Real-life V2X Measurement Results for 5G NSA Performance on a High-speed Motorway

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***Abstract*—One of the key application target areas of 5G mobile technologies is the Vehicle to Everything (V2X) communication. The first 5G deployments for Non-Standalone Architecture (NSA) have been successful worldwide, although the success itself should be supported by published performance results – which are still hard to find. This paper aims to make up for this missing information in the area of 5G NSA capabilities for fast-moving vehicles. Since the core network in the NSA is the Evolved Packet Core (EPC) for 4G, network slicing is not yet an option, and other guarantees for keeping certain Quality of Service (QoS) promises are limited. The contributions of the current paper are twofold: first, it describes a reference measurement methodology for V2X communication measurements under motorway conditions, and second, it provides initial real-life, practical results for the 5G NSA setup – which can already provide better KPIs than 4G, and can only get better with the advent of 5G Standalone (SA) architecture deployments.**

The results described here are part of a comprehensive measurement campaign for autonomous vehicles and their Digital Twins, carried out in June 2020 by BME, TU Graz, Magyar Telekom, ZALAZone, vehicle and ITC vendors, and the Hungarian Road Authority on the M86 national freeway.

***Keywords*—Cellular Mobile Networks, 5G, Practical Measurements, Latency, Jitter, Throughput**

I. INTRODUCTION

5G technologies are aiming to provide great servicing environment for V2X communication. In general, the offered technology set involves features known as massive MIMO, beamforming, network slicing, and multi-access edge computing (MEC), just to name a few. The network-related requirements of V2X depend on the use-case scenario: while safety-related cases (such as emergency trajectory alignment) may require sub-5ms latency, other applications could tolerate 100 ms latency (e.g., information sharing for automated driving), according to the standard [1]. Video-sharing could require data rates between 10 Mbps to 700 Mbps data rates for lower and higher degree of automation, respectively – and this also depends on environmental factors. The combination of these needs means that V2X use-cases represent the combination of the otherwise separated 5G application areas: Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB) and massive IoT (mIoT).

978-3-903176-32-4

Debates are still heated regarding many V2X use-cases – whether the decision will be made within the car or by the network edge. Network edge or edge server is a distributed computing paradigm where the computation and data storage not necessarily built-in to the end-device instead placed to an external server –near to the end-device– to improve response times and save onboard computational resources. It can be directly part of the 5G system but also independently operating systems. If the decision is made outside the car, it is clear that a huge information-volume must be sent by the car's sensor and monitoring system continuously. If the computational elements for the decision-making process are in the vehicle, input information from the outside world could still be needed. Either way, wireless connection latency characteristics are one of the most crucial parameters for real-time decision making.

The main difference between NSA and Standalone Architecture SA is that NSA anchors the control signaling of 5G Radio Networks to the 4G Core, while in the case of SA, 5G Radio directly connects to the 5G core network, and the control signaling does not depend on the 4G network at all. In this paper, a measurement methodology is presented to extensively investigate the latency and RTT (Round-Trip Time) characteristics of a live 5G NSA network. This methodology can later be used for 5G SA architecture measurements as well, where end-to-end traffic characteristics can be further optimized (e.g., through network slicing, which requires a 5G core network, not only 5G New Radio). Our goal with the *real-life* measurement setup was to measure the network's real-time data transfer capabilities in conditions close to real-life situations, rather than to reach artificially pretty results in sterile laboratory environments. In order to force real-life V2X conditions, we carried out our measurements in a motorway, involving vehicles moving at 140 km/h speed. Naturally, there is room for improvements for these real-life results through using state-of-the-art 5G technologies in all aspect [2], and then applying those for network fine-tuning; but even the presented raw 5G NSA setup can satisfy various use-case requirements set in [1].

The rest of the paper is organized as follows. Section II describes the related work, Section III, the M86 freeway measurement setup by large, and Section IV is its 5G-related measurement architectural part. Section V details the traffic measurement methodology, and the actual results are presented and discussed in Section VI. Section VII concludes the paper.

