web

1 Introduction

1.1 Objective of the document

The main objective of the actual Deliverable D3.3 is to present all the trial results conducted by enhanced Mobile Broadband (eMBB) trial work package (i.e., WP3) partners during the project time period in various 5G-DRIVE trial sites with specific focus upon eMBB. This deliverable includes all three aspects of the measurements results and analysis, that is: performance measurement and results analysis of radio access technologies; performance measurement and results analysis for 5G network technologies, and joint eMBB trials with Chinese twin project.
The consideration of very high data-rate use cases and architectures defined in the framework of the respective Deliverable D2.2, have been mapped into WP3's measurement tests planned in the Deliverable D3.1 together with 5G-DRIVE trial site architecture, components and capacities regarding the respective technical features at the radio and the core net. Selected KPIs reported in the Deliverable D3.2 have been measured during the tests over 3.5 GHz at Europe's trial sites and 2.6 GHz at China's sites.

1.2 Structure of the document

This deliverable is structured in five chapters, as follows:
Chapter 1 presents an introduction of the Deliverable by focusing on its objectives, structure and target audience.
Chapter 2 presents the conducted measurement results and analysis for performance measurement results and analysis of radio access technologies. It contains the eMBB basic performance measurements for both outdoor and indoor as well as the 5G three-dimensional (3D) beamforming analysis and field trials' results calibration.
Chapter 3 presents the performance measurements and results' analysis for 5G network technologies. It contains the network slice orchestration performance measurement, results and analysis; vCache performance measurement and fronthaul performance measurement results and analysis.
Chapter 4 presents the joint eMBB trials with the Chinese twin project. It covers the basic performance measurement indoor and outdoor for both SA and NSA 5G architecture.
The conclusion is presented in Chapter 5.

1.3 Target audience

This deliverable is open to the general public and targets the scientific/research community, as well as industry stockholders working on 5G trials with focus on eMBB. It aims to offer a better understanding of the trial measurement results and analysis of WP3 within the framework of the 5G-DRIVE project effort.

2 Performance measurement results and analysis of radio access technologies

In this chapter, measurements' results achieved through planned tests with the focus on radio access technologies are reported. First, non-standalone (NSA) basic performance measurements have been carried out in both outdoor and indoor scenarios, by the involved WP3 partners at both 5GIC trial site[2] (Surrey, UK), VTT trial site (Espoo, Finland) and Orange trial site (Warsaw, Poland). The results of single user equipment (UE) scenario have been presented and analysed. Then, the performance of 3D beamforming has been analysed and calibrated with the actual performance achieved through field trials. Finally, some recommendations have been provided, based on our trial results' analysis.

2.1 Outdoor eMBB performance measurement results and analysis

In this subsection, the outdoor measurement results over three eMBB trial sites will be presented.

2.1.1 Outdoor eMBB measurement results at 5GIC trial site

The outdoor eMBB NSA basic performance measurements have been conducted in 5GIC trial site at Surrey, VTT trial site at Espoo and Orange trial site at Warsaw. The measurement tests have been conducted according to the plan already reported in the Deliverable D3.1 [1].

2.1.1.1 Measurement environment setup

The outdoor eMBB NSA basic performance measurements in 5GIC trial site were conducted in the Stag Hill campus of the University of Surrey. The test network targeted on providing state-of-the art 5G test and demonstration platforms, which include a C-RAN test platform to support clusters of remote radio heads (RRH) supported, in turn, by high performance core processing facilities for experimental research on advanced techniques such as joint transmission coordinated multi-point transmission and reception schemes. In addition, the test network provides a unique environment to test operation of heterogeneous access networks in a real-life environment. In the context of the WP3, the conducted tests were focused on the considered eMBB scenarios.

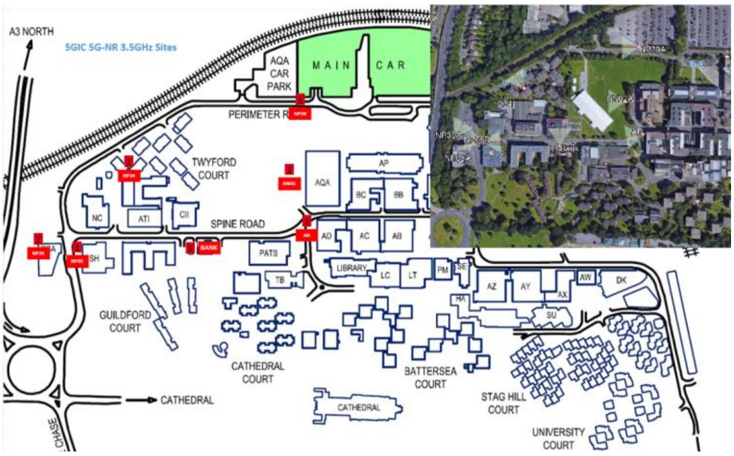


Figure 1: The outdoor deployment layout of 5GIC trial site, Surrey, UK.

The test network is connected to the Vodafone Core Network and as shown in Figure 1, the outdoor deployment consists of 7 sectors and 9 gNB. The height of the gNBs is either 5 meters or 10 meters, based on the regulation of the University. The one designated LTE eNB operating at 2.6 GHz is

[2] For more details about 5GIC see: https://www.surrey.ac.uk/institute-communication-systems/5g-innovation-centre

employed as the "anchor node" to support all the tested 5G gNB operating at 3.5 GHz. The current network configuration currently is NSA Option 3[3], as shown in Figure 2. Therefore, the tested 5G device used 4G for control plane (CP) and 5G for data plane (DP) services as the data spin services has been turned off.

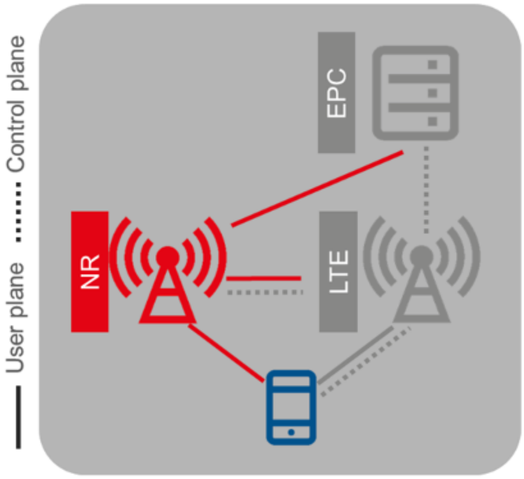


Figure 2: High-level architecture of NSA option 3x [2].

Different types of 5G UEs have been tested during our outdoor performance tests, as shown in Figure 3. The iPerf3[4] has been used as traffic generator to test the maximum network throughput during our tests for both DL and UL.

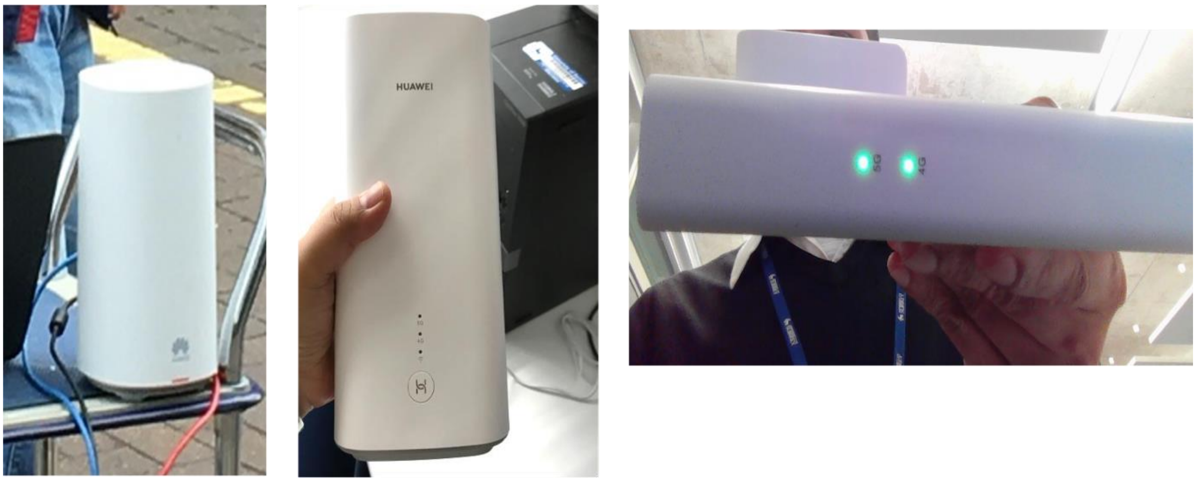


Figure 3: Tested CPEs at 5GIC trial site.

2.1.1.2 Planned performance measurement tests

According to the trial plan in [1], six trial measurements (as listed in Table 1) have been designed to test the following selected KPIs as shown in Table 1.

[3] For further details also see, *among others*: https://www.gsma.com/futurenetworks/wiki/5g-implementation-guidelines/

[4] The iPerf3 is a tool for active measurements of the maximum achievable bandwidth on IP networks. It supports tuning of various parameters related to timing, buffers and protocols. For further information also see: https://iperf.fr/iperf-download.php

Trials Date	Measured KPIs
June 2019	Stationary Tests Peak Data Rate UL/DL
June 2019	Drive Tests Cell Capacity
July 2019	Drive Tests
December 2019	Latency Tests
December 2019	Drive Tests
December 2019	User-Experienced Data Rate

Table 1: Summary of the conducted outdoor trials at 5GIC site.

2.1.1.3 Measurement results

Several measurements have been carried over Stag Hill Campus as shown in Figure 4 and the results were used to optimise the 5G test network in Stag Hill campus, in terms of signal strength optimization, rank optimization, etc.

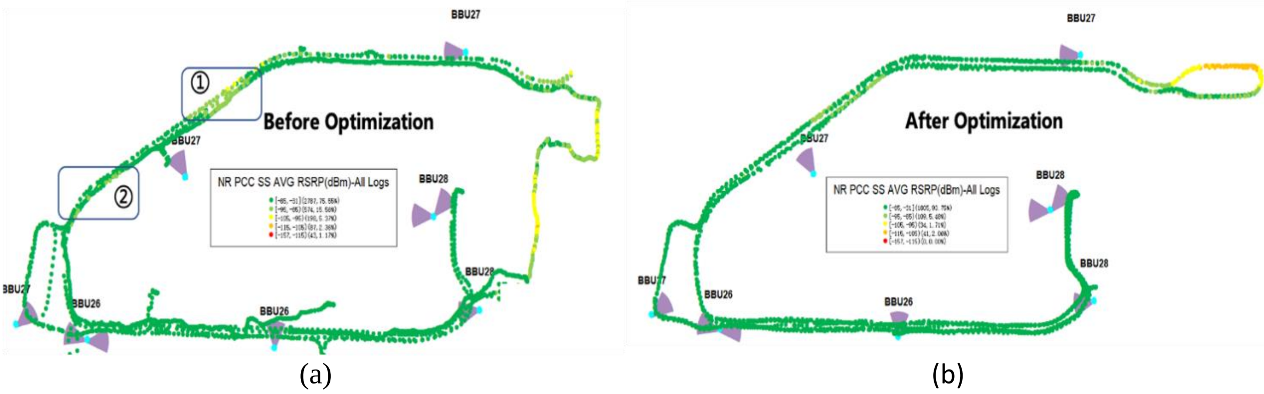
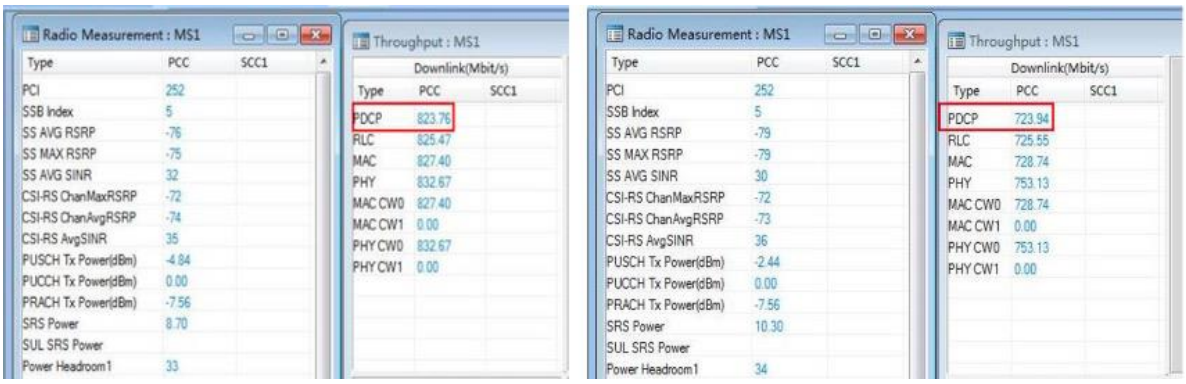


Figure 4: Received signal strength drive test measurement optimization (a) before optimization; (b) after optimization.

As shown in Figure 4, the drive test of received signal strength for BBU26, BBU27 and BBU28 were measured before and after optimization. It is observed that overall 5G network received signal strength is high. This is because the small intra-site distance and low antenna heights. However, as in Figure 4 (a), the areas highlighted by number 1 and 2 are relatively low, compared to others. After modified the mechanical and digital tile angle, the received signal strength of these two areas has been improved as the measured results show in Figure 4 (b).

Single UE peak data rate for UL and DL in stationary test

A stationary measurement approach has been employed in our tests to measure the single UE peak data rate for UL and DL. Exhaustive points have been selected from each sector to find the peak data rate and measurements were conducted at least within a 2-minute time period for each pint. As in the example shown in Figure 5, the measured DL UDP peak data rate during a stationary test can be higher than 800 Mbps for UDP and higher than 700 Mbps for TCP (cf. Figure 5). Here it is worthy to point out that the peak data rate reaches the maximum performance of the measured UE.



(a) UDP protocol (b)TCP protocol

Figure 5: An example of measured DL UDP and TCP protocol peak data rate.

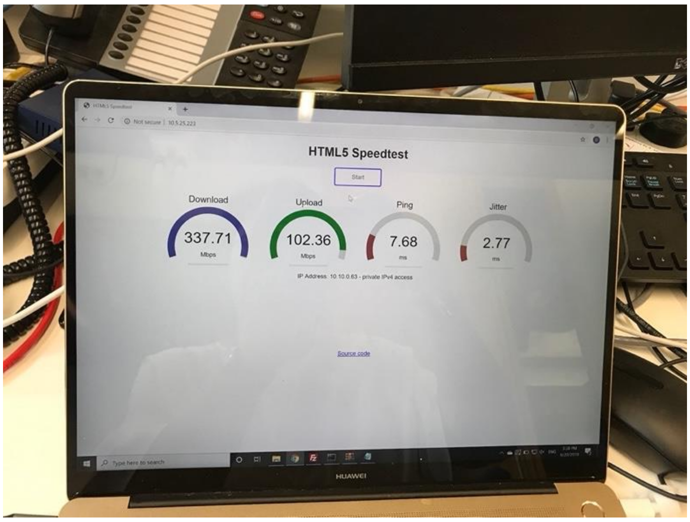


Figure 6: An example of measured UL UDP peak data rate.

The DL single UE peak data rate in stationary test is around 824M for UDP and 724M for TCP during these tests. This is due to the maximum rate has reached the limits of the test device.

Cell capacity

After stationary test measurements, drive tests have also been conducted to measure the DL throughput results to compare with the results achieved during stationary measurements.

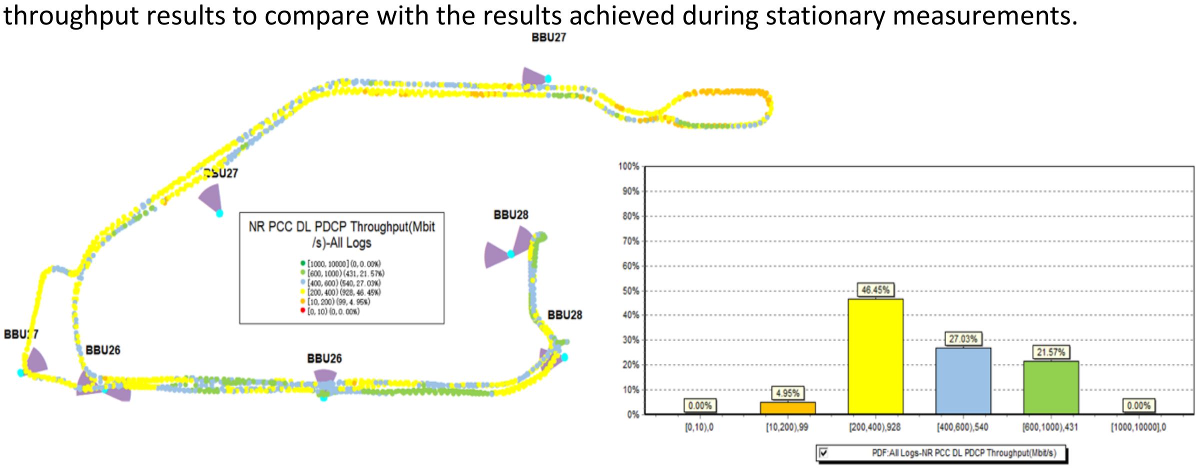


Figure 7: DL throughput measurement results after tilt angle optimisation.

As shown in Figure 7, around 95% of the measured sample points can provide results higher than 200 Mbps DL data rate, while around 48.6% of the measured sample points can provide results higher than 400 Mbps.

Control plane latency

The definition of control plane latency given in the 3rd Generation Partnership Project (3GPP) TR 38.913 is "the time to move from a battery efficient state (e.g., IDLE) to the start of continuous data transfer (e.g., Active)". The trial 5G at Surrey trial site is NSA architecture as shown in Figure 2. The control plane latency includes 4G random access, 4G bearer setup, 5G measurement and secondary cell group (SCG) addition. As SCG has not been enabled at Surrey site, there are only three parts of latency has been measured during our test as shown in Figure 8, Figure 9 and Figure 10.

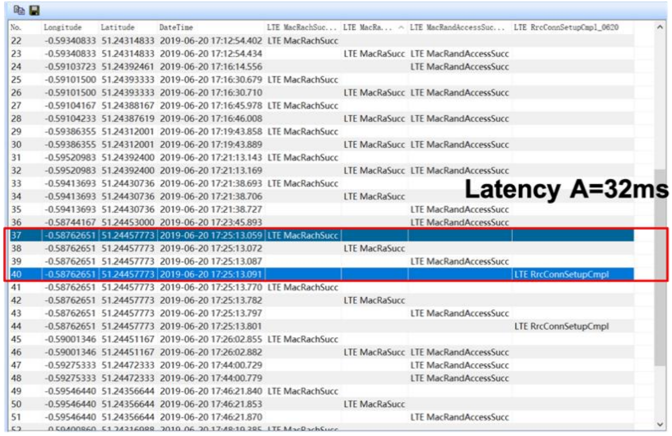


Figure 8: Measurement of 4G random access (latency A).

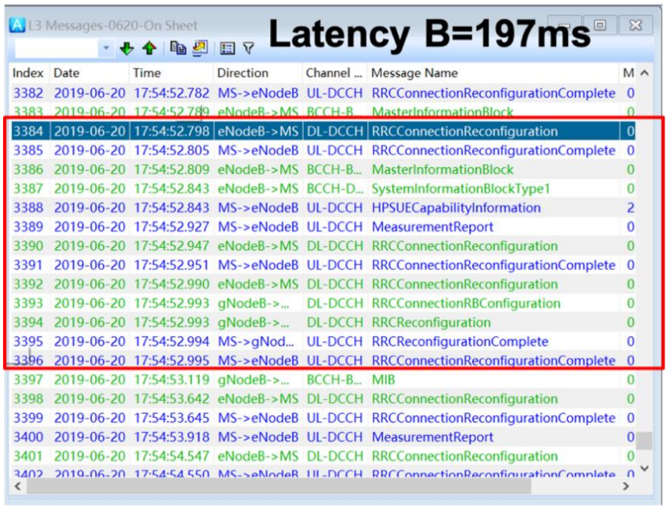


Figure 9: Measurement of 4G bearer setup (latency B).

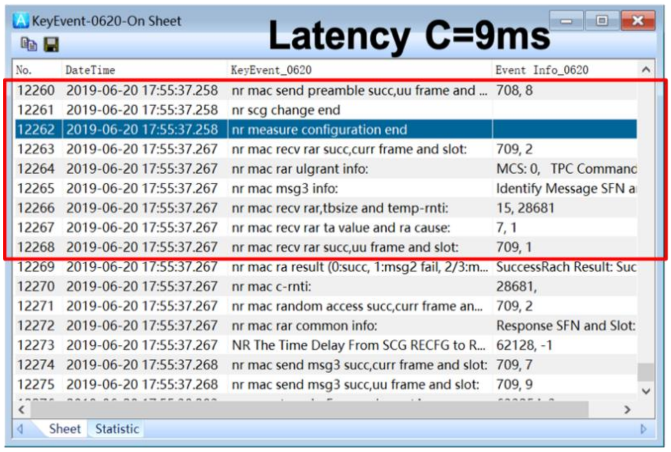


Figure 10: Measurement of 5G measurement (latency C).

User-experience data rate

In our joint kick-off meeting with China Mobile in November 2018, our first joint Augmented Reality (AR) demo has been setup between China Mobile in Beijing, China and University of Surrey in Surrey, UK. During the demo, the peak data rate measured at Surrey is around 45-55 Mbps and the fps is around 30 fps.

During November and December 2019, the second joint AR demo was tested again between Surrey site and China Mobile site, several times. However, due to the updated network firewall security issues in China, the network performance (i.e., data rate and E2E latency) could not meet the requirements that were expected for this type of service. The achieved average frame rate during the test was below 20 Mbps at 20 fps, which could not meet the minimum requirement for demo.

KPIs	Demo with China Mobile in November 2018 kick-off meeting	Tests with China Mobile in November 2019	Demo with VTT in December 2019
Peak Data Rate	45-55Mbps	18-22 Mbps	45-50 Mbps
fps	30 fps	20 fps	30 fps

Table 2: Average data rate measured during AR demo in December 2019.

To overcome this practical situation, another joint AR demo was then set up between the Surrey trial site and Espoo trial site in December 2019. EU partners from the 5G DRIVE project and partners from the Chinese twin project participated to this demo at the Surrey site as shown in Figure 11. Realtime video was captured through Kinect sensor (as shown in Figure 11 on the left). Then the video was transmitted through 5G core network of Surrey trial network to VTT trial site as shown in Figure 11 on the right handside.

Figure 11: Kinect sensor used in cloud-based AR demo at University of Surrey (left). The 5G-DRIVE project coordinator and partners from the Chinese twin project participated to the joint AR demo at Surrey site (middle) and video shown at VTT site (right).

2.1.2 Outdoor eMBB trial results at Espoo trial site

In Espoo eMBB trial site, the 5G tested network works on the NSA mode, in which the gNBs operate at 3.5 GHz and the 4G anchor eNodes operate at 1.8 GHz. The stationary measurements were conducted with different types of 4G and 5G devices. The 5G terminals used in the trials were OnePlus 5G Pro[5] and Huawei CPE. The terminals were connected to Nemo Outdoor[6] 5G version 8.60, to collect

[5] For further details see, *for example*: https://www.oneplus.com/gr/8-pro/specs

[6] Also see, *among others*: https://www.scribd.com/document/463645406/Nemo-Outdoor-User-Manual-pdf

information at different layers. For eMBB research, both drive and stationary measurements were conducted with a set of mobile applications including IPERF3 TCP/IP and UDP, Ookla SpeedTest, Fast SpeedTest, and Ping applications. The studied performance parameters included uplink and downlink data rates at different layers, packet error rates, coverage, signal-to-noise ratio (SNR) and latency. Figure 12 shows a measurement setup used in stationary 4G/5G measurements with multiple terminals. The white box in the upper right corner is a Huawei 5G CPE. As shown in Figure 13, the data rates were measured at four layers to understand better the UL and DL data flows through 5G gNBs[7] and 4G eNodeBs[8].

Figure 12: Stationary measurement setup with Nemo Outdoor and a set of 4G/5G terminals.

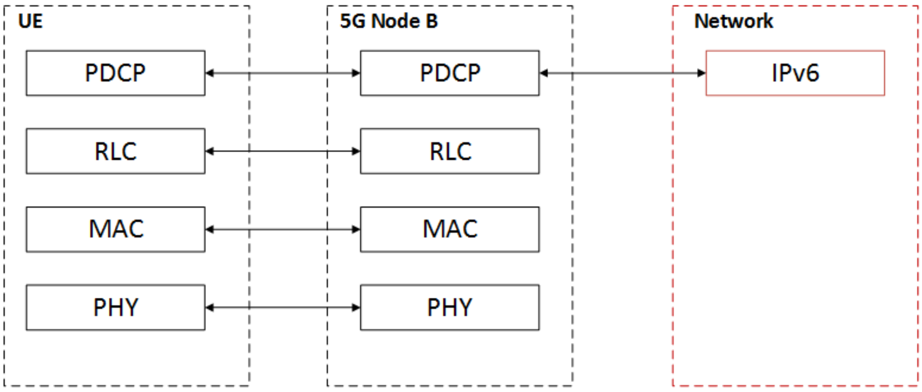


Figure 13: Data rates monitored at different layers.

Outdoor measurements were conducted with VTT and Indagon's[9] cars equipped with 4G/5G communication and positioning devices. For 5G NSA measurements, a OnePlus 5G Pro terminal was connected to Nemo Outdoor 5G. The drive test was performed three times to measure RTT latency with Ping and data rates at different layers with IPERF3 and with TCP/IP traffic. In order to measure peak throughputs, multiple TCP/IP connections were created to a dedicated IPERF3 server. The accurate locations for measurement samples were obtained by using Indagon's ZED F9K[10] (with an

[7] The "g" in gNB stands for "Next Generation NodeB". 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 gNB.

[8] The evolved NodeB. Is the base station in LTE systems. Each eNodeB serves one or more E-UTRAN cells.

[9] https://indagon.com/

[10] Also see, *for example*: https://www.u-blox.com/sites/default/files/ZED-F9K_ProductSummary_%28UBX-19047326%29.pdf

inertial sensor) and ZED F9P[11] RTK modules providing location at 10 Hz frequency. The drive test also included route segments inside parking halls. In those spaces, the locations for measurement samples were obtained afterwards, from lidar data produced by Velodyne VLP-16[12] (Puck LITE).

Figure 14: Drive tests focusing on eMBB and positioning with GNSS/RTK/INS devices.

Figure 14 and Figure 15 show the equipment used in the drive measurements. An Indagon's measurement car is equipped with power supplies and this enables having the laboratory setup inside the vehicle.

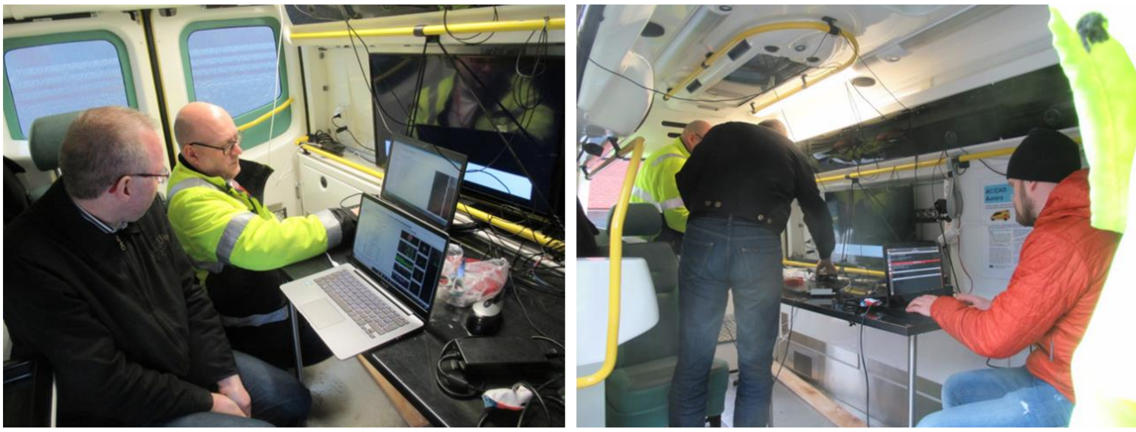


Figure 15: Communication and positioning equipment inside the measurement car.

The 5G measurement values were monitored from the Nemo Outdoor laptop, as shown in Figure 16. The mobile services started either from the Nemo Outdoor or from the mobile terminal. The communications and positioning results were analysed by focusing on data rates, locations of handovers and availability of location information to help with handovers. The measured KPIs were RSRP, RSRQ, etc., as defined in D3.1 [1]. Figure 17 shows the PDCP level data rates in DL direction and observed location accuracies along the route. The trial plans and measured KPIs were adjusted according to the tests at China's site(s).

[11] Also see, *for example*: https://www.u-blox.com/sites/default/files/ZED-F9P_DataSheet_%28UBX-17051259%29.pdf

[12] Also see, *for example*: https://velodynelidar.com/products/puck-lite/

Figure 16: Nemo Outdoor used for monitoring 5G measurements.

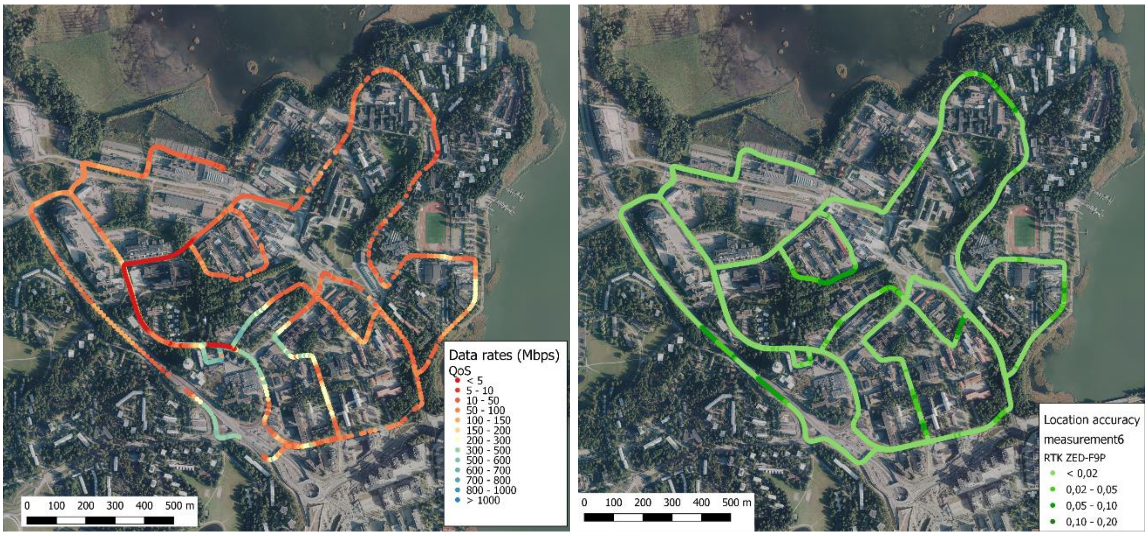


Figure 17: Communication and positioning results for eMBB.

2.1.3 Outdoor eMBB NSA performance measurement results and analysis at Orange trial site

The outdoor eMBB NSA performance measurements have been conducted in the Orange 5G NSA Trial (Pre-Commercial) site located in Warsaw premises. The results can be treated as an extension of the 5G eMBB measurements presented in other sections of the deliverable.

2.1.3.1 Measurement environment

The measurements were conducted in the urban area, in 4 measurement points, approximately 50, 100, 150 and 200 meters away from the test gNB. The tests were performed in the vicinity of the station to prevent undesired handover to nearby commercial LTE network. The measurement locations (marked with red dots) and location of the station (orange dot) have been presented in Figure 18.

Figure 18: The measurement locations (left) and equipment used to collect the network data (right).

The selected area was a part of the Pre-Commercial 5G NSA Trial Site connected with the operating Orange Core Network and targeting 5G-LTE interworking option 3x. Secondary Node Terminated Split Data Radio Bearer (SN Terminated Split DRB) is used in the test environment.

To efficiently use two radio interfaces and the Downlink User Plane Aggregation function was active to enable simultaneous data transfer in downlink using both LTE and 5G (in the examined case, one LTE cell and one 5G cell). In the case of uplink, all transmitted data was carried over 5G. The configuration of the gNB is presented in Table 3

RAT	Bands	Channel width	Duplex mode	MIMO
5G NR	B42 (3400-3480 MHz) - test	80 MHz	NR TDD	Massive MU (64 TX/64RX)
LTE	B1 (2100 MHz)	5 MHz	FDD	MU

Table 3: Parameters of the gNB used during tests.

The configured station enables measurements within 5G eMBB, i.e. registration, end-to-end call setup, throughput measurement, etc. Moreover, the edge server installed close to the gNB enables accurate latency measurements.

The measurements were collected with Samsung Galaxy A42 5G (A426B/DS) smartphone that was controlled (via USB cable) by Accuver's XCAL software[13] – a test tool designed to troubleshoot, monitor, maintain and optimize wireless voice and data network performance. To extract and analyse the data from the collected logs, Accuver's XCAP[14] was used, i.e., the platform extending XCAL by

[13] For further details also see: http://www.accuver.com/sub/products/view.php?idx=6

[14] http://www.accuver.com/sub/products/view.php?idx=14

analysis and mining capabilities. Latency measurements were performed using the Ping application installed on the UE.

2.1.3.2 The measurement scenarios

The following tests were conducted at each of the 4 measuring points:

- The sequence of downloading 2 GB files from the Orange server for 60 seconds with the maximum possible speed with 10 seconds breaks (5 repetitions).
- The sequence of sending 2 GB files to the Orange server for 60 seconds with the maximum possible speed, then 10 seconds idle (5 repetitions).
- Test of communication delays with the Orange server by sending 200 packets (1 packet every 1 ms).

The post-processed results have been presented in section 2.1.3.3.

2.1.3.3 eMBB measurement results

Downlink throughput measurements

The temporary 5G physical channel throughput values registered during each downlink measurement scenario have been presented in Figure 19.

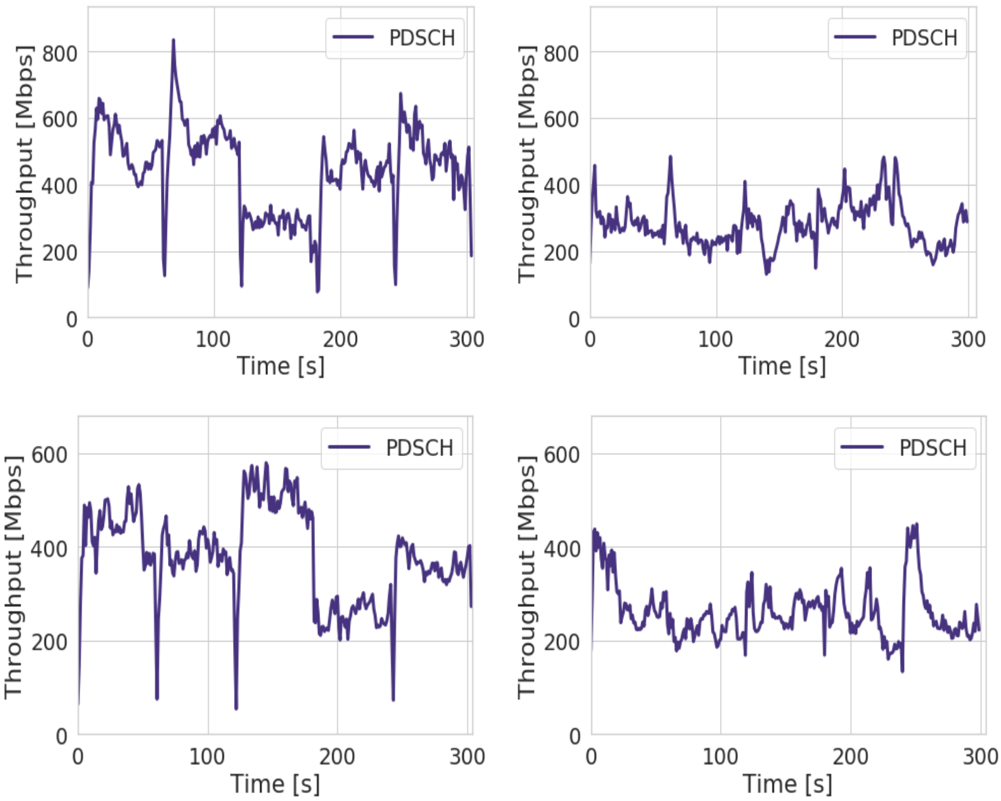


Figure 19: Temporary physical channel throughput in DL (PDSCH) for 5G during download measurement scenario. Results for 50m (top left), 100m (top right), 150m (bottom left), 200m (bottom right).

