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A C-V2X/5G Field Study for Supporting Automated Driving

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***Abstract*—This article focuses on reviewing the results of a series of trials conducted in Europe and China to benchmark 5G's benefits for automated driving challenges. The measurements have been conducted for studying the influence of the current 5G/LTE-V2X connectivity and optimizing antenna height, driving speed, and performance variation due to landscape variation. The results have been aggregated in real-world testing conducted in Finland and China. The vehicles have been equipped with onboard units (OBUs) and the infrastructure with the latest available 5G or LTE technologies.**

The outcome of this study indicates that LTE-V2X highly depends on antenna height. However, the latencies are quite stable, being 20–50 ms unless line-of-sight connection is lost. The communication range is increased by 5G, and also package size can be increased by up to 1 MB without increasing the package error rate, which in the LTE-V2X case starts increasing when 0.5 MB is exceeded. This is not a problem for traditional C-ITS messages, but if considering "see through" or "remote video operation," then the package size demand is much higher and goes beyond LTE-V2X's capacity.

I. INTRODUCTION

Vehicle-to-everything (V2X) technology does not change land transportation today. But it will make it more efficient, sustainable, and safer tomorrow. Although the rate of deaths per 100 k habitants is declining, the number of deaths has been steadily rising since the year 2000, reaching globally 1.35 million victims in 2016 [1]. According to [2], congestions are responsible for 8.8 billion hours of delay in 2017 in the US only. This is an increase of 14% compared to the data from 2012. The congestion delay caused an extra 3.3 billion gallons of fuel to be wasted. All in all, the congestion cost for the US in 2017 amounted to 179 million US dollars. Due to the increase in the global population and in motorization, this trend is perceived all over the world. Cellular vehicle-to-everything (C-V2X) technology provides responses to these three big issues of modern transportation; C-V2X can help reduce traffic casualties, improve traffic efficiency, and increase productivity/comfort while driving or being transported. Besides this, it will set the ground for expediting the introduction of levels 4 and 5 of automated driving systems.

The European 5G-DRIVE and Chinese 5G Large-Scale Trial projects were established for benchmarking the connected driving messages and networks between the continents. The automotive industry is keen on the availability of networks and the interoperability of the communication equipment needed in this globalizing business. Thus, the main motivation is to validate interoperability of the connected and automated driving functions between EU & China when shifting towards 5G networks operating at 3.5 & 5.9 GHz bands.

The high bandwidth requirement is because, in the future, automated driving functions will need supervision and even sharing both light detection and ranging (LiDAR) and camera data to remote operation centers with reasonable roaming expenses [3]. The 5.9 GHz (5850–5925 MHz) band has been allocated to the transport industry for V2X safety-related applications [2], [6]. There have been two compelling technologies, C-V2X (regulated by 3GPP R14) and ITS G5, based on IEEE 802.11p. In Europe the 5855–5925 MHz band has been allocated for short-range transport safety and non-safety messages [7]. Recently, splitting the band between ITS-G5 and C-V2X technologies has been proposed, like in the US where C-V2X operates in the upper band (5895–5925 MHz) whereas ITS G5 is located in the lower band (5855–5895 MHz) [4], [8]. However, recently there have been negotiations to free the whole 5.9 GHz band for other application areas [5]. However, the application layer architecture and message standards are mainly similar, which helps the application developers introduce new services and ignore the communication channel. The main organizations that are pushing automotive 5G and C-V2X standards forward are 5GAA, 3GPP, and ETSI, each having its own role in either communication protocols or message formats [9]. However, a typical 5G Uu connection is based on an allocated cellular channel for the operator and there are multiple bands, starting from 2600 MHz, ranging up to 71000 MHz. Therefore, the properties in terms of latencies, coverage, and bandwidth are

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different, and the selection of the optimal channel is not straightforward. Furthermore, the evaluation of 5G releases (14, 15, etc.) makes the network technologies even more versatile since the new radio in release 16 also offers, for example, slicing features [5].

II. TEST ARRANGEMENTS

A. Test sites

The tests in Finland were carried out in a specific public area that is dedicated for the development and validation of automated driving sub-systems. The test route length is about 350 m, including a hill, pedestrian crossings, and a four-way intersection (see Fig. 1). This is real traffic environment where the automated vehicles will operate in the future. There are hills, intersections, big buildings, etc., which influence to the` communication performance. The antennas in a test vehicle (a car) were located on the roof at 1.4 m height. Fig. 2 shows that the LTE-V2X antennas in the trailer varied, being three different heights from the ground (1.4, 2.8, and 3.8 m). The C-V2X antennas used were NMO4E5350B antennas by LARSEN.

