C-V2X Supported Automated Driving

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Abstract—**Automated driving is expected to improve road safety and traffic efficiency. Host vehicle onboard sensing systems typically sense the environment up to 250 m ahead of the vehicle. Today's LiDARs can see approximately 120 m, and recognition of small objects, such as animals or dropped cargo, however, today reliably drop when range is more than 50m. Connected driving adds an electronic horizon to the onboard sensing system which could extend the sensing range and greatly improves the efficiency. Therefore, collaborative sensing in which the vehicle exchanges not only status messages but also real data has recently been intensively discussed. Current cellular 3G/4G networks have enhanced the downlink capacity for sharing large data blocks. However, uplink is limited and therefore vehicles are unable to share point clouds of what they see in front. This article investigates the opportunities of 5G-based cellular vehicle-to-everything (C-V2X) collaborative sensing based on the results of trials conducted at test sites in China and Finland. The results indicate that the round-trip is stable (< 60 ms) even when exchanging 1 MB/s between vehicles. Finally, the automotive industry perspective is taken into account in identifying and prioritizing potential use case scenarios for utilizing 5G based connected driving applications.**

Keywords— 5G, C-V2X, automated driving, automotive

I. INTRODUCTION

The automotive industry has been intensively involved in the development of connected and automated driving over the past five years. However, the connectivity challenge has intensified due to the increasing automation demands arising from efforts to extend the range and conditions in which automated vehicles can drive. The range of the ego-vehicle sensing system is limited in practice to less than 120 m ahead of the vehicle, which is too short for motorway or highway driving at more than 120 km/h. The solution is to share data between vehicles, which in turn requires an uplink bandwidth capacity capable of sharing point clouds from Light Detection and Ranging (LiDAR), cameras and radar sensors.

Table I shows the intended joint trial issues to be investigated for validating the performance and opportunities of 5G networks for data sharing of automated driving functions. One of the key enabling technologies is edge-computing, which creates a smart road infrastructure that enables computing to be locally shared with vehicles with less capacity. One of the expected challenges is achieving the latencies that automated driving functions need to maintain smooth traffic flow. Analysis of the whole chain, from subscription to the network, communication and computing time provides valuable information for optimizing the balance between in-vehicle and mobile-edge computing (MEC) platform side data processing [1].

TABLE I. 5G-DRIVE TRIAL: SCENARIOS, OBJECTIVES AND EXPECTED OUTCOMES

Trial scenarios	**Objective**	**Expected outcome**
Uplink bandwidth capacity / eMMB	Exchange raw sensor data between vehicles and digital local infrastructure (MEC) connected via 5G. Focus on uplink capacity.	Raw sensor data delivery rates (Mbits/sec) vs. automated driving data sharing requirements.
Inter-operability between different mobile network band frequencies	Switching between different frequency bands (2.6; 3.5; 28 GHz).	Switching latency between different frequency bands - overhead/latency increase.
Mobile edge computing	Data transmission and receiving from local edge-computing sites.	5G-MEC server connectivity to vehicle terminals. C-ITS message exchange between MEC and vehicle.
Message formats	C-ITS vs. Chinese message formats. Compare service quality levels. Take into account SENSORIS work group proposals.	Feasibility of the SENSORIS compatible message formats
Latency times / uRLLC	V2V, V2I latency times with using low payload ping-messages.	Latency time comparison in milliseconds.
E2E Uu-based V2X service validation and performance evaluation	To experimentally validate the functionality and performance of an E2E V2X service over a 3.5GHz Uu interface.	Two vehicle-embedded UEs send/receive V2X messages over the Uu interface (i.e., via the 3.5GHz base station).
E2E PC5-based V2X service validation and performance evaluation	To experimentally validate the functionality and performance of an E2E V2V service over a 5.9GHz PC5 interface.	Two vehicle-embedded UEs send/receive V2V messages over the PC5 interface (i.e., direct link without eNB involvement)

The challenge of introducing data-enrich digital clouds is not only uplink bandwidth capacity but also the use of data formats that enable databases to be synchronized. The SENSORIS work group [2] is tackling this problem from the map provider perspective in order to offer an interface for adding new dynamic elements. However, the problem of raw data sharing remains, as each sensor provides its data content in a different format. For example, the LiDAR data comprises a point cloud containing both outliers and real data (see Fig 1). On one hand, removing outliers in-vehicle before sending makes sense, yet on the other hand cloud-based data processing probably has more power to do so accurately without losing valuable information. This article therefore also examines the exchange of raw data between vehicles and digital infrastructure and the practical challenges that this entails.