The maximum throughput has been obtained for the measurement point located 50 m away from gNB. The significant drops of throughput are caused by the end of measurement repetition (drops occur with a period of 60s). For 100m and 200m, the measurement series are not easily distinguishable, probably due to the multipath propagation.

The data rates of PHY (PDSCH channel), the MAC and RLC layers and related qualitative parameters (i.e. the Reference Signal Received Quality and the Rank Indicator) were collected. The parameters mentioned above are presented in

5G	PDSCH [Mbps]		MAC [Mbps]		RLC [Mbps]		RSRQ [dB]			RI		
Distance [m]	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Min	Avg	Max	Min
50	445.2	834.3	397.2	715.3	393.3	710.6	-11.77	-8.72	-17.83	4.00	4	4
100	279.1	483.5	250.1	440.8	242.4	436.1	-10.66	-10.34	-11.17	3.03	4	3
150	380.1	578.7	339.2	511.6	337.0	513.6	-10.35	-5.22	-10.61	3.00	3	3
200	261.4	448.4	230.1	401.5	223.2	399.1	-10.40	-8.93	-10.73	3.00	3	3

Table 4 and Table 5 for 5G and 4G, respectively, are depicted in Figure 20.

5G	PDSCH [Mbps]		MAC [Mbps]		RLC [Mbps]		RSRQ [dB]			RI		
Distance [m]	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Min	Avg	Max	Min
50	445.2	834.3	397.2	715.3	393.3	710.6	-11.77	-8.72	-17.83	4.00	4	4
100	279.1	483.5	250.1	440.8	242.4	436.1	-10.66	-10.34	-11.17	3.03	4	3
150	380.1	578.7	339.2	511.6	337.0	513.6	-10.35	-5.22	-10.61	3.00	3	3
200	261.4	448.4	230.1	401.5	223.2	399.1	-10.40	-8.93	-10.73	3.00	3	3

Table 4: Downlink throughputs and radio signal quality parameters for 5G.

4G	PDSCH [Mbps]		MAC [Mbps]		RLC [Mbps]		RSRQ [dB]			RI		
Distance [m]	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Min	Avg	Max	Min
50	13.13	29.55	11.94	28.45	8.57	22.32	-8.94	-6.86	-11.28	1.66	2	1
100	8.54	29.48	7.71	23.18	3.88	10.93	-9.13	-7.48	-11.07	1.99	2	1
150	11.95	21.35	10.86	21.00	8.89	18.53	-8.86	-6.42	-12.09	1.86	2	1
200	8.14	27.80	7.31	27.03	2.59	9.81	-8.92	-7.65	-10.90	1.94	2	1

Table 5: Downlink throughputs and radio signal quality parameters for 4G.

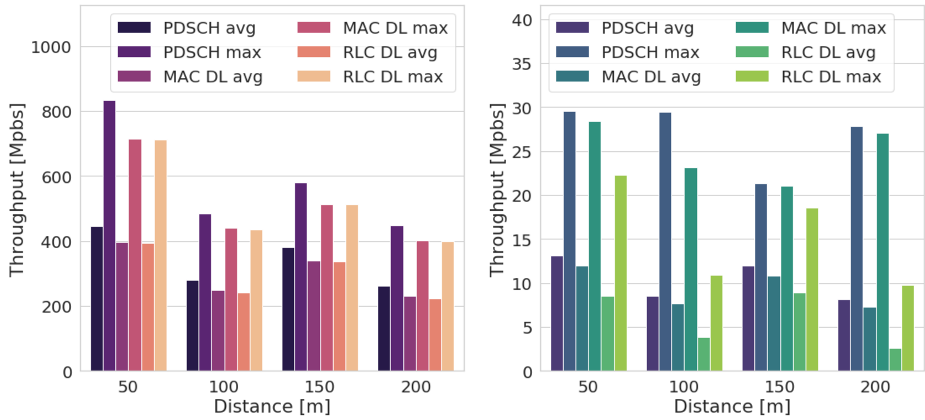


Figure 20: Downlink throughputs obtained in PHY (PDSCH), MAC and RLC layers for 5G (left) and 4G (right).

The maximum obtained transmission speeds in the PDSCH channel reached around 835 Mbps for 5G and almost 30 Mbps for 4G, which was registered near the gNB (50m). On average, the achieved throughput exceeds 400 Mbps for 5G and 13 Mbps for LTE (best case). A considerable drop of throughput can be observed for a 100m measurement point, caused probably by the tall buildings in the area. A similar issue can be observed for LTE. The qualitative parameters measured and calculated by the UE are presented in Figure 21 and Figure 22.

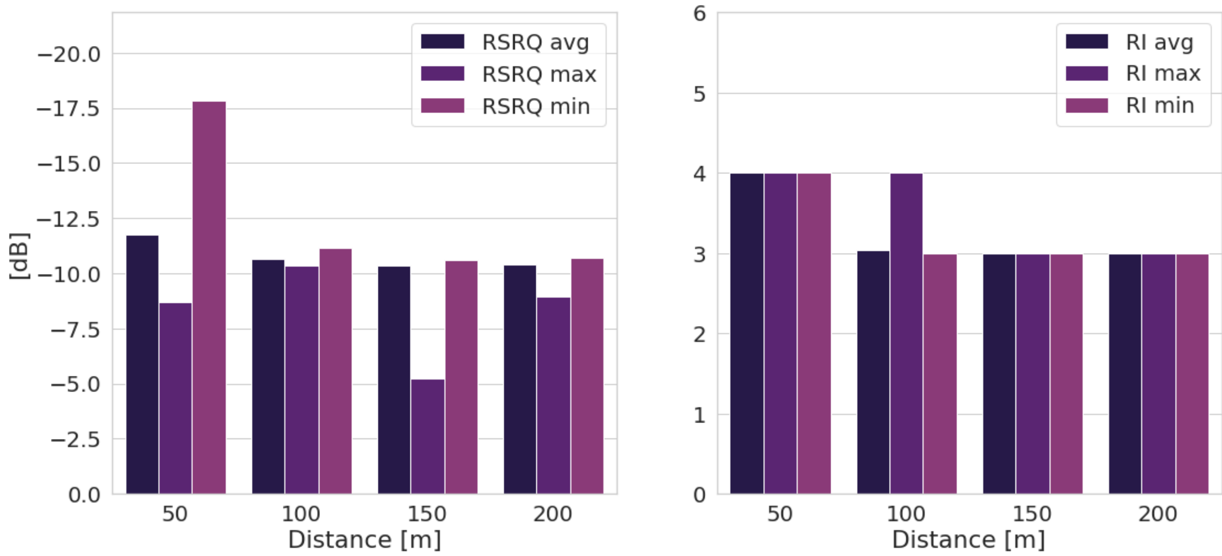


Figure 21: 5G radio signal quality parameters: RSRQ (left), RI (right).

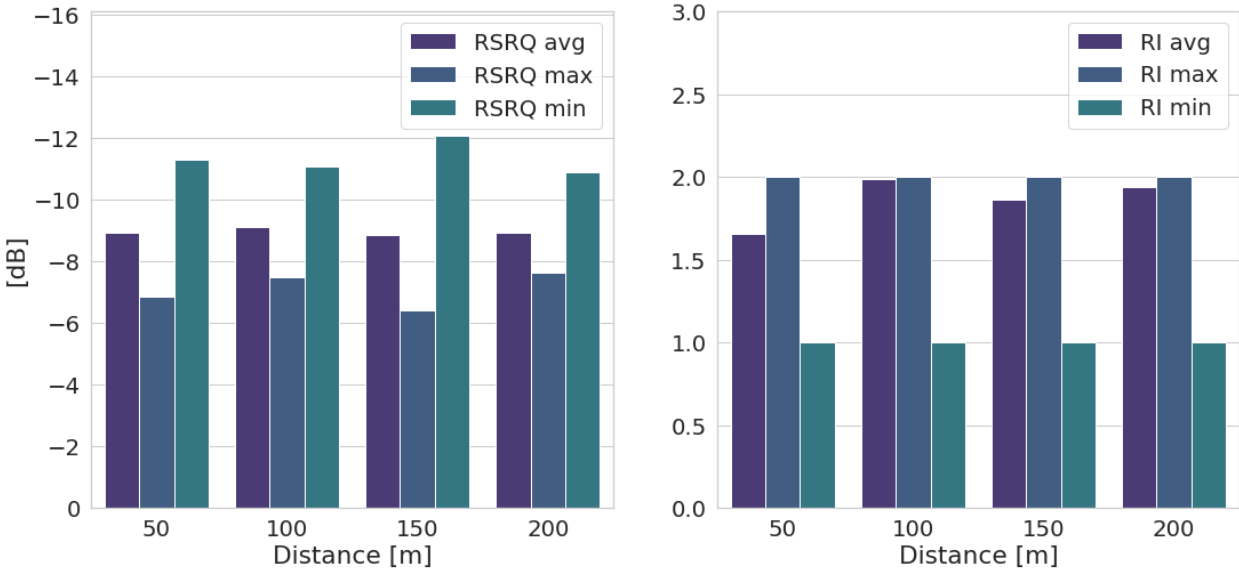


Figure 22: 4G radio signal quality parameters: RSRQ (left), RI (right).

The average RSRQ values are in the range of –10 dB and –15 dB for 5G and around –8 dB for 4G, which can be treated as good radio conditions. Nonetheless, a significant drop of RI can be observed (from 4 to around 3), signifying interferences between RX antennas and therefore reduced throughput (5G case). For 4G, RI values were equal to 2 during most of the measurements with occasional drops to 1 (indicated by average larger than 1.5).

Uplink throughput measurements

Afterwards, the uplink measurements were carried out. In this case, the data transmission was performed only over 5G. The temporary 5G physical channel throughput values registered during each uplink measurement scenario have been presented in Figure 23.

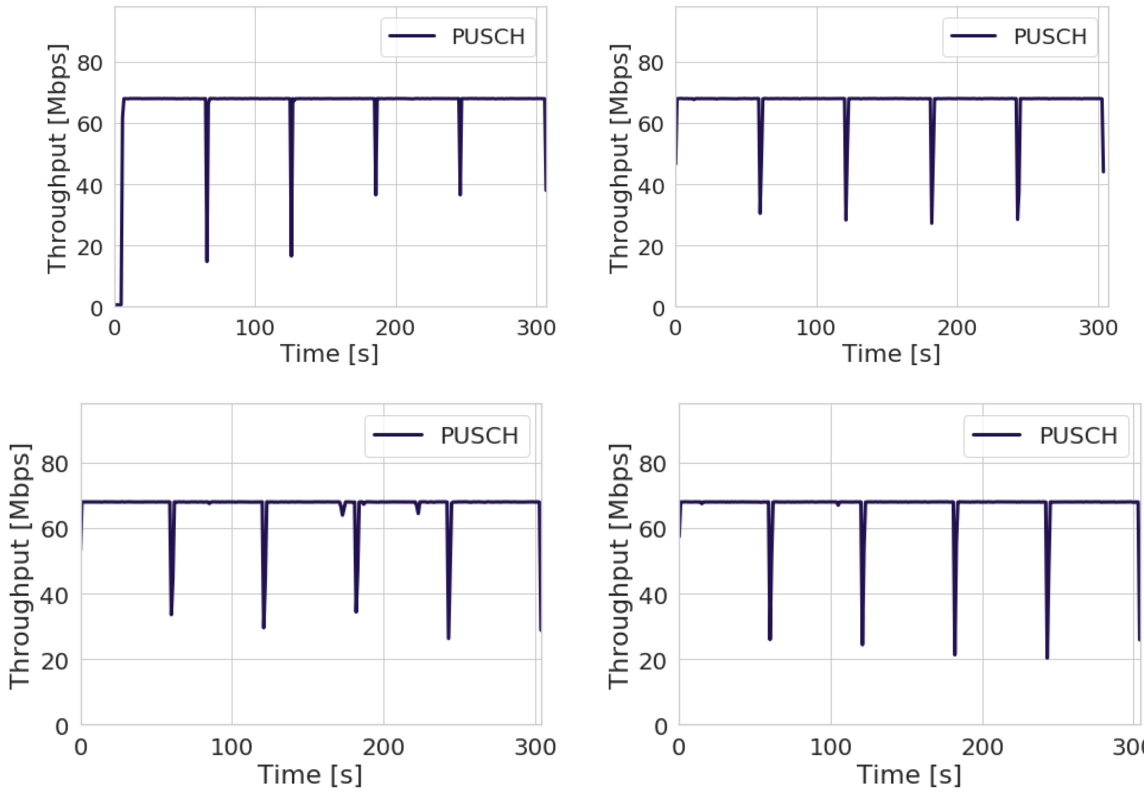


Figure 23: Temporary physical channel throughput in UL (PUSCH) for 5G during upload measurement scenario. Results for 50m (top left), 100m (top right), 150m (bottom left), 200m (bottom right).

Similar throughput values were observed for each of the measurement points. The change in the distance from the base gNB (within the measurement points from 50m to 200m) did not cause any significant changes in throughput. The considerable drops of throughput are caused by the end of measurement repetition (drops occur with a period of 60s). Moreover, there are slight deviations from the mean value, which urban conditions may cause. The data rates obtained on PHY (PDSCH channel), MAC and RLC layers as well as RSRQ and RI for 5G were collected and presented in Table 6 and depicted in Figure 24.

5G	PUSCH [Mbps]		MAC [Mbps]		RLC [Mbps]		RSRQ [dB]			RI		
Distance [m]	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Min	Avg	Max	Min
50	66,47	68,05	66,46	68,05	66,63	68,04	-11,51	-10,40	-14,97	4,00	4	4
100	67,04	68,05	67,04	68,05	67,01	68,17	-10,49	-10,23	-11,40	3,00	3	3
150	66,99	68,05	66,99	68,05	66,87	68,04	-10,38	-8,31	-10,58	3,30	4	3
200	67,01	68,05	67,01	68,05	67,12	68,04	-10,49	-6,88	-11,56	3,09	4	3

Table 6: Uplink throughputs and radio signal quality parameters for 5G.

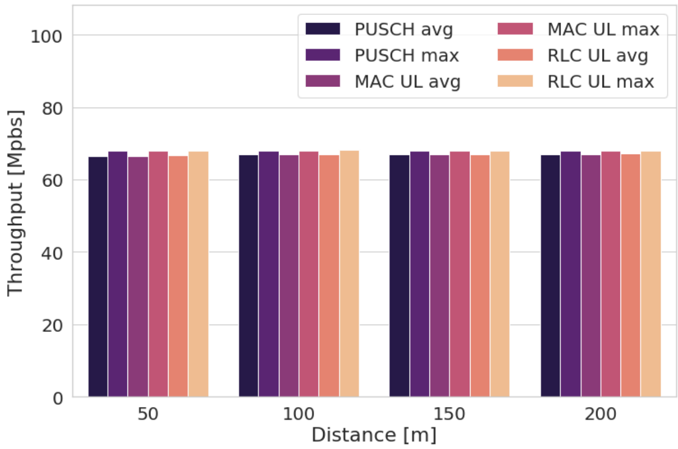


Figure 24: Uplink throughputs obtained in PHY (PUSCH), MAC and RLC layers for 5G.

The maximum obtained transmission speed in the PUSCH channel reached 68.05 Mbps for each of the measurement points. On average, the achieved throughput of about 67 Mbps is also very similar for each point. The qualitative parameters measured by the UE are presented in Figure 25.

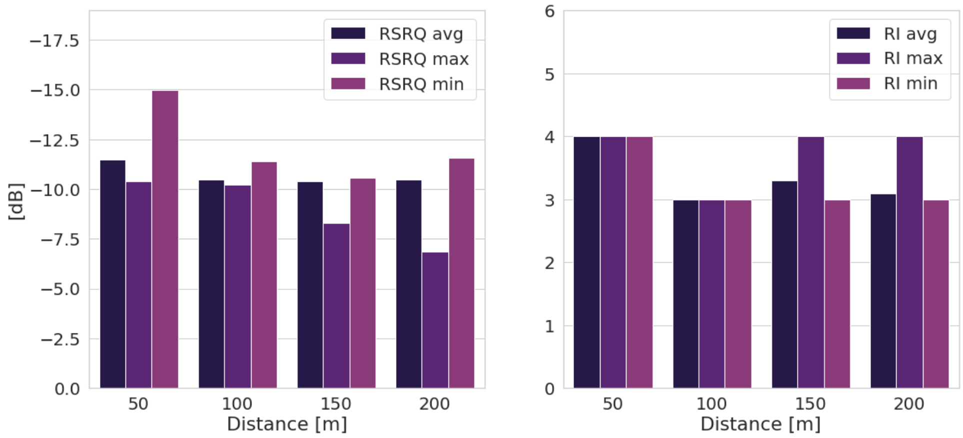


Figure 25: 5G radio signal quality parameters: RSRQ (left), respective RI (right).

The average RSRQ values are in the range of –10 dB and –11.5 dB, which can be treated as good radio conditions. For all measurement points, it was observed that the RI parameter varies between 3 and 4. Increasing the RI to 4 (as it was for entire measurements for 50 m) does not increase throughput. RI=3 is sufficient to achieve the maximum throughput in the tested conditions.

User data transfer – DL/UL (5G+4G)

A comparison of average and maximum of the user-experienced throughput (application layer, APP) for downlink (5G and 4G in total) and uplink is presented in Table 7 and depicted in Figure 26.

Distance [m]	APP DL avg [Mbps]	APP DL max [Mbps]	APP UL avg [Mbps]	APP UL max [Mbps]
50	382.47	671.94	63.61	65.37
100	231.14	431.71	63.59	64.71
150	328.39	518.41	63.47	67.30
200	211.50	386.26	63.57	66.46

Table 7: User data transfer.

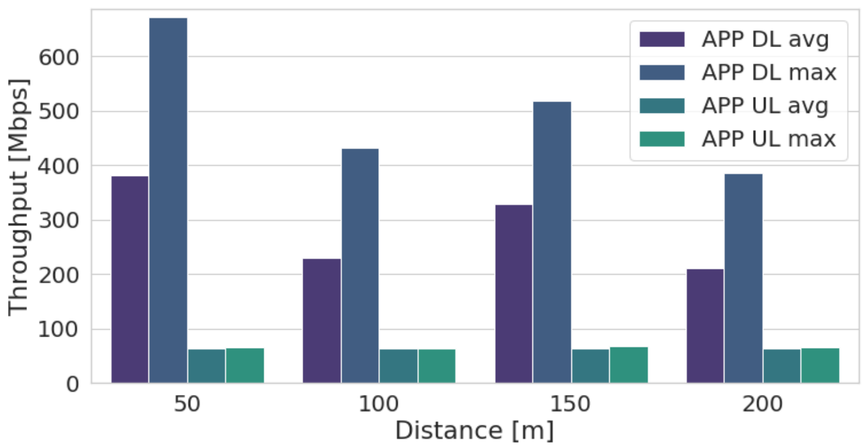


Figure 26: Throughputs in the application layer (5G+4G) for UL and DL.

The best user-experienced throughput reaches over 670 Mbps for DL and over 67 Mbps for UL. On average, around 380 Mbps for DL and 60 Mbps transfer speed was maintained.

5G delay measurements

The Round Trip Time (RTT) measurements obtained during communication with the preconfigured edge server located near the gNB is presented in Table 8.

Distance [m]	RTT Min [ms]	RTT Avg [ms]	RTT Max [ms]	RTT Mdev [ms]
50	9	13	25	2.5
100	9	13	34	3.4
150	9	14	73	5.4
200	9	13	26	2.9

Table 8: RTT parameters for local edge server located close to gNB.

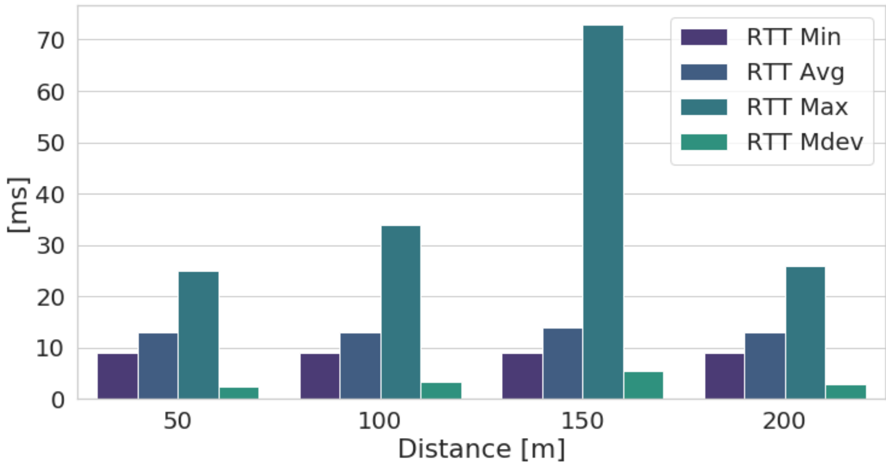


Figure 27: RTT parameter obtained for the local edge server.

The minimum achieved latency was 9 ms, while the average was 13-14 ms. The most significant deviation reached 5.4 ms for 150m. The maximum value of 73 ms delay (150m) was caused by operation in a live environment (probably by the server issues).

2.2 Indoor eMBB performance measurement results and analysis

2.2.1 Indoor eMBB NSA performance measurement results and analysis at Espoo trial site

The indoor eMBB performance measurements are a sort of continuation to outdoor trials carried out by WP3 and the Chinese twin project partners in Hangzhou China, Espoo Finland and Kent UK. This subsection focuses upon indoor trials that were planned according to D3.1 eMBB test plan [1].

2.2.1.1 Measurement environment setup

In Finland, the eMBB indoor measurements were performed at VTT Espoo building, possessing connectivity to 5G test network, dedicated for research purposes. The 5G test network was built together with VTT, Nokia and Aalto University and it covers multiple buildings and outdoor areas in the Otaniemi area. The measurement setup at VTT building contained 4G and 5G picocells that were placed on different building floors to support both communications and cellular positioning research needs. Therefore, the network was denser than a conventional indoor network.

Figure 28: 4G and 5G picocells and indoor robot used in the trial.

In the test network, 4G picocells were operating at LTE FDD 2600 MHz band 7. The allocated bandwidth for it is 10 MHz. NR picocells were operating at TDD 3500 MHz n78 band and the allocated bandwidth is 60 MHz. Thus, the total bandwidth of network was significantly smaller than in a commercial mobile network. The network configuration was also Non-Standalone (NSA) Option 3x, as shown in Figure 2. This allowed a quick deployment of the 5G network to support eMBB services. Only minor modifications to the existing 4G indoor network were needed. Option 3x primarily focused on eMBB while sub-6GHz frequencies were used for increased data capacity and utilized the existing 4G infrastructure. The radio access network was composed of eNBs (evolved NnodeBs) acting as master nodes, and gNBs (Next generation nodeBs) were secondary. The existing 4G picocells were used as anchor nodes for 5G picocells. The radio access network was connected to EPC (Evolved Packet Core). The network supported both legacy 4G devices and 5G devices with NR protocols. The 5G devices were using 4G for control plane and 4G/5G for data plane services. The NSA Option 3x is a logical transition to move gradually from NSA to SA.

The eMBB performance trials were performed in September and December 2020, with different network configurations. Altogether, five separate trials were carried out to test equipment and to validate the performance of the test network and of its core network components. Figure 29 presents the test setup that includes non-extended and extended coverage scenarios. The core configuration included two eNB-gNB pairs installed on the same building floor. The first eNB-gNB pair was installed next to the stairs (as shown in Figure 28) having LOS conditions along the corridor. The second eNB-gNB pair was installed on a laboratory having NLOS conditions to the corridor. The first set of measurements was performed with this setup. During the second phase, the pRRH chaining feature was used to extend 5G coverage along the corridor. An additional pRRH and a 4G picocell were placed at the end of the corridor. The pRRH was connected to the 5G gNB in the laboratory with a fibre connection shown as a grey line in Figure 29.

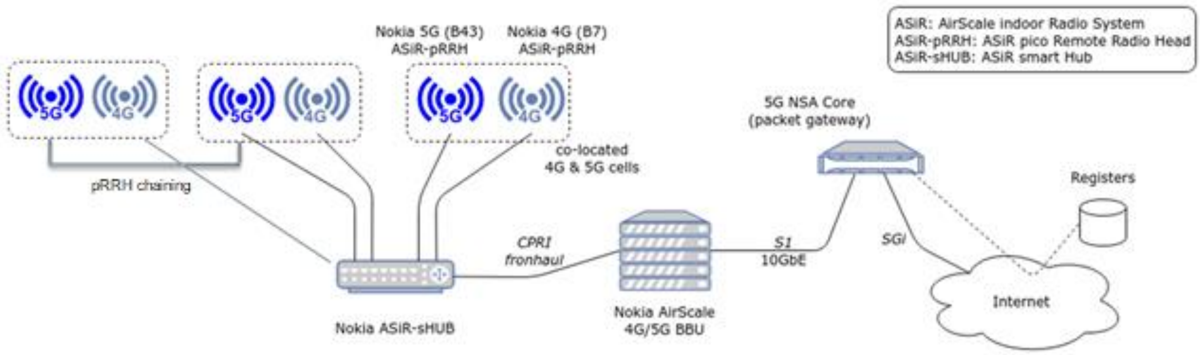


Figure 29: NSA test network configuration.

As a part of the performance measurements, remote and local EPC placements were tested to assess their impacts on latency in the network. During September trials, the remote EPC was installed at VTT's premises in Oulu, 600 km away from the trial site and during December trials the local EPC was placed in a lab next to the measurement site.

The measurements were performed with three 5G phones. The test phones were OnePlus 7 (Nemo Outdoor firmware), OnePlus 8 (Nemo Outdoor firmware) and OnePlus 8 (Nemo Handy firmware). The firmware of the phones was updated to support Keysight's Nemo Outdoor and Handy tools. The phones were connected via a USB to a laptop running Keysight's 5G Nemo Outdoor shown in Figure 30.

Figure 30: Nemo Outdoor with connected 5G phone.

The 5G measurements were conducted in idle (coverage), maximum throughput (iPerf3 UL and DL TCP/IP traffic), and RTT modes. Ookla Speedtest and Internet FAST tools were also utilized to compare throughput results. To achieve similar throughput with iPerf3, 10 parallel TCP/IP connections and window size 512K were used. UL and DL directions were measured in parallel, using Android Debug Bridge (ADB) application [3]. It allows executing pre-made scripts on the measurement phones using Windows PowerShell[15] application. For RTT measurements, both local iPerf3 server and public Google server (8.8.8.8) were used. The measurements were complemented with one-way latency measurements conducted with Qosium tool[16]. This tool requires accurate Precision Time Protocol (PtP) synchronisation and installation of measurement probes at both endpoints. Time services [4] from the National Metrology Institute VTT MIKES were utilized to achieve sufficient time synchronisation precision. The measurement results were analysed with Keysight's Nemo Outdoor Analyze tools.

[15] For further information see, *for example*: https://en.wikipedia.org/wiki/PowerShell

[16] For further details also see: https://www.kaitotek.com/qosium

Further processing was done with VTT's own analysis tools and QGIS application[17].

2.2.1.2 Performance test design

The trials were performed according to the trial plan [1]. The objective was to assess the performance of NSA Option 3x for indoor eMBB services, effects of extended coverage using pRRH chaining and deploying local and remote EPC configurations. Furthermore, the trials were used for investigating differences between OnePlus 8 5G Pro and OnePlus 7 5G Pro phones and to see how 5G test network behaves when multiple phones are connected to the same gNBs. The measurement process included four stationary measurements and a robot route along a corridor as shown in Figure 31. The stationary measurements were done in excellent (green), good (yellow), medium (orange) and bad (red) radio conditions. Stationary measurements lasted for 2 minutes. The average sampling rate of the phones was around 0.5 s. The robot measurements were performed along a pre-defined route that included both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) regions. The measurements were done in both directions in order to study locations of handovers and their impacts on eMBB services. Each measurement was repeated at least two times. More repetitions were made if the two previous measurements were deviating too much.

The measurement setup is shown in Figure 31. One gNB-eNB pair (PCI 259/257) has been placed next to the stairs and another one (PCI 261/263) to the laboratory. The third location was allocated for the pRRH chaining. The pRRH and eNB were placed at the opposite end of the corridor, to offer extended coverage.

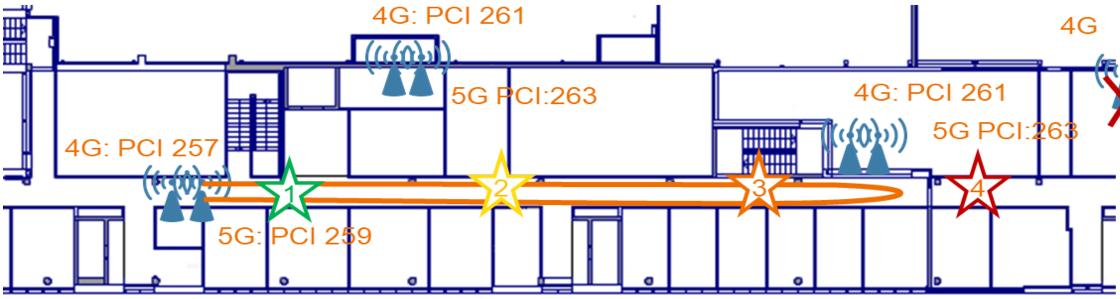


Figure 31: eMBB measurement route.

The iPerf3 server used in UL and DL throughput measurements and the local EPC were placed in the same lab where gNB-eNB pair (PCI 263/261) was installed. The remote EPC was running at VTT's premises in Oulu, 600 km away.

2.2.1.3 Measurement results

The summary of conducted measurements is presented in Table 9. The idle measurements were done to assess indoor coverage, throughput measurements to assess maximum UL and DL throughputs for eMBB services, and RTT and one-way delay (OWD) measurements to assess latencies and jitters. The main KPIs studied were RSRP, RSRQ, SINR, CQI, and RTT and both directions modulation, PDCP and PHY throughputs, jitter, and delay.

[17] Also see, *among others*: https://en.wikipedia.org/wiki/QGIS

Type	Stationary measurement 1	Stationary measurement 2	Stationary measurement 3	Stationary measurement 4	Robot measurement
Local EPC and all gNBs (2 gNBs + 1 pRRH)	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT
Local EPC and two gNBs	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT
Local EPC and one gNBs	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT
Remote EPC and two gNBs	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT
Remote EPC and one gNB	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT OWD	Idle PDCP and PHY throughputs RTT

Table 9: The summary of eMBB measurements.

The first measurement example shows the effects of using of pRRH chaining to extend coverage. An additional pRRH was placed at the end of the corridor. Figure 32 and Figure 33 show the extended coverage in 5G and 4G. Figure 34 and Figure 35 show the non-extended coverage in 5G and 4G. In extended coverage case, high RSRP levels in 4G and 5G are obtained at both ends of the corridor. The picture shows also handover locations with star icons. Since the test network is NSA Option 3x, 4G is the master system and HOs are controlled by it.

Figure 32: Extended 5G coverage with the pRRH chaining.

Figure 33: Extended 4G coverage with the pRRH chaining.

When non-extended coverage is used, then RSRP values degrade along the corridor in both 4G and 5G. There were no handovers. The serving / primary gNB and eNodeB were the same ones along the whole route.

Figure 34: 5G coverage without the pRRH chaining.

Figure 35: 4G coverage without the pRRH chaining.

Figure 36 shows, in the form of graphs, the measured primary cell RSRP values in 5G and 4G, along the measurement route. The figure indicates that HOs (vertical lines) are dictated by 4G eNodeBs. In some cases, the gNB change is not optimal. The RSRP levels in 5G keep degrading after the handover between gNB (PCI=263) and gNB (PCI=259) is performed. The figure also shows that the chained pRRHs cannot be differentiated, based on the measurement results. This is a bit challenging for cellular network based positioning.

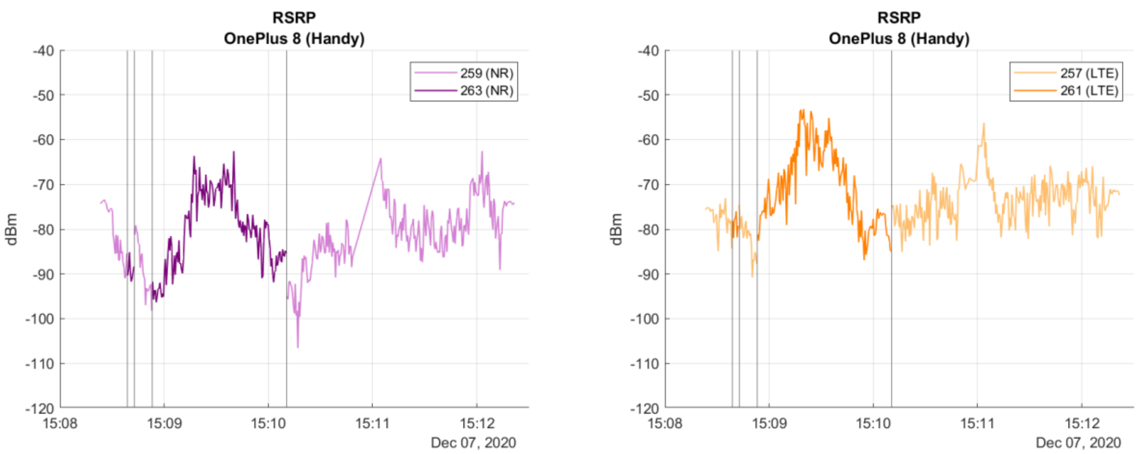


Figure 36: RSRP values and handover locations in the extended coverage case.

When extended coverage was not used, the gNB (PCI=259) located near the stairs was strong enough to serve the mobile terminal along the whole route. No handovers were detected, neither in 4G nor in 5G.

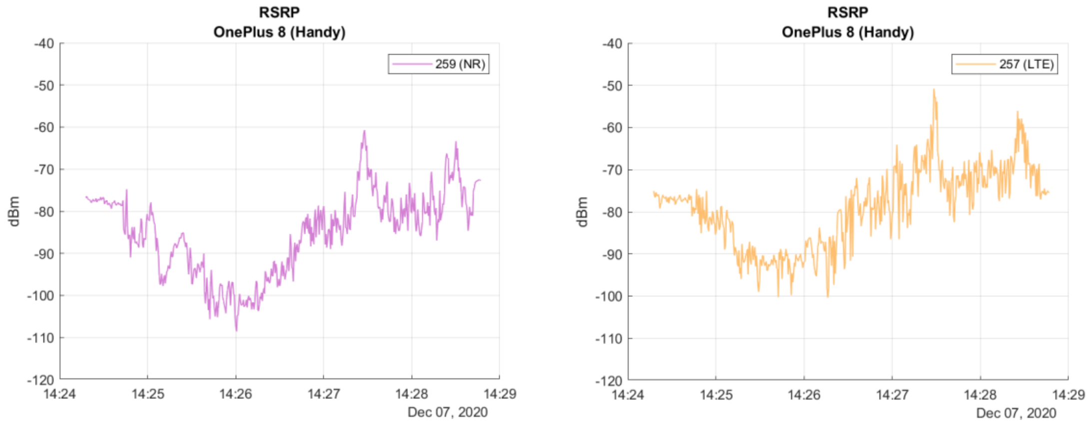


Figure 37: RSRP values and handover locations in the non-extended coverage case.