II. RELATED WORK

Existing standards and recommendations mainly reflect bandwidth, latency, and jitter requirements in respect to generic use-case requirements [3], and especially the needs of automated vehicles [1]. The 5G architecture [4] was created with these requirements in focus. These standards and the quality of service offered by mobile network operators need to be reinforced by accurate and relevant measurements for autonomous vehicles. The main question is whether the data transmission technology – 5G – meets the needs of the autonomous car use-cases. In addition to the higher available bandwidth offered by 5G, another huge advantage is the seamless handover between cells without packet loss. The bandwidth provided by 5G, both for the up- and downlink, offer significantly more options regarding use-cases. Sensor data can be transferred between an edge server and the vehicle real-time; hence the V2X approach of efficient collaboration between environment monitoring and mobile edge computing becomes reality. 3GPP standards specifies the key V2X scenarios and use-cases in the following areas with diverse performance requirements [1]:

- General Aspects: These aspects are consisting of interworking, communication-related requirements valid for all V2X scenarios.
- Vehicles Platooning: It enables the vehicles to dynamically form a group travelling together, while the vehicles in the platoon receive periodic data from the leading vehicle.
- Advanced Driving: The benefits of this use case group are safer traveling, collision avoidance, and improved traffic efficiency with the enabling of semi-automated and fully-automated driving.
- Extended Sensors: Extended Sensors catalyze the exchange of data gathered through local sensors or live video streams among vehicles, devices of pedestrians and edge servers.
- Remote Driving: It enables a remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive themselves or a remote vehicle located in dangerous environments.
- Vehicle quality of service support: Vehicle quality of service support enables a V2X application to be timely notified of expected or estimated change of quality of service before actual change occurs.

In general, the environment of the 5G-targeted vehicles can be very diverse, ranging from slow-moving industrial AGVs (Automated Guided Vehicle), through urban traffic scenarios with great number of endpoints, to vehicles moving on a high-speed motorway. Potentially 5G-supported V2X use-cases (including not only cars but drones) are gathered well in [5]. While V2X and 5G standardization are still ongoing, early adaptations of the technology set are already available and deployed (i.e., 5G NSA). While real-life, application-related 5G measurement results start to appear different fields such as IoT [6] or healthcare [7], Comprehensive reports of the current state-of-the-art "on the road" (i.e., 5G-capable automated vehicles on motorways) are still missing. The authors of [8] describe a 5G V2X testbed already as early as in 2016 when 5G standardization was in the requirement study phase at 3GPP; and indeed, the paper merely discusses radio-subsystem details and capabilities.

Note that our real-life measurement scenario also involved the core network - not to mention the physically moving vehicles on a motorway. While various 5G V2X application scenario-based papers are available, they mostly focus on optimizing communication (such as collision avoidance [9] or platooning [10] rather than on network traffic capabilities - not to mention real-life measurement results – which provides the uniqueness of the current paper.

The protocol sets for automated vehicles are still changing [11]. Real-environment researches support to fill the missing gaps of the research domain. The various use-cases would generate diversified data needs as well, where different throughput, latency, jitter, packet loss, and other SLA parameters will be critical. From a mobile network operator point of view, network slicing will be the solution to serve these needs. Network slicing can help to prioritize traffic during end-to-end data transmission. A time-critical data stream will get higher priority over a static but non-interactive stream. Furthermore, the critical data stream can even receive latency guarantees [12].

III. THE M86 FREEWAY MEASUREMENT CAMPAIGN IN JUNE 2020

The measurement campaign was carried out on a highway section, nearby the town of Csorna, in the North-Western part of Hungary (Győr-Moson-Sopron county, Western Transdanubia Region). The goal of the measurement campaign was to record vehicle and infrastructure data being essential to the implementation of the technologies to be developed in later phases of the R&D projects in the area of automated vehicles. This campaign helped to test features and collect data in real conditions instead of the laboratory environments. Several universities and automotive companies of four countries participated in the measurement campaign.