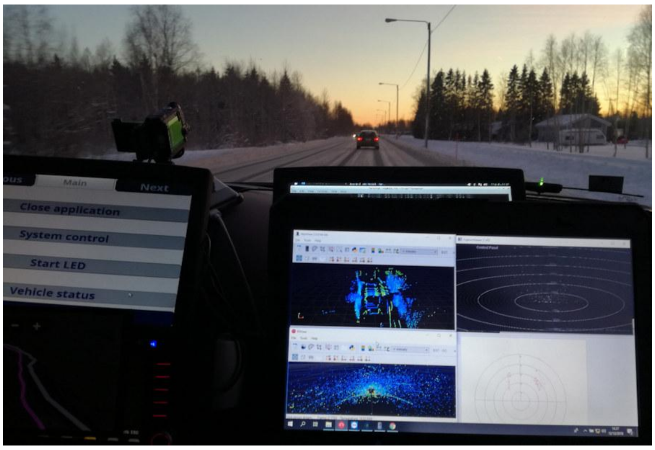

Fig. 1. LiDAR point cloud acquisition and analyses in self-driving vehicle.

II. CONNECTED DRIVING

With improved data transfer rates and minimized latency, the future 5G mobile standard provides significantly improved technical possibilities regarding data transfer, which can also be used to enhance vehicle connectivity compared to existing C-ITS use cases [3]. This is especially crucial for autonomous driving in which 5G is indispensable for a number of basic functions and has the potential to significantly improve user experience.

- **Telematics**: VR, conference calls, HD video download/upload. When driving autonomously, vehicles will serve as a space for work, rest and leisure. Passengers will spend their time on the road in new ways; vehicles will not only be a means of transportation but will provide a range of services.
- **Platooning/convey driving:** only the head vehicle in an autonomous driving fleet uses powerful sensors, it transfers its awareness of the environment to the rest of the vehicles, which are also autonomous driving vehicles but may not use all its sensors or may be equipped with very few or, even no, sensors. Besides the sensor data, the front vehicles will share their speed, acceleration or brake intention with the followers; this will reduce the headway between vehicles, also increasing the capacity of roads. This will require massive data exchange between vehicles.
- **Tele-operation:** involves 2 scenarios. First, in one area all vehicles are autonomous driving, but they upload everything to and receive commands from the cloud, which means fully centralized control via the cloud. Second, all autonomous vehicles are controlled independently, but in the very rare case that the decision module suddenly encounters a problem, the vehicle can receive sensor data, but cannot perform calculation, and needs support to continue autonomous driving. The vehicle then uploads its sensor data to the cloud, enabling a remote operator to view the vehicle’s surroundings as if they would sit in the vehicle, and then drive the vehicle to a safe location, e.g. emergency parking strip, by remote control.
- **Navigation**: Firstly, 5G has more accurate positioning ability due to satellite error correction, which can help the autonomous vehicle find its exact location for navigation. Secondly, the HD map size is too large and cannot be fully stored in the vehicle for long trips, and thus needs to be uploaded/downloaded from/to the cloud. Thirdly, the road situation may change frequently, especially in China where rapid and extensive infrastructure construction is underway. If a vehicle finds the environment to be different to that in the navigation system, it will instantly upload updates to the navigation cloud and also broadcast them to enable following vehicles to update their in-vehicle navigation systems accordingly.

Thus, data transfer between vehicles and the cloud with high definition, low latency, high speed and stable connection is necessary for the above use cases.

III. C-V2X CHINA TRIALS

The implemented C-V2X system is designed for LTE-V2X and is valid for 5G-V2X technical architectures. The former is based on a Long-Term Evolution (LTE) cellular network, the latter on a 5G NR (New Radio) cellular network. Due to their different network capacities, LTE-V2X and 5G-V2X can support different V2X services.

The LTE-V2X system has two wireless communication interfaces: LTE Uu and PC5. Taking the 20M bandwidth of 2.6GHz as an example to illustrate the TD-LTE (time division long-term evolution) network capacity, the frame transmission periodicity is 5ms and each frame structure is set to DDDSU (where D = downlink subframe, U = uplink subframe, and S = special subframe consisting of downlink slot, uplink slot and guard period). Each base station is equipped with 8Tx and 2Rx path antenna.