Next figures show SINR levels along the route in 4G and 5G. SINR has a direct link to UL and DL modulation schemes that define UL and DL throughputs. This KPI is used to give theoretical upper bound to the channel capacity.

In 5G test network setup, the network configuration was a bit too dense for communications, so it was important to analyse SINR levels along the measurement route. In a similar manner, also CQI values could have been used. Typically, excellent SINR values are above 20 dB, good values are between 10 - 20 dB, average values are 0 - 15 dB, and bad values are below 0 dB.

The measured SINR values in 4G and 5G are shown in Figure 38 and Figure 39. Bad SINR levels (too much interference) were obtained in 5G in the middle of the route where the coverage of gNBs overlap. The HOs dictated by 4G eNodeB worsen the situation, since the power of the 5G signal of interest decreases, which in turn increases the interference level. In contrary, SINR levels at the 4G side were increasing after the handovers as expected.

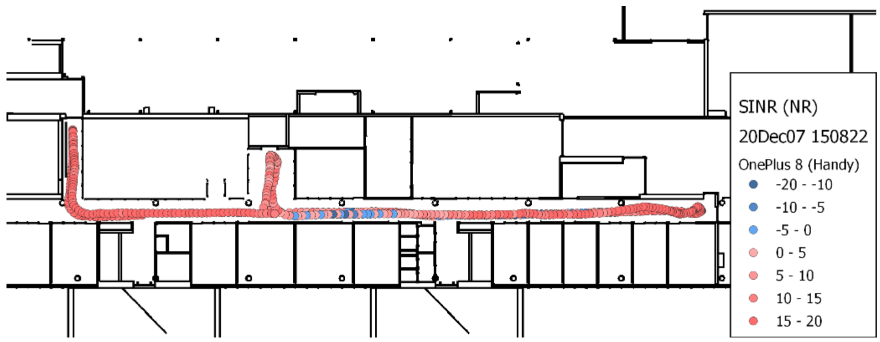


Figure 38: 5G SINR levels in the extended coverage case.

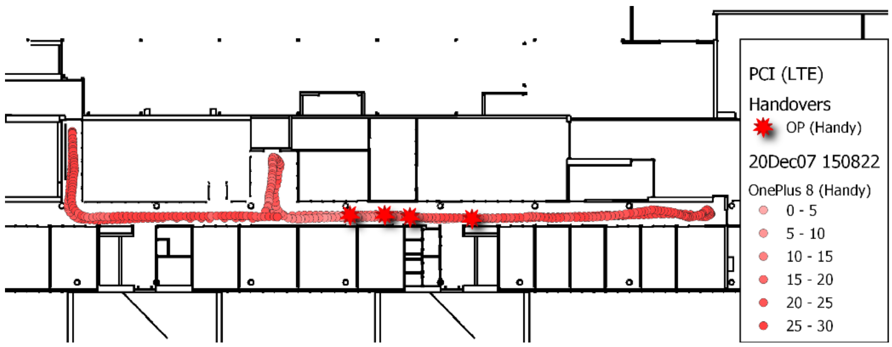


Figure 39: 4G SINR levels in the extended coverage case.

Figure 40 shows SINR results as a function of time. The SINR levels in 5G are lower than in 4G. The SINR levels in 4G are roughly 5 dB higher than those in 5G. This indicates that 5G gNBs are more interfered than the 4G eNBs in our test configuration. In the 5G side, below 0 dB is reached in three locations. Some UL and DL throughput problems could be expected in those “small” areas.

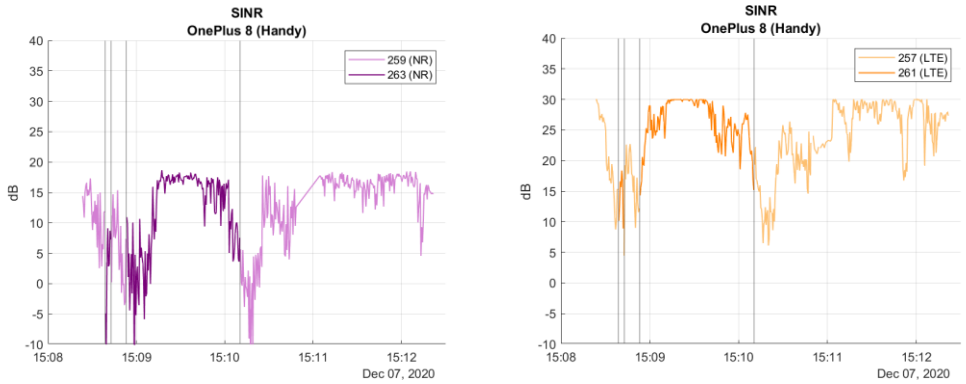


Figure 40: SINR values in 5G and 4G networks (extended coverage).

Figure 41 shows the non-extended coverage case. The effects of interference are still visible in the results, so the source is the gNB placed in the lab. The chained pRRH placed in the right side of the corridor is switched off.

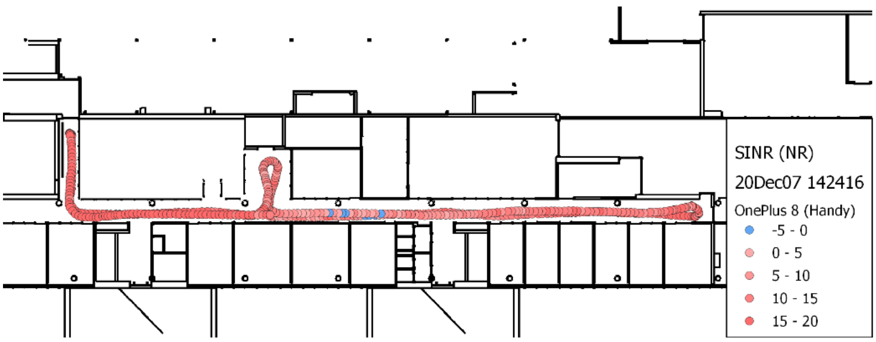


Figure 41: SINR levels along the corridor in the non-extended coverage case.

Figure 42 shows SINR results in case of non-extended coverage. The primary cells in 4G and 5G were the same along the whole route. SINR levels in 5G are again lower than those in 4G. When compared to the extended coverage case, the 5G SINR levels were more constant. In the contrary, 4G SINR values are lower, so an additional 4G picocell in the extended coverage case was improving the situation. Below 0 dB, SINR values were measured in both scenarios, while some local interference was affecting the measurements.

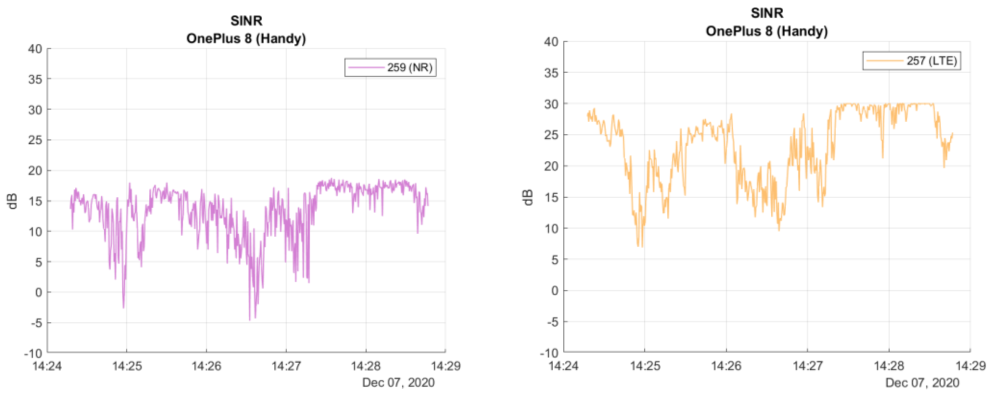


Figure 42: SINR values in 5G and 4G networks (non-extended coverage).

Next, only one gNB-eNB pair was left active, and the SINR levels improved significantly indicating that the transmission powers of gNBs were a bit too high for the trial configuration.

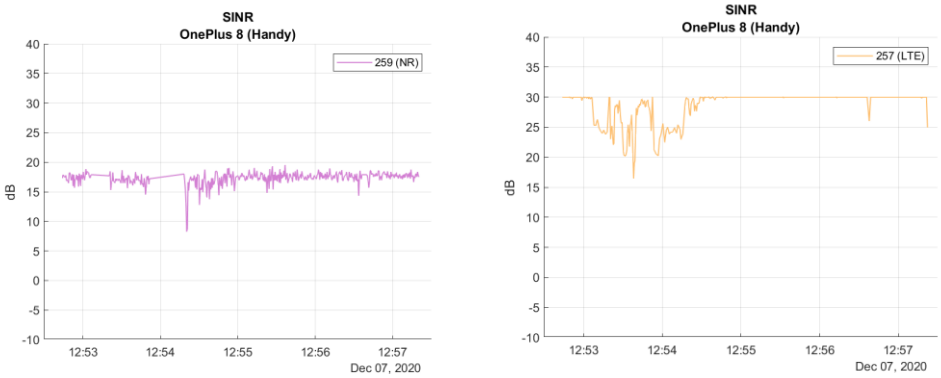


Figure 43: SINR values in 5G and 4G networks (one gNB-eNB pair).

A summary of stationary performance measurements in case of the extended coverage, non-extended coverage, and one gNB-eNB pair is presented in Table 4. The table presents the average values of RSRP, RSRQ and SINR over a 2 min period. In location 4, the extended coverage provides the highest RSRP values. The gNB-eNB pair provides best SINR values, since there are no interfering gNBs. In case of gNB-eNB, the values decrease when moving further away from the gNB.

Scenario	KPI	Location 1	Location 2	Location 3	Location 4
Extended coverage	RSRP	-87.2	-98.5	-84.3	-84.1
	RSRQ	-10.5	-10.9	-10.4	-10.4
	SINR	15.0	8.3	14.5	15.8
Non-extended coverage	RSRP	-84.3	-94.7	-104.6	-104.9
	RSRQ	-10.4	-12.1	-10.9	-10.5
	SINR	14.76	2.8	8.25	12.4
gNB-eNB pair	RSRP	-84.3	-99.7	-97.5	-102.9
	RSRQ	-10.3	-10.4	-10.4	-10.3
	SINR	17.9	16.43	16.7	16.48

Table 10: Summary of stationary 2 min measurements.

Single UE uplink and down link peak data rate

UL and DL throughputs were measured with Keysight's Nemo Outdoor and Qosium tools. The measured traffic to UL and DL directions were generated with an iPerf3 server running next to the measurement site. The number of parallel connections was set to 10 and the window size was 512K. The throughput values were measured in all four layers, but in this deliverable, we are mainly focusing on PDCP and PHY (PDSCH/ PUSCH) layers.

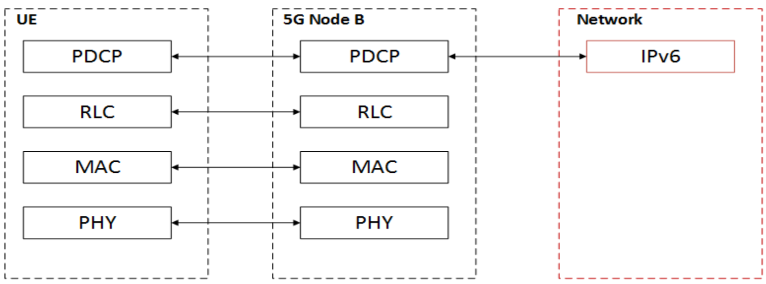


Figure 44: Measured data rates at different protocol stack layers.

UL and DL throughputs depend on the modulation, which is in turn affected by SINR levels. UL and DL throughputs can be estimated by using the NR throughput calculator [5]. It is implemented according to 3GPP TS 38.306 standard [6]. The estimated data rate in Mbps can be calculated by using the equation below:

$$\text{data rate (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^{J} \left(v_{Layers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{\max} \cdot \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} \cdot \left(1 - OH^{(j)}\right) \right) \tag{2.1}$$

where J is the number of aggregated component carriers in a band or band combination, R_{max} = 948/102, $v_{Layers}^{(j)}$ is the maximum number of supported layers for downlink and uplink, $Q_m^{(j)}$ is the maximum supported modulation for downlink and uplink, $f^{(j)}$ is the scaling factor (1, 0.8, 0.75, and 0.4), μ is the numerology, T_s^{μ} is the average OFDM symbol duration in a subframe for numerology μ and $N_{PRB}^{BW(j),\mu}$ is the maximum RB allocation in bandwidth $BW^{(j)}$ with numerology μ.

By entering the test network configuration parameters (i.e.: 2 MIMO layers, 1 aggregated carrier and TDD with 256-QAM DL, 64-QAM UL, 60 MHz FR1, scaling factor 0.75, and UL/DL data slot ratio 1:4), the estimated UL and DL throughputs were respectively 84 Mbps and DL 416 Mbps. The maximum UL and DL throughputs are heavily restricted due to the limited bandwidths in 4G and 5G.

The modulation changes dynamically and depends on the noise level. Nemo Outdoor reports the modulation as a probability distribution, so the following figures are presented according to the most dominant modulation scheme at the given time. In the extended coverage case (cf. Figure 45), the modulation in DL direction is mainly 256QAM. In interference-limited locations, also uses of QPSK and 16QAM are shortly detected.

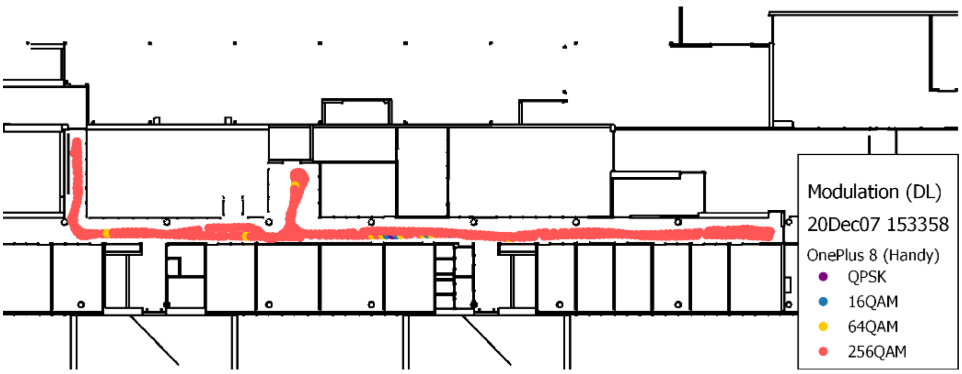


Figure 45: DL modulation in the extended coverage case.

In UL direction, the main modulation is 64QAM. In interference-limited locations, the modulation degrades occasionally to 16QAM or even QPSK (cf. Figure 36).

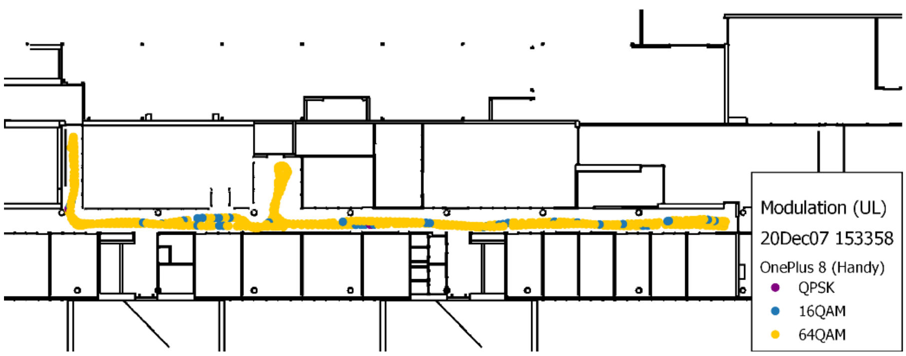


Figure 46: UL modulation in the extended coverage case.

The modulation schemes in the non-extended coverage case are shown in the next figures. The DL modulation changes from 256QAM to 64QAM when moved towards the door on the right. In the middle of the route, use of 16QAM and even QPSK modulations are detected. The results indicated that use of the pRRH chaining increased the modulation schema in the right part of the route.

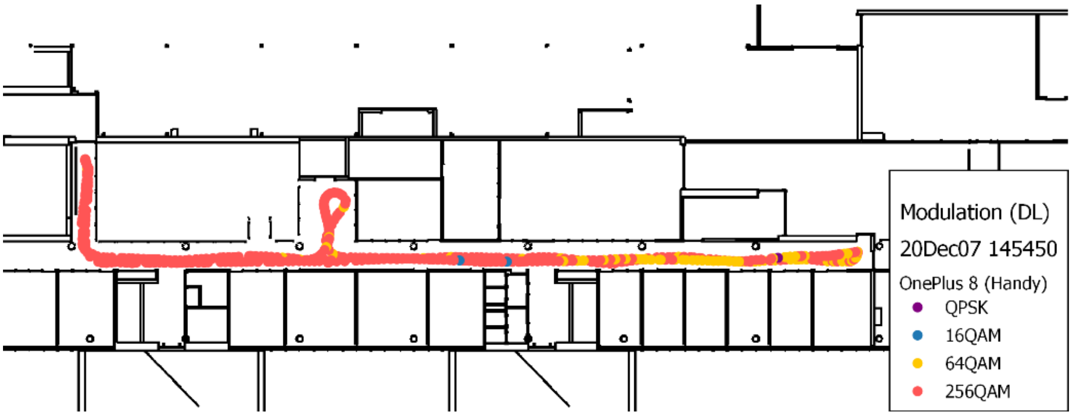


Figure 47: DL modulation in the non-extended coverage case.

In the UL direction, the 64QAM was used along the whole route. Only few locations with 16QAM were detected. The modulation was actually slightly better than in the extended coverage case, due to less interference.

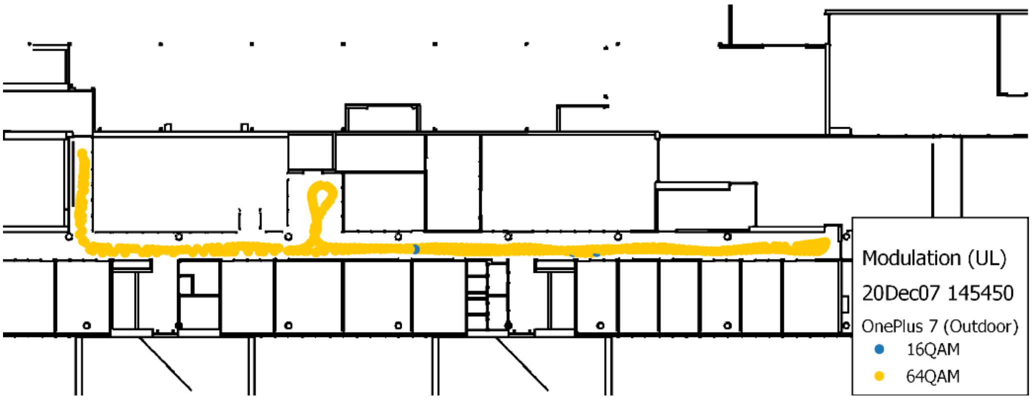


Figure 48: UL modulation in the non-extended coverage case.

The bitrates to UL and DL directions were measured with iPerf3 server, using 10 TCP/IP connections. The first set of measurements were done in September 2020 without extended coverage. OnePlus 7 Pro phone was used in measurements. UL and DL throughputs were measured separately, with TCP/IP traffic. The maximum DL throughput was around 400 Mbps and UL throughput was 36 Mbps. There were also regions where UL and DL throughputs degraded significantly down to few Mbps.

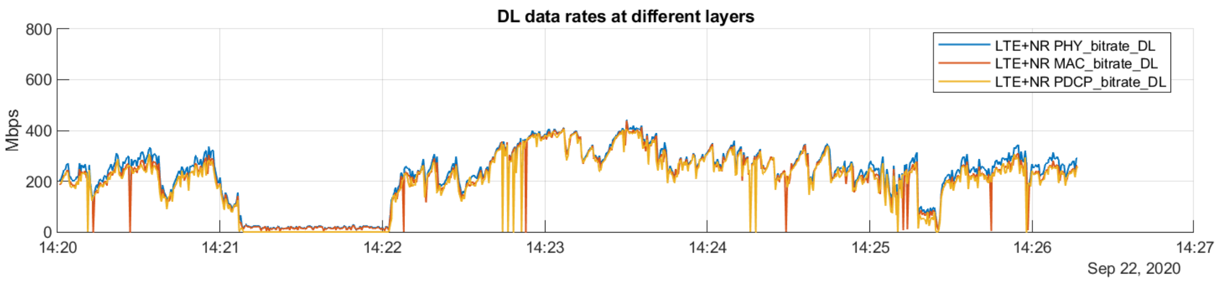


Figure 49: DL throughputs in the non-extended coverage case.

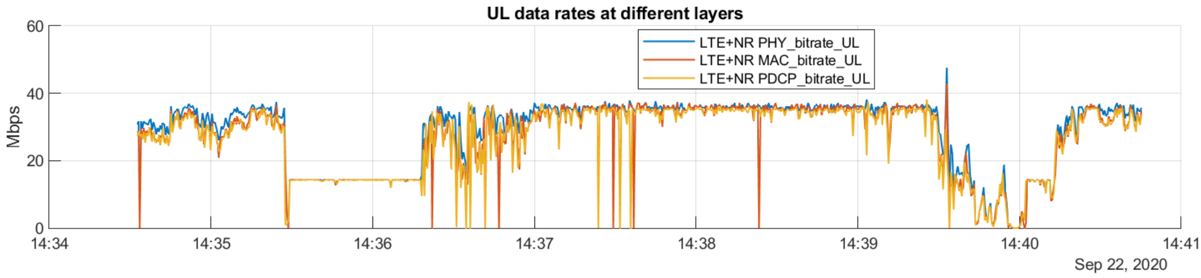


Figure 50: UL throughputs in the non-extended coverage case.

The UL and DL PDCP throughputs along the route are presented in Figure 51 and in Figure 52. The degraded DL throughputs are seen in the middle of the route (shown in black). In this area, the interference levels are the highest and SINR values are the lowest.

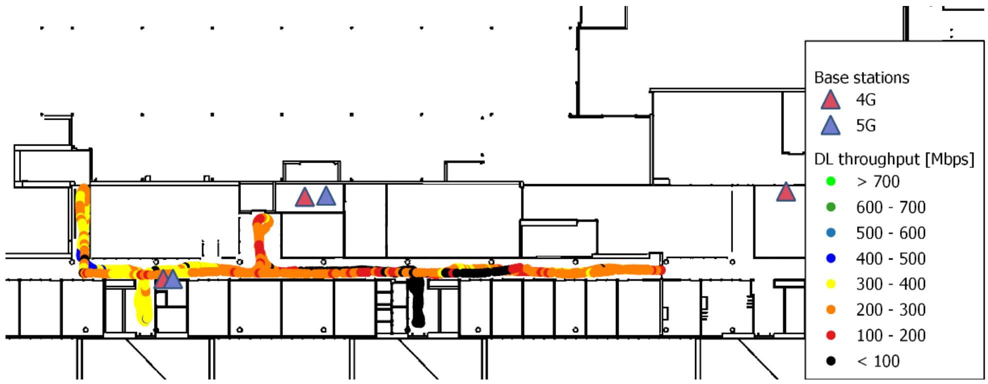


Figure 51: DL throughputs in the non-extended coverage case.

The UL throughput values degrade when moving from left to right. Below 1 Mbps (in red) are measured in a part of the route. The interesting fact is that DL throughput values start increasing again when getting closer the door. This is resulted from the fact that the SINR levels actually increase when moving towards the door. The highest interference is in the middle of the route. The other reason is the shape of the corridor that creates a strong multipath effect (fast fading) that strengthens and weakens the propagating signal along the route.

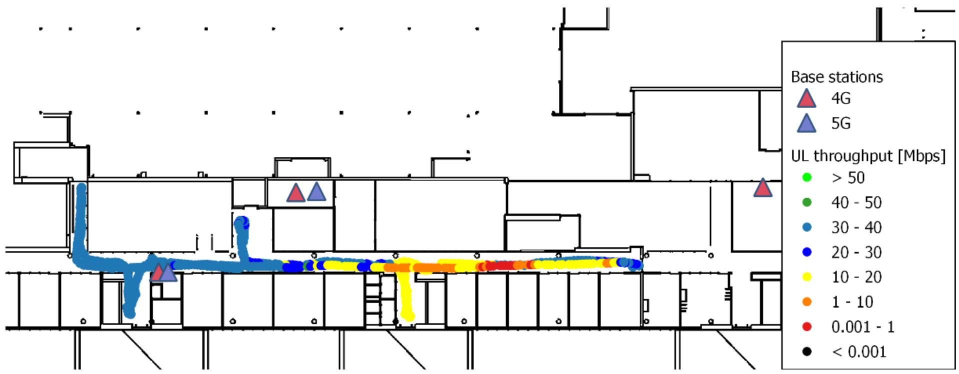


Figure 52: UL throughputs in the non-extended coverage case.

In December 2020, an additional pRRH was added at the end of the corridor to enhance coverage and to improve UL and DL throughputs in the problematic areas. Similar measurements as in the September 2020 trial were repeated, by using three phones. This time, iPerf3 traffic was sent to the UL and DL directions, in parallel. The measurement was done with local and remote EPC configurations. Respect to throughputs, no significant performance difference was observed between the EPC configurations. A more significant difference was observed between results in September 2020 with one OnePlus 7 and in December 2020 with two phones (OnePlus7 and OnePlus 8).

Figure 53 shows the measured UL PDCP throughputs in case of the extended coverage. The majority of the values are above 20 Mbps, but regions below 10 Mbps have also been detected.

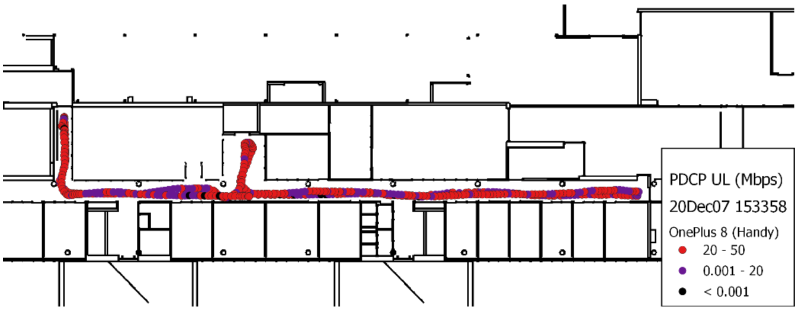


Figure 53: UL PDCP throughput in the extended coverage case.

Figure 54 shows the results in the non-extended coverage case. The UL throughputs are lower. Most of the values stay below 20 Mbps.

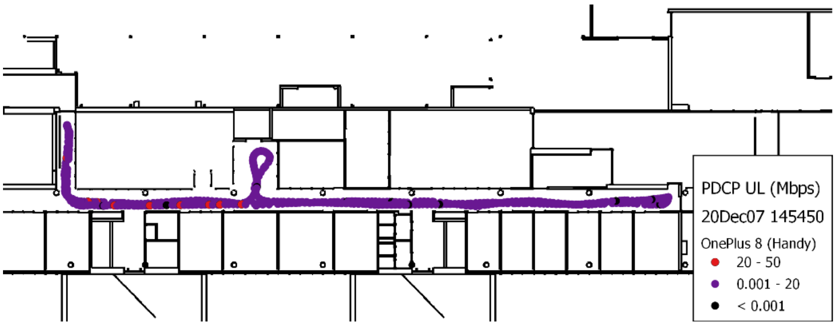


Figure 54: UL PDCP throughput in non-extended coverage case.

Figure 55 shows the UL throughputs of the extended (on the left) and the non-extended coverage (on the right) in a function of time. The measurements were carried out with three phones. In the extended coverage case, one phone was connected to the test network (blue) and two (yellow and red) to the commercial 5G network that has a significantly wider bandwidth. In the non-extended coverage case, two different types of terminals (OnePlus 8 and OnePlus 7) were connected to the test network. By analysing the pictures, it seems clear that the use of two phones is affecting measurements in both 5G test and commercial networks. In the test network case, UL throughputs with one phone (the extended coverage) are roughly double compared to the two phones (non-extended coverage) case. In the left picture, the two phones connected to a commercial network (red line and yellow line) are getting very different UL throughputs. OnePlus 8 (Outdoor) gets up to 150 Mbps (peaks) whereas OnePlus 7 (Handy) gets only around 20 Mbps. An interesting thing is also that the phones' minimum and maximum UL throughput locations keep alternating. The peak UL throughput in the 5G test network is around 36 Mbps, that is significantly less than the 150 Mbps peak achieved in the commercial 5G network. This difference is mainly due to the narrower bandwidth.

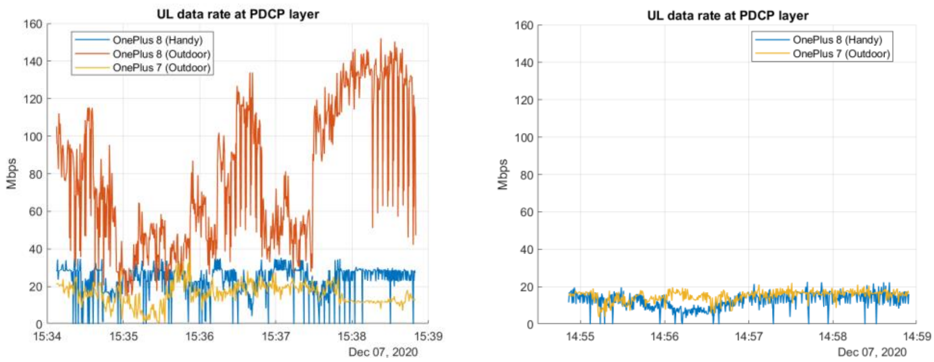


Figure 55: UL PDCP throughput in extended and non-extended coverages cases.

Figure 56 shows the measured DL PDCP throughputs in the extended coverage case. The DL throughput is rather constant around 200-220 Mbps along the route except in the middle interference regions where below 50 Mbps are measured.

Figure 56: DL PDCP throughput in the extended coverage case.

Figure 57 shows the DL throughputs in case of non-extended coverage. The values are 50 - 150 Mbps. The values drop from 120 Mbps to 80 Mbps when the robot moves towards the right door.

Figure 57: DL PDCP throughput in the non-extended coverage case.

The DL throughput measurements also indicated that two phones connected to the same 5G network were affecting each other. This can be seen in Figure 58. In the left picture, OnePlus 7 (yellow) and OnePlus 8 (red) are connected to the commercial network and have similar 350-370 Mbps DL throughputs in the beginning of the measurement. The results change very differently in the end of the measurement. DL throughput of OnePlus 8 (red) increases up to 650 Mbps whereas OnePlus 7 (yellow) decreases to 100 Mbps. The total DL throughput stays in the same 800 Mbps level. A similar phenomenon is visible also in the 5G test network case, as shown in the right picture. DL throughputs of the two phones are fluctuating and the phones alternate their maximum and minimum peak values. The DL throughput in test network with one phone is around 200 Mbps, whereas with two phones both are getting roughly half of it ~100 Mbps. This indicates that two measurement phones are affecting each other in both commercial and 5G test network cases.

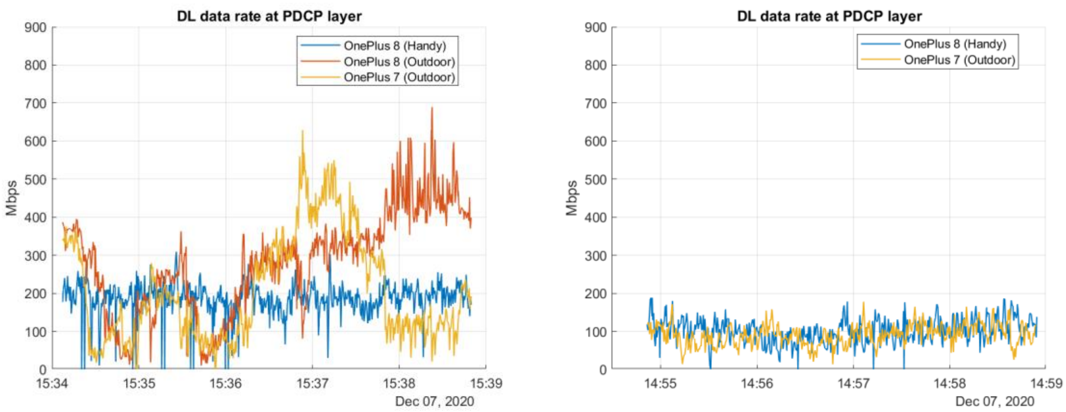


Figure 58: DL PDCP throughputs in the extended and non-extended coverage cases.

The influence of two phones in case of 5G test network is clearer in another measurement round, as presented in Figure 59. The blue line presents the OnePlus 8 phone and the yellow one presents the OnePlus 7 phone. In the beginning of the measurement, both phones are reporting similar UL and DL throughputs. In the end of the measurement, something happens to OnePlus 7 phone and its UL and DL throughputs drop close to zero. Consequently, OnePlus 8's UL and DL throughputs (blue line) nearly double up to 36 Mbps and 220 Mbps, respectively.

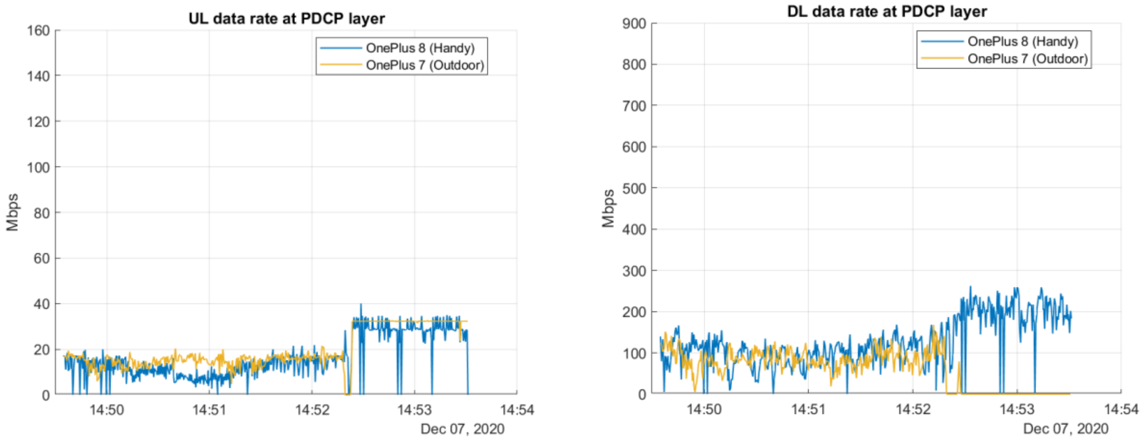


Figure 59: DL/UL throughputs with two 5G terminals in non-extended coverage case.

Handover duration was also investigated in the extended coverage case to study differences between the test and commercial 5G networks and between the OnePlus 7 and OnePlus 8 phones. The results in Table 11 show that the traffic type does not affect handover duration. In average, handovers in the 5G test network take longer than in the commercial network. When comparing different phones, handovers in OnePlus 8 are in average shorter and more consistent than in OnePlus 7. Some of the long handovers in OnePlus7 could cause data connection breaks that were experienced earlier with outdoor measurements by car.

	OnePlus 8 Test network		OnePlus 8 Commercial network		OnePlus 7 Commercial network	
Traffic mode	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Idle	39	49	34	34	28	28
Idle	40	50	26	26	34	34
RTT	39	40	27	31	32	36
RTT	26	50	28	50	32	35
iPerf	40	50	25	35	27	114
iPerf	40	49	23	34	35	52
iPerf	40	50	29	34	29	29

Table 11: Handover durations with different traffic types.