The road section was entirely closed to traffic and only the measuring vehicles used the road. These vehicles were installed with a GPS transmitter (with 1 cm accuracy) so the dynamic parts of the scenarios were fully detected automatically. The key objective of the initiative was to incorporate fully comparable measurements, i.e., data detected by vehicles and sensors installed in the infrastructure. In the meantime, with ex-post assessment, the

Fig. 1. Sections of the test site

connectivity architecture (5G cellular network) was continually checked on vehicles and networks both in terms of latency and data transmission.

Measurements were primarily carried out using parts 1 and 2 of both carriageways simultaneously. Only in section 1 were the 5G-related measurements run. There was still 4G coverage in the testing area, so the UE (User Equipment) dropped back to 4G in sections 2, 3 and 4. A high bandwidth fiber optic communication network was accessible along the entire section in addition to the physical infrastructure, and many sensors, cameras and Variable Message Sign (VMS) portals were deployed with a fixed power supply. During the experiments, additional sensors (cameras, laser scanners, etc.) and mobile 5G base stations were deployed using this infrastructure.

IV. THE 5G MEASUREMENT ARCHITECTURE

A non-commercial 5G modem – still under development phase – was used for the measurement, while the packets were generated on three end-devices. Three measurement traffic generators (device A1, A2, A3) were installed in a moving vehicle. Option 3.X network architecture was used (Figure 2), due to Mobile Network Operator and Vendor limitations, only NSA 5G networks were operating at the time of the measurement campaign. The most critical characteristic of Option 3.X is that only the downlink channel 5G capable; the uplink still remains 4G [13]. The measurement traffic was generated on the end-devices (A1, A2, A3) and traveled towards the UE modem via Gigabit Ethernet connection. The modem was responsible for the 5G NSA Radio Access Network connections. Frome the UE modem packets traveled always traveled through the eNB on the uplink channel towards server B direction. The next mobile network entity in the connection is the EPC; after that, the packets arrived at server B. Backwards on the downlink channel, the packets transmitted on a wired connection through the EPC to the gNB. Finally, via the UE modem, the packets returned to the end-devices on the Gigabit Ethernet interface.