Based on two data streams and a 64QAM modulation scheme, the downlink peak rate of the single UE can be as high as 110Mbps. Similarly, the uplink peak rate is around 9Mbps based on single data streams and a 16QAM modulation scheme. The round-trip time (RTT) is about 20ms in theory. The actual end-to-end delay naturally varies from 20ms to a few hundred milliseconds depending on network load, user location, and network architecture deployment.

For the PC5 interface, MIIT (the Ministry of Industry and Information Technology of China) has allocated 5.905GHz-5.925GHz for direct communication about on-board units (OBU) and road-side units (RSU). In the early stage, a series of tests were carried out to assess the coverage of the PC5.

Throughout the trial, the transmission power of the RSU is 23dBm and the antenna gain is 8dBm for the RSU and 4dBm for the OBU. In the LOS (Line-of-Sight) scenario, the maximum coverage of the PC5 is 1.8 km and the target PER (packet error ratio) is below 10 %. In the NLOS (Non-Line-of-Sight) scenario, around high buildings the maximum coverage is 250m, and in the scenario around tall trees, the maximum coverage is about 1km.

LTE-V2X can support a lot of services. Many cities in China have launched LTE-V2X service demonstrations, including open roads and closed roads. Wuxi has achieved a city-level open road service demonstration covering 170 square kilometers and 200 intersections and more than 100,000 terminals. Based on the communication of TD-LTE Uu and PC5, consumers can benefit from a wide range of services, such as Traffic Light Optimal Speed Advisory, Speed Limit Warning, Traffic Jam Warning, Road Work Warning, Emergency Vehicle Priority, Forward Collision Warning, Emergency Electronic Brake Lights, and Emergency Vehicle Priority.

5G-V2X can support more services than LTE-V2X. 5G is designed to provide diverse capabilities, e.g. extremely high data rate, extremely low latency, extremely high reliability, high traffic density and high capacity connections for eMBB (enhanced mobile broadband), URLLC (ultra-reliable low latency communications) and mMTC (massive machine type communication) usage scenarios.

There are two network architectures: Non-Standalone (NSA) and standalone (SA). The key difference between them is the core network. In the NSA architecture, the terminal needs to interact with the 4G core network through the LTE base station for signaling, such as registration, authentication, etc. The 5G NR cannot work independently and only serves as an enhancement of the LTE data pipeline.

In the SA architecture, the NR is independent of LTE, and signaling is transmitted via the 5G base station to the 5G core network.

Considering that SA is the ultimate goal of the 5G NR network due to its advantages of introducing a new core network, flexible networking, and low terminal power consumption, we focus in this paper on the SA architecture.

The spectrum of the 5G mobile communication system consists of two segments, one segment is sub-6GHz，such as 2.515-2.675GHz, 3.4-3.6GHz, 4.8-4.9GHz; the other segment is mmWave, such as 24.75-27.5GHz, 37-42.5GHz. MIIT has allocatd 2.515-2.675GHz, 3.4-3.6GHz, 4.8-4.9GHz to different operators for the 5G test.

Taking the 100M bandwidth of 2.6GHz as an example to illustrate the network capacity, the frame transmission periodicity is 5ms and each frame structure is set to DDDDDDDSUU to ensure alignment with LTE. Each base station is equipped with 64 TRx path antennas, and each antenna unit consists of 192 elements (16 horizontal elements multiplied by 12 vertical elements). The terminal is equipped with 2 Tx and 4 Rx antennas.

Based on four data streams and a 256QAM modulation scheme, the downlink peak rate of a single UE can be as high as 1.74 Gbps. Similarly, the uplink peak rate is 190 Mbps based on two data streams and a 256QAM modulation scheme. Due to the large-scale antenna, massive space freedom is introduced to the 5G NR. Multiple terminals can use the same PRB resource to receive and send data. The downlink and uplink peak rate of a single cell are 6.9 Gbps and 760 Mbps, respectively.

The RTT is about 13ms in theory. Many optimization schemes, such as uplink preschedule, MEC (mobile edge computing) architecture, slicing, etc. can further reduce the latency time, although the latency time has been reduced to 8ms based on the uplink preschedule scheme.

In the field test, the terminal initiates ping service to the core network (CN) and obtains the end-to-end delay. The RTT is around 6~22ms as shown in Table 2. The delay varies according to the network deployment, network load and user distribution location.