A summary of stationary throughput measurements in the extended and the non-extended coverage cases is presented in Table 12. The table presents the peak values over a 2 min measurement period. The highest UL and DL PDCP throughputs are obtained in location 1, in the extended coverage case. In location 4, the gNB-eNB pair configuration was working better than the non-extended coverage configuration. The gNB-eNB in the lab is causing interference that affects throughput levels. In location 4, higher UL and DL PDCP throughputs are achieved than in location 3, even in the gNB-eNB pair case. This resulted from the better SINR levels and multipath effect along the corridor.

Scenario	KPI	Location 1	Location 2	Location 3	Location 4
Extended coverage	UL PDCP	35.7	19.9	43.2	39.5
	DL PDCP	282.8	206.9	267.3	253.6
	UL PHY	35.9	17	32.1	35.6
	DL PHY	383.2	251.2	269.2	291.3
Non-extended coverage	UL PDCP	30.1	28.2	14.6	3.7
	DL PDCP	208.8	233.9	144.6	113.6
	UL PHY	28.7	53.3	11.7	4
	DL PHY	263.4	442	166.3	123.7
gNB-eNB pair	UL PDCP	23.1	19.2	17.2	28.3
	DL PDCP	206.7	172.2	136.1	220.9
	UL PHY	37.4	16	19	32.3
	DL PHY	309.9	184.4	150.7	247.6

Table 12: Summary of stationary 2 min measurements.

Single UE control plane latency

RTT and jitter measurements were carried out with Nemo Outdoor using Ping traffic. The measurements were done at four stationary locations and also by tracing a route using a moving robot. The stationary RTT measurements were complemented with one-way latency measurements carried out with the Qosium tool. A local iPerf3 server and a public Google server were used for measuring RTT (roundtrip time), UL/DL latency and UL/DL jitter. The measurements were performed in extended and non-extended coverage cases, using local and remote EPC configurations.

The reference RTT measurement with the remote EPC configuration was done in September 2020. The RTT values were in average around 50-52 ms, which was significantly higher than obtained in a commercial 5G network around 24-32 ms.

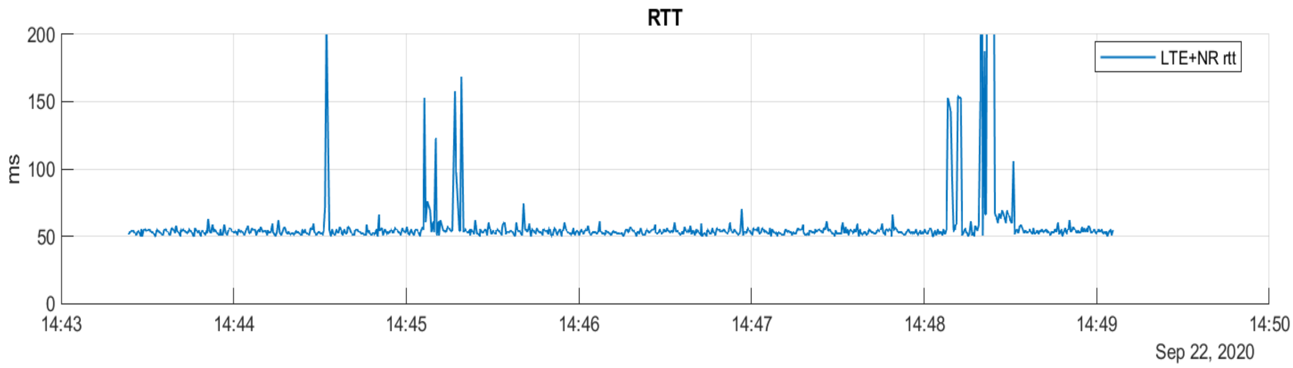


Figure 60: RTT values in the case of far EPC configuration.

During November-December 2020, the network configuration was improved and new measurements with local EPC and extended and non-extended coverage cases were conducted. The measurements were performed with three phones to investigate differences between test and commercial networks as well as between OnePlus 7 and OnePlus 8 phones.

Figure 61 shows the RTT values in the extended coverage case. RTT values are rather constant between 25-35 ms to the public Google server.

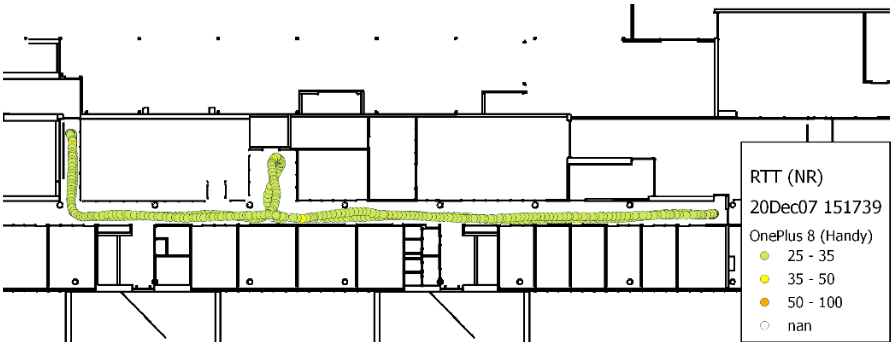


Figure 61: RTT values in ms in the extended coverage case.

Similar results were also obtained in the non-extended coverage case.

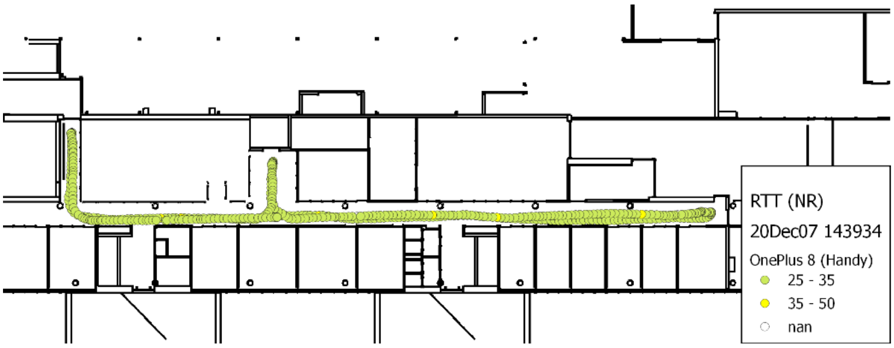


Figure 62: RTT values in ms in the non- extended coverage case.

Figure 63 shows the RTT results of different phones when the public Google server was used in the extended, the non-extended and one gNB-eNB pair case. The left picture shows the extended coverage case where blue line indicates values measured from the 5G test network and red and yellow lines from the commercial network. The left figure shows that RTT values in test network (in blue) are constant around 29 ms (one peak around 55 ms) along the whole route. In the commercial network case , RTT values are at the 18-27 ms level until a handover occurs and RTT times increases to 40-55 ms. The central picture shows the non-extended coverage case in the 5G test network only with OnePlus 8 (blue) and OnePlus 7 (yellow). The picture indicates that the OnePlus 7 phone has 3-5 ms higher average RTT values than the OnePlus 8 phone and there exists higher latency peaks up to 200 ms in the handover region. The third picture shows configuration where only a gNB-eNB pair is used. All three 5G phones are connected to 5G test network. OnePlus 8 (Handy) has RTT values 26-37 ms that are roughly 3-5 ms lower than in OnePlus 7. The red line presents the OnePlus 8 (Outdoor) phone that was not able to connect 5G network and was actually sending the data over a 4G connection. The average RTT was 37-42 ms, but also some high 100 ms high latency peaks were measured.

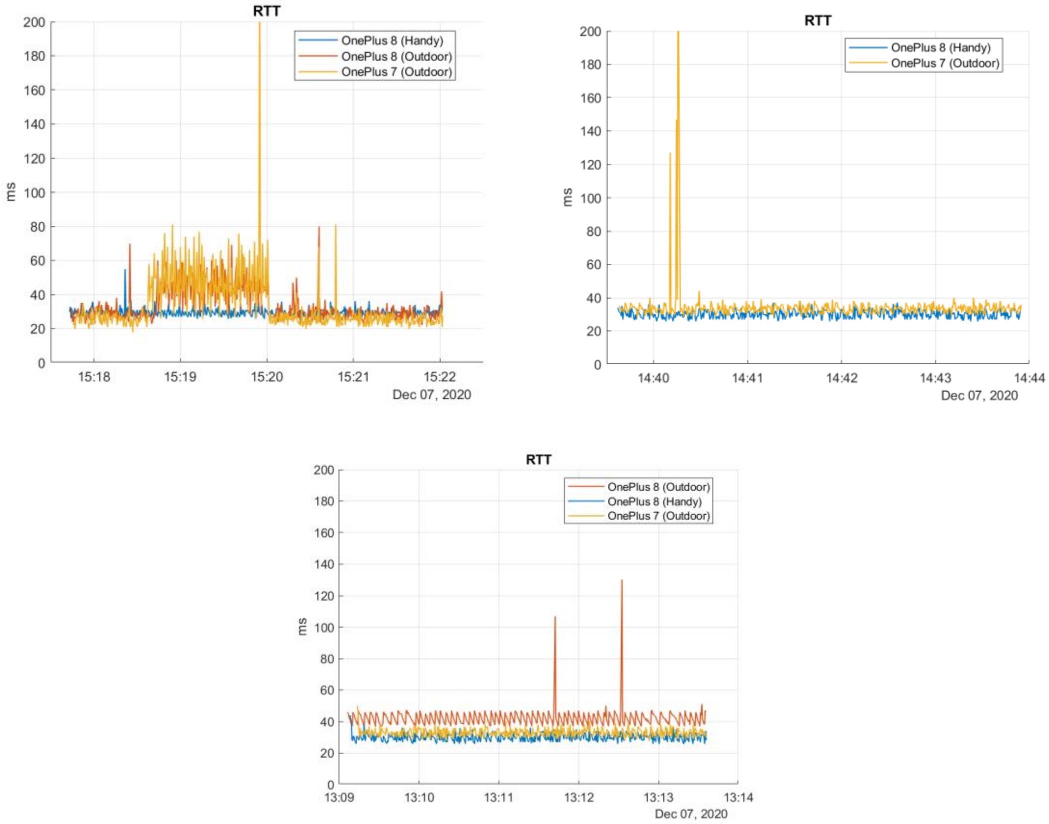


Figure 63: RTT values in a) extended coverage, b) non-extended coverage, and c) one gNB-eNB cases.

The comparison of RTT values between a local iPerf3 server and the public Google server were conducted with stationary measurements. Figure 64 shows the RTT values in the extended coverage case. The left picture shows RTT values to the local iPerf3 server and the right one to the public Google server. The latencies in 5G test network are presented with a blue line, while red and yellow lines present measured RTT values in a commercial network as a reference. In case of the 5G test network, RTT values are 6-17 ms (average 9.2 ms) to the local iPerf3 server and 26-41 (average 29.9 ms) to the public Google server. In the commercial 5G network case, corresponding RTT values are 13-86 ms (average 22.1 ms) to the local iPerf3 server and 19-74 (average 31.8 ms) to the public Google Server. There exist also higher fluctuations in RTT values in the commercial network (variance is 75.2 ms compared to 4.9 ms in test network). The red lines in graphs present the OnePlus 8 (Outdoor) phone that is only connected to the commercial 4G network. Its RTT values 22-153 (average 45.3 ms) are significantly higher than those measured in the 5G network. Moreover, there exists a high periodical fluctuation pattern in both local iPerf3 and the public Google server cases.

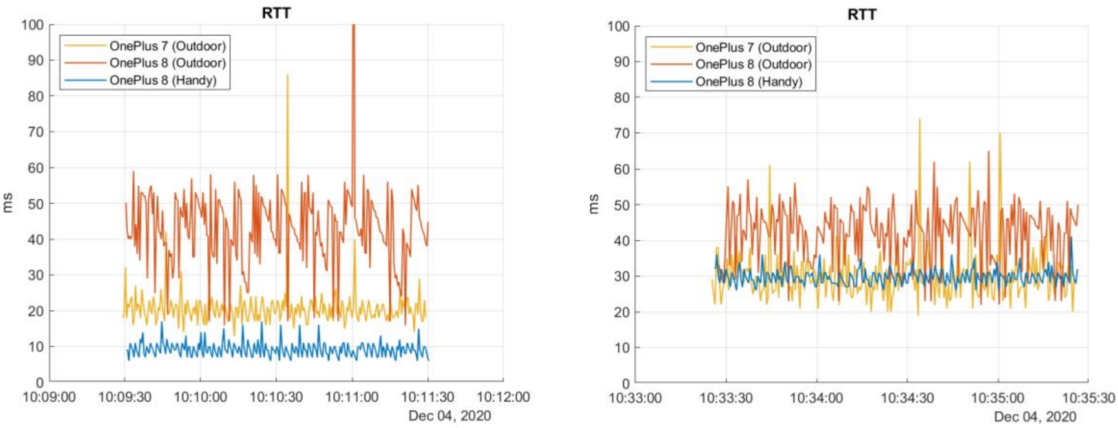


Figure 64: Stationary RTT measurements in the extended coverage case using a local iPerf3 server (left) and a public Google server (right).

Figure 65 presents RTT values measured in the non-extended coverage case. Two phones, OnePlus 7 (yellow) and OnePlus 8 (blue) were used to measure RTT values to the public Google server in the 5G test network. The results were similar to the extended-coverage case. OnePlus 8 has values 26-157 ms (average 33.4 ms) and OnePlus 7 has values 29-119 ms (average 41.0 ms). The RTT values are rather constant, except OnePlus 7 has high latency peaks in handover regions.

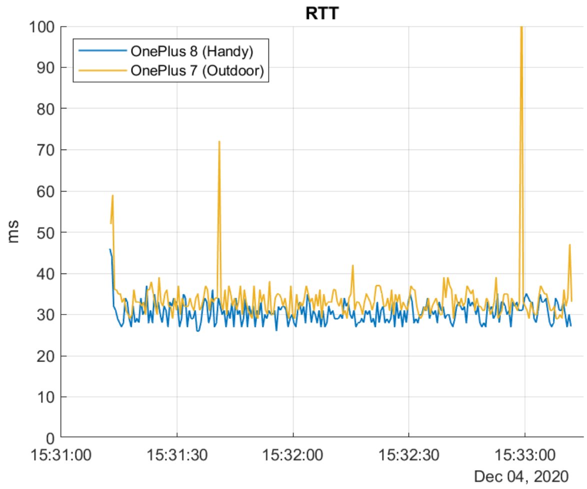


Figure 65: Stationary RTT measurement in the non-extended coverage case.

As a last test, RTT measurements were performed with Oulu EPC in the extended coverage case to investigate effects of the remote EPC on the response time. Yellow (OnePlus 7) and blue (OnePlus 8) lines present RTT latencies in the 5G test network. RTT values in case of the remote EPC are very high even compared to the commercial 5G network. OnePlus 7 phone was getting values 50-68 ms (average 55.3 ms) and OnePlus 8 phone 48-76 ms (average 52.4 ms). This time latencies were roughly 3 ms smaller in OnePlus 7 phone case. The latencies in a commercial network were 26-48 ms (average 36.2 ms). The interesting thing is that RTT values (average 52.4 ms) via the remote EPC and the public Google server are more than five times larger than values obtained with the local EPC configuration and iPerf3 server (average 9.2 ms). The measurement indicated that the remote EPC configuration and internet connections are causing significant core network delays that overrun all of the radio access network delays.

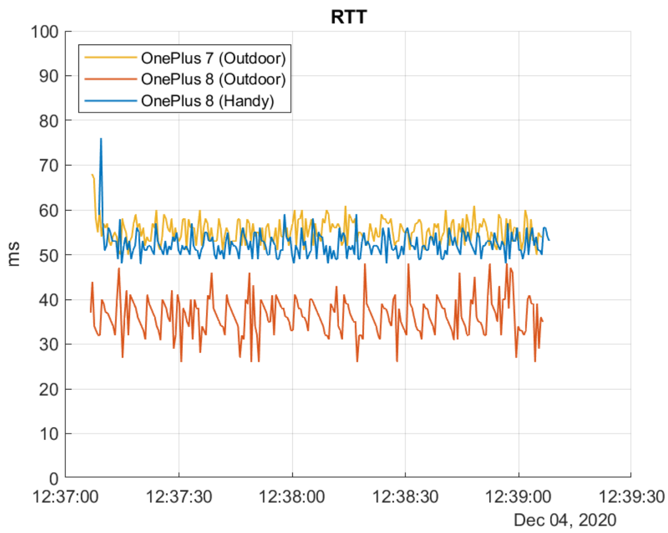


Figure 66: Stationary RTT measurement with Oulu EPC.

The summary of latency measurements with different network configurations is presented in Table 13. Locations did not have an effect on the RTT, one-way latency or jitter values. Therefore, only different network variations are presented. The highest latencies were with the remote EPC configuration and the Google server. The latencies in case of the local EPC and the Google server were similar to those obtained in the commercial network. The smallest latencies were achieved in case of the local iPerf3 server and the local EPC around 16-24 ms in average. The DL delay was 6.2 ms and UL delay 10.5 ms in average. The DL jitter was around 1.8 and UL jitter 1.0 ms.

Scenario	KPI	Value (ms)
Local iPerf3 server and local EPC with extended coverage	RTT	16 - 24
	DL delay	6.2
	UL delay	10.5
	DL jitter	1.8
	UL jitter	0.95
Public Google server and local EPC with extended coverage	RTT	24 - 32
Public Google server and local EPC with non-extended coverage	RTT	24 - 32
Public Google server and remote EPC with extended coverage	RTT	50 - 58

Table 13: A summary of latency measurements.

2.3 MIMO performance measurement results and analysis

In WP3, 5G-DRIVE partners and Chinese twin project partners have been working together to: 1) investigate massive MIMO beamforming characteristics and the effect of array antenna configuration on 3D beamforming, especially according to the building height; and 2) evaluate the field trial and measurement results for single and multiple mobile users.

2.3.1 Panel antenna array system, gain and radiation patten

In WP5, the theoretical 3D beam pattern is analysed and reported in D5.2 [7]. In WP3, the beam pattern of a panel antenna array is obtained through live test to verify the theoretical results. In the MIMO test platform, the gain and radiation pattern measurements were performed on a 2x8–elements antenna array system shown in Figure 67, where the individual patch elements are WDP.2458.25.4.B.02 with the following specifications:

- Dual-band 2.4/5 GHz.
- Embedded Ceramic Patch Antenna.
- 6 dBi + at 2.4 to 2.5 GHz.
- 6 dBi + at 5.15 to 5.850 GHz.

The antenna array is designed to have half lambda separation in between each patch element on both vertical and horizontal.

Figure 67: 16-elements TDD antenna array system.

First, the anechoic chamber was set up to measure the different antenna elements combinations on the 16-elements antenna array. As shown in Figure 68, a horn antenna connected in the left hand side served as the receiving (Rx) point, while the gold horn antenna on the right hand side served as a transmitting (Tx) point.

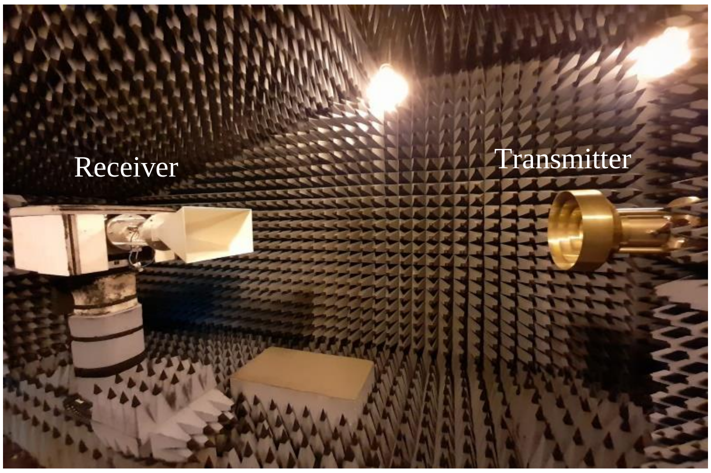


Figure 68: Anechoic chamber calibration setup.

Following the calibration at 2.4 GHz, the horn antenna that served as Rx was replaced by the antenna array as shown in Figure 69. The connection from the anechoic chamber system to the antenna array takes place through a single output and a low noise power amplifier driven by the external system. In order to merge the output of the individual patch antenna elements, power splitters were used.

To be noted that the transmitter shown in Figure 68 had a fixed position on the horizontal while the height was adjusted accordingly to the patch elements connected (always cantered on the subarray connected).

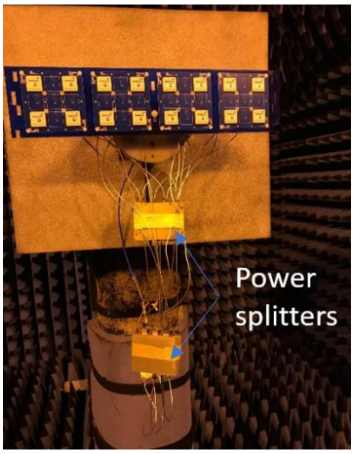


Figure 69: 16-elements antenna array set as receiver in the anechoic chamber.

The second step was to measure the radiation pattern of the array under different configuration. Each radiation pattern measurement was performed into four cuts as shown in Figure 70. The four measurements differ one from another in the way the Rx (WDP.2458.25.4.B.02 antenna array) and the Tx horn antenna are positioned with regards to their own X and Y – axis. As it can be seen in Figure 70 the top left square represents the first measurement which is performed with the antenna array at its original position (0^{o}) while the Tx is at its original position (0^{o}) only that the horn antenna at its original position has the radiating elements on the vertical plane (cross-polarised with regards to the antenna array). For the second measurements the antenna array was kept at the same position on the horizontal, while Tx is moved (90^{o}) so the radiating elements are now on the horizontal, therefore meaning that both Tx and Rx are exchanging signals in a co-polarised manner. These two measurements because the antenna array is on the horizontal results in the electric field (E-field) measurement of the radiating pattern.

For the last two measurements, the Rx antenna array is turned 90^{o} therefore resulting in measurements of the antenna array on the vertical plane which is also known as the magnetic field (H-field). For the first measurement shown in the bottom right square, the Tx is at its original position (radiation elements on vertical) resulting in the co-polarised measurement of the H-field. The last measurement is the cross-polarised H-field resulted from turning the Tx at 90^{o} (radiating elements on horizontal) while the antenna array is positioned on the vertical.

All four measurements were taken by rotating the pole where antenna array was mounted, 360^{o} while measurements were taken in steps of 3^{o}.

As it will be shown and discussed later on, the antenna array being designed to be used on the horizontal has its co-polarised transmission in measurement 2 and 3 represented in Figure 70.

In the measurements, in order to investigate the antenna pattern under different spacing of antennal elements, two types of configuration with total 8 elements and 16 elements are used, respectively.

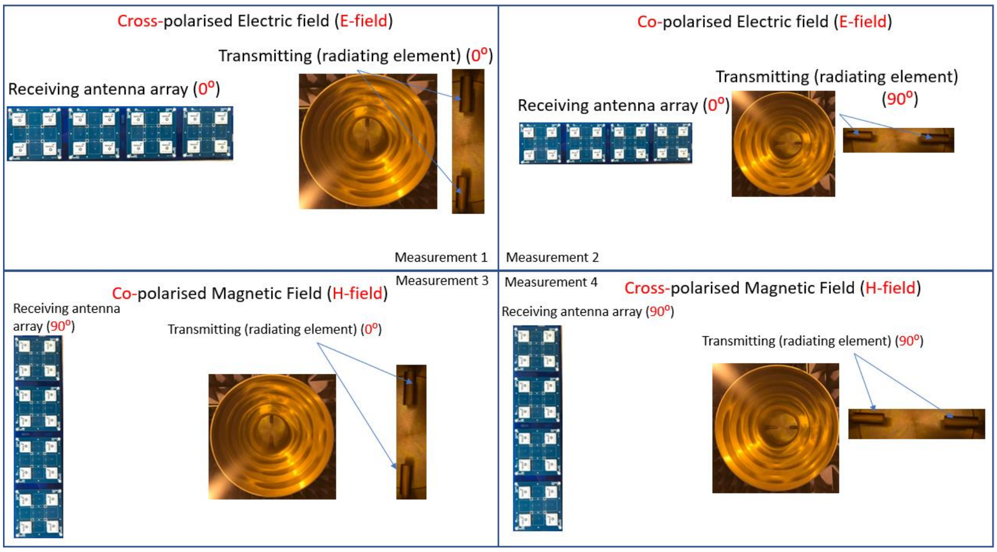


Figure 70: Radiation pattern measurement E-field and H-field for co/cross – polarisation.

2.3.1.1 Radiation Pattern: 1x8 – elements antenna system

For the 1x8 linear-array antenna system setup, as shown in Figure 71, the top 8 antenna elements were connected to form one main beam. In order to achieve a single output for measurements, two 4 to 1 power splitters were used while the resulted two outputs were fed into a 2 to 1 power splitter which was then measured by the system.

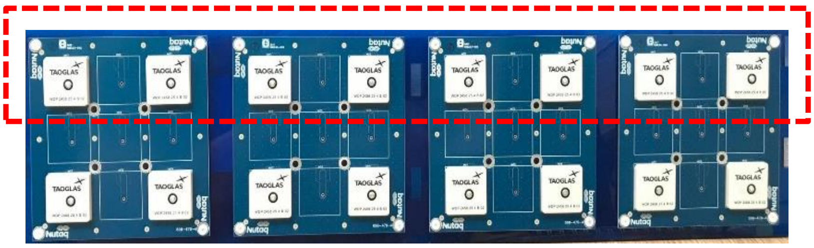


Figure 71: 8x1 (top) antenna system configuration.

The H-field measurement shown in Figure 72 represents horizontal beam generated. Compared to the beam pattern generated through simulation with beam width around 17°, which is shown in Figure 73, the beam width is slightly narrow in the test.

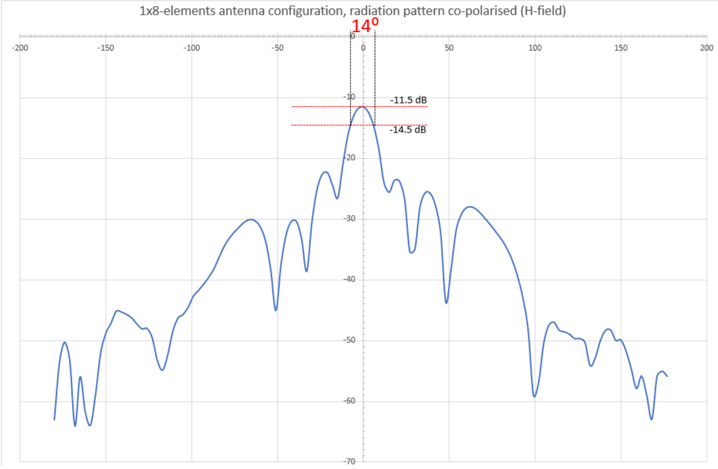


Figure 72: 1x8 - elements antenna system beam pattern tested in in the anechoic chamber.

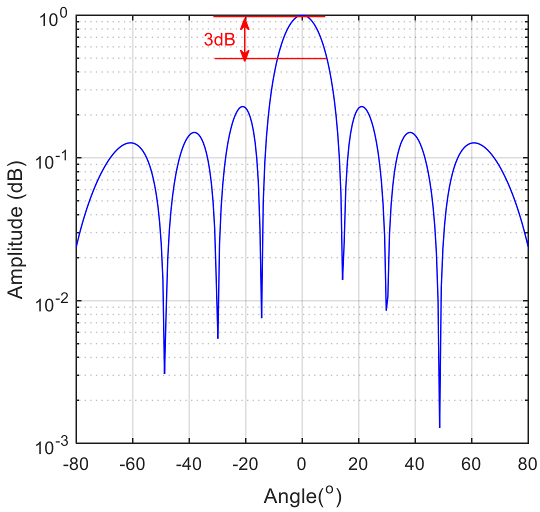


Figure 73: 1x8 - elements antenna system beam pattern based on simulation.

2.3.1.2 Radiation Pattern: 2x4– elements antenna system

Two types of 2x4 elements antenna array structures were set up. The structure of first 2x4 antenna array is shown in Figure 74, which has an array length of 2 antenna elements on the vertical which characterises the beam width on the horizontal and 4 antenna elements on the horizontal that characterises the vertical beam width.

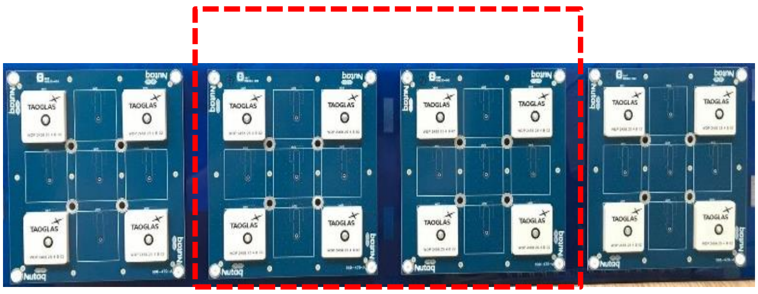


Figure 74: 2x4-(centre) elements antenna configuration.

Since the 2x4 setup has vertical array length of 2 antenna elements, the same as the 2x2 setup, a similar horizontal width of 58^o was achieved, as it can be seen in the left-hand side of Figure 75.

The same for the array length on the horizontal which is of 4 antenna elements the same as for the 1x4 setup, leading to a vertical beam width of 29^o. However, for the 2x4 setup where we have 4 extra antenna elements in comparison to the 1x4 setup, there is also a 1dB increase in the main lobe.

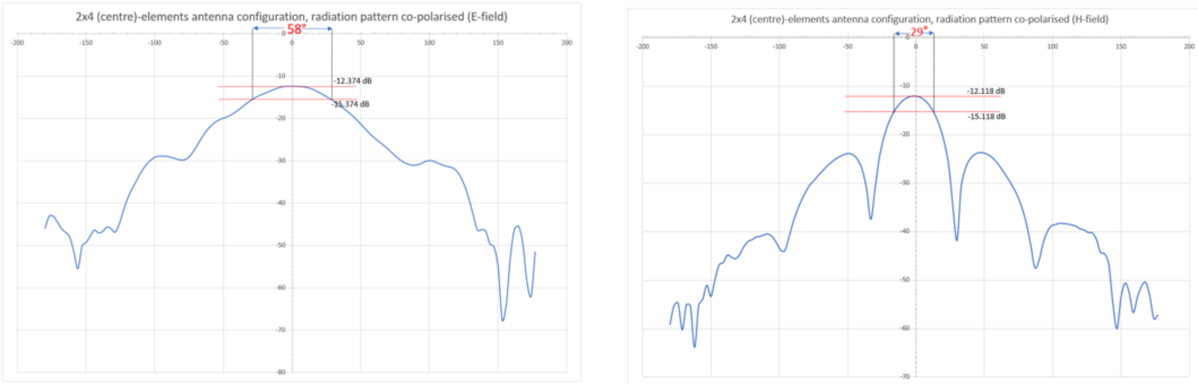


Figure 75: 2x4 antenna system, vertical pattern (left) and horizontal pattern (right) plot.

As shown in Figure 77, in the second type of 2x4 antenna array, two subarrays of 2x2 antenna elements were formed. The difference between this setup and the previous 2x4 setup is that the space between the two subarrays is equal to 2.5λ, different from the antenna element spacing of 0.5 λ.

Figure 76: Two 2x2(ends)- elements antenna configuration.

Figure 77 shows the vertical beam pattern with the main to be about 8^o narrower than the one for previous 2x4 antenna system. It also indicates that the 2.5λ spacing in between the subarray has not affected the main beam significantly in the vertical plane.

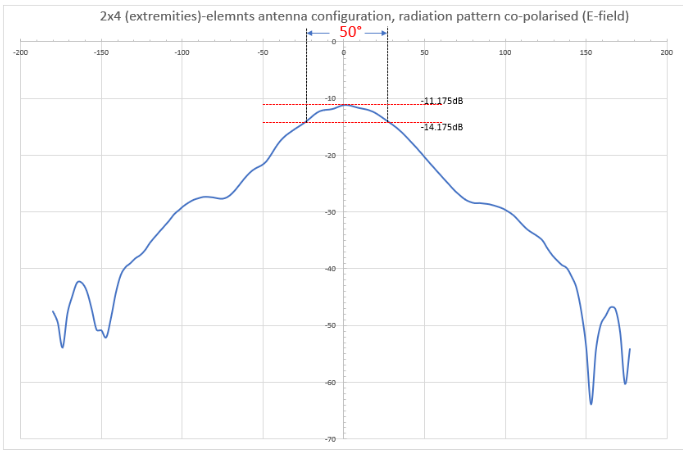


Figure 77: Two 2x2 subarrays: vertical pattern.

Figure 78 shows the horizontal beam pattern. As explained in D5.2 [7], the increment of the spacing between the two subarrays from 0.5 λ to 2.5 λ leads to more beams with high gains. It can be seen that the increased spacing leads an extra of 2 different beams at the -3dB point. Different from the beam pattern for the 2x4 antenna system shown in the right-hand side of Figure 75, where the main beam has 29^o, at the -3 dB point, we have 3 different beams of 9, 11 and 9 degrees. The main difference is that now instead of a main beam of 29^o we have 3 different beams of 9^o, 11^o and respectively 9^o which in total gives the same coverage of 29^o but covered by 3 different beams.

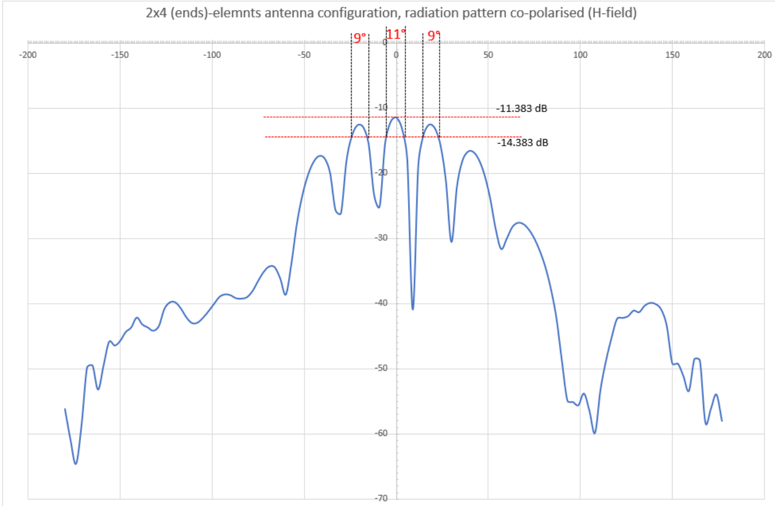


Figure 78: Two 2x2 subarrays: horizontal pattern.

2.3.1.3 Radiation Pattern: 2x8 – elements antenna system

The other measurement was taken for the 2x8 configuration as shown in Figure 79.

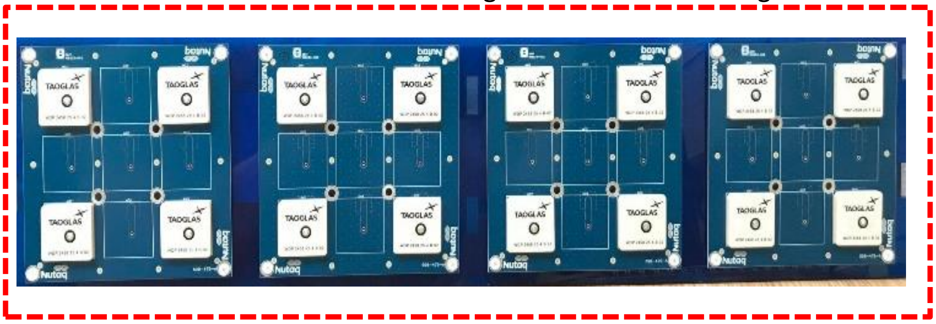


Figure 79: 2x8-elements antenna configuration.

Figure 80 shows the vertical beam pattern. Compared to the vertical beam patterns for 2x4 antenna array, shown in Figure 75 and Figure 89, there is no significant difference in term of the main beam gain.