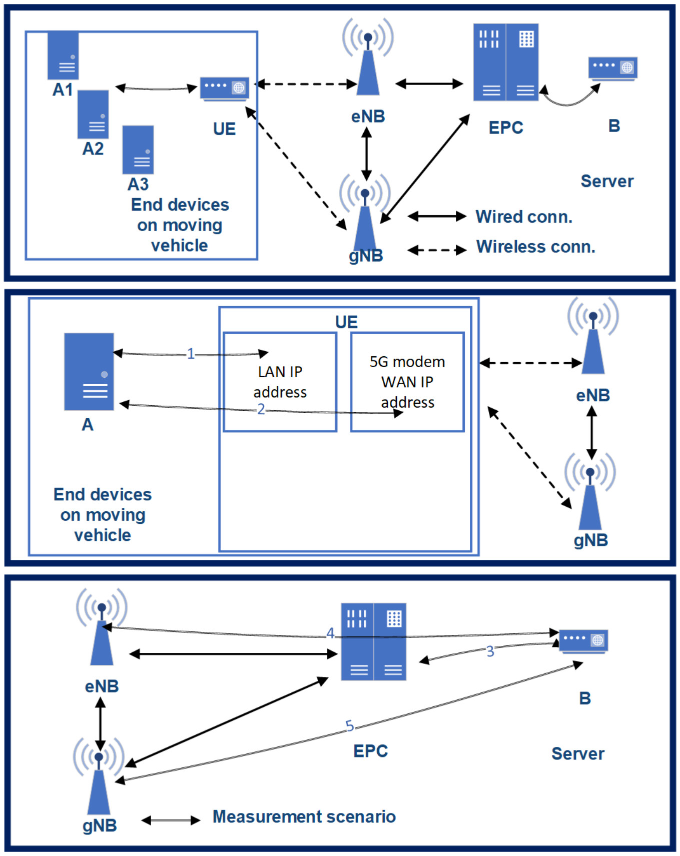

Fig. 2. The architecture of the 5G testbed – as 3GPP Option 3X

A. Measuring the 5G downlink NR latency

End-to-end RTT (Round Trip Time) is not characterize well the 5G capabilities of the architecture as only the downlink channel is 5G capable in 3GPP 3.X 5G solution. Furthermore, one-way downlink latency is also a poor characteristic of the network. The most crucial parameter is the latency between the UE and the gNB. However, we cannot measure this connection directly as the protocol encapsulation makes it impossible. 3GPP based data-plane encapsulation is established between the UE and the EPC. The eNB or gNB is not aware and not allowed to open the packet for encapsulation (in case of close access to the eNB/gNB software, this could be monitored, but we did not have access.). We had access only to the interfaces of EPC, UE, and the measurement servers. Therefore, we measured the one-way latency, RTT – sum of uplink and downlink latency – and some other supplementary connections to get the latency between the gNB and EPC. This gNB-EPC latency characterize the network capabilities of 5G in contrast to the previous mobile networks. The supplementary connections are as follows in Figure 2:

- 1-way latency (T_0): latency between (*l-bw*) A1 and B.
- Connection 1 (T_1): *l-bw* the UE's LAN interface (i/f) and the end-devices.
- Connection 2 (T_2): *l-bw* UE's WAN i/f and end-devices.

- Connection 3 (T_3): *l-bw* EPC SGi i/f and server B.
- Connection 4 (T_4): *l-bw* eNB’s s s1u i/f and server B.
- Connection 5 (T_5): *l-bw* gNB’s s1u i/f and server B.

V. MEASUREMENT METHOD

A. Measurement methodology

Under different radio conditions, tests were carried out. To define some primary parameters of the 5G network, we selected a state space approach. One of them was the speed of the car controlled by cruise control. While the vehicle speed, the Inter-Arrival-Time (IAT) between the packets, and the Packet Length (PL) varied, latency was measured. As most of the V2X use cases have strict time-critical specifications, these are among the most basic characteristics in potential 5G vehicle use-cases.

Based on our previous works in [6], we identified three measurement scenarios with different PL and IAT parameters. Also, one reference scenario was measured with constant parameters. The examined state-space scenarios are as follows:

- Scenario 1: From 2 ms IAT and 60 Byte PL to 62 ms IAT and 960 Byte PL, incrementing 60 Byte PL by every iteration and 20 ms IAT by every fourth iteration;
- Scenario 2: From 10 ms IAT and 250 Byte PL, to 310 ms IAT and 4000 Byte PL, Incrementing 250 Byte PL by every iteration and 100 ms IAT by every fourth iteration;
- Scenario 3: From 10 ms IAT and 700 Byte PL, to 610 ms IAT and 11200 Byte PL, Incrementing 700 Byte PL by every iteration and 200 ms IAT by every fourth iteration;
- Const: 2 ms IAT and 40 Byte PL.

We find that the maximum MTU size on the network is 1450 bytes without segmentation, based on preliminary measurements [6] and [14]. Still, as measurement scenario 2 and 3 indicates, to describe this form of network characteristic, we used packets with PLs greater than 1450 bytes as well. The related measurement results have been included in the meantime in a greater aggregated analysis work of ours [15].

VI. RESULTS

A. E2E RTT results

In this section, in the various measurement scenarios, the RTT results are presented as box and whisker plots. As expected, the median values increase as the car speed increases, particularly in the case of scenarios 1 (Fig. 3).