TABLE II. TEST RESUTL OF RTT IN 5G

	Localized CN	Cross-province CN
RTT	6~18ms	16~22ms

The 5G large-scale trial will be carried out in five cities in China. The total number of 5G base stations is more than 100 per city. Each base station is equipped with a 64T64R antenna configuration and each antenna unit consists of 192 elements.

The goals of the 5G large-scale trial are: to verify key technologies and scale the network capacity; to explore network planning, construction, and operating experience optimization; to achieve 5G basic services, fully verified by personal characteristics, vertical field of the business, and to promote industrial end-to-end maturity and prepare for large-scale commercial deployment of 5G.

IV. COLLABORATIVE SENSING TRIALS

Preliminary trials using Pre5G C-V2X data exchange have been carried out using mobile roadside units in Tampere and Sodankylä, Finland. The first is located in south-west Finland and the second in the far north of Finland where winter temperatures frequently drop below -20 °C.

The mobile roadside unit uses the 2.3 GHz band and has been used for delivering data from the vehicle to a mobile road unit via 5G and then to the traffic management center and then to a second vehicle via the road side unit (RSU) (see Fig 2). The system was able to transmit the entire point cloud from two 4-layer laser scanners to the database via a Message Queuing Telemetry Transport (MQTT) interface and provided about 0.5 Mbit/s with a less than 200 ms latency time. The aim is to create a hierarchic data processing setup where part of the data is processed in-vehicle and part in a mobile edge computing unit, which is also connected to a centralized data management center.

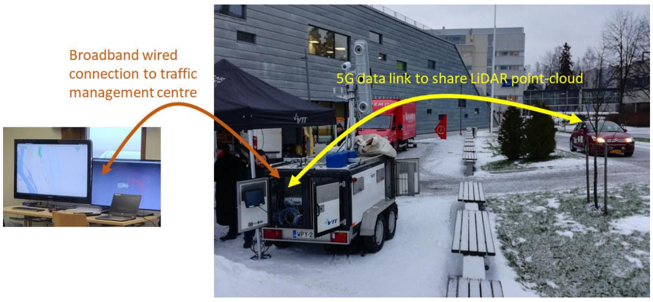

Fig. 2. The mobile roadside unit (Marsu) for developing and adapting automated driving functions locally using 5G connectivity.

Fig 3 shows the closed test area in northern Finland where different automated driving functions have been tested and developed. The 5G connectivity enables automated driving using an LiDAR-based 'see through' function between two cars delivering 1.2 Mbits/s and driving 25 km/h at the test site utilizing the high uplink capacity, which enables sending the whole point cloud from vehicle to cloud in order to share the processing with the infrastructure.

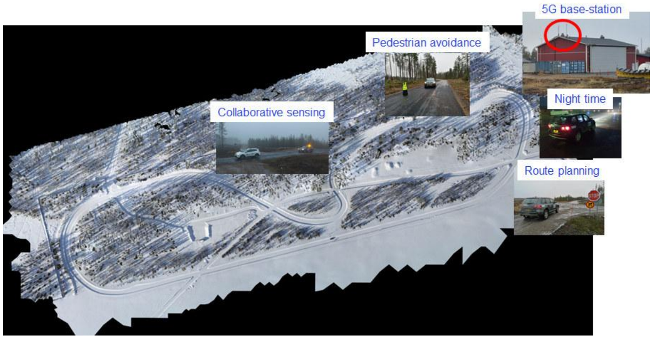

Fig. 3. Sodankylä 5G test site and automated driving scenarios in adverse winter weather.

In addition to 'see through', provision of a low friction warning message to the vehicle driver from a cloud-based weather service was also tested at the 5G test site. Fig 4 shows a visualization of low friction message in the user interface of the test vehicle. The warning message was provided with ultra-low latency from infrastructure to the car.