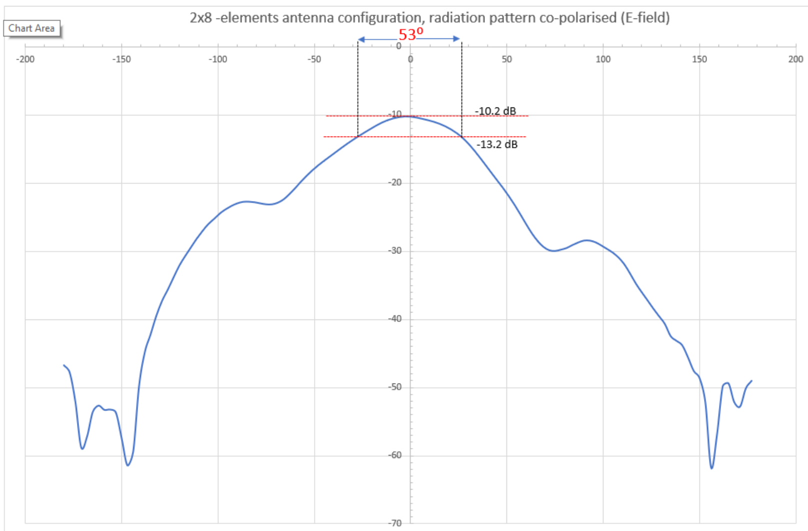


Figure 80: 2x8- elements antenna system: vertical pattern.

Figure 93 shows the horizontal pattern. Compared to the beam pattern generated by 1x8 linear antenna array, as shown in Figure 72, the horizontal beam pattern for 2x8 panel array is similar to the one for 1x8 setup. The same beam width of 14⁰ was achieved due to the fact that both setups have an array length on the horizontal of 8 antenna elements. However the 2x8 setup achieved 2 dB more in the main beam when compared to the 1x8 setup.

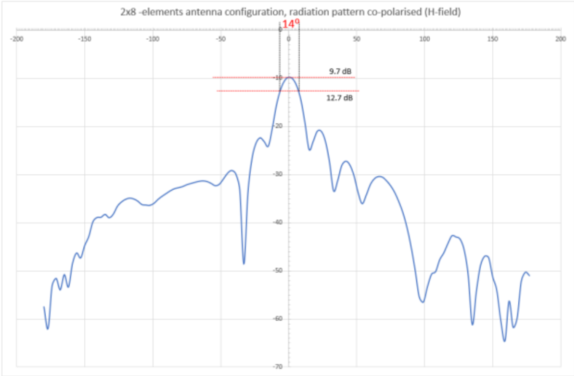
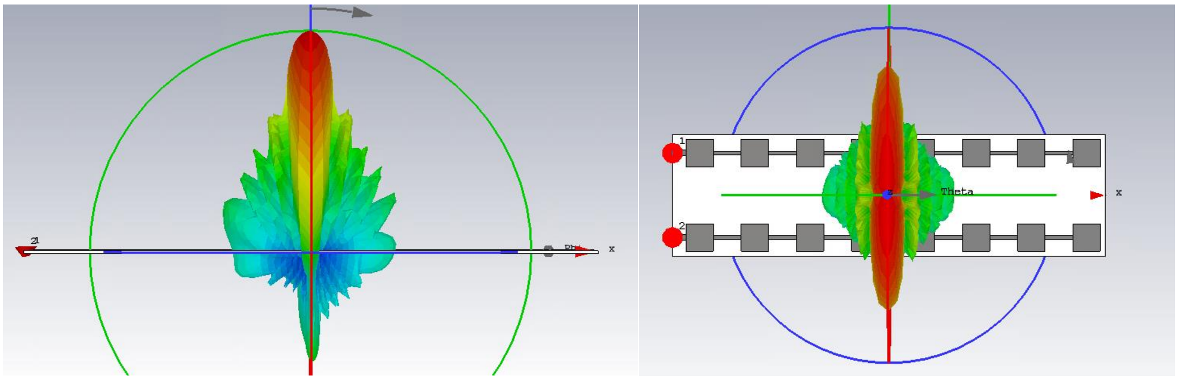


Figure 81: 2x8- elements antenna system: horizontal pattern.

3D beam pattern achieved by the 2x8 panel antenna array is shown in Figure 82. Figure 82 (a) shows the horizontal view and Figure 82 (b) shows the vertical view. It matches the theoretical results obtained based on D5.2.



(a) Horizontal view (b) Vertical view

Figure 82: 2x8- elements antenna system: horizontal pattern.

2.3.2 Field trial results

In this section, some representative field trial results are presented. Single and multiple users are considered. The field trials are specified as follows. In the urban area, a total of 30 or 60 gNBs are deployed and the distance between two gNBs is around 450 to 500 meters. The main system parameters and specifications are listed in Table 14.

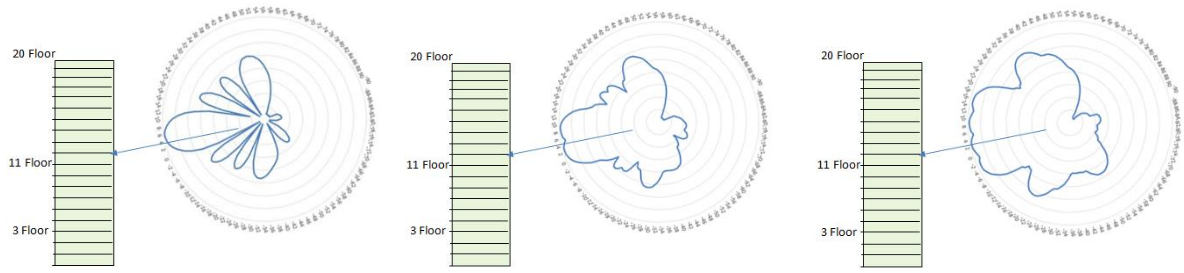
System	5G new radio (NR) stand alone (SA) under 3GPP Rel-15 [9].
Bandwidth	100 MHz at 2.6 GHz
Subframe configuration	period of 5ms, DDDDDDDSUU, where D, S, and U stand for downlink subframe, special subframe, and uplink subframe, respectively.
Special subframe configuration:	DwPTS: GP : UpPTS = 6 symbols : 4 symbols : 4 symbols, where DwPTS GP and UpTPS indicate downlink pilot time slot, guard period, and uplink pilot time slot, respectively.
Antenna configurations	base station 64T64R; terminal: 2T4R

Base station total transmit power	200W (53 dBm)
Terminal transmit power	total 26 dBm (23 dBm per single antenna)
Multi-user scheduling algorithm	proportional fairness method (PF)

Table 14: Main system parameters and specifications.

2.3.2.1 RSRP comparison for multiple broadcast vertical beams in a building

In the trial system, each targeted building is covered by vertical multicast beams generated at an individual BS which is located at a height similar to the height of the building. The coverage method is different for different heights and locations of the buildings. We distinguish the following: (1) For a medium-rise building (e.g. below 75m) located near the middle point of the BS coverage area (abbreviated as midpoint), as demonstrated in Figure 83, 2 or 4 beams are used to cover the building. The middle and high levels of floors could be covered by the main beam(s), and the reference signal received power (RSRP) indicated by the synchronisation signal block (SSB) is relatively high, about 1 ~ 17 dB， compared to single vertical beam; (2) For a large high-rise building (e.g., over 140m) near the midpoint, due to the limited dynamic range of the SSB scan, the upper floors are covered by the side lobes of beams. The RSRP and SINR gains of the upper floors are reduced to about 2 dB for 2 or 4 vertical beams, compared to single beam.



(a) One beam (b) Two beams (c) Four beams

Figure 83: A medium-rise building covered by 1, 2 or 4 vertical beams.

In order to demonstrate the impact of using multiple beams, a trial system was set up for a medium-rise building surrounded by multiple medium-rise and high-rise buildings in a dense urban area. The reference building with a height of 57 meters is 120 meters away from the BS. The BS has a height of 54 meters. Figure 84 shows the impact of multi-beams on the RSRP gain, which is defined as the ratio of RSRP of 2 or 4 vertical SSB beams to that of 1 vertical SSB beam. It can be seen from Figure 84 that the vertical 2 or 4 SSB vertical coverage area is significantly larger than that of the single SSB in the lower and upper levels where the main lobe of the single SSB is not aligned. It is shown that the maximum gain of 2 SSB RSRP is 8 dB, while the maximum gain of 4 SSB RSRP is 17dB.

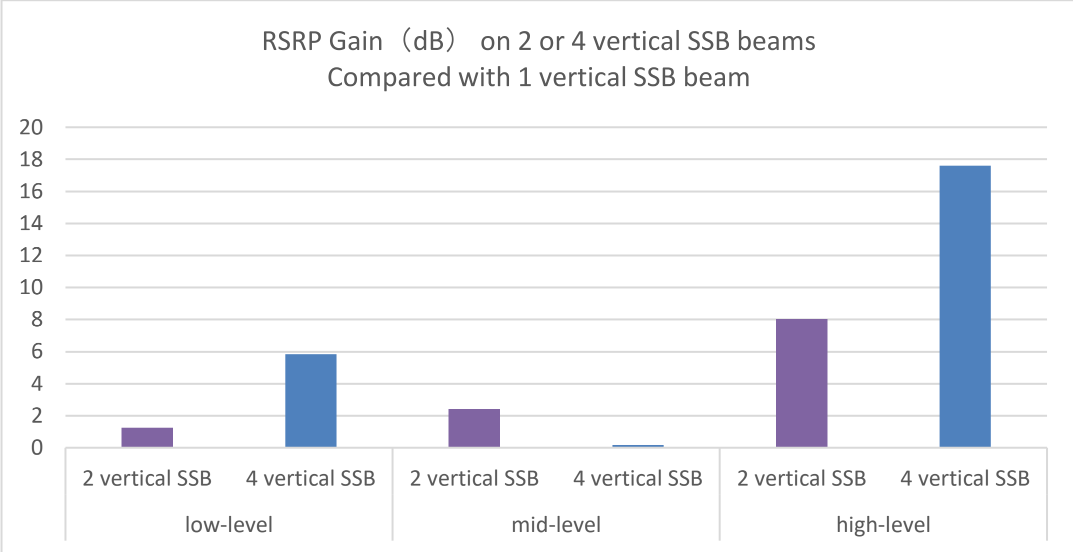


Figure 84: RSRP comparison for different floor level in a medium-rise building.

2.3.2.2 Performance of single and multiple users in case of 2D beamforming

In this section, the data rate for both DL and UL transmissions is demonstrated when a single user and multiple users are located on the horizontal plane in case of 2D beamforming.

1) Single User

In the trial of single user scenarios, SA outdoor road traversal tests were carried out and the measured throughputs of the mobile terminal were recorded. The trial roadmap is shown in Figure 85, where different colour shows different moving routes. In the trial, with a moving speed of around 30km/h, the testing mobile device was moving in a field covered by 20 BSs, including about 60 small cellular sectors. The distance between any two BSs is about 350 meters to 400 meters.

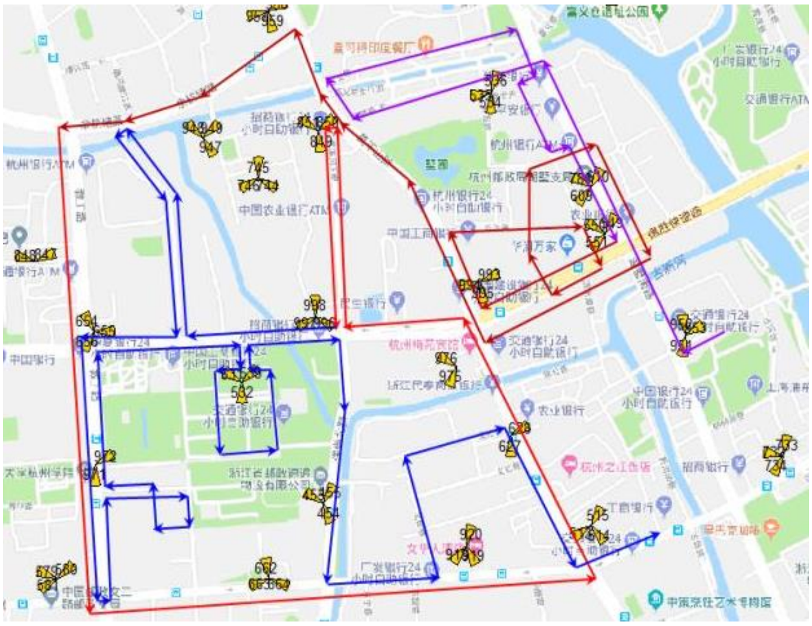


Figure 85: Single-user trial roadmap.

When the testing mobile device was located in the coverage area of one cellular sector, it was served with the full resources of this sector. At the same time, other sectors in the trial area added up to 50% load as interference. That is, the full transmit power of each BS was used to add up to 50% physical resource blocks (PRBs) or orthogonal channel noise generation (OCNG). The traffic load from other sectors caused interference to the testing mobile device.

Table 15 lists the downstream number and rate in outdoor traversal test, while Table 16 lists the upstream number and rate in outdoor traversal test. It can be seen from the two tables that when the neighbouring zone is unloaded, the ratio of downlink four streams is about 10%, the ratio of downstream three streams is about 67% and the average downlink data rate can reach up to 900Mbps; the ratio of uplink dual streams can reach 100%, and the average uplink data rate can reach about 109Mbps. Under the loading condition of 50% downlink in the neighbouring area, due to increased interference, the ratio of large streams decreases, the ratio of downlink three-streams drops to 44%, the ratio of downlink four-streams drops to 0, and the average downlink data rate drops by 30%-40% to 483 Mbps.

	DL Rank 1&2 ratio	DL Rank 3 ratio	DL Rank 4 ratio	DL user data rate(Mbps)
neighbour cells 0% loaded	22%	67%	11%	895
neighbour cells 50% loaded	56%	44%	0%	483

Table 15: Downstream number and rate in outdoor traversal test.

	UL Rank 2 ratio	UL user data rate (Mbps)
neighbour cells 0% loaded	100%	109

Table 16: Upstream number and rate in outdoor traversal test.

2) 1 to 9 Users

In order to investigate the performance of cell throughput and stream number adaptively changing with the number of users, first we conducted the following tests: 1, 3, 5, 7, 8 and 9 users, respectively, being served simultaneously and recorded the cell throughput. The precoding technology of minimum mean square error (MMSE) was used for the multiuser communications. Figure 86 shows the multiuser trial site. Data streams were transmitted at the same time for three minutes for a varying number of users. The cell throughputs of 1/3/5/7/8/9 users, respectively, were measured.

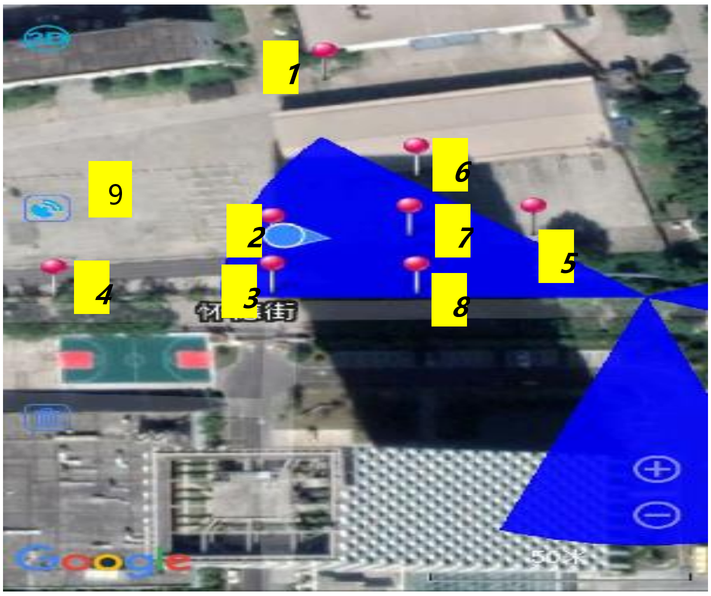
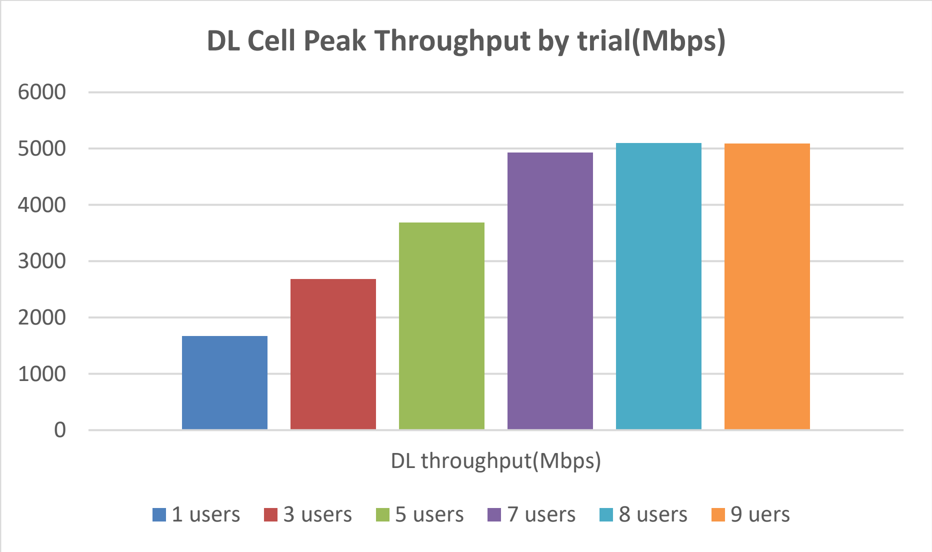


Figure 86: Multiuser (less than or equal to 10 users) trial site.

Figure 87 shows the testing peak throughputs for 1/3/5/7/8/9 users, where all users were located at good points in absence of adjacent cell interference. In order to better ensure the effect of pairing [8], in the multi-user pairing process, the number of streams for each user is 2 downstreams and 1 upstream. It can be seen from the figure that when the number of users is small, increasing the number of users increases the peak throughput for both DL and UL. When there are 8 users, corresponding to 8 horizontal beams, the maximum number of streams in the cell is reached (16 streams downstream, 8 streams upstream); when the number of terminals (i.e. users) continues to increase beyond 8, the cell throughput will be relatively stable.

Through using the 64T64R base station equipment, the service beam is narrower, and the number of layers is larger. With a 2T4R terminal, the maximum number of downlink streams for a single user is 4 and the maximum number of uplink streams is 2; while the typical maximum number of downlink streams in a cell can reach up to 16 and the typical maximum number of uplink streams can reach up to 8. Theoretically, this is about 4 times the peak rate of a single user. The peak throughput of the cell under multiple users is determined by the maximum processing capacity of the network and its performance is closely related to the algorithm of 5G key large-scale antenna technology [8]. When there is enough space separation or beam isolation between multiple users and the signal is good, the peak throughput of the cell can be reached. In the trial, the measured peak throughput of the cell is about 3 times the peak throughput of a single user, and the downlink and uplink can reach more than 5 Gbps and 650 Mbps, respectively.



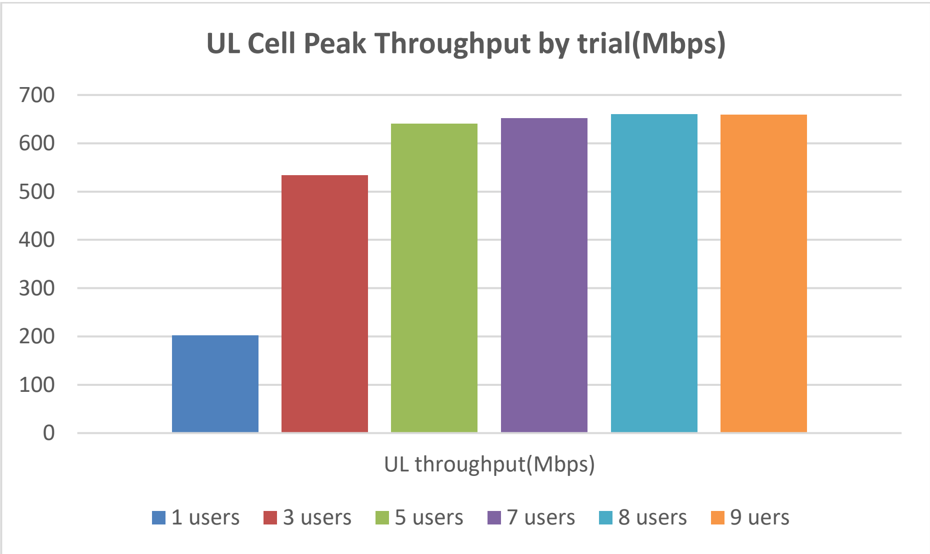


Figure 87: Cell throughput when the number of users is 1, 3, 5, 7, 8, 9, respectively.

In practice, the distribution of users is random, which cannot ensure good separation between different users. At this time, the average cell throughput should be smaller and the peak throughput of the cell will be reduced. The main factors impacting the average cell throughput include user random distribution and moving speed. Assume 10 users in the field testing of average cell throughput. Figure 88 and Figure 89 illustrate the downlink and uplink cell throughputs, in which 4 cases are considered: (1) all users are located at good points, in absence of adjacent cell interference; (2) Evenly static distribution, where 1/2/3/4 users are located at excellent/good/fair/bad points, respectively, in presence of 50% adjacent cell interference; (3) Concentrated static distribution where the separation of users should be less than 1 meter in presence of 50% adjacent cell interference, and; (4) evenly moving distribution in presence of 50% adjacent cell interference. Of the 10 users, 4 users slowly move among excellent/good/fair/bad points, 4 users move at the speed of 3km/h between good and bad points, 2 users move at a fast speed of 60km/h between good and bad points. It can be seen from the figures that in the centralized distribution of users relative to even distribution, the impact of spatial separation between users becomes worse, so that the performance of multi-user pairing degrades and the average throughput of the cell decreases by 35% to 50% for DL and UL, respectively. In a multi-user moving scenario, since the channel information between different users varies greatly, the accuracy of channel state information (CSI) estimation degrades, the rate is 50%-70% lower than that of the fixed-point even distribution.

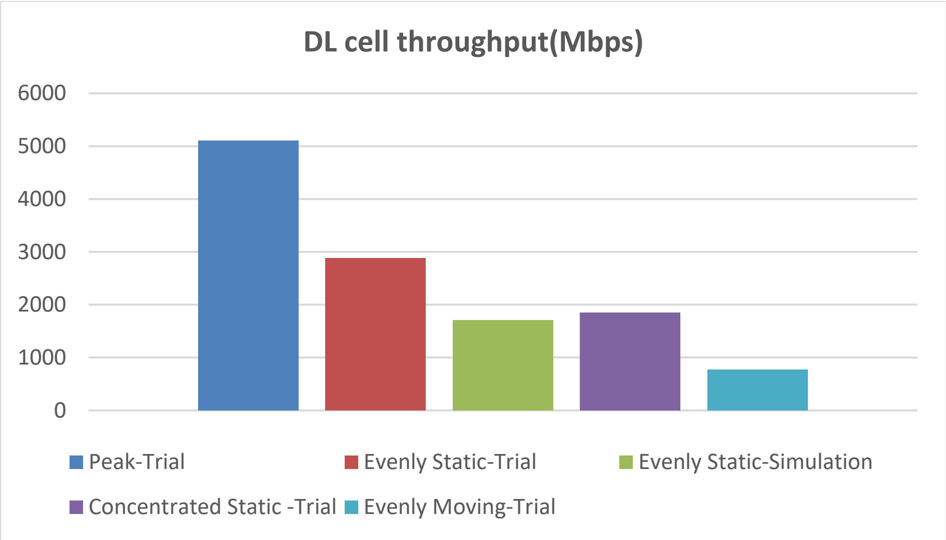


Figure 88: Impact of user distribution and mobility on downlink cell throughput.

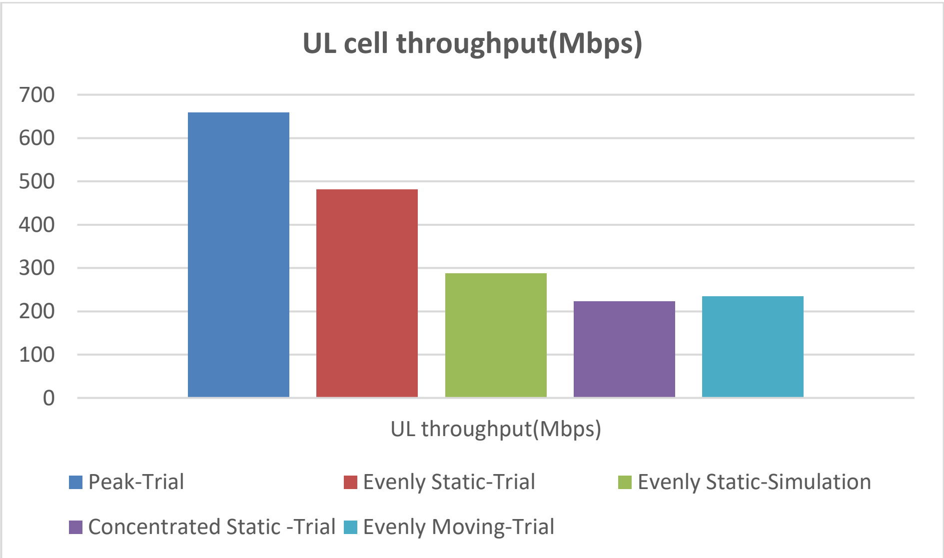


Figure 89: Impact of user distribution and mobility on uplink cell throughput.

In order to show some performance comparison between trial and simulation results, the multiuser simulation has been carried out specifically by considering case (2): the evenly static scenario. The simulation results in case (2) have been added in Figure 86 and Figure 87. It can be seen from the figures that the simulated cell throughputs are 1.71 Gbps, and 288 Mbps for downlink and uplink, respectively, whereas the trial cell throughputs are 2.88 Gbps, and 482 Mbps for downlink and uplink, respectively. Therefore, the trial results are higher than simulation results. The main reason is that in the actual trial, the locations of the user distribution have specially been selected in the way that different users are located in different beams so that the number of pairing data streams among multiple users is relatively high.

3) Larger Than 10 Users

In order to further verify the network performance in large-capacity access, we measure the peak performance of 20-100 users in a static state after simultaneously accessing the network. As shown in Figure 90, 15 points in the cell are selected, each of which accommodates 1 to 7 user terminals. The maximum number of users is 100. First, after 20 users in a static state are simultaneously connected with the full buffer traffic, we measure the throughput of each user and the throughput of the whole cell; then increase to 40 users, 60 users, 80 users, 100 users gradually, and repeat the above steps. All the users are located at the premeasured and selected good points of the signal and are distributed as uniformly as possible within each service beam of the base station. The measured downlink cell throughput is 4.2 Gbps - 4.5 Gbps, and the uplink cell throughput is about 450 Mbps – 480 Mbps. When increasing from 20 users to 100 users, due to increased interference between multi-user streams, the average throughput of the uplink and downlink is reduced slightly by 5% to 10% as shown in Figure 91.

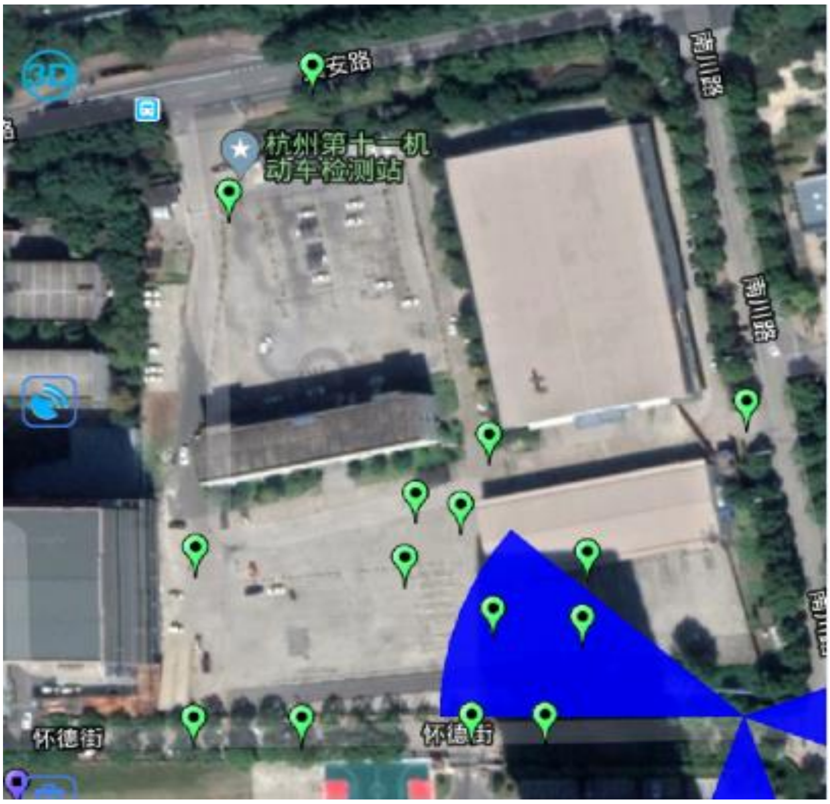
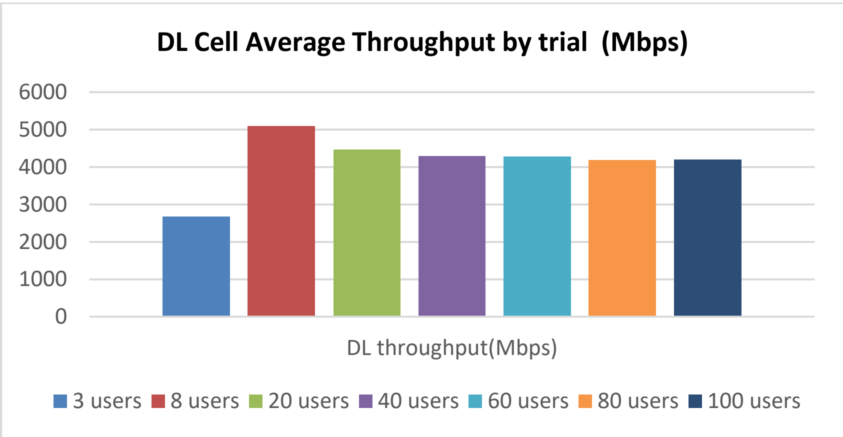


Figure 90: Multiuser (larger than 10 users) trial site.



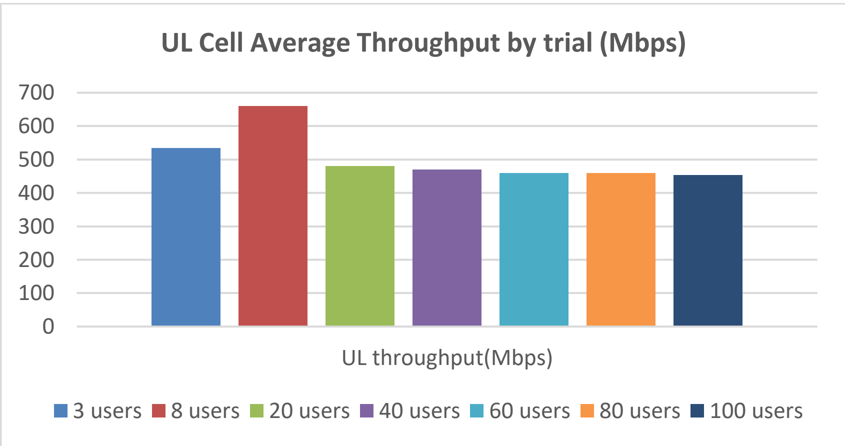


Figure 91: Impact of the number of users on cell throughput in large-capacity scenario.

2.3.2.3 Performance of single user in case of 3D beamforming

In order to evaluate the coverage performance of 3D beamforming with 2/4 vertical beams, we consider the simple scenario of single user. The test building is located at about 120 meters away with height of 57 meters from the 5G gNB, which is 54 meters high. Therefore, the building is located in the straight direction of the 5G gNB sector. The building has a total of 20 floors. For testing, the single user is located on Floors 3, 11, and 20 as low, medium, and high floors, respectively. The average throughput over 2/4 vertical beams is shown in Figure 92. It can be seen from the figure that because the dynamic range of the dimensional beam is increased, and the coverage performance of the vertical dimension is enhanced. For a typical building with a medium distance from the gNB, good coverage performance can be achieved in all the low, medium, and high-rise floors. Specifically, the DL rates of about 660-750 Mbps and DL rates of around 40-78 Mbps are obtained.

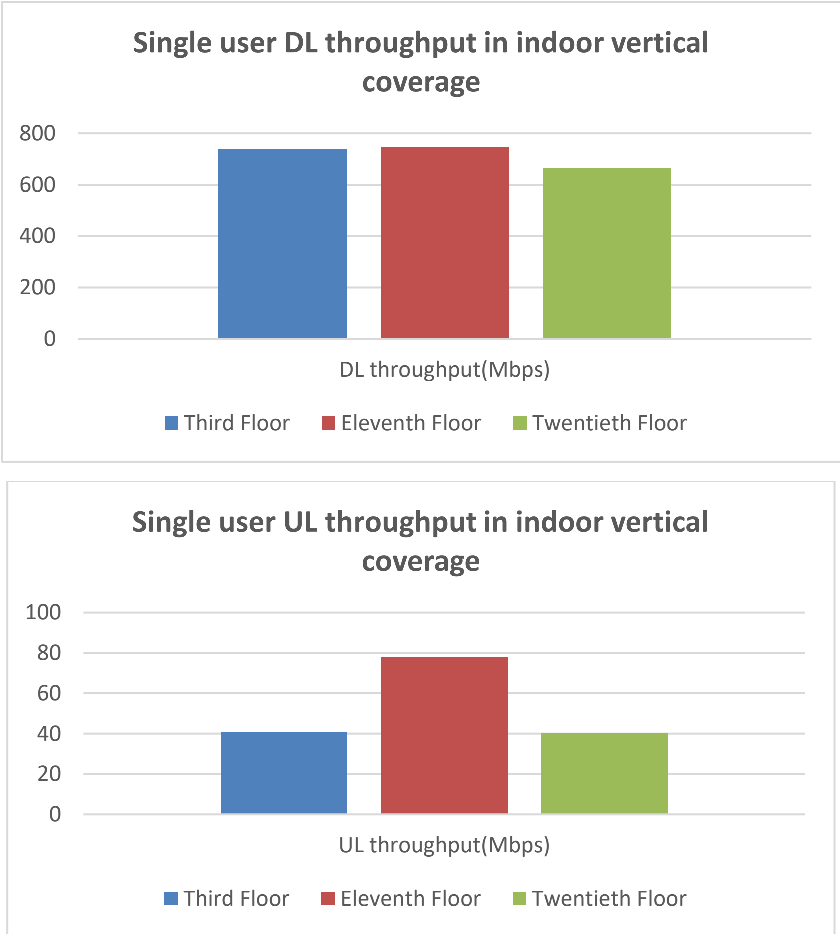


Figure 92: Throughput of single user in case of 3D beamforming.

2.3.3 Conclusion

From the field trial results, the following conclusions have been drawn:

1) The multilayer beams from 64 transmit/receive antennas at a base station (gNB) can cover high-rise buildings with a height of 140 meters with good receive signal quality.
2) For 2D beamforming, in the case of single user with 4 receive antennas, 3 and 4 data streams can be accommodated with 67% and 10%, respectively. However, if a neighbour cell is 50% loaded, the 3 and 4 streams may be supported with 44% and 0%, respectively, so that the data rate is reduced significantly due to intercell interference.
3) For 2D beamforming, in the case of a number of users, the total sum rate from all users can be increased multiple times (i.e., 3 to 4 times) as large as that of a single user. When the number of

users is larger than 8, the sum rate has been saturated.

4) Users with uniform distribution can achieve larger sum rate than users with centralized distribution due to space separation.
5) Under static user conditions, the performance of the multi-antenna system is the best; under low-speed mobile conditions, the performance of the multi-antenna system drops sharply, even by more than 50%.
6) For 3D beamforming, in a typical building with a medium distance from the gNB, good coverage performance can be achieved in all the low, medium, and high-rise floors.

