

5G Enabled Cooperative Collision Avoidance: System Design and Field Test

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Abstract—We explore the feasibility of 5G for enhancing cooperative automated driving. A V2X solution for enhancing road safety through connected cars based on 5G radio technology is shown. Based on a flexible, re-configurable software defined radio test-bed, we examine the benefit of ultra low latency and high reliability (URLLC) profile for enhanced emergency brake maneuver. This use case reveals the advantages and additional requirements of using 5G for automated emergency braking based on vehicle-to-vehicle communication. We analyze the impact of communication latency and reliability on the maneuver performance and associated safety aspect. The results provide insights into the joint-design of a V2X communication system for enhancing road safety through cooperative automated driving.

I. INTRODUCTION

Communication between vehicles and road infrastructure systems has been extensively researched during the past decades. State-of-the-art Vehicle-to-X (V2X) communication systems use a dedicated WLAN-based ad-hoc network called IEEE 802.11p [1] for exchanging standardized messages. Despite many advantages such as short latency, well-defined protocol stack and message formats, there are other ITS solutions based on mobile radio. The upcoming 5th generation mobile radio system (5G) [1] for vehicular applications is being investigated to define the requirements for use cases and selected customer functions concerning automated driving [2] [3] and explore the feasibility of 5G for automotive applications. The current paper addresses the communication requirements of cooperative emergency maneuvers to increase safety.

Modern cars are equipped with a multitude of advanced sensors [4] and on-board electronics with fast real-time processing capabilities. Sensors such as Automotive radar, LiDAR, cameras and so forth provide independent measurements that are fused together by specialized on-board Electronic Control Units (ECUs) that fulfill a particular function. An example of such a function is environment perception which builds an environment model of static and moving obstacles and road geometry surrounding the car. These sensor-based systems have proved their value in augmenting vehicle safety, however

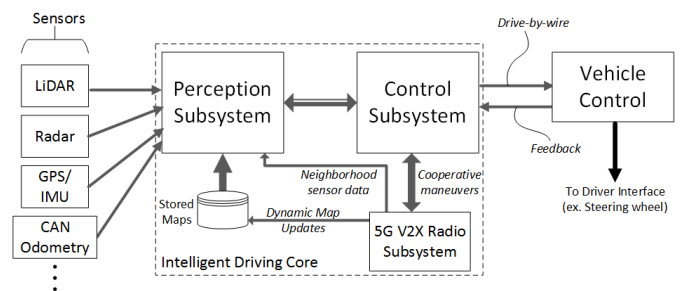


Fig. 1. Intelligent Vehicle System with 5G V2X Radio

they have two serious limitations: 1) they require Line-of-Sight (LOS) conditions to provide good perception and 2) They have poor situation/contextual awareness capabilities. The first drawback is well-known as automotive sensors cannot provide perception in Non-Line-of-Sight (NLOS) scenarios such as blind intersections, obstacles between cars etc. The second drawback is evident in hazardous environmental conditions where specific sensors fail, for example: heavy snow (camera), bright reflections (LiDAR), high-resolution multi-target classification (Radar). 5G radio can alleviate some of these drawbacks by extending the vehicle's environment perception in NLOS scenarios and in inclement weather conditions. Furthermore, the high reliability and low latency of 5G communication promises to enhance vehicle safety by enabling tight cooperation between future automated vehicles.

Together with the perception and control subsystems, the 5G V2X Radio can form an integral part of the future intelligent driving system of automated vehicles [5] as depicted in figure 1.

II. SYSTEM CONFIGURATION

Two 5G radio prototypes have been integrated with the experimental vehicles for studying the mobile communication performance and the cooperated driving performance in the field. One radio prototype features the cellular connectivity over the Uu [6] interface, while the other one features the direct connectivity over the PC5 [6] interface. The integration of

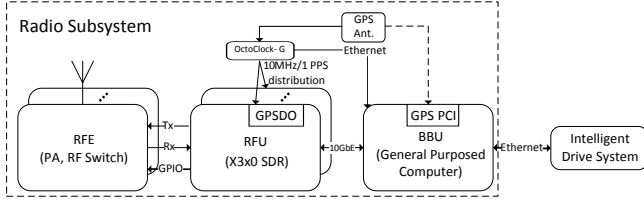


Fig. 2. Overall system design of the flexible radio testbed

both cellular and direct communication embraces the complete configuration of V2X connectivities, including V2N, V2I, V2V and V2P [7].