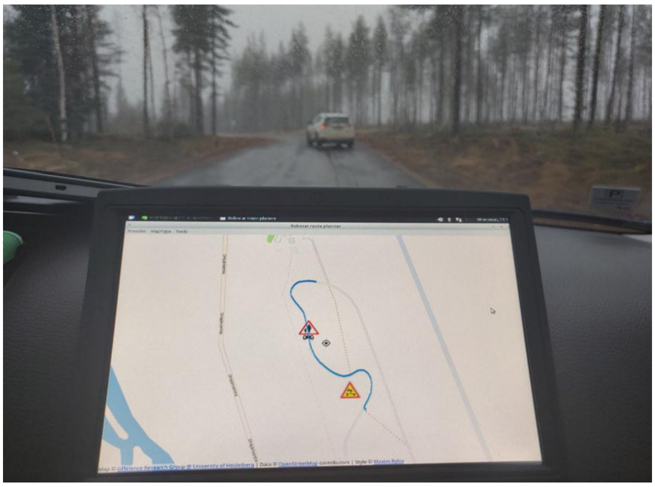

Fig. 4. Sodankylä 5G test site and automated driving scenarios in adverse winter weather.

Fig 5 shows the latency times at different parts of the Sodankylä test site with and without LiDAR point cloud sharing. The 1.2 Mbit/s of LiDAR data reduced latency time in some parts of the test circuit by 15-20 % but in most parts there was no negative influence. The darkness of the color indicates higher latency time.

Testing of the 2.6 GHz network indicated that the median data delivery time from vehicle to mobile edge computing unit and back to the car was 50-60 ms. This is faster than achieved at the test site using normal 4G cellular data. The latency provides sufficient time for the mobile edge computing unit to calculate and process the data if the vehicle speed is less than ~30 km/h.

Fig. 5. Ping measurements at the 5G test site. Left: without collaborative sensor data; Right: LiDAR data delivered over the 5G network.

To examine the network traffic caused by individual sensors, the following round-trip times from vehicle to the MEC server via the MQTT interface and back to vehicle were tested, see Table 3. The sensors used were:

- LiDAR for range measurement in front of the vehicle, with two 4-layer SICK LD-MRS laser scanners providing point cloud data in front of the vehicle
- Odometer for measuring vehicle speed based on tire rotations
- Inertia Unit (IMU) for measuring accelerations and vehicle heading
- Satellite positioning (GNSS) for measuring vehicle GPS and Glonass coordinates
- Route trajectory as a set of waypoint coordinates in front of the vehicle.

The measured signals represent typical sensing data required for automated driving and for ensuring safety and sufficient situation awareness. Heading and positioning data are needed for mapping the position of the vehicle. Maximum latency time is a critical factor and is heavily dependent on the data throughput rate Although the latency of the network alone can be less than 60 ms, computation and unexpected packet losses increase the latency to up to 250 ms, which makes collaborative sensing unreliable and requires a very low average vehicle speed (< 10 km/h).

TABLE III. MEASURED LATENCY AND DATA THROUGHPUTS IN TEST SITE [4]

	LiDAR	**Odometry**	**IMU**	**GNSS**	**Route**
Latency median [ms]	57	49	49	46	55
Latency max. [ms]	252	200	153	146	175
Throughput [kbit/s]	1 236	81	115	2,2	300

V. CONCLUSIONS

The tests indicate that the uplink bandwidth is better when using 5G networks compared to LTE-4G networks even if the trial network was advanced LTE instead of standardized 5G. However, there are still future work needed for optimizing usage and benefits of the 5G network. One of the key challenges is the susceptibility to network coverage and capacity changes depending on antenna alignment and position. Bandwidth capacity can drop by 60% within 200 m ahead if solid obstacles prevent line-of-sight communication. In addition, latencies highly depends on place where vehicle is driving and may exceed 0,5 s which is too long for reliable data exchange. Therefore, one of the future avenues is optimize driving speed according external data quality.

It is currently expected that C-V2X-PC5 devices [5] will enter the market in Q3/2019. These interfaces will enable direct communication between devices without a base station. This area will be the main focus of further research as communication latency is expected to be low, enabling vehicle-to-vehicle communication even in areas not covered by 5G.

Data sharing also raises questions of security [6] and privacy which limit access to open data. Not everybody is willing to allow their vehicle to be continuously monitored, and this is an important aspect of future C-V2X development. In some cases, people are allowed to shut-down monitoring which may also mean unavailability of automated driving functions.

All major OEMs are intensively involved in the development of C-V2X functionality [7]. The goal is not automation alone, but also a data sharing economy in which vehicles are part of the connected world as IoT nodes. Vehicles, digital infrastructure, mobile devices and homes are becoming integrated with cloud-based services enabling a vast range of innovations from car sharing and diagnostics to mobile restaurants.

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