2.4 Summary

In this chapter, eMBB trial results with focus on radio access technologies have been presented. First, NSA outdoor basic performance measurements over three trial sites have been reported. Then some NSA indoor measurements results have been discussed afterward. Then the performance of 3D beamforming has been studied with the various antenna patterns and calibrated with the actual performance achieved through field trials.

3 Performance measurements and results analysis for 5G network technologies

3.1 Network slice orchestration performance measurement, results and analysis

3.1.1 Network slicing KPIs

A new approach to network slicing KPIs has been proposed in 5G-DRIVE Deliverable D5.1. The devised KPIs focus only on parameters that are related to network slicing in an agnostic way. The KPIs related to the solution, which is implemented as a network slice, are out of the scope of this analysis since they should be the same as those defined for the non-sliced implementation of the solution. For example, if 4G EPC is implemented as a slice, KPIs that concern EPC implementation in a non-sliced (or virtualized) environment are applicable. In further subsections, the experiments that were made to measure the proposed KPIs have been described.

3.1.1.1 Network slicing KPIS

The list of the measured KPIs includes:

- **Slice Deployment Time (SDT)** is a parameter that describes the interval between the slice deployment request and the moment in which the slice is ready for operation. The problem with this parameter is that this interval depends on "slice template (blueprint) complexity", the performance of the orchestrator, and the allocation of resource time by the virtualized infrastructure. The slice complexity may deal with the footprint size of VNFs, their interconnection topology, and the number of configuration parameters. Therefore, in a generic case, it is impossible to define the required value of SDT. It can be noted that SDT can be critical for some network slices, for example, in the case of on-demand or short-lived ones, but much less critical for long-lived slices.
- **Slice Deployment Time Scalability (SDTS)** is a measure of scalability of slice deployment operations. To evaluate the scalability, it is possible to send N slice deployment requests of the same slice template and calculate SDTS as presented in equation (3.1).

$$SDTS = \frac{GSDT}{N*SDT} \tag{3.1}$$

where *GSDT* is the overall time for the deployment of N identical slices and *SDT* is the deployment time of a single slice (as defined above). It is hard to determine the N value *a priori*. If the N value is too big, then there can be a problem with the availability of the requested resources. If it is too small, then the obtained result may not express the scalability of the orchestration well. It can be recommended to calculate the SDTS parameter for N = 10. The SDTS is expected to be lower than 1.

- **Slice Termination Time (STT)** is a parameter that describes the interval between the slice termination request and the moment in which all slice allocated resources are released. If the time is long, it decreases the efficiency of the infrastructure resources usage.
  Slice Termination Time Scalability (STTS) is a measure of the scalability of slice termination operations. The evaluation of the STTS is parallel to the calculation of SDTS and is performed as shown in equation (3.2).

$$STTS = \frac{GSTT}{N*STT} \tag{3.2}$$

where GSTT is the time needed for termination of N slices at once. The STTS lower than 1 shows better scalability regarding slice termination and resource deallocation.

3.1.1.2 Network slicing KPIs computation in the NFV MANO case

In the presented approach, the 5G-DRIVE proposes to use the OSS/BSS of the standard NFV/MANO architecture [10], to calculate and collect the network slicing KPIs. To collect information required for KPI calculation, the OSS/BSS must interact with other components of the MANO architecture. The proposed lifecycle KPIs can be obtained using the interaction between the OSS/BSS and NFVO. Hence, the OSS/BSS can determine both the beginning and the end of the procedure, also in case of disturbances of intra-MANO communication (e.g. OSS/BSS is notified about the delay of procedure execution due to the need of retrying).

There are two possible ways of calculation of these KPIs: (i) based on events logging in the on-board OSS/BSS log – each event is logged with a time-stamp, and correlated search of beginning/finishing event for a specific procedure is sufficient; (ii) the API for OSS/BSS-MANO communication will typically use the time-out mechanism and the time-out timer can be implemented – its value at the end of the procedure may be instantly passed to the Performance Management engine of the OSS/BSS. During the measurements, the first approach has been taken. Additionally, the measurements of the load of the used infrastructure (CPU, memory) during slices orchestration operations have been performed. The details are presented in section 3.1.4.

3.1.2 Instantiated network slice templates

During preliminary measurements, the lifecycle KPIs have been collected for simple VNFs (i.e., different lightweight Linux distributions) which is described in detail in [11]. However, the KPIs obtained for mentioned VNFs might not be in line with the ones obtained during more demanding tasks (i.e., orchestration of slices requiring a high amount of resources). As recently, considerable effort has been put in providing compatibility of OSM MANO and Magma solution developed by Facebook; we have decided to further investigate the OSM MANO orchestration capabilities [12], already tested in [11], by conducting measurements of lifecycle KPIs during deployment and termination of the EPC Network Slices. Due to the size and complexity of the orchestrated VNFs, the obtained measurement results enable better assessment of the real-life OSM MANO performance.

Facebook Magma [13], is an open-source software platform enabling the creation of the cloudified 3GPP core networks (2G, 3G, 4G and 5G) for different access networks. The solution is composed of three main components:

- Access Gateway (AGW) – component providing network services and policy enforcement (in LTE network case, the AGW implements a single vEPC),
- Orchestrator – cloud service that is providing a way to configure and monitor the wireless network,
- Federation Gateway – a proxy that integrates AGWs and specific MNO core network entities that contain subscribers' identities or charging policies (HSS, PCRF, etc.)

The interconnected AGW and orchestrator form the single Magma EPC Network Slice as depicted in Figure 93.

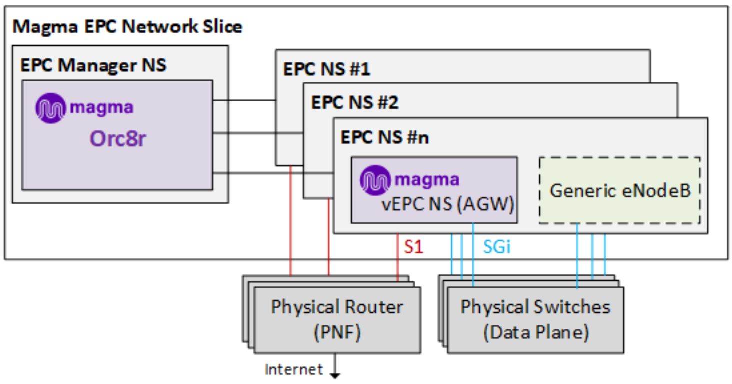


Figure 93: The high-level view of Magma EPC Network Slice (with multiple EPC NS).

The Federation Gateway is an optional component not included within the Magma EPC Network Slice template. Moreover, the number of Federation Gateways would also be largely dependent on the spatial distribution of MNO's core network entities (one gateway can proxy for multiple instances of Magma EPC slices). Therefore, the measurements have been performed for EPC NS (Magma AGW) only.

3.1.3 Measurement environment and methodology

The measurements of network slicing lifecycle KPIs have been conducted in the environment depicted in Figure 94.

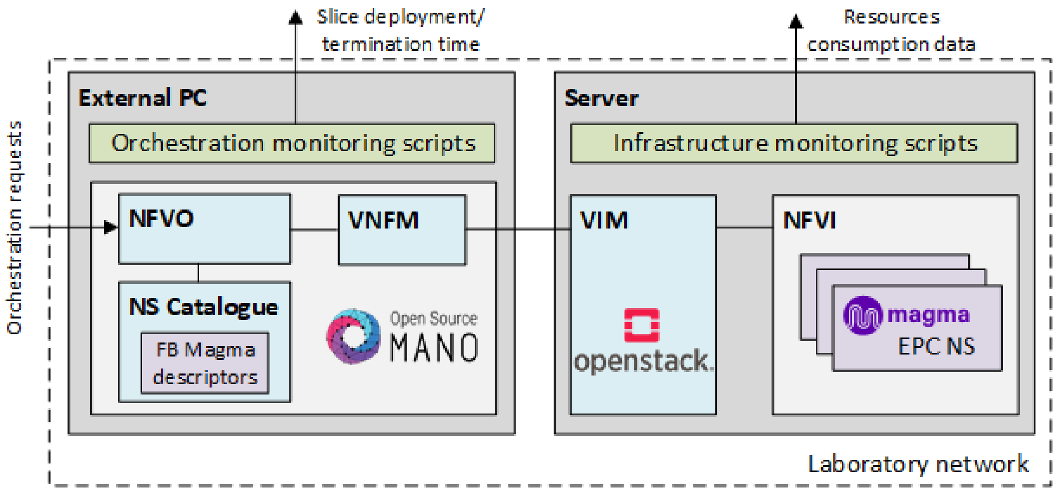


Figure 94: The configuration of the system used during slice lifecycle KPIs measurements.

The measurement environment was composed of two machines, a PC hosting the OSM MANO[18] rel. 9.1 and the server which realises the functions of VIM (installed OpenStack) as well as NFVI for the deployment of EPC Network Slices. The parameters of used hardware are presented in Table 17.

[18] Also see: https://osm.etsi.org/

Hardware component	CPU	Memory	Disk
External PC	Intel® Core™ i7-8700 CPU @ 3.2 GHz	16 Gb	256 Gb
Server	Intel Xeon Silver 4216 2.1GHz, 16C/32T, 9.6 GT/s	32 GB RDIMM, 3200 MT/s	1 TB

Table 17: Hardware components used to deploy the KPIs measurement environment.

Monitoring scripts were used on both machines during the orchestration operations. The scripts have collected and extracted the desired information - timestamps from OSM MANO logs (PC case) and data related to resources consumption i.e., RAM and CPU utilization (server case). The orchestration requests were issued by scripts using OSM MANO CLI commands. Prior to testing the deployment and termination of EPC NSs, one Magma Orc8r instance has been instantiated. To deploy the EPC NS instances, the following packages have been used:

- NS package: magma-agw_nsd
- VNF package: magma-agw_vnfd
- Image: magma101.qcow2

Each EPC slice also required 2GB of memory, 50GB of storage and 2 CPU cores to operate.

Due to resource limitations, the largest possible number of concurrently running slices equals 18. Therefore, the conducted KPI measurements were performed by deployment and termination from 1 to 18 identical instances using the abovementioned templates (previously properly translated into the new ETSI GS NFV-SOL 006 format). To assess the scalability parameters (see section3.1.1.1), the operations have been done both in a simultaneous way, as well as a one-by-one approach (deploying each additional instance once the previous deployment is finished). Moreover, to minimise the impact of random and undesired fluctuations of parameters during measurements, the tests have been conducted ten times each, and the obtained results have been averaged. Before performing the planned measurement tasks, the CPU and RAM usage has been measured in the idle state of the system. The presented results take that overhead into consideration, showing a relative change of parameters (in comparison to the averaged CPU and RAM utilization in idle state).

3.1.4 Experiment results

We have measured the slice deployment time by deploying 1, 2, 3, 5, 7, 10, 14 and 18 AGW instances simultaneously and one-by-one using the same template. We have measured the Slice Deployment Time (SDT) – the interval between the slice deployment request and the moment in which slice is reported by the orchestrator as instantiated. We have used the GSDT parameter as the overall time for the deployment of N identical slice templates. The obtained results are presented in Table 18 and visualized in Figure 95.

Number of instances	GSDT [s]	N*SDT [s]	SDTS
1	31.85	31.85	1.00
2	33.60	63.70	0.53
3	42.60	95.55	0.45
5	63.90	159.25	0.40
7	92.35	222.95	0.41
10	160.55	318.50	0.50

Number of instances	GSDT [s]	N*SDT [s]	SDTS
14	282.40	445.90	0.63
18	443.65	573.30	0.77

*Table 18: Time required to deploy N slices simultaneously (GSDT), one-by-one (N*SDT) and the deployment scalability (SDTS).*

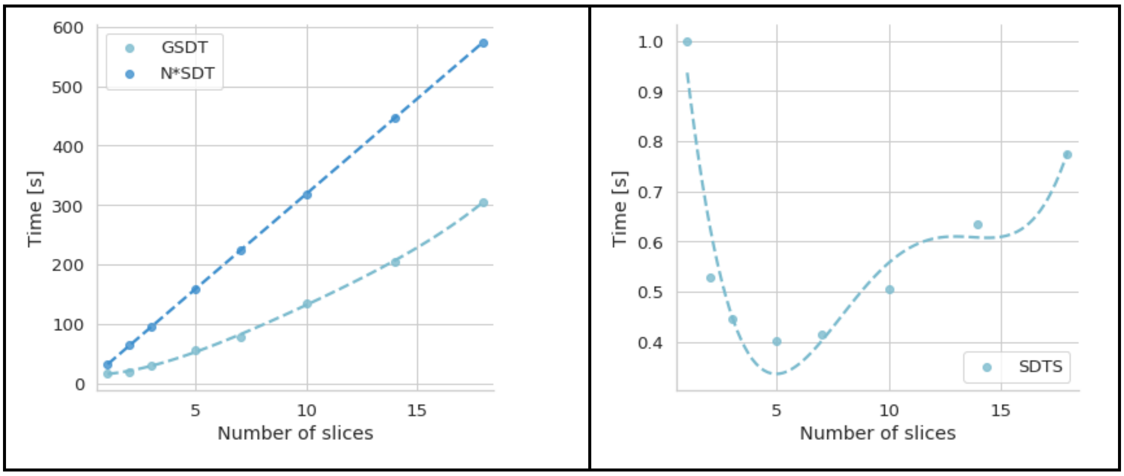


*Figure 95: Values of GSDT and N*SDT (left) and resulting SDTS (right) together with the approximation curves (respectively, second and fourth-order).*

The obtained GSDT is much higher than N*SDT in the analysed range of the number of deployed slices. The observed SDTS curve also shows decent deployment scalability. Nonetheless, the approximated N*SDT curve shows that the instant deployment of a massive number of slices might become more time consuming due to the polynomial character of the curve. Therefore, deployment of slice batches might be proficient. Measurements of CPU and RAM consumption (average and maximum values), during slice deployment, are presented in Table 19 and Figure 96.

Number of instances	RAM avg [%]	RAM max [%]	CPU avg [%]	CPU max [%]
1	0.19	0.5	1.83	6.82
2	0.46	1.1	3.27	9.22
3	0.94	2.0	3.87	10.02
5	1.56	2.8	4.83	12.92
7	1.88	3.6	5.12	14.52
10	2.59	4.7	4.92	14.32
14	3.78	6.3	4.81	15.32
18	5.23	9.6	4.71	14.12

Table 19: CPU and RAM consumption during simultaneous deployment of N slices.

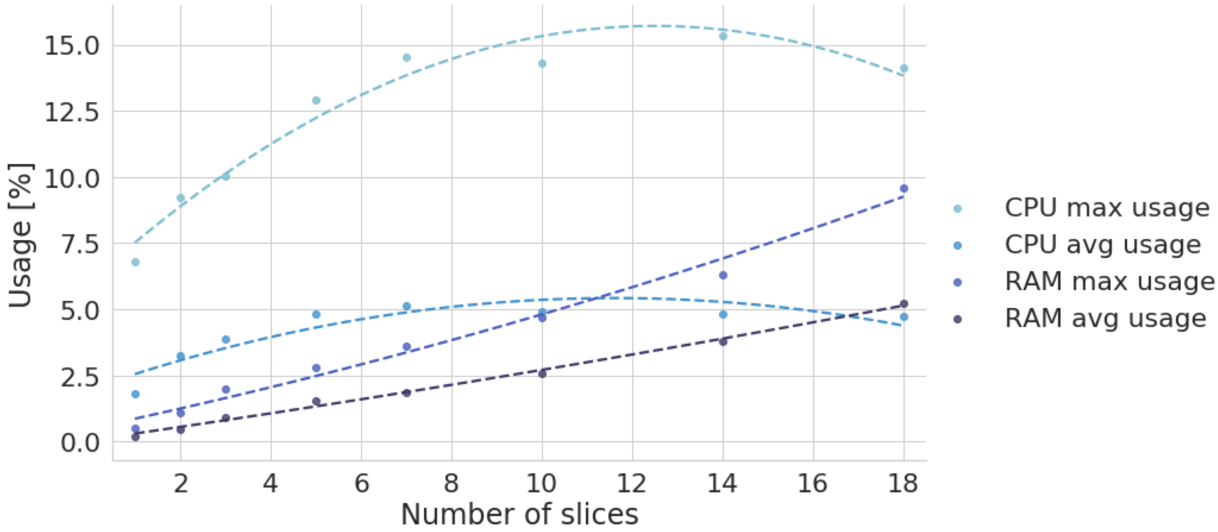


Figure 96: Values of CPU and RAM usage together with the approximation curves (second order).

The RAM consumption during simultaneous deployment of the respective number of slices is presented in Figure 97 and Figure 98.

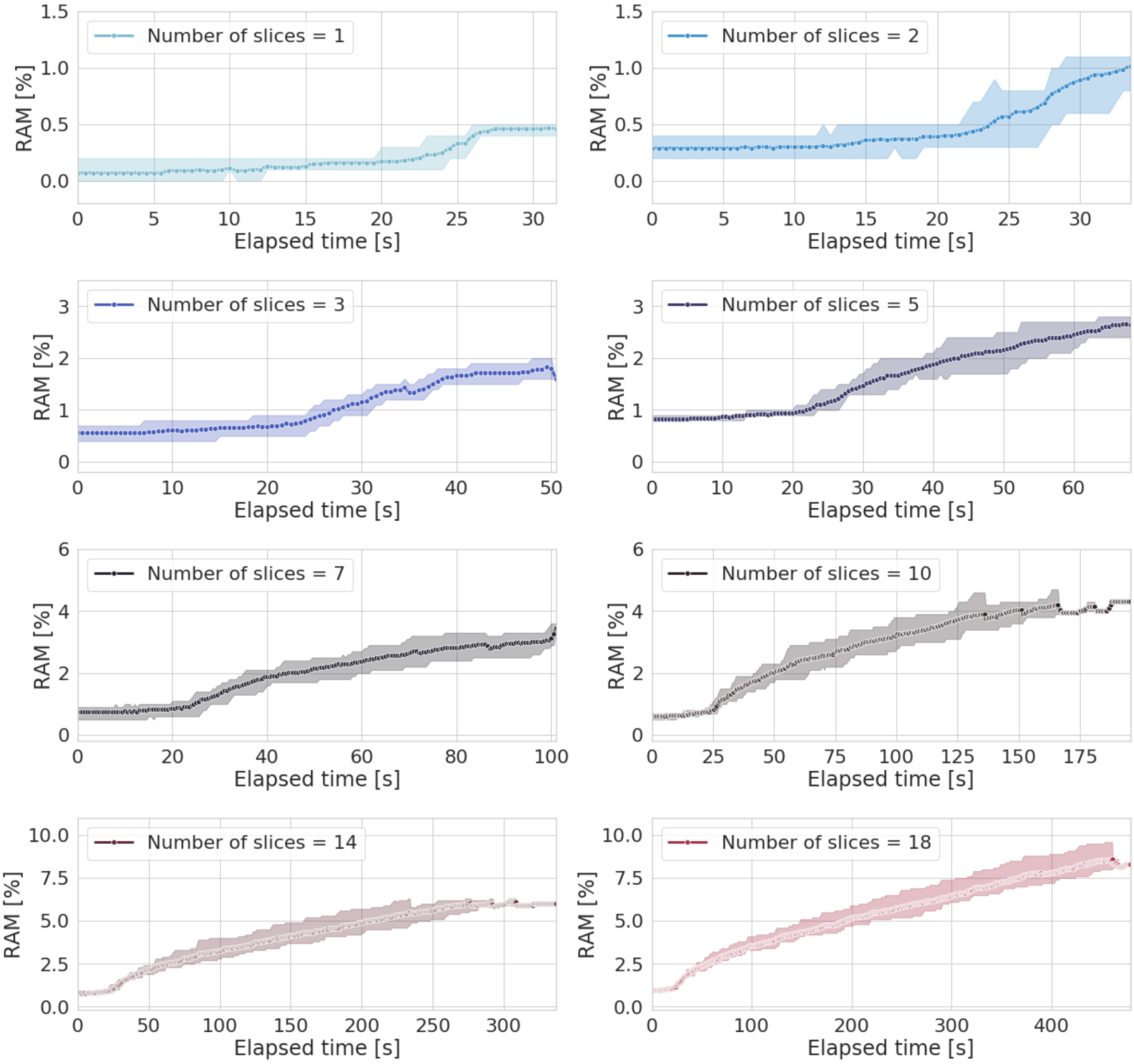


Figure 97: RAM usage measurement for different number of slices deployed.

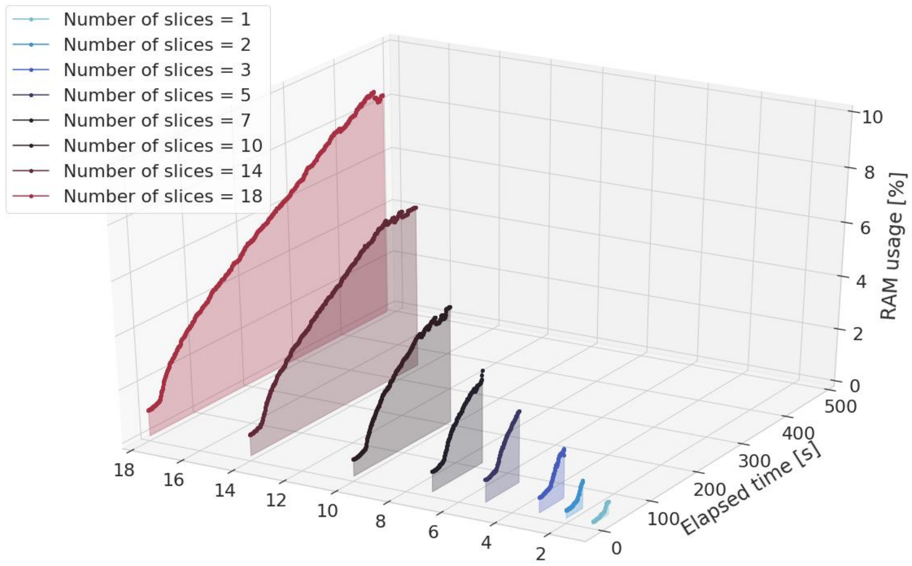


Figure 98: RAM usage measurement for a different number of slices deployed - comparison.

As predicted both RAM consumption and deployment time is visibly increasing as the number of simultaneously deployed slices increases. It is not a linear increase, but rather a polynomial growth. It may also be noticed that there is a trend according to which the first 25 seconds in all cases characterize in low consumption of RAM (below 1%). Presumably, during the first 25 seconds initialization tasks are performed preceding the slice deployment (and is constant regardless of the number of slices). After that the significant growth of RAM consumption over time can be observed.

The CPU consumption during simultaneous deployment of respective number of slices is presented in Figure 99 and Figure 100.

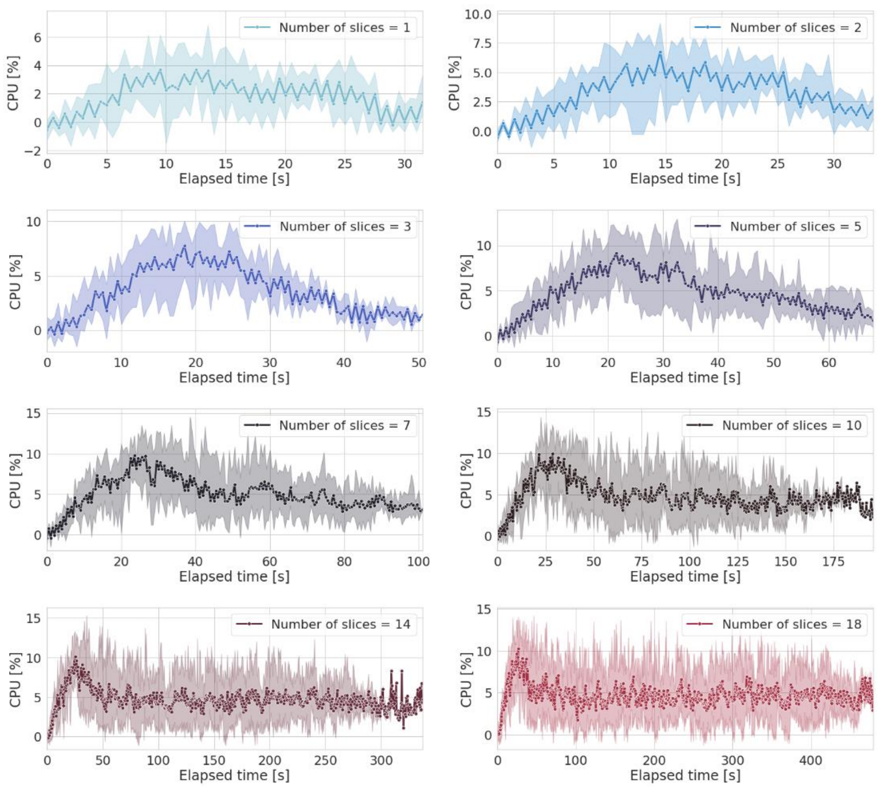


Figure 99: CPU usage measurement for a different number of slices deployed.

The CPU consumption is at a similar level for all cases and it increases by small amounts as the number of simultaneously deployed slices increases. Average CPU consumption for more than three slices deployed simultaneously, fluctuates around 5%. It may also be noticed that there is a trend according to which the first 30 seconds of simultaneous deployment in all cases characterize a significant increase of CPU consumption. After that, the CPU utilization decreases by about half of the value and then fluctuates around this value.

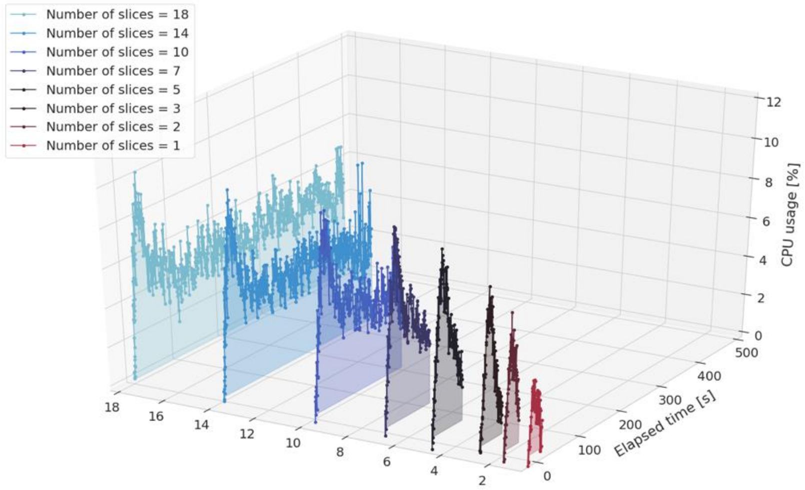


Figure 100: CPU usage measurement for a different number of slices deployed - comparison.

The RAM consumption after the deployment of a respective number of slices is presented in Figure 101.

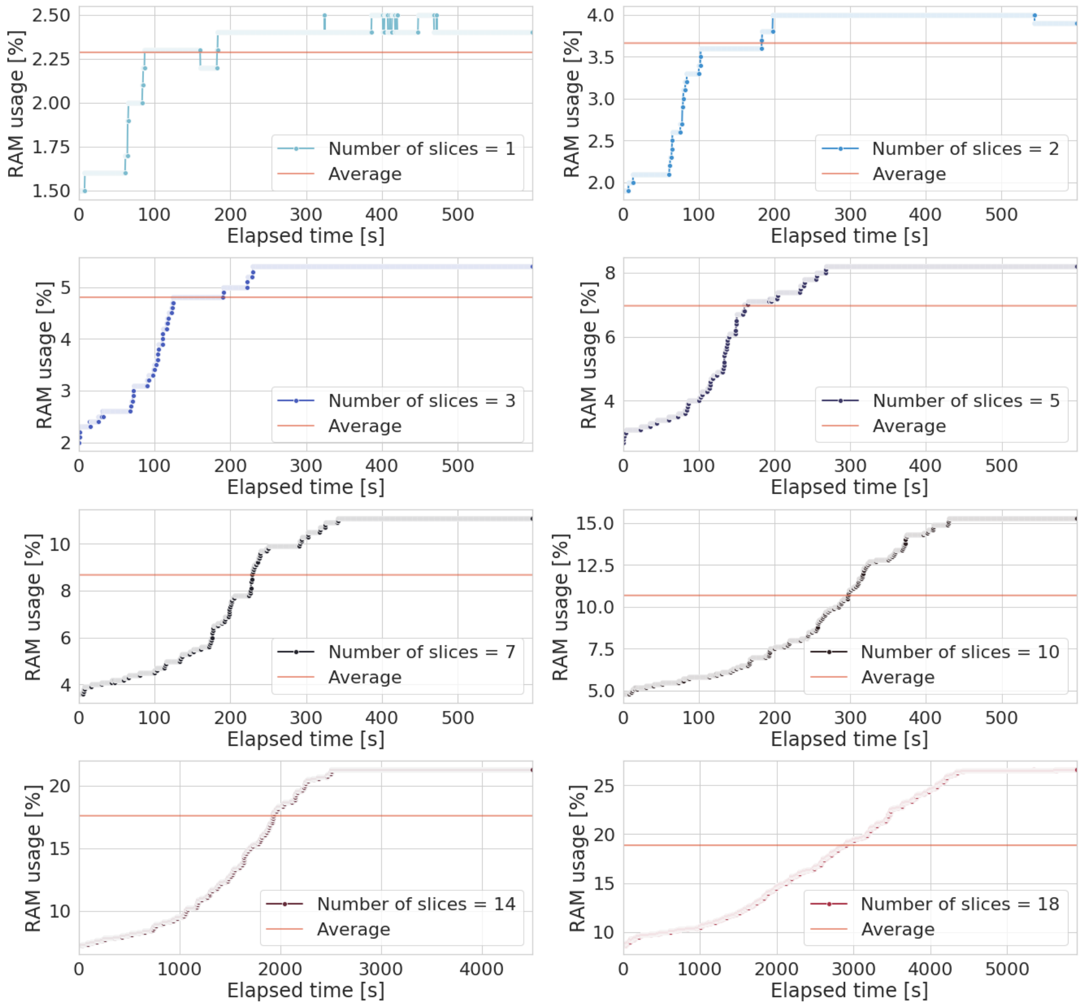


Figure 101: RAM usage measurement after deployment of a different number of slices.

Interestingly, the RAM utilization greatly grows after the slices are already deployed. Probably it means that the slices finished initialization state and started operation triggering resource scaling mechanisms. Afterwards (depending on the number of slices deployed), the RAM consumption stops growing and stabilizes. The operation of the resource scalability mechanism can still be observed later (as in the case of deployment of one slice or three slices in Figure 101).

The CPU consumption after the deployment of the respective number of slices is presented in Figure 102.

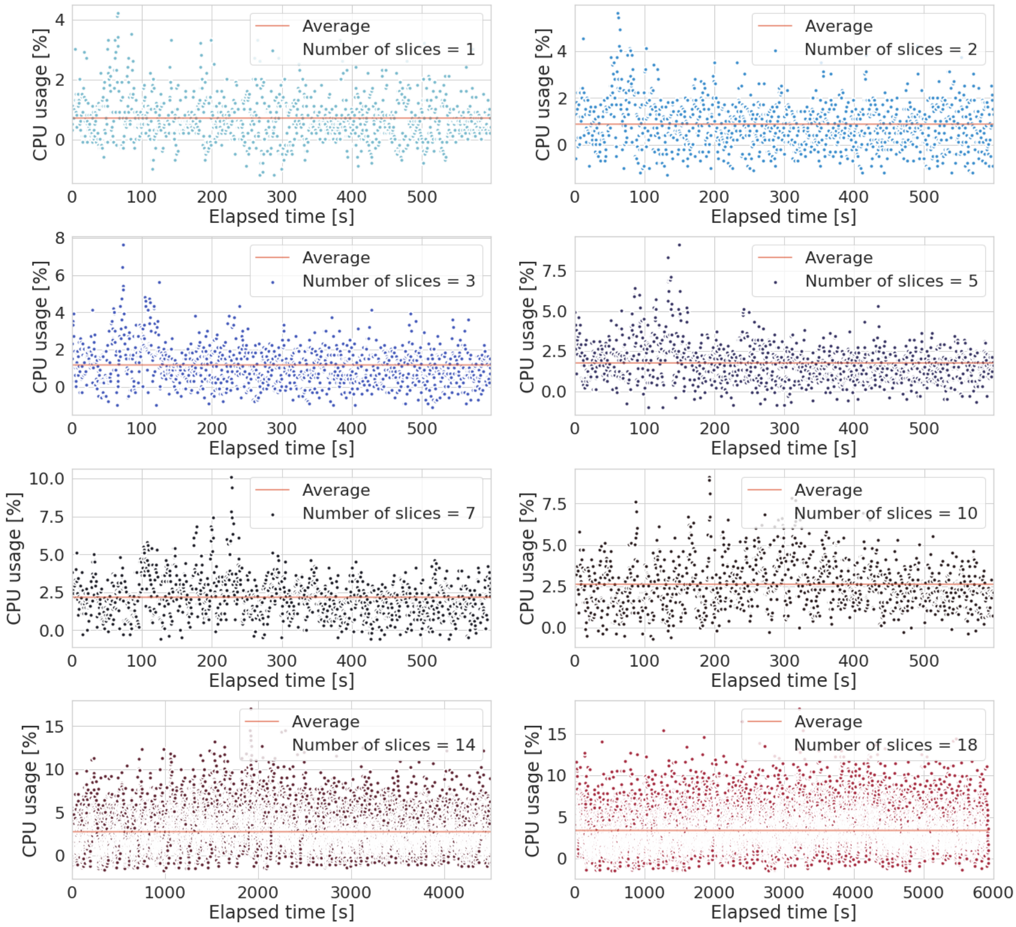


Figure 102: CPU usage measurement after deployment of different number of slices.

When the slices are already deployed, the CPU usage is relatively stable and fluctuates on average at around 1-3% (depending on the number of slices deployed).

3.1.4.1 Slice termination KPIs

We have measured the slice termination time by terminating 1, 2, 3, 5, 7, 10, 14 and 18 AGW instances simultaneously and one-by-one using the same template. We have measured the Slice Termination Time (STT) – a parameter that describes the interval between the slice termination request and the moment in which all slice allocated resources are released. STT is a total time, i.e., if it concerns ten slices, we just notice the moment when the last slice is terminated. We also calculated the STTS (Slice Termination Time Scalability) parameter (see definition in section 3.1.1.1. Results are presented in Table 20 and Figure 103.