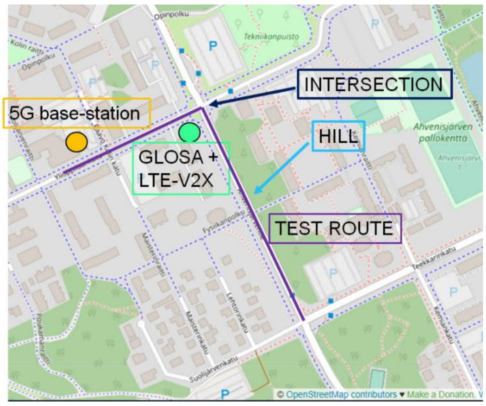

Figure 1. The test intersection for automated driving in Tampere, Finland

Figure 2. Antenna installations in the LTE-V2X trials. The trailer installations are shown on the left, and the 5G and LTE-V2X antennas of the test vehicle "Martti" were located on the roof.

The selected parameters for measuring connectivity performance were:

- **latency times** : *low latency needed for urgent vehicle reaction*
- **bandwidth** : *high amount of data coming modern vehicle sensors*
- **package error rate** : *number of lost packages for comparing network performance*
- **antenna height** : *three different height for measuring influence of line-of-sight and non-line-of-sight*

B. Equipment

The equipment used at the Tampere site were the following: 5G-capable Huawei CPE Pro router for the 5G measurements and 5.9 GHz Qualcomm® Cellular Vehicle-to-Everything (C-V2X) Development Platform for the C-V2X measurements. Both the test vehicle and the trailer had this same hardware installation. The used 5G network was the commercial 3,5 GHz Elisa network [11]. Unfortunately, the trial execution time window, the 5G-NR was not available and therefore, the tests have conducted Release-14 Non-Standalone devices for both Uu and PC5 interfaces. However, the C-V2X and 5G were tested separately in different runs due to avoid conflicts between communication gateways.

The vehicle integration tests were conducted in a private test track in Aschheim, near Munich. In order to evaluate the modification needed to implement C-V2X capabilities to an actual serial production vehicle it was used:

- *A development C-V2X box*
- *A traffic light equipped with C-V2X (RSU)*
- *CarPC with an interface converter and GUI capabilities*

The tests in China were carried out in the National Intelligent Connected Vehicle, Shanghai. Enclosed test zone in Shanghai. Traffic lights are deployed at each intersection. Roadside units (RSUs) from different vendors are deployed at the No. 51 intersection (the red circle in Fig. 3).

Figure 3. The test site for automated driving in Shanghai, China

The equipment in the Chinese field trials consists of the following network and onboard unit (OBU) devices (see Fig 4 and Fig. 5):

- The LTE network (2.6 GHz)
- 5.9 GHz RSU and OBU
- 5.9 GHz NEBULA OBU

Figure 4. The RSUs from different vendors are deployed on a light pole at the No. 51 intersection.

Figure 5. The OBU is placed on the top of the test car. The height of the antenna is about 1.5 m.

III. EXPERIMENTAL RESULTS

The test session carried out several measurements with varying antenna heights, message sizes, and vehicle speeds. Fig. 6 and Fig. 7 shows the latency plots of both C-V2X and 5G measurements, where the antenna height was 1.4 m, vehicle speed was 30 km/h, and message size 250 bytes. For the C-V2X case, the latency varies from 18 ms to 52 ms, resulting in a mean value of 35 ms and jitter of 9 ms. The same results for the 5G measurements are a mean of 208 ms and jitter of 29 ms. However, the mean higher than real value since during the measurement campaign the connection was always lost in one point thus, causing high jitter. More than 95 % of the road section the jitter was less than 50 ms.