In the case of different packet lengths, Figure 4, 5 and 6 present the RTT distribution. Figure 4 does not indicate such a pattern as the previous one; however, an obvious skewness can be seen in the latency distribution as Q3 in Figures 5 and 6, and maximum scores increase as the packet length increases. It is not surprising that, when these packets become segmented, there is a positive skewness at broad packet lengths. In any case, the median and Q1 and minimum scores remain the same as there are physical limitations to the lower latency limit, such as delay of active system CPUs, NIC buffers, adapt packet to copper, optical and optical links, and so on. There was no strong trend in the latency distribution with regard to IAT data, so it is not presented in this article.

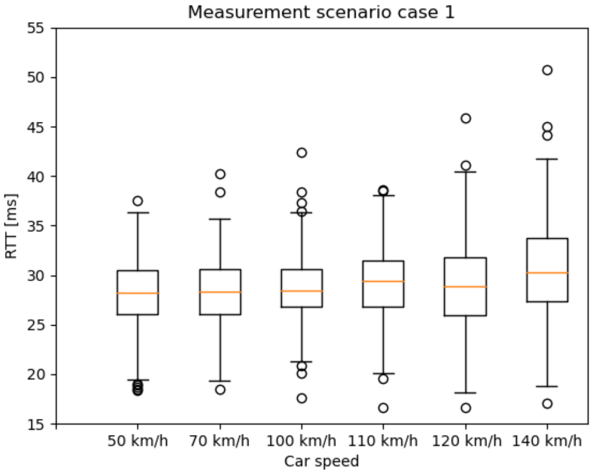

Fig. 3. RTT results of measurement scenario 1 with different car speeds

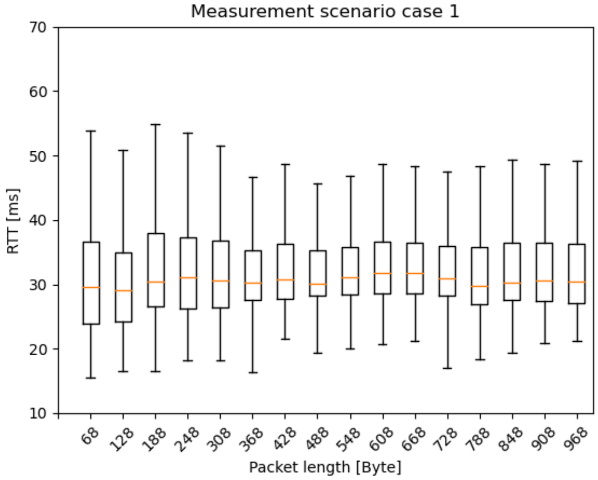

Fig. 4. RTT results of meas. scenario 1 with different packet lengths

B. 5G NR latency results

Compared to similar 5G and experimental networks utilizing the same architecture, the e2e RTT measurement results demonstrate high values. Since only the downlink was 5G, the primary explanation is the 3GPP 3.X NSA 5G architecture. We analyzed the latency between the network elements of the presented architecture (Figure 2) to identify more aspects. We got some assistance to calculate the latency on connections 3, 4, and 5 from the mobile core and radio network side. The network elements in the figure are physically far apart; some elements in the design in Figure 2 are also not presented. While these network components do not play an important role in the 3GPP architecture, they add latency to the paths of data transfer:

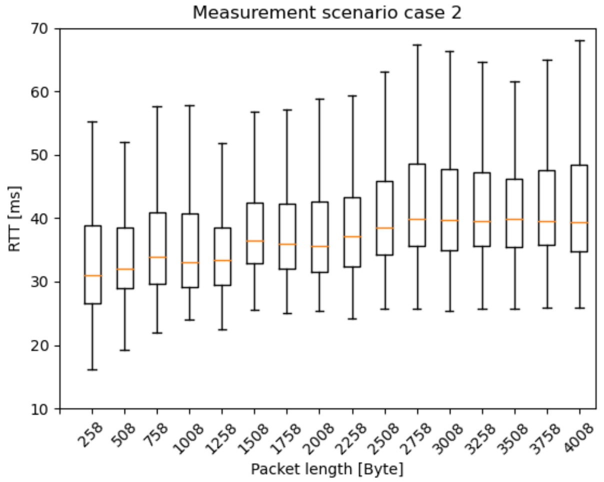

Fig. 5. RTT results of meas. scenario 2 with different packet lengths

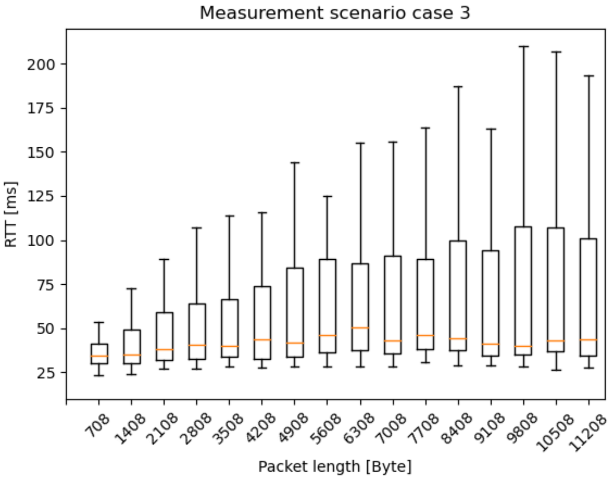

Fig. 6. RTT results of meas. scenario 3 with different packet lengths

- 1 (T_1): The UE was connected to the end-devices (A1-A2-A3) through a Gigabit Ethernet switch. Since the latency between the end-devices and the switch was below 0.2 ms, the A1-A2-A3 devices can be considered as an A device for this measurement-type.
- Connection 2 (T_2): In the connection between the A end-devices and the UE 5G WAN interface, packets generated by the end-devices passed through the UE via Network-Address-Translate or Packet-Address-Translate. This is performed by the UE, and although its CPU load was low (20%) throughout the tests, this link contributed significantly to the e2e latency. The average latency here was 1.9 ms and the jitter was 0.8 ms.
- Connection 3 (T_3): There were only a few active devices in this path. Each data link has at least a 10 Gigabit Ethernet connection. Our measurements resulted 2.1 average latency, and less than 0.01 ms jitter regardless of the packet size.
- Connection 4 and 5 (T_4, T_5): Although the eNB and the gNB performs different tasks in this setup, they are physically the same device. While sharing the same link, the eNB/gNB and the EPC were physically quite far from each other (cca. 140km). The connection included a variety of optical tracks, microwave sections, and even gigabit bridges with various active L2-L3 devices. The available data rate over the connection is at least 1 Gbps, average latency was 5.7 ms, jitter was less than 0.9 ms, regardless of packet size.
- End-to-end RTT (T_{RTT}): The average RTT of the different measurement scenarios was 29.8 ms.
- End-to-end 1-way latency (T_0): The average one-way latency from A1 to B is 17.8 ms (on 4G connection).

The latency of the data transmission between the gNB and the UE from the gNB to the UE direction,($TgNB-UE$) can be easily calculated after specifying the required additional measurements, where the latency of the *radio network* can be calculated. It is essential to highlight that these measurements do not include processing delays, but they can are negligible compared to the transmission latencies.

$$T_{gNB-UE} = T_{RTT} - T_0 - T_5 - T_2 \tag{1}$$

$$T_{gNB-UE} = 29.8 - 17.8 - 5.7 - 2.1 = 4.2 \tag{2}$$

The latency between gNB and UE is only an estimate of approximately 4.2 ms, as these latency values come from various sources and methods of measurement. However, such a result is aligned with the expectations and the future use-case requirements of 5G and V2X use-cases.