Number of instances	GSTT [s]	N*STT [s]	STTS
1	16.1	16.1	1.00
2	19.0	32.2	0.59
3	29.5	48.3	0.61
5	56.4	80.5	0.70
7	77.2	112.7	0.68
10	133.9	161.0	0.83
14	205.5	225.4	0.91
18	304.0	289.8	1.05

*Table 20: Simultaneous termination time of N slice instances (GSTT, N*STT, STTS).*

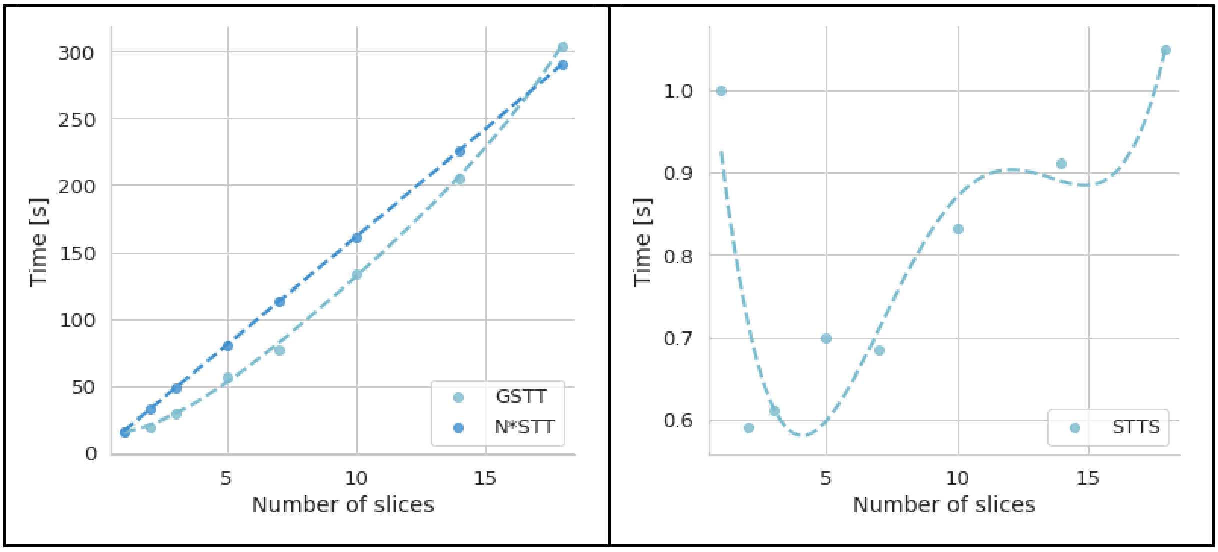


*Figure 103: Values of GSTT and N*STT (left) and resulting STTS (right) together with the approximation curves (second and fourth order).*

The obtained GSST is slightly lower than N*STT (STTS<1) for less than 18 instances. Nonetheless, the trend is turning for over 18 terminated slices. The observed STTS curve also shows decent deployment scalability. The approximated N*SST curve shows that the simultaneous termination of the huge number of slices can become more time-consuming.

Measurements of CPU and RAM consumption (average and maximum values), during slice termination, are presented in Table 21 and Figure 104.

Number of instances	RAM avg [%]	RAM max [%]	CPU avg [%]	CPU max [%]
1	0.72	1.4	1.48	6.52
2	1.65	2.8	2.52	9.62
3	2.35	4.1	2.99	10.82

Number of instances	RAM avg [%]	RAM max [%]	CPU avg [%]	CPU max [%]
5	3.32	7.3	3.24	14.22
7	3.15	5.3	3.40	13.72
10	4.67	11.9	3.43	12.82
14	5.23	8.3	3.19	13.02
18	8.05	20.8	3.56	15.52

Table 21: CPU and RAM usage for terminating N slices.

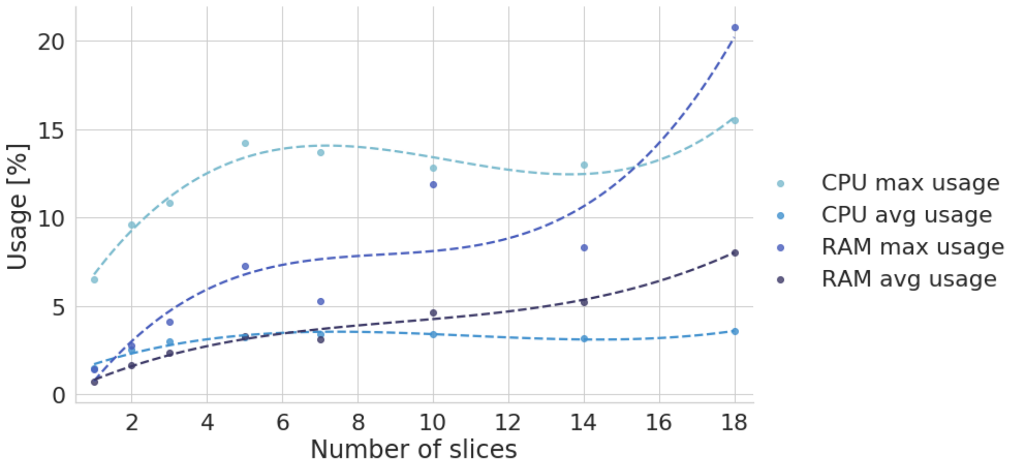


Figure 104: Values of CPU and RAM usage together with the approximation curves (second and fourth-order).

The RAM consumption during simultaneous termination of the respective number of slices is presented in Figure 105 and Figure 106.

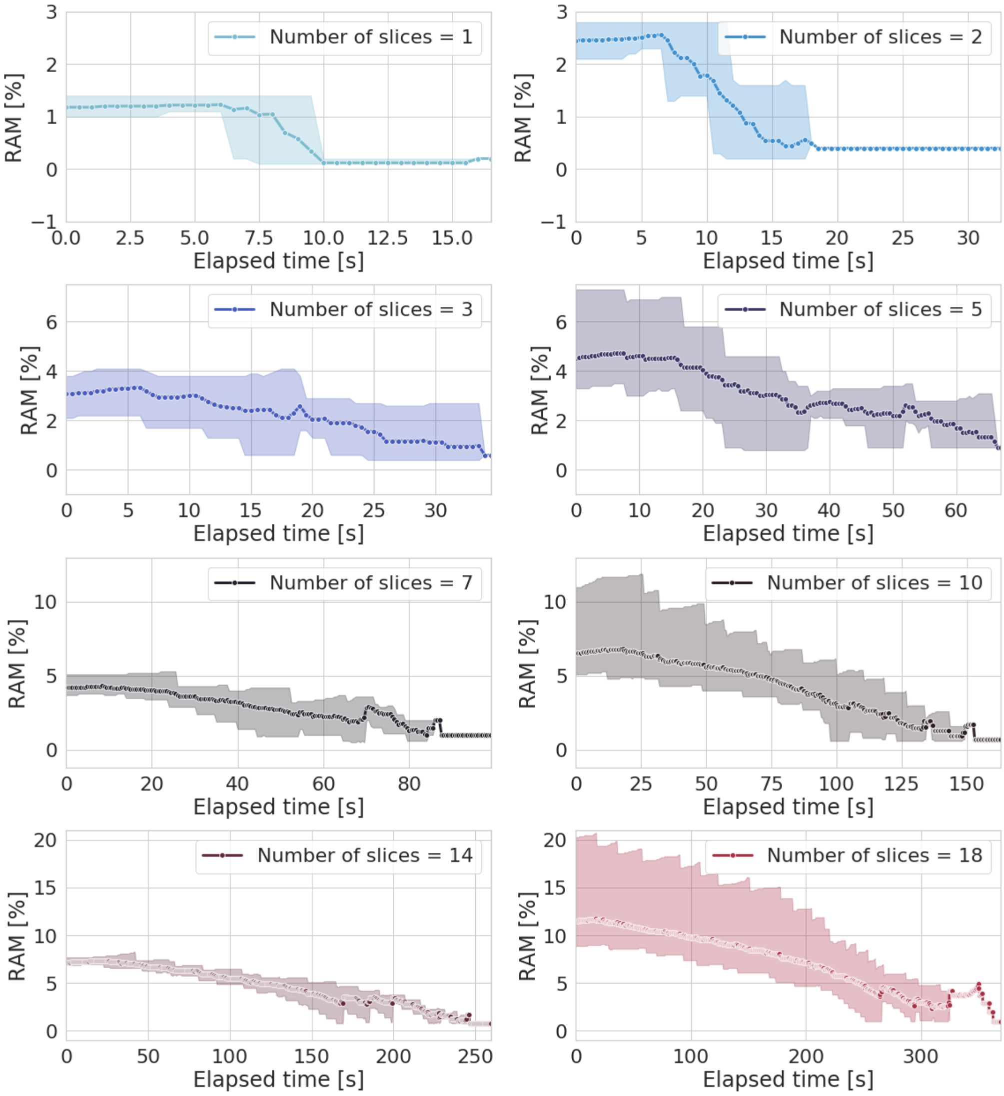


Figure 105: RAM usage measurement for a different number of slices terminated.

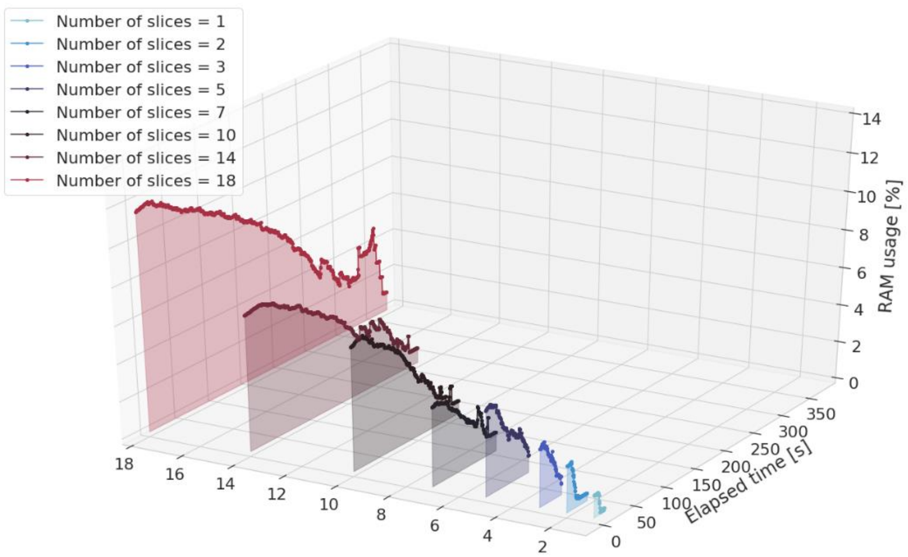


Figure 106: RAM usage measurement for different number of slices terminated - comparison.

As predicted both RAM consumption and deployment time is visibly decreasing as the number of running slices decreases. It is not a linear decrease, but rather a polynomial drop. It may also be noticed that there is a trend according to which in the last phase of slice simultaneous termination, the increase in RAM consumption can be observed (it is especially visible for 18 slice termination graph in Figure 105). The CPU consumption during simultaneous termination of respective number of slices is presented in Figure 107 and Figure 108.

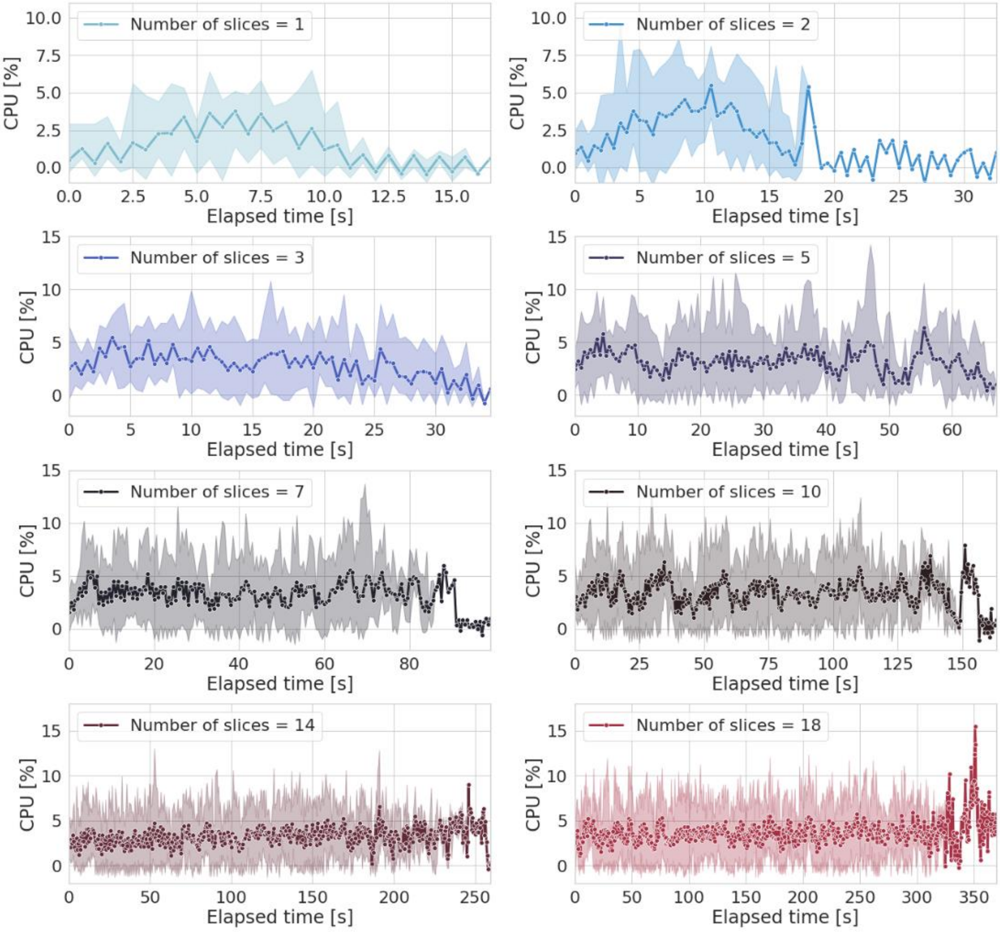


Figure 107: CPU usage measurement for a different number of slices terminated.

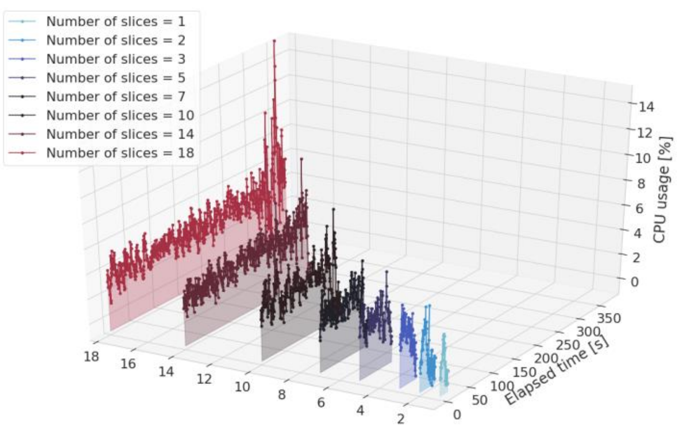


Figure 108: CPU usage measurement for different number of slices terminated - comparison.

The average CPU consumption increases by small amounts as the number of simultaneously terminated slices increases. It may also be noticed that there is a trend according to which in the last phase of slice simultaneous termination, the increase in CPU consumption can be observed (it is especially visible for 18 slice termination graph in Figure 107).

3.1.4.2 Slice deployment/termination KPIs comparison

The comparison between times during simultaneous termination of the respective number of slices is presented in Table 22 and Figure 109.

Number of instances	GSDT [s]	GSTT [s]
1	31.85	16.1
2	33.60	19.0
3	42.60	29.5
5	63.90	56.4
7	92.35	77.2
10	160.55	133.9
14	282.40	205.5
18	443.65	304.0

Table 22: Deployment and termination time of N slices.

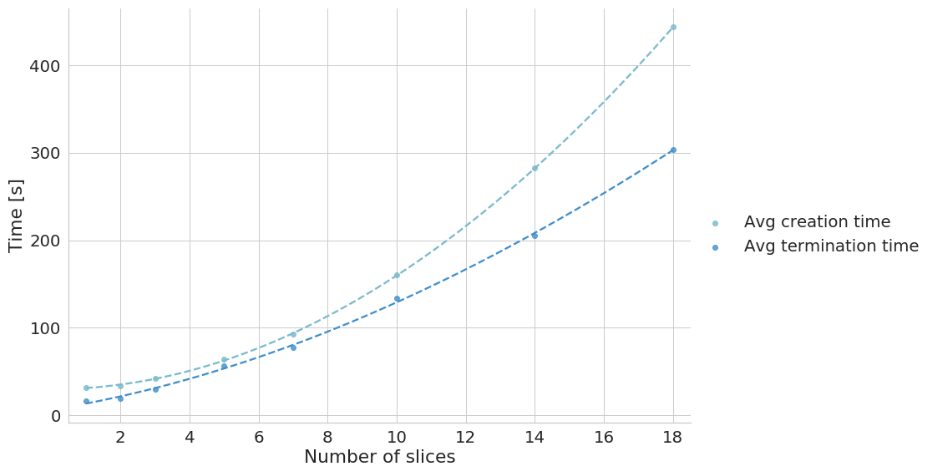


Figure 109: Deployment and termination time of N slices.

As depicted in Figure 109, the average slice deployment time is greater than the average slice termination time. Simultaneously the difference between the creation and termination times grows bigger as the number of simultaneously deployed/terminated slices increases.

Slice deployment and termination measurements for simultaneous and *one-by-one* methods are presented in Table 23. A one-by-one method is about deploying/terminating 18 instances one after the other (not at the same time as in the simultaneous method).

	Parameter	18 slices simultaneously	18 slices one-by-one
Deployment [GSDT]	Time [s]	443.65	656.65
	CPU avg [%]	4.71	4.03
	RAM avg [%]	5.23	12.9

	Parameter	18 slices simultaneously	18 slices one-by-one
Termination [GSTT]	Time [s]	303.95	289.85
	CPU avg [%]	3.56	3.87
	RAM avg [%]	8.05	14.13

Table 23: Statistics for simultaneous and one-by-one methods of deployment and termination of 18 slices.

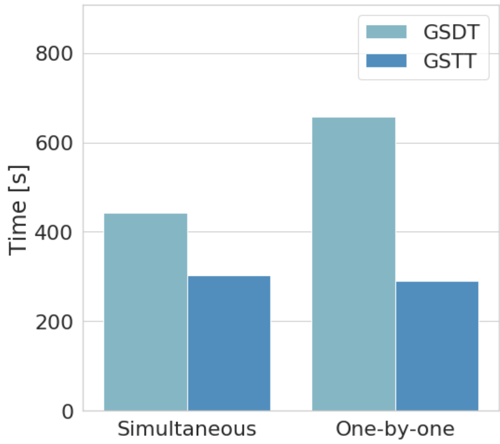


Figure 110: Time for simultaneous and one-by-one methods of deployment and termination of 18 slices.

As it is presented in Figure 110, the average slices deployment time using the *one-by-one* method is longer by approximately 50% than using the simultaneous method. Meanwhile, the average slices termination time using the *one-by-one* method is slightly lower than using the simultaneous method.

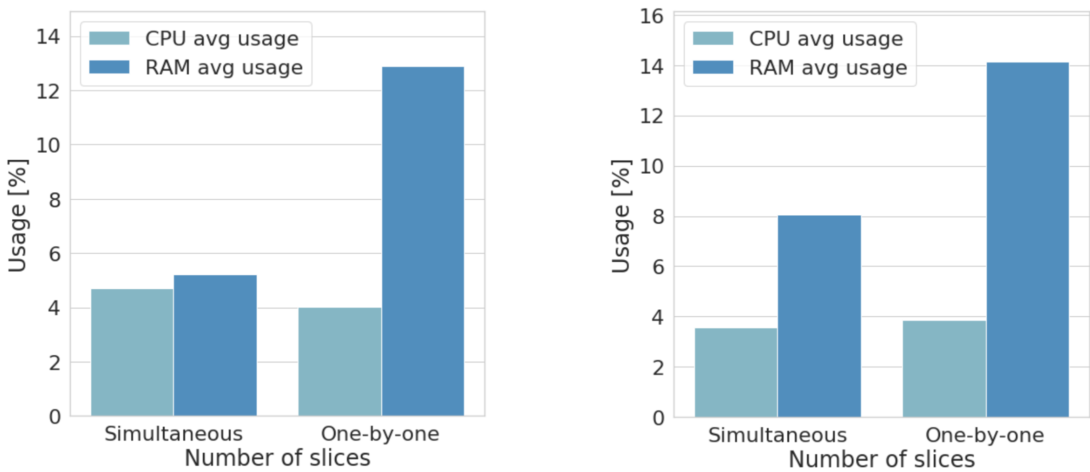


Figure 111: Average values of CPU and RAM usage for slices deployment (left) and termination (right).

As shown in Figure 111, the average CPU utilization is very similar for both methods (both during deployment and termination). During slice termination, the average CPU usage is slightly smaller than during slice deployment. Whereas the average RAM consumption is noticeably higher when using the *one-by-one* method. For slice deployment, it is over 100% higher than when using the simultaneous method. For slice termination, it is about 75% higher than when using the simultaneous method. It is also worth noticing that during slice deployment, the average CPU usage is higher than during the slice termination (for both methods). Simultaneously, the average RAM usage is higher during the slice termination than during the slice deployment (for both methods).

3.1.5 Conclusions

In this subsection, the results of the experiments conducted to assess the scalability of network slices lifecycle management of the OSM orchestrator have been presented. The obtained results show decent scalability of the used platform in the analysed range of numbers of deployed slices – the parallel slice deployment and termination time is considerably lower than in the one-by-one approach. The slice instance termination is much longer than anticipated, lasting approximately 51% to 88% of the slice deployment time, showing lower complexity of the operation. Nonetheless, the time needed for resources deallocation is much higher than anticipated, most probably due to specific operation of VIM used by the orchestrator (deleting VMs is typically more time consuming than, e.g., terminating containers). The results also show that in all analysed cases, the consumption of infrastructure resources was not linear, which might become problematic for deployments of the huge number of slices.

The experiments were conducted using complex and resource-demanding slice templates, i.e., Magma EPC slice; the results can be treated as the close approximation of the KPIs achieved in the real-life deployments. Nonetheless, the slice deployment and termination time can be impacted by several factors such as slice complexity (VNF number, size, VNF interconnections), the number and the location of the datacentres in which the VNFs will be deployed, etc. The complex character of the problem shows that, in general, defining the slice deployment or termination time *a priori* is problematic. Therefore, the conducted tests can be treated as an entry point for further assessment and research related to MANO performance. Despite the obtained results are satisfactory – the absolute slice deployment and termination time in the range of tens of seconds is acceptable, and it shows that the MANO orchestrator is not a bottleneck in the orchestration process for a relatively small number of slices.

3.2 vCache performance results and network slicing measurements

Apart from the individual efforts in implementation and demonstration discussed in the previous sections, there is also a service level joint demonstration between OTE and ORION that will be showcased within the 5G DRIVE project. The demonstration will be based on the integration of the ORION developed services and VNFs, namely the vCache, in the OTE trial testbed. The planned architecture of this joint demonstration is shown in Figure 112. Firstly, a VPN link will be established between ORION and OTE to migrate the necessary services and descriptors needed for the deployment. Apart from the VNF descriptors a compatible version of the OSM will be integrated, in order to facilitate the seamless deployment and orchestration of the Cache/Reverse Proxy service. Additionally, various modifications on the SDN control plane will be enforced in order to verify the proper service of the VNF and evaluate its performance.

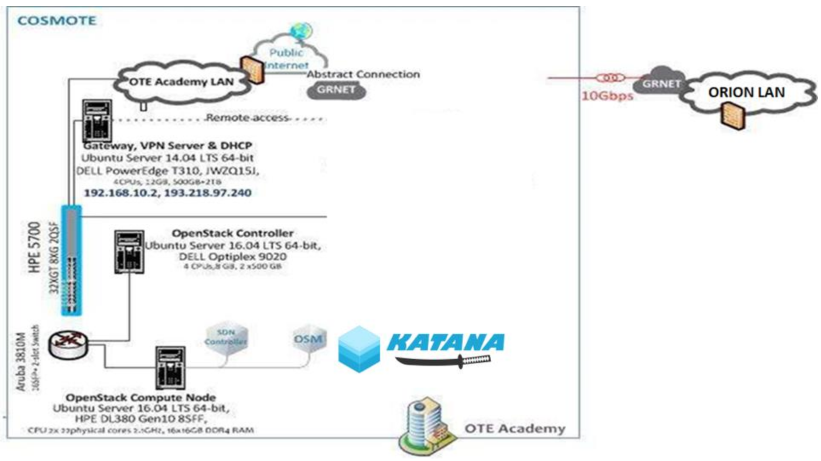


Figure 112: Joint testbed architecture.

In the scope of the joint demonstration a set of measurements were performed in order to validate and quantify the performance of a virtualized caching mechanism. The measurements were initially performed in terms of latency in a set of HTTP and HTTPS websites. The results can be seen in Figure 113 and Figure 114.

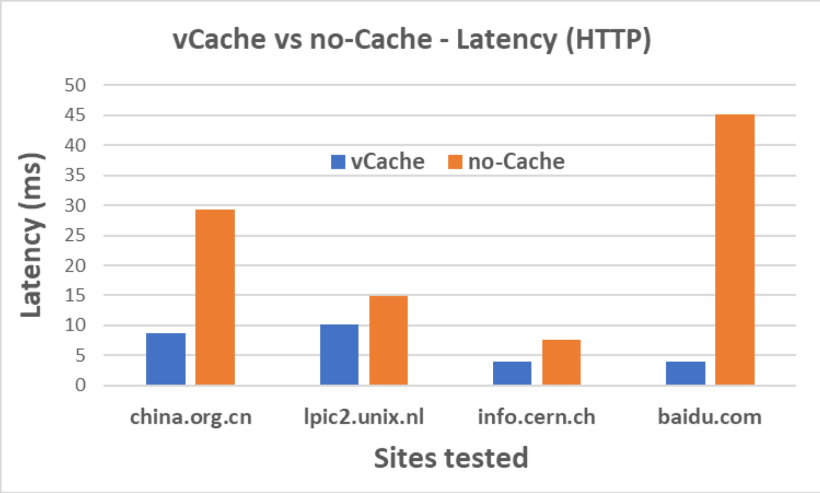


Figure 113: Latency (ms) cache results for HTTP sites.

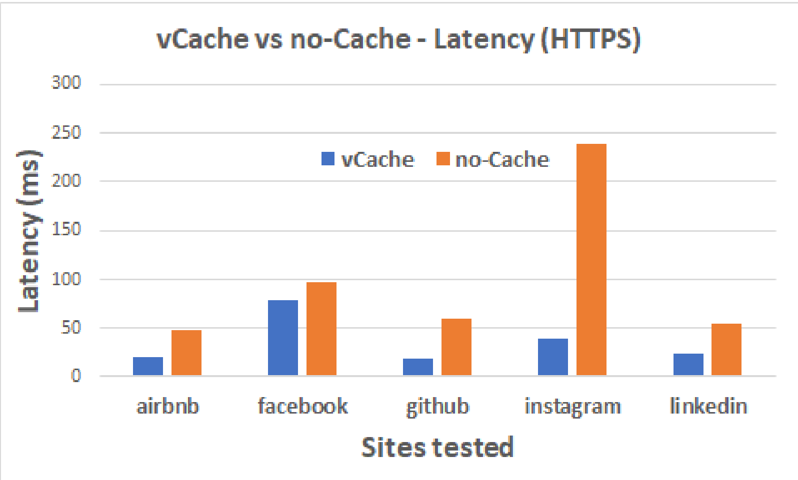


Figure 114: Latency (ms) cache results for HTTPs sites.

It can be deducted that the average latency reduction for a webpage access ranges from 50ms up to 200ms. This, of course, ranges depending on the content and the size of the page. However, the latency reduction clearly shows the benefits that a caching mechanism can have when installed at the edge.

In order to further explore the performance and scaling of the caching mechanism, the vCache was tested in stress test scenarios, where multiple threads of the wrk service measured the latency performance of the vCache VNF. The webpage set selected for these measurements included a wide variety of websites both HTTP and HTTPs, with the total number exceeding 500. Based on this set the wrk requested various webpages, increasing each time the threads and the parallel connections made to the vCache VNF. The thread parameter depicts the virtual thread/core in the OS that wrk allocates to perform the connection requests. For the case of connection parameter, it depicts the number of concurrent connections established to the vCache, per thread. The connection parameter in some way emulates the number of users, so the 5_10 case is about (5 * 10) 50 users. In our case, the vCache for the edge runs on a 4 vCPU with 8GB of RAM flavor, and in some cases the scalability of the system is limited, as it will be concluded from the results to be seen. The stressing experimental results are shown in detail in Figure 115, Figure 116 and Figure 117.

Initially, Figure 115 presents the latency experienced by the wrk request when multiple sites are requested at the same time. On average, the vCache responds at approximately 100ms for 50-200 users.

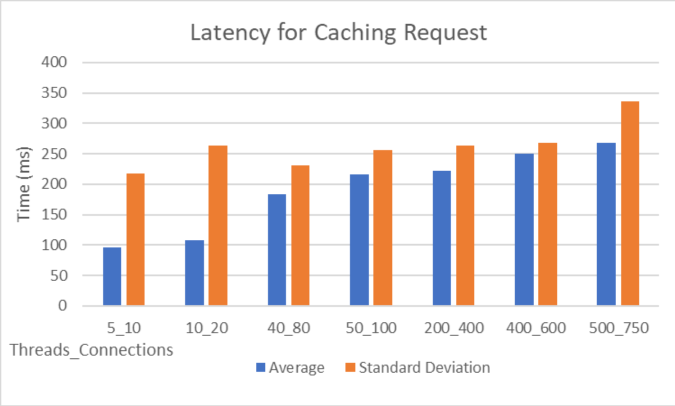


Figure 115: Caching latency for various threads and connections loads.

The rest of the results, as we increase the load of concurrent requests show a reasonable increase in the latency. The caching mechanism repletes onwards the higher thread_connection cases of 200_400 to 500_750, as it reaches its limit and cannot scale further. However, it must be noted that for these cases the system manages to server up to ~77,000 requests (Figure 116) at the same time, which are more than enough for an edge scenario. Furthermore, the vCache is designed to be deployed at the edge and be lightweight and efficient, and this number replicates the number of user sessions.

In Figure 116 and Figure 117, the total number of requests served and the total MBs cached by the vCache. Again, it can be clearly seen that the system for the cases of 400_600 and 500_700 reaches its limit, at about 77,000 requests.

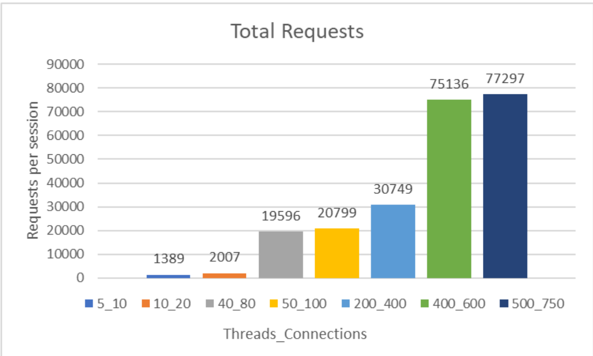


Figure 116: Total number of requests for various threads and connections loads.

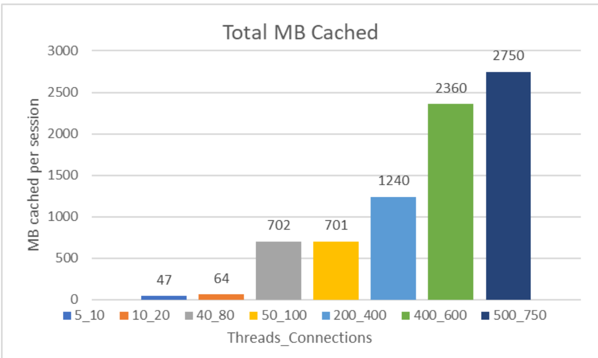


Figure 117: Total MBs cached for various threads and connections loads.

In the case of total MB cached, at its peak the vCache stores at its RAM up to 2.7 GB of data, including html, and multimedia content (i.e. jpeg, mp4, etc.). For each session the vCache was cleared beforehand so that the results could emulate a spike demand scenario and stress the system.

In the next step of the experimental vCache results, various system performance metrics were gathered during the tests, and the correlation map was calculated based on the vCache metric (squid_misses, requests) s and the system metrics (CPU, RAM), generating an overview of the impact of caching mechanisms on the host's performance.

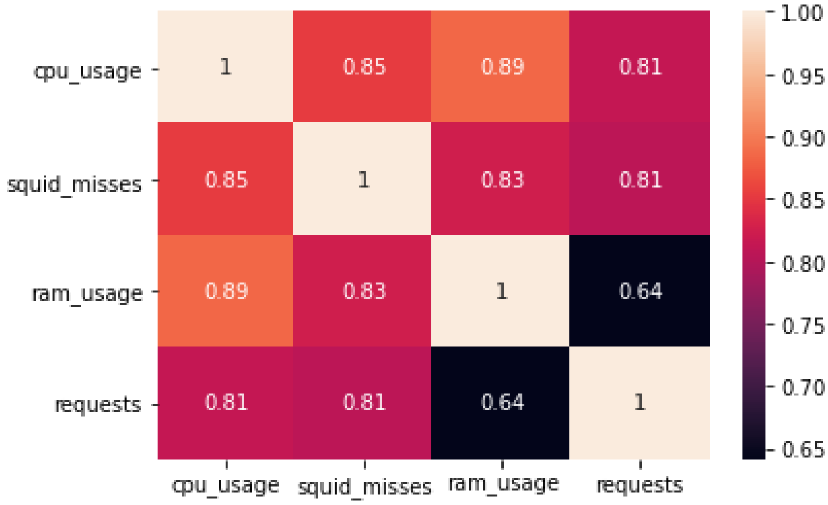


Figure 118: Correlation map for the various vCache metrics.

As it can be deducted from Figure 118, RAM and CPU are equally stressed by the caching process. Hard disk metrics were also measured but they did not export a meaningful conclusion, as the options set on the vCache were primarily set to memory caching and as a backup to hard disk caching. Consequently, even when stressing to the limit the vCache with over 500 sites, the overall caching size as seen in Figure 117 did not exceed 3 GB, or the VNF's memory of 8 GB, therefore hard disk was hardly used. It can also be deducted that squid_misses, which happen during the start of the session, as the cache is clear, the request is a miss, and the content needs to be retrieved and cached, present a similar behaviour and effect on host's performance as typical requests.

3.3 Fronthaul performance measurement results and analysis

Performance measurements are carried out over the X-haul section of the mobile network. Key Performance Indicators (KPIs) are collected in real-time under background traffic impairments and Software Defined Networking- (SDN) controlled traffic steering/load-balancing. The KPI system includes virtual test agents each one optimised for a specific type of test.

The KPI system is based on the Viavi FUSION system. A view of how it is used for these tests is shown in Figure 119. It comprises virtual Performance Monitoring Agents (vPMAs), a test controller and a test data collector which aggregates all test results. The vPMAs are essentially virtual test and performance monitoring probes running on generic x86 servers[19] that provide test functionality by measuring network performance and evaluating network quality. The virtual probes support test functionality for

[19] https://en.wikipedia.org/wiki/X86

network layer 2 and up to the application layer (Y.1564[20], Y.1731[21], RFC 6349[22]-TrueSpeed[23], RFC 5357[24]-Two-Way Active Measurement Protocol (TWAMP)). The system is managed through the controller entity which also includes a boundary clock for process synchronisation using Precision Time Protocol version 2[25] (PTPv2).

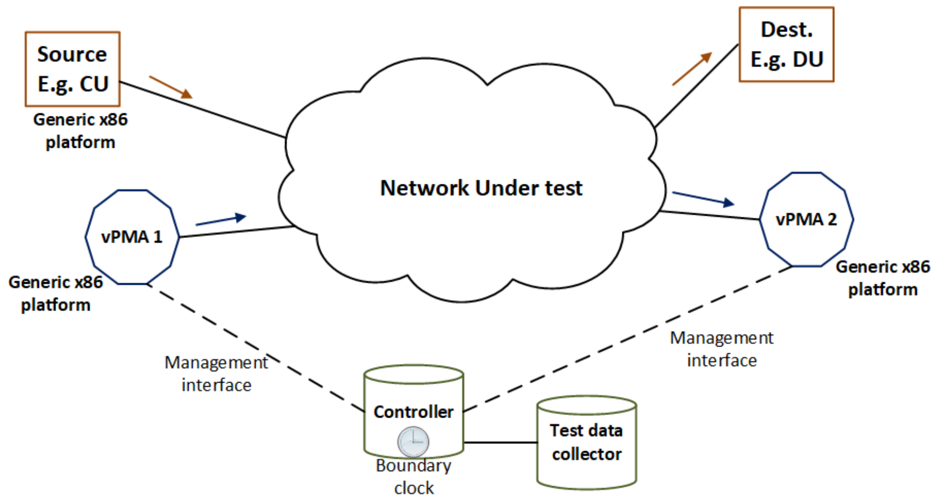


Figure 119: Correlation map for the various vCache metrics.