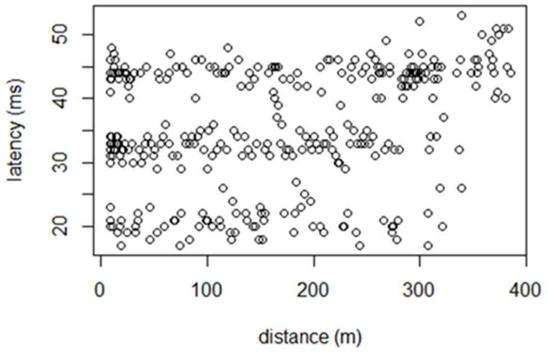

Figure 6. Latency measurements for LTE-V2X when antenna height is 1.4 m, the message transmission interval is 100 ms, and size is 250 bytes.

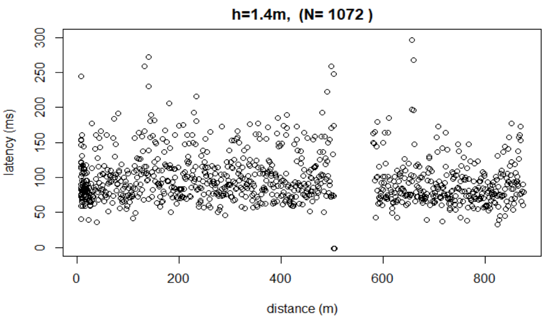

Figure 7. Latency measurements for the commercial 5G network measurement to share a GLOSA message

Fig. 8 and Fig. 9 presents latency histograms for both C-V2X and cellular measurements, where the message size was 277 bytes and the transmission interval was varied. For the C-V2X case, the mean latency is between 25 and 32 ms in all cases and only slightly higher for the 1 ms message interval case. The LTE/5G cellular network measurements reveal distinctly higher latency values, varying from 61 ms to 133 ms, caused by the mobile cell handover along the test route. In particular, this can be seen in the case of 1 ms interval where the mean latency value is the highest.

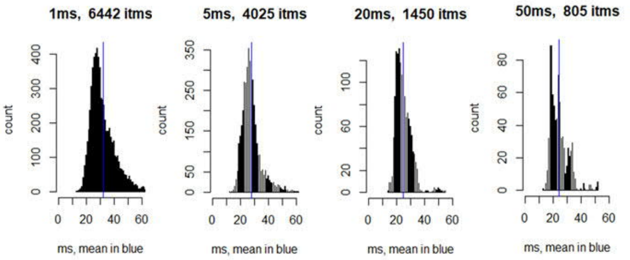

Figure 8. Latency measurements for using the C-V2X connection to share a 277 byte GLOSA message. The headline above shows the transmission interval, and the histogram shows the receiving message response times.

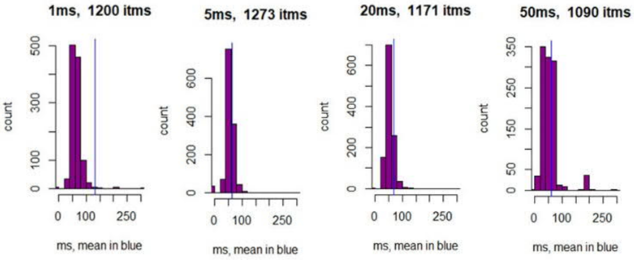

Figure 9. Latency measurements for the commercial LTE/5G cellular network, used to share a 277 byte GLOSA message. The headline above shows the transmission interval, and the histogram shows the receiving message spreading.

Table 1 presents how the different driving speeds affect the mean latency and the jitter values in both C-V2X and LTE/5G scenarios. The C-V2X connection shows very consistent values regardless of the vehicle speed, whereas the LTE/5G connection gains higher latency values and significantly higher jitter values due to the handover. Table 2 presents the results with a fixed message interval (100 ms) and fixed driving speed (30 km/h). In this case, there was no handover in the LTE/5G connection. Both the C-V2X and LTE/5G scenarios are coherent, with the exception that the packet-loss rate (PLR) increases with bigger packet sizes in the C-V2X connection. This could be caused by the UDP connection used.

Table 3 presents the PLRs with different RSU antenna height variations and fixed driving speed. The measurements conducted with three different antenna height installations on trailer: 1.4 m, 2.8 m and 3.8 m. Such heights were chosen to represent the most common positions where a C-V2X antenna could be installed, being the average height of a vehicle, a roadside traffic light height and an over-the-road traffic light gantries height respectively. It can be seen that the 2.8m antenna height shows higher PLRs compared with the 1.4m and 3.8m antenna heights. This could be caused by branches obscuring the line of sight between the RSU and the vehicle antennas.