C. 5G E2E reference RTT results

Independent reference measurements were performed on the network of a large MNO's 5G network in Hungary. In contrast to the M86 NSA 5G network, this architecture provided 5G connection both on the uplink and the downlink channel and there were no additional network elements in the communication path. Therefore, in the case of this measurement setup some distortion aspects was eliminated. Figure 7 presents the e2e RTT results, where the server was connected directly to the SGi interface – this interface is defined between the core network and external networks, for example, Internet access, corporate network access –, while on the client-side, the UE (5G modem) was connected to a 5G macrocell. Table I presents the summarized latency results of these tests. These measurements aimed to show what RTT values can be achieved with the currently available 5G modem on a commercial 5G network. With 40 Bytes packets, 9 ms RTT can be reached stably without any parameter tuning, such as Time Division Duplex ratio tuning. Similarly to the M86 latency results, the median and average increase if the packet length rises even in non-segmented packets (smaller than 1450 Bytes). Also, the latency distribution becomes significantly more spread based on the Q3 and max score.

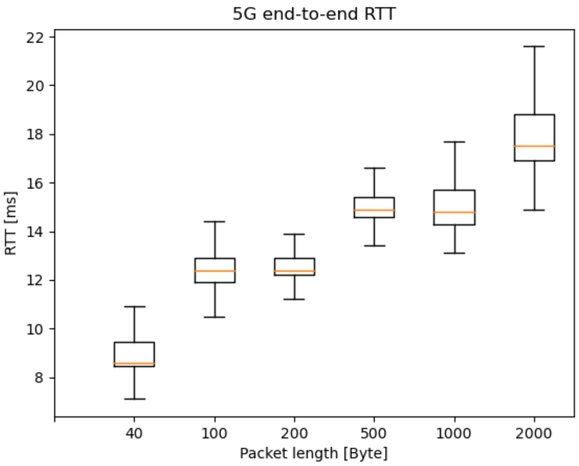

Fig. 7. End-to-end 5G RTT results with different packet lengths

TABLE I
PUBLIC NETWORK STATISTICS OF THE E2E 5G RTT

Packet Length	Minimum	Average	Maximum	Standard deviation
40 Byte	6.958 ms	9.247 ms	25.135 ms	1.486 ms
100 Byte	10.002 ms	12.739 ms	25.796 ms	1.463 ms
200 Byte	10.511 ms	12.837 ms	32.174 ms	1.489 ms
500 Byte	13.095 ms	15.380 ms	34.815 ms	1.560 ms
1000 Byte	13.223 ms	15.470 ms	136.886 ms	3.280 ms
2000 Byte	14.944 ms	18.580 ms	129.536 ms	3.883 ms

VII. CONCLUSION

This paper aims to provide some insights into the current state of 5G deployment characteristics regarding network latency issues in real conditions for V2X use-cases. It introduces the M86 freeway measurement campaign executed in Hungary during June 2020, and presents the results of the 5G network measurement segment. As the main contribution for validating practical 5G capabilities and architectural examinations of the 5G NSA implementation, the paper presented multiple, end-device-originated measurements in a moving vehicle. As network slicing was not possible due to the NSA setup, the end-to-end latency requirements regarding completely optimized 5G setups were not met for all V2X scenarios, mostly because of the 3.X architecture 4G uplink channel. Still, the radio link already shows good results, and even the e2e communication can be used for certain V2X scenarios, such as platooning.

The results are already better than LTE latency performance with QoS Class Identifier preference settings [16]. As expected, 5G RTT increase with greater packet lengths, especially due to packet segmentation over 1450 Bytes. When further examining the current state of public 5G networks – on 5G downlink and uplink channel – and 5G capable modems, reference e2e measurements were performed, and the results are included in this paper. We have received very promising RTT results, as 9 ms RTT was measured with 40 Byte packets, while in the case of 100 and 200 Byte packets, 12-13 ms were possible on average, end-to-end.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contribution and the help of Magyar Telekom for the 5G network connectivity of the measurement campaign.

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