The overall X-haul network is shown in Figure 120. It incorporates 10 GbE switches and SDN functionality. Mobile traffic is generated by using the Open-Air Interface software[26] libraries, running on x86 platforms while wireless transmission is carried out through Software-Defined Radios (SDRs). Timing synchronisation is provided through a GPS-disciplined PTP server which feeds directly into the KPI controller. The SDN operation is carried out at the Ethernet (Layer-2) level and performs traffic steering and/or load balancing across Ethernet trunk links that transport X-haul and generic background traffic flows. The SDN controller is implemented on "Pox", an open-source networking framework written in Python[27], while the OpenFlow communication protocol is used to control the SDN switch. The SDN implementation is used to effect X-haul reconfiguration so that transported flows can adhere to latency and latency variation constraints. It also enables slice isolation (soft or hard) and can be employed in traffic protection scenarios.

[20] International Telecommunication Union – Telecommunications Standardization Sector (ITU-T): Recommendation Y.1564 (02/2016): Ethernet service acticvation test methodology. Available at: https://www.itu.int/rec/T-REC-Y.1564-201602-I/en

[21] International Telecommunication Union – Telecommunications Standardization Sector (ITU-T): Recommendation G.8013/Y.1731 (08/2015): Operation, administration and maintenance (OAM) functions and mechanisms for Ethernet-based networks. Available at: https://www.itu.int/rec/T-REC-G.8013-201508-I/en

[22] Internet Engineering Task Force (IETF): RFC 6349 (2011-08): Framework for TCP Throughput Testing. Available at: https://tools.ietf.org/html/rfc6349

[23] Also see: https://www.viavisolutions.com/en-us/literature/rfc-6349-testing-truespeed-viavi-solutions-experience-your-network-your-custom-application-notes-en.pdf

[24] Internet Engineering Task Force (IETF): RFC 5357 (2008-10): A Two-Way Active Measurement Protocol (TWAMP). Available at: https://tools.ietf.org/html/rfc6349 https://tools.ietf.org/html/rfc5357

[25] Also see: https://tools.ietf.org/html/rfc8173

[26] For further detaiuls also see: https://openairinterface.org/

[27] https://www.python.org/

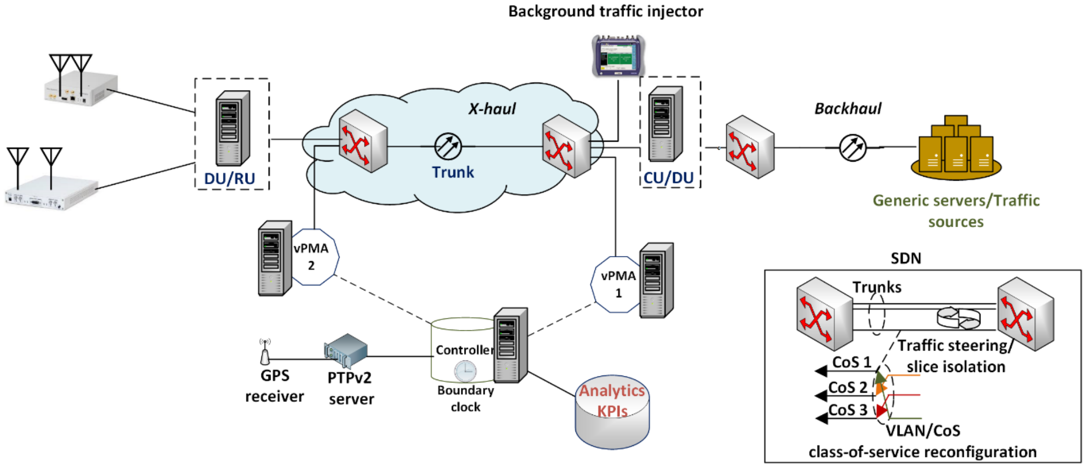


Figure 120: X-haul network incorporating SDN control, KPI Measurement and collection system and background traffic injection.

Figure 121 (Top) shows the SDN configuration template with one traffic steering entity. The entity configures two traffic flows, each with a different VLAN ID tag, for a 1 GbE link. The “measurement” flag can be set to “internal” in which case the SDN switch performs KPI monitoring (e.g. link utilisation) or to “external” whereby the KPIs are monitored by the external KPI system and measures are provided to the SDN controller for decision making. In this example configuration, both flows are configured to be transmitted over the same trunk link (port 52) while one of the flows is configured as “steerable” and can be steered onto a different trunk link (port 49) if the utilisation in the original link exceeds a threshold. The additional captures/traces in Figure 121 show the flows being set-up from the SDN controller side and from the SDN switch side. Figure 122 shows an example trace of measured trunk utilisations. The aggregate data rate over the trunk link exceeds a specified threshold which causes the controller to steer one of the flows to a different trunk link. At a future time, once the utilisation over the original trunk link has dropped below the specified threshold, the traffic flow is steered back.

```
<?xml version="1.0"?>
<Config>
    <Switch dpid="6790944927334401337">
        <StartFlow inport="18" outport="52" vlan="80"/>
        <StartFlow inport="1" outport="52" vlan="70"/>

        <TrafficSteering period="15" inport="18" outport="52" newport="49" vlan="80" measurement='internal'/>
    </Switch>
</Config>
```

```
INFO:openflow.flow_tracker:Set QueryInterval:1.0 LinkMaxBw:1000.0Mbps LinkCongThreshold:300.0Mbps AvgSmoothFactor:1.0 LogPeakUsage:1.0
INFO:openflow.flow_tracker:Writing flow tracker info to file: flowtracker_21-11-33_April-07_2018.txt
INFO:core:POX 0.2.0 (carp) is up.
INFO:openflow.of_01:[48-6e-73-02-05-39|24126 1] connected
48-6e-73-02-05-39|24126
INFO:openflow.discovery: Installing static flow for 48-6e-73-02-05-39|24126
INFO:openflow.discovery: Static flows installed.
```

PICA8 Configuration Monitor Help Log Out

Switch Resource | br0

Basic Controller Port Tunnel LAG Flow Table Group Table Meter Table Visibility

Table: 0

Priority	Cookie	Match Fields	Actions	Duration	Packets	Bytes
32768	0x1	in_port=18,	mod_vlan_vid:80,output:52	67.634s	n/a	88431616
32768	0x3	in_port=1,	mod_vlan_vid:70,output:52	67.596s	n/a	0
32768	0x2	in_port=52,vlan_vid=80,	strip_vlan,output:18	67.597s	n/a	0
32768	0x4	in_port=52,vlan_vid=70,	strip_vlan,output:1	67.595s	n/a	0

Figure 121: (Top) Configuration template with one traffic steering entity. (Middle) Pox controller has installed start flows. (Bottom) Pica8 web-based API showing that start flows have been configured in the SDN switch.

```
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 232.846812869 Time: 1523131959.45
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 457.81534986 Time:1523131960.48
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 228.90767493 Time: 1523131960.48
INFO:openflow.flow_tracker:Port 52 Utilization is 456.623948586
INFO:openflow.flow_tracker:Steering to port 49
INFO:openflow.flow_tracker:Steering Completed.
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 456.623948586 Time:1523131961.52
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 228.311974293 Time: 1523131961.52
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 458.307574501 Time:1523131972.82
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 229.153787251 Time: 1523131972.82
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 457.231275644 Time:1523131973.86
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 228.615637822 Time: 1523131973.86
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 452.82947998 Time:1523131974.88
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 226.41473999 Time: 1523131974.88
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 457.395584981 Time:1523131975.91
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 228.69779249 Time: 1523131975.91
INFO:openflow.flow_tracker:Port 52 Utilization is 0.0
INFO:openflow.flow_tracker:Steered Back.
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 458.292421359 Time:1523131976.91
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 229.146210679 Time: 1523131976.91
```

Figure 122: Example trace of traffic steering test results.

The SDN configuration template allows multiple load balancing and traffic steering entities to be configured at the same time across a user-defined number of trunk links. Figure 123 shows the SDN configuration template with two load-balancing entities. The entity configures two traffic flows, each with a different VLAN ID tag that can be load-balanced over two trunk links. At different time instances the algorithm determines best links (ones with lowest utilisation) and moves traffic to these to balance the load across all output links.

The KPI system is used to monitor latency, latency variation and data rate experienced by the X-haul traffic when it is being impaired by generic background traffic, and when steering/load balanced is carried out through SDN control.

```
<?xml version="1.0"?>
<Config>
    <Switch dpid="6790944927334401337">
        <StartFlow inport="18" outport="52" vlan="80"/>
        <StartFlow inport="1" outport="52" vlan="70"/>

        <LoadBalancing period="10" measurement='internal'>
            <In port="18" vlan="80"/>
            <Out port="49"/>
            <Out port="52"/>
        </LoadBalancing>

        <LoadBalancing period="7" measurement='internal'>
            <In port="1" vlan="70"/>
            <Out port="49"/>
            <Out port="52"/>
        </LoadBalancing>
    </Switch>
</Config>
```

```
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 91.3904093487 Time:1523133339.21
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 45.6952046743 Time: 1523133339.21
INFO:openflow.flow_tracker:Optimizing (Port: Vlan) - {1: 70, 18: 80} out of [49, 52]out ports
INFO:openflow.flow_tracker:Port 49 Utilization is 0
INFO:openflow.flow_tracker:Port 52 Utilization is 91.7495127183
INFO:openflow.flow_tracker:New best port is 49
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 91.7495127183 Time:1523133340.22
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 45.8747563592 Time: 1523133340.22
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 45.8707196219 Time: 1523133348.43
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 91.3428415502 Time:1523133349.46
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 45.6714207751 Time: 1523133349.46
INFO:openflow.flow_tracker:Optimizing (Port: Vlan) - {1: 70, 18: 80} out of [49, 52]out ports
INFO:openflow.flow_tracker:Port 49 Utilization is 91.6013677655
INFO:openflow.flow_tracker:Port 52 Utilization is 0
INFO:openflow.flow_tracker:New best port is 52
INFO:openflow.flow_tracker:Network peak link throughput (Mbps): 91.6013677655 Time:1523133350.46
INFO:openflow.flow_tracker:Network avg link throughput (Mbps): 45.8006838828 Time: 1523133350.46
```

Figure 123: (Top) Configuration template with two load-balancing entities. (Bottom) Example trace of load.

3.4 Summary

In this chapter, eMBB trial results with focus on 5G network technologies have been presented here. First, the results of the experiments conducted to access the scalability of network slices lifecycle management of the OSM orchestrator have been presented and discussed. Second, the vCache performance has been measured over the joint trial, and results were discussed. Then a fronthaul performance measurement was carried out over X-haul section of the mobile network. The results have also been presented in this chapter.

4 Joint eMBB trials with Chinese twin project

In this chapter, a number of joint eMBB trials, carried out by WP3 partners and Chinese twin project partners during 5G-DRIVE project period, have been presented here. The results have been discussed and categorized into twofold according to the 5G network structures, i.e., joint NSA eMBB trials and joint SA eMBB trials.

4.1 Joint NSA eMBB trials

4.1.1 NSA outdoor coverage

During May and July 2019, the UoS, UKent and VTT partners participated in the basic performance measurements of NSA 5G NR in Hangzhou, China. The trial scenarios were mainly focused on dense urban areas (e.g., office building, exhibition centre, etc.) and suburban areas (e.g., residential areas, industrial park, etc.). The measured area is shown below in Figure 124.

It contained more than 50 base stations to form a large-scale urban trial site. The network configuration was NSA, with CU-DU split, and the bandwidth for 5G was 100 MHz at an operating frequency of 2.6 GHz. The transmit power of the gNB was 200 W. Every run of the measurement route took around 1.5 hour and the selected KPIs included RSRP, RSRQ, etc., as defined in the respective 5G-DRIVE Deliverable D2.2. Different types of user equipment (UE) have been tested during the test as shown in Figure 125**.**

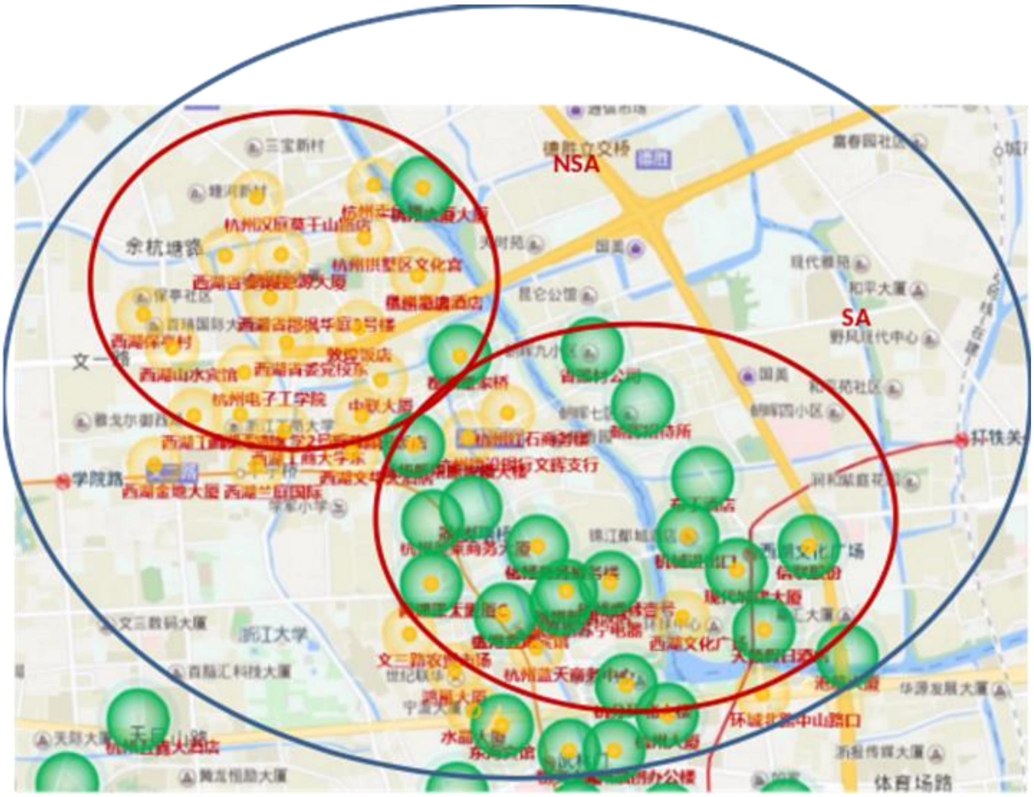


Figure 124: NSA basic performance measurement area in Hangzhou, China, May and July 2019 (yellow colour is for NSA base station and green colour is for SA base station).

The measurements were conducted with one smartphone having 4 Rx and 1 Tx antennas (NSA case). The transmission power of the terminal was set to 20 dBm. The measurements were conducted with a van shown in Figure 126. The smartphone (shown in Figure 125) was placed in the middle of a van in the upright positioning shown in Figure 126. The UE was connected with USB to the measurement laptop.

Figure 125: Tested UE.

The conducted measurement cases were full buffer TCP and UDP services in the uplink and downlink directions without interference from neighbouring cells. The driving speed was around 20 to 35 km/h depending on the traffic.

Figure 126: The placement of the 5G smartphone and measurement tool inside the van.

The RF coverage conditions were categorized as good where RSRP is around -70 dbm and low where RSRP is around -90 dBm. Only at the southwest corner of the measurement route, there was a small area where 5G connection was shortly lost. The LTE-1800 network was available during the whole measurement route.

The next tables show KPI statistics according to the five coverage classes (good and low). The results presented below were achieved at static tests.

<u>Good RF conditions:</u> One terminal TCP traffic (DL) without DL interference

Parameter	Value
SSB RSRP	-71 dBm
SSB SINR	16dB
PDCP throughput	1013Mbps

Low RF conditions: One terminal TCP traffic (DL) without DL interference

Parameter	Value
SSB RSRP	-90dBm
SSB SINR	1.6 dB
PDCP throughput	547Mbps

After the measurement without interference from neighbouring cells, the network configuration was changed to include 50% DL interference from neighbouring cells. Measured RSRP levels were very similar in both cases. Only changes were seen in DL throughput values. In low RF conditions, throughput was decreased roughly 30 % compared to the non-interference case.

Good RF conditions: One terminal TCP traffic (DL) with DL interference

Parameter	Value
SSB RSRP	-73 dBm
SSB SINR	12 dB
PDCP throughput	916 Mbps

Low RF conditions: One terminal TCP traffic (DL) with DL interference

Parameter	Value
SSB RSRP	-93 dBm
SSB SINR	2 dB
PDCP throughput	399 Mbps

The summary of peak data rate on DL and UL are summarized in Figure 127 and Figure 128. Different colours indicated the different tested UEs.

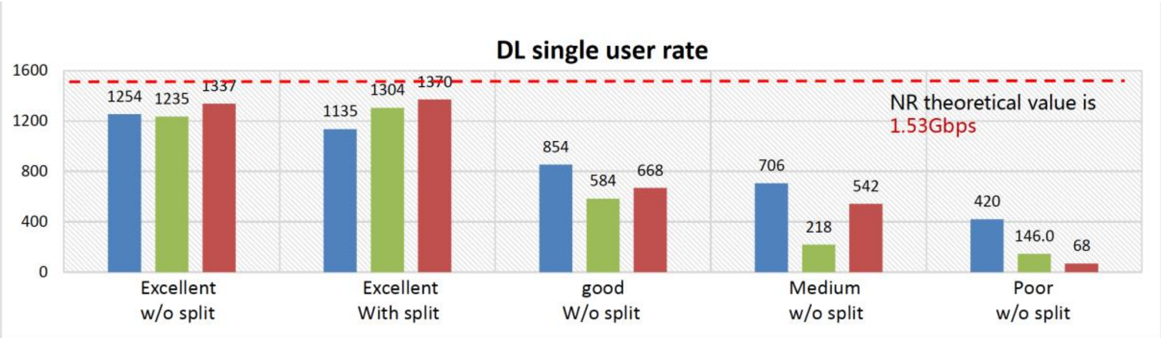


Figure 127: DL single UE peak data rate over 2.6 GHz.

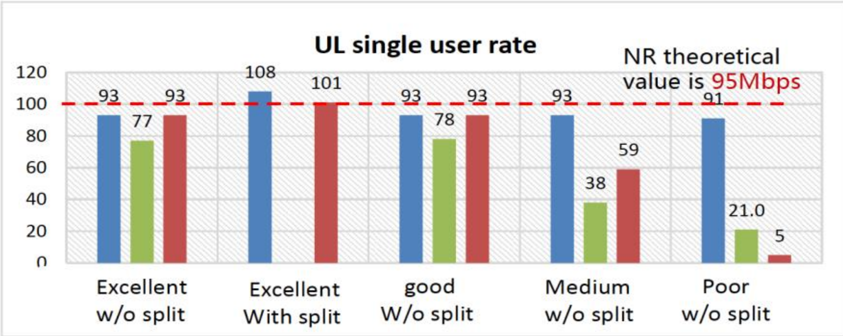


Figure 128: UL single UE peak data rate over 2.6 GHz.

4.1.2 NSA indoor coverage

The indoor coverage measurement was performed in a new office building on one of the top floors (11th floor). The measurement site is shown outside and inside in Figure 129 and Figure 130. The network configuration was 5G NSA (non-standalone) and no CU-DU split was used. The bandwidth for 5G was 100 MHz and for LTE-1800 20 MHz.

Figure 129: A new office building used for 5G NSA indoor coverage measurements.

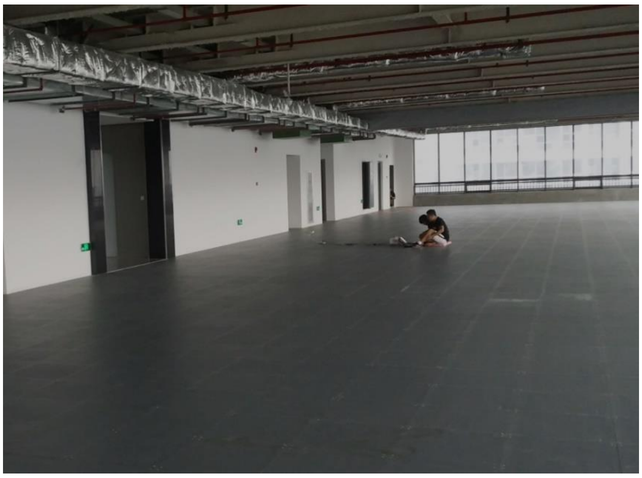


Figure 130: The open office space used for 5G NSA indoor coverage measurements.

The indoor coverage network configuration included three integrated 5G-2600 TDD and LTE-1800 FDD pRRUs (picocells) placed on the ceiling of an open office space. The pRRUs were roughly 15-20m apart from each other. The locations of three pRRUs were selected so that good coverage was ensured to all measurement points. The leftmost pRRU in the left picture in Figure 131 was used in the indoor coverage measurements in good, medium, and bad transmission conditions.

Figure 131: pRRUs of the test network installed on the ceiling.

The transmission power of each pRRU was set to 250 mW and 2x2 MIMO was used. The maximum downlink throughput was expected to be 1.3 Gbps with 5G alone and 1.4 Gbps (1.3Gps + 0.1Gbps) when aggregated with LTE-1800 FDD. The pRRUs were connected with fibre to a RHUB that was located in a small maintenance room next to the office space, which is shown in Figure 132.

Figure 132: RHUB used for connecting pRRUs in the test network configuration.

Five test points at three locations were selected according to transmission conditions (SINR values) based on the first cell following the ratio 2 points (good): 2 points (medium): 1 point (bad). Outdoor gNB was roughly 200m from the building shown in Figure 133 and it did not have significant impact on SINR levels. The BBU of the pRRUs was located in the basement of the building and it was connected with fibre to the measurement floor RHUB.

Figure 133: Outdoor 5G gNB outside the building.

At three measurement locations, the smartphones were connected with USB to measurement laptops. Figure 134 shows one of the measurement locations. The results from each terminal were recorded separately. The measurements were conducted with five smartphones having 4 Rx and 1 Tx antennas (NSA case). The transmission power of terminals was 125 mW.

The conducted measurement was done with one pRRU located near terminals 1 and 2. The other pRRUs were switched off. The measurements with multiple pRRUs and CPEs were conducted earlier. Four smartphones were located in the open space and the fifth on in the other room next to the open space. The connection to the pRRU was NLOS and the transmission condition was considered as bad.

The conducted measurement case was full buffer TCP service using IPv4. The downlink and uplink measurements were performed separately. In downlink measurement, the L3 TCP data was downloaded from a server to five terminals, and in uplink case, the terminals were uploading L3 TCP data to the server. The data transmission time was 2 min after the TCP connections were stabilized for 30 secs. The terminal side was responsible for starting and stopping the data downloading service. The measured parameters were RSRP, RSRQ, SINR, PDCP throughput and PHY throughput.

Figure 134: Mobile and stationary measurement points with two terminals connected to a laptop running the measurement tools.

The next table shows the KPIs achieved during the 2 min measurements. The measurements were repeated several times to ensure that the results were consistent. For a comparison, also a single UE measurement with UDP traffic was performed to the uplink direction. The next table shows the values obtained from UE 1 in good RF conditions. UEs 1 and 2 provided very similar results. No major differences between UEs were detected. The measurement results are presented in the same order as the actual measurements were performed.

Measurement 1: Five terminals downloading TCP traffic (DL) from a single pRRU, where 2 in good, 2 in middle and 2 in poor point. Measurement result from one of UEs in the good point.

Parameter	Value
RSRP	-75 - -77 dBm
SINR	23 - 25
Tx power	250 mW
PDCP throughput	200 - 230 Mbps

Measurement 2: Five terminals uploading TCP traffic (UL) to a single pRRU, where 2 in good, 2 in middle and 2 in poor point. Measurement result from one of UEs in the good point.

Parameter	Value
RSRP	-76 - -78 dBm
SINR	29 - 30 dB
Tx power	125 mW
PDCP throughput	12 - 14 Mbps

Measurement 3: One terminal uploading UDP traffic (UL) to a single pRRU. No other active UEs.

Parameter	Value
RSRP	-74 dBm
SINR	30.7 dB
Tx power	125 mW
PDCP throughput	90 - 92 Mbps

4.2 Joint SA eMBB trials

During September and October of 2019, the UoS, UKent and VTT partners also participated in the basic performance measurement of SA 5G NR in Hangzhou, China.

4.2.1 SA outdoor coverage

The SA outdoor coverage measurement was performed along a highway from the southern part of Hangzhou city to the airport. The trial route was 35 km. The average distance between gNBs was roughly 300m. The area consists of medium height buildings and highway bridges. The measurement started from a gas station and ended at the airport. The route with the starting and ending points are presented in Figure 135. The test network configuration included around 140 macro gNBs 5G-2600 TDD. The network configuration was SA, no CU-DU split, and the bandwidth for 5G was 60 MHz instead of 100 MHz, because 40 MHz is reserved as a guard band to avoid interference with the LTE network. The transmission powers of micro-cell gNBs are 120 W and 160 W. The uplink downlink ratio was configured as 2:7. The gNBs measurement start point and route are presented in Figure 123. The measurement route took about 35 min, and the measured KPIs were RSRP, RSRQ, SINR, iBLER[28], MAC throughput and PHY throughput.

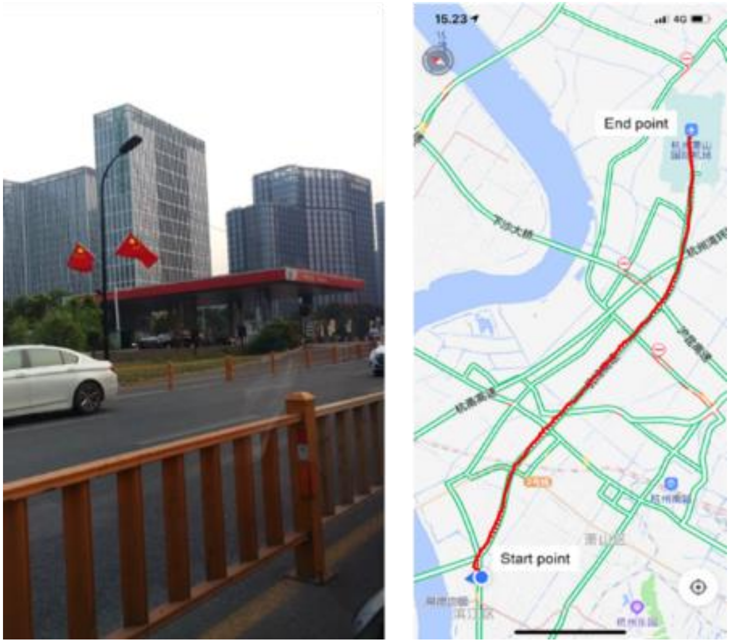


Figure 135: The starting point and the route (in red) to the airport along the highway.

The measurements were conducted with a Huawei Mate 20 X (5G) 345 smartphone running Android 9 and having 4 Rx and 2 Tx antennas (SA case has 2 Tx antennas and NSA has only 1 Tx antenna). The transmission power of the UE was set to 26 dBm. The UE was placed on behind the passenger seat inside a car in the horizontal positioning. The UE was connected with USB to the measurement laptop running measurement software that was collecting terminal side measurements. A GPS receiver was mounted on the roof of the car to provide the location for each measurement sample.

The conducted measurement case was full buffer TCP service with IPv4 to the uplink and downlink directions without interference from neighbouring cells. The downlink measurement was conducted when driving from the gas station to the airport and the uplink measurement back from the airport to the gas station. The driving speed was set to 80 km/h.

The RF coverage conditions were categorized as excellent (dark green) where RSRP >-75 dBm, good (green) where RSRP >-90 dbm, medium (blue) where RSRP >-110 (yellow) where RSRP > -120 dBm, and bad (red) where RSRP < -120 dBm. The excellent RF conditions were discovered roughly 45% of the time along the measurement route. Good radio conditions were detected roughly 55% of the time and only few places the RF condition was medium (blue). The medium level results were shortly detected near the airport. The peak throughput DL direction was 835 Mbps with 256-QAM and MIMO rank count 4.

The next table shows KPI statistics according to the excellent and good coverage classes

<u>Excellent RF conditions:</u> One terminal TCP traffic (DL) without interference

Parameter	Value
RSRP	> -75dBm

[28] Foir further details also see, *for example*: https://telecompedia.net/block-error-rate-in-lte/

SINR	10 - 25 dB
MAC throughput	400 - 500 Mbps (rank 2) 500 - 600 Mbps (rank 3) 600 - 835 Mbps (rank 4)
iBLER	0 - 5 %

Good RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
RSRP	-90 dBm < value < -75 dBm
SINR	7 - 10 dB
MAC throughput	300 - 400 Mbps (rank 2)
iBLER	3 - 10 %

At the airport, the measurement was switched to UL. Measured RSRP, RSRQ, SINR levels were similar to both directions. Only changes were seen in MAC throughputs and rank values. The medium levels were experienced more in UL direction. In some locations the throughput was dropped to 5-15 Mbps due to failure in handovers although the CQI levels remained above 13.

Excellent RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
RSRP	> -75 dBm
SINR	10 - 25 dB
MAC throughput	120 - 140 Mbps (rank 2)
iBLER	0 - 5 %

Good RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
RSRP	-90 dBm < value < -75 dBm
SINR	7 - 10 dB
MAC throughput	100 - 120 Mbps (QAM-256 rank 2) 80 - 100 Mbps (QAM-64)
iBLER	2 - 8 %

Medium RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
RSRP	-110 dBm < value < -90 dBm
SINR	3 - 7 dB
MAC throughput	60 - 80 Mbps (QAM-16)

iBLER	- 10 %

4.2.2 SA outdoor gNB supporting indoor coverage

In October 2019, UoS participated in this outdoor gNB supporting indoor coverage test. The measurements were conducted in a 20-floor shopping mall in the city centre. The gNB was deployed on the top of a building opposite of the measured area as shown in Figure 136 and 8 pre-selected points were measured at both 2.6 GHz and 4.9 GHz. The distances between outdoor base station and the selected indoor points were between 140 and 180 m. The network configuration was 5G SA (standalone) and no CU-DU split. UEs operating at 2.6 GHz and 4.9 GHz, respectively, were tested at each measurement point, as shown in Figure 137.

Figure 136: The 2.6 GHz and 4.9 GHz base station on the roof of the opposite building and the location of the selected measured points.

Figure 137: Measured UL/DL peak data rate.

The other indoor coverage measurement was jointly performed by VTT and the Chinese twin project partners in a 23-floor office building in the city centre as shown in Figure 138. The measurement cases were uplink and downlink vertical direction service coverage capability tests in zero interference, using a 64-channel equipment. The 32 beam MIMO gNB was placed on the roof of a neighbouring building approximately 200-300m from the measured building (far points case).

The transmission power was 200 W. The measured building and gNB are presented in Figure 138. The network configuration was 5G SA (standalone) and no CU-DU split. The bandwidth for 5G was 100 MHz.

Figure 138: The 32-floor office building and the location of the 32 beam MIMO SA antenna on the roof of the neighbouring building.

The first set of measurements was performed at the first floor in good and bad conditions. The DL and UL directions were measured separately. The downlink uplink ratio was 7 : 2.

The following tables show the KPI value ranges achieved during the 3 min measurements. The UL and DL throughputs degraded significantly in the bad RF condition case. Measured RSRP, RSRQ, SINR levels were similar to both directions.

<u>Good RF conditions:</u> One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	2
RSRP	-108 - -105 dBm
SINR	7 - 10 dB
PDCP throughput	385 - 420 Mbps (64-QAM / 256-QAM)
iBLER	7 - 11 %

<u>Good RF conditions:</u> One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	2
RSRP	-105 - -95 dBm
SINR	6 - 10 dB
PDCP throughput	33 - 40 Mbps (16-QAM / 64-QAM)
iBLER	8 - 10 %

Bad RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	1
RSRP	-120 - -113 dBm
SINR	2 - 8 dB
PDCP throughput	92 - 150 Mbps (64-QAM)
iBLER	7 - 15 %

Bad RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	1
RSRP	-120 - -116 dBm
SINR	-2 - 0 dB
PDCP throughput	200 kbps - 2 Mbps (QPSK / QAM-64)
iBLER	4 - 11 %

The second set of measurements was performed at the 12th floor in good and bad conditions. The DL and UL directions were measured separately. The downlink uplink ratio was 7 : 2.

The following tables show the KPI value ranges achieved during the 3 min measurements. The CQI in both UL and DL directions was 13 - 14 in good RF conditions and in bad RF conditions 6 - 11.

Good RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	2
RSRP	-90 - -88 dBm
SINR	6 - 11 dB
PDCP throughput	370 - 530 Mbps (64-QAM / 256-QAM)
iBLER	5 - 10 %

Good RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	1.7 - 2
RSRP	-94 - -90 dBm
SINR	6 - 12 dB
PDCP throughput	33 - 51 Mbps (QAM-16)
iBLER	6 - 12 %

Bad RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	1
RSRP	-111 - -108 dBm
SINR	0.2 - 4 dB
PDCP throughput	40 - 165 Mbps (16-QAM/ 64-QAM)
iBLER	8 - 22 %

Bad RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	1
RSRP	-111 - -106 dBm
SINR	0.4 - 2.2 dB
PDCP throughput	1.2 - 4 Mbps (QPSK)
iBLER	6- 15 %

The last set of measurements was performed at the 23rd floor of the building in good and bad conditions. The DL and UL directions were measured separately. The downlink uplink ratio was 7 : 2.

The following tables show the KPI value ranges achieved during the 3 min measurements. The CQI in both UL and DL directions was 11 - 13 in good conditions and in bad RF conditions 4 - 6.

Good RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	2
RSRP	-92 - -90 dBm
SINR	1 - 9 dB
PDCP throughput	350 - 420 Mbps (64-QAM / 256-QAM)
iBLER	3 - 11 %

Good RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	2
RSRP	-93 - -87 dBm
SINR	7 - 10 dB
PDCP throughput	0.8 - 1.5 Mbps (16-QAM / 64-QAM)
iBLER	7 - 11 %

Bad RF conditions: One terminal TCP traffic (DL) without interference

Parameter	Value
Rank count	2
RSRP	-109 - -100 dBm
SINR	4 - 8 dB
PDCP throughput	62 - 125 Mbps (16-QAM / 64-QAM)
iBLER	4 - 15 %

Bad RF conditions: One terminal TCP traffic (UL) without interference

Parameter	Value
Rank count	1 - 1.5
RSRP	-111 - -101 dBm
SINR	0 - 8 dB
PDCP throughput	1 - 3 Mbps (QPSK)
iBLER	3- 11 %

4.3 Summary

In this chapter, joint eMBB trials of NSA and SA 5G network have been presented here. Both outdoor and indoor coverage measurements have been carried out over NSA 5G network in China Mobile trial site (Hangzhou, China). In SA 5G network, outdoor coverage was also tested as well as the outdoor gNB support the indoor coverage. Higher single UE peak DL/UL data rate can be observed in the stationary tests, which can be due to the different operating frequency band used in China (i.e., 2.6 GHz) as well as supported by the latest version of tested UEs.

5 Performance measurements and results analysis for 5G network technologies

In this Deliverable, all the trial results conducted by WP3 partners during 5g-DRIVE project period were presented. The measurements were focused on eMBB and carried over various trial sites including both EU and China side. Different types of UEs were tested over 3.5GHz in EU and 2.6 GHz in China accordingly. Tests have been designed into twofold, i.e., 5G radio access technologies and 5G network technologies. In 5G radio access technologies parts, basic performances have been tested over both NSA and SA 5G architectures. Moreover, different antenna beam patterns have been discussed in 3D beamforming and calibrated the results with field trials. In 5G network technologies parts, network slice orchestration performance has been measured by a set of new KPIs proposed in Deliverable D5.1. Then vCache technique was tested and selected KPIs were measured. Moreover, the performance was also measured over the X-haul section of the mobile network. At the end of this Deliverable, we also reported the joint trials done between WP3 partners and our Chinese twin projects.

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