TABLE 1. A COMPARISON BETWEEN DIFFERENT DRIVING SPEEDS AND NETWORK MEAN LATENCY AND JITTER. MESSAGE TRANSMISSION INTERVAL: 50 MS.

	C-V2X		*LTE/5G*	
Driving speed [km/h]	***Mean [ms]***	***Jitter [ms]***	***Mean [ms]***	***Jitter [ms]***
10	24	40	66	4696
20	25	41	130	3258
30	24	40	73	4799
40	24	39	94	944

TABLE 2. A COMPARISON BETWEEN C-V2X AND THE CELLULAR NETWORK AGAINST THE TRANSMITTED PACKET SIZE. MESSAGE TRANSMISSION INTERVAL: 100 MS; DRIVING SPEED: 30 KM/H.

	C-V2X			*LTE/5G*		
Packet size [bytes]	***Mean [ms]***	***Jitter [ms]***	***Packet loss rate [%]***	***Mean [ms]***	***Jitter [ms]***	***Packet loss rate [%]***
250	15	5	0	43	20	0
500	15	9	0	58	23	0
750	13	6	2	61	26	0
1000	13	6	6	50	14	0

TABLE 3. THE PACKET LOSS RATES FOR C-V2X WHEN THE RANGE IS BETWEEN 250 AND 400 M AND THE DRIVING SPEED IS 30 KM/H.

Antenna height in the RSU [m]	***Message size [bytes]***	***Packet loss rate [%]***
1.4	250	9
1.4	750	12
2.8	250	19
2.8	750	11
3.8	250	9
3.8	750	7

The C-V2X test sessions in Shanghai can be divided into three categories: interoperability tests between different vendors, V2I/V2V (C-V2X technology) coverage tests, and finally, LTE-V2X (PC5) performance tests. The experimental results of all three categories are shown due to their experimental designs and results gained through joint EU–China trials under the 5G-DRIVE and 5G Large-Scale Trial projects, which leads to the possibility for parallel comparison.

First, the interoperability tests between different terminal (RSUs and OBUs in this case) vendors are performed under the GLOSA use case. To test the interoperability of the Signal Phase and Time (SPaT) messages and Basic Safety Messages (BSMs) being transmitted and received among RSUs and OBUs from different vendors, two scenarios were designed: one RSU transmits SPaT messages and multiple OBUs from different vendors receive them; one OBU transmits BSMs and multiple RSUs from different vendors receive them. The results of both scenarios confirm the successful transceiving of SPaT messages and BSMs among terminals, and thus confirm the interoperability of RSUs and OBUs from different vendors.

Second, the V2I/V2V coverage tests were performed with C-V2X technology-based OBUs and RSUs. For the scenario of the V2I (OBU–RSU) coverage test under non-line of sight (NLOS; in the test case, regular greenery on the test site), an OBU in a test vehicle was moving away from an RSU (installed ca. eight meters above ground level on a light pole). SPaT messages were transmitted from the RSU to the OBU, and the end-to-end PLRs were measured.

Fig. 10 shows that the PLRs of both RSUs (from two vendors: Vendor A and Vendor B) significantly increase when the distance between the OBU and RSU is further than 800 meters, which indicates that the RSU coverage could be around 800 meters in NLOS conditions, considering the end-to-end reliability KPI, such as the PLR.

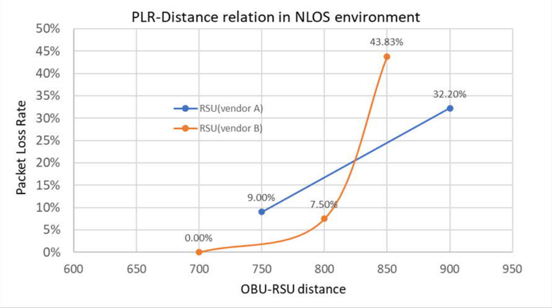

Figure 10. The PLR and OBU–RSU distance relationship in an NLOS test environment

For the scenario of the V2V (OBU–OBU) coverage test under line of sight (LOS) and NLOS conditions, two sub-scenarios were performed at a Shanghai test site: two vehicles (OBUs) in driving mode under LOS/NLOS conditions and two vehicles (OBUs) in fixed positions under NLOS conditions.

TABLE 4. THE MEAN LATENCY OF VARYING OBU–OBU DISTANCES

Driving mode: LOS/NLOS	***OBU–OBU distance [m]***	***Latency mean [ms]***	***PLR***
Near point	0	16.29	0%
Far point	400	15.5	0%

Table 4 shows the end-to-end latency and PLR between two OBUs in driving mode in both LOS/NLOS environments. The measurements show that the average latency is around 16 ms. When the distances of two OBUs are within communication range, the latencies were not affected. The PLR was stable at 0% when the two OBUs were within a communication range of 400 meters.

Table 5 shows the end-to-end latency and PLR between two OBUs, measured at fixed positions in an NLOS environment. Some degradation on the average latency can be observed when the two OBUs are placed more than 400 meters apart in the NLOS environment. The PLR increases from 0% to 17%, which indicates the communication range in this case is around 400 meters.

TABLE 5. THE MEAN LATENCY OF FIXED OBU–OBU DISTANCES

Fixed position: NLOS	***OBU–OBU distance [m]***	***Mean latency [ms]***	***PLR***
	400	15.32	0%
	450	18.81	17%

Third, the LTE-V2X performance tests include latency and PLR tests under single and multiple transmitting stations. To illustrate, the “Intersection Warning” use case is tested here by sending BSMs. In this test category, two scenarios are tested: a single terminal transmits and four terminals receive (transmission between one OBU and four RSUs); multiple terminals transmit and multiple terminals receive (transmission among twenty OBU/RSU stations: six RSUs and fourteen OBUs). In these two scenarios, the performance of LTE-V2X is evaluated with the end-to-end latency and packet loss.

For the first scenario, where a single OBU transmits and multiple terminals receive, the average end-to-end latency was within 25 ms and the differentiation of the measurements were low when the distances between the OBU and multiple RSUs are at far, middle, and near points (all within a communication range of 800 meters). This latency of less than 25 ms proves the performance of LTE-V2X devices. The end-to-end PLRs of all receivers are all less than 10%, which confirms the performance reliability of the LTE-V2X and devices. For the second scenario of multiple terminals transmitting and a single terminal receiving, a large-scale feasibility test, focusing on the intersection warning use case, was carried out first using twenty RSU/OBU stations. Then, the end-to-end latencies were measured among all transmissions. The results analysis shows that the average latency was less than 38 ms and the PLR was less than 10%

For the test in Munich, there was a main goal in mind: to ensure that C-V2X could be implemented as an OBU in today's production vehicles and that the communication with all the other modules and sensors that are already in the architecture could take place as designed, without errors. For that, two use cases were chosen—a SPaT case and Red Light Violation Warning case—to showcase V2I communication with traffic lights equipped as RSUs. The vehicle was equipped with an OBU running an iTS software stack.

Since the C-V2X modem available was a test unit and it was not set as a proper OBU, we needed to integrate it into the vehicle's electronic distribution system. Due to the array of different protocols and wired networking technologies, this could not be done without an interface converter connected to a computer via PCIe. This enabled a software application to run in the computer to read the relevant messages (such as position, blinker status, the angle of the wheels, and speed) in the controller area network (CAN) bus. The computer is connected to the C-V2X modem, which handles the PC5 communication. In addition, data from the system has to be available to the driver. This is managed via a converter that sends the information from the program in the PC to the centre information display (CID) so it can be visualized. In the future this will be integrated in a single electronic control unit (ECU).

For both use cases, the traffic light has a control unit and a C-V2X module (see Fig. 11). It will send the SPaT and location information to the vehicle. The CID will display the actual status of the traffic light and the time until the next state. Also, with that signal timing and the location, speed, and acceleration from the vehicle, the application running on the computer will calculate the status (*red* or *green*) of the traffic light and the time until the next state by the time the vehicle reaches the position of the traffic light. If such status is *red light*, a warning will be displayed on the CID. If automated cruise control (ACC) is activated, some instructions ("slow down," "speed up") could be implemented to be carried out automatically by manipulating the target speed for ACC.

Figure 11. Traffic lights with C-V2X

IV. KPI ANALYSIS

Section III presented the experimental results of the joint EU–China trials performed in Tampere, Finland, and in Shanghai, China, under the collaboration that was part of the 5G-DRIVE and 5G Large-Scale Trial projects [14]. This section compares the measurement results of both trial sites in the following aspects: trial configuration parameters, message type comparison, end-to-end average latency, and end-to-end PLR. The collaboration of the 5G-DRIVE and 5G Large-Scale Trial projects ensures that the trial set-up of the two joint-use cases is similar [13]. This section compares the measurement results of both trial sites in the following aspects of joint EU-China use cases (GLOSA and the intersection warning): trial configuration parameters, message type comparison, end-to-end average latency, and end-to-end PLR.

For the message types, it has been identified in [14] and [15] that the message types used in the GLOSA use case and the intersection warning use case in Europe and China are different. For the GLOSA use case, SPaT and CAM messages are used at the Finnish trial site while SPaT messages and Basic Safety Messages (BSM) are used at the Shanghai trial site. For the intersection warning use case, Decentralized Environmental Notification Message (DENM) and cooperative awareness messages (CAM) messages are used in Finland while BSMs are used in Shanghai. The similar usage of SPaT messages is simple to understand. In this paper, we focus on the difference of a BSM in China and DENM and/or CAM messages in Europe (see Table 6).

The BSM in China is likely to be a combination of a DENM and CAM message in Europe considering the functionalities in different use cases, which means the application layer protocol interoperability solutions of C-V2X across inter-continental regions need to take these differences into account.

For the mean end-to-end latency, it is shown that the driving speed of the automated vehicle (ranging from 10 to 40 km/h) and message packet size did not affect the latency of C-V2X at the Finnish trial site. But the message transmission interval—for example, 50 ms (20 messages/s, emulating twenty C-V2X device stations) and 100 ms (10 messages/s, emulating ten C-V2X device stations)—has a noticeable effect on the mean latency. The latency is increased from around 15 ms to 25 ms when the number of emulated stations is increased from 10 to 20 (see Table 1 and Table 2 for details). This is as expected as the latency of C-V2X is expected to increase when the channel load increases, and the bandwidth occupation worsen. A parallel comparison to the Shanghai trial shows that the latency mean is around 15 ms as well when there are around five stations devices that did not congest the communication channel. Moreover, the large-scale use cases' feasibility tests in Shanghai also showed that the latency mean is increased to around 38 ms when the number of physical devices stations (e.g., multiple RSUs and multiple OBUs in multiple vehicles) participants increases to twenty in a multiple-use case overlay scenario across the site. The impact of multiple stations on latency were previously simulated and studied in a few literatures [16], [17]. The trial data in this paper verified the impact using either emulated or physical stations (up to twenty) on urban road environment.

TABLE 6. A MESSAGE TYPE COMPARISON OF THE GLOSA AND INTERSECTION WARNING USE CASES IN CHINA AND IN EUROPE

Message format	***China***	***EU***
BSM	V2V basic safety, regular vehicle status	-
BSM	V2V basic safety, regular vehicle incident	-
BSM	V2V basic safety, emergency vehicle status	-
BSM	V2V basic safety, emergency vehicle status incident	-
BSM	V2V basic safety, post-installed vehicle UE	
DENM		Informing of a hazardous event and other information relevant for safety
CAM		Vehicle (OBU) status and infrastructure (RSU) status

V. CONCLUSIONS

The KPI comparison between the joint trials in Europe and in China implies the following key findings: When the trial configuration parameters and road test environment are similar, the chosen KPI metrics (mean end-to-end latency and the PLR) share quite a few similarities in C-V2X tests, despite some initial differences, such as differences in the message type, equipment, and terminal providers. The end-to-end PLR between the RSU and OBU is around 10% within the communication range (antenna height 3.8 meters) in Finnish trials. In comparison, the end-to-end PLR between the RSU and OBU in Shanghai trials had a similar packet loss (around 10%) within the communication range (< 800 meters). The latency at both the Finnish and Shanghai sites experienced degradation when the user stations (emulated or physical) increased from a single transmission to multiple (around twenty) transmissions.

This is probably first time when the C-V2X and cellular V2X applications are compared with using real automated vehicles and devices between China and EU which is biggest difference compared to prior art. One important aspect is to consider what are the main benefits of new 5G releases (16/17), which area expected to reduce jitter and make slicing available in automated driving scenarios. The second important scenario is to consider how handover between base-stations influence to the network performance parameters. Additionally, the use of multi-access edge computing enables distributed intelligence between vehicles and road infrastructure are interesting aspects with which to extend comparison between China and EU trials.

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