A. 5G-V2X

Considering these requirements, we selected the following components to build the radio subsystem:

- The NI/Ettus USRP X310 SDR platform as the RF Unit (RFU) with flexible configurations, mature development tool and good community support.
- High performance Intel CPU based PC as the Baseband Unit (BBU) allows for fast real-time processing with minimal programming effort.
- Lightweight linux distribution optimized for run-time performance and stability of the radio software.
- Real-time processing framework implemented using C/C++ with efficiency optimization based on Intel's x86 Single instruction, multiple data (SIMD) features such as AVX/2 and SSE4.
- Algorithm simulation environment in Matlab, which facilitates fast implementation and verification of algorithms and also generates the configuration parameters which are loaded by the above real-time processing framework.
- A self-built RF external (RFE) module with power amplifier and TDD switch for boosting the transmit power up to 20-30dBm and keeping good receiver sensitivity.

It is widely accepted that GNSS-based synchronization is an essential component for V2X particularly in out-of-network coverage scenarios, thanks to its ubiquitous availability and high accuracy [8].

B. 5G-Cellular

5G cellular system (5G-UU) provides good coverage, and it can reduce the cost of V2X application by reusing the available infrastructure of cellular system. To quickly verify the feasibility of various 5G technologies applied to V2X, we design a flexible and configurable prototype as shown in Fig. 3 [9], which greatly increases the development efficiency.

- Flexible cloud baseband processing platform (CBPP) implements the prototype related algorithm with software based on E9000 server. The E9000 server is assembled by 16 blades within one frame, and all the blades communicate through InfiniBand (IB) cards. The CBPP enables fast verification of various 5G-V2X algorithms.

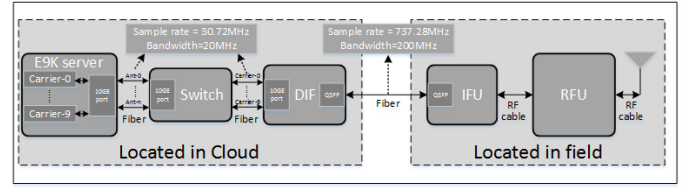


Fig. 3. Overall system design of the configurable cellular base-station

- Configurable hardware architecture mainly includes digital intermediate frequency unit (DIF), mixed-signal intermediate frequency unit (IFU) and radio frequency unit (RFU). The system can be configured to support 200MHz bandwidth with 64 antennas which offers many benefits to V2X application. Larger bandwidth meets the requirements of enhanced mobile broad band (eMBB) scenario, such as transmission of trajectory information and entertainment data, meanwhile, multi-antenna provides better coverage and gets diversity and array gains that is significantly important to ultra-reliability and low-latency communication (URLLC) scenario, such as emergency brake.
- Innovative frame structure is designed to achieve low-latency communication, which lowers the accident risk. The system transmit data based on subframe by time division duplexing, and each subframe includes a 0.5ms down-link and 0.5ms up-link transmission. Also, the prototype is implemented based on optimized real-time Linux core and AVX2 based Intel multi-core processor to improve the computation efficiency.

III. AUTOMATED CARS PLATFORM

The automation of parts of the driving task is nearly as old as the automobile itself. First vehicles with automated control gear were introduced 1940. Today, whole parts of the driving task are automated by advanced driver assistance systems (ADAS) to improve the comfort, safety and efficiency of modern cars [10]. In most cases, the automation handles either the lateral or the longitudinal control. A well-known example is adaptive cruise control (ACC), where the car is guided longitudinally on the lane and keeps a safety distance from vehicles ahead. ACC is classified as a level 1 automation system, based on the definitions of SAE International [11]. The HAVEit-project and its successor adaptIVe are examples of European efforts to investigate conditionally- and highly automated driving functions (autom.-level 3 and 4) [12]. CityMobil2 is an example for projects that study fully automated people movers (autom.-level 5) [13]. It is expected that in the next decades different cars will have different automated driving capabilities (level 0 to 5) and thus form a mixed traffic, until the technology evolve to enable a fully automated traffic system. The cars that participate in mixed traffic can benefit from V2X especially in use cases where cooperative and anticipatory behavior can lead to safer and comfortable driving. As such, V2X technology can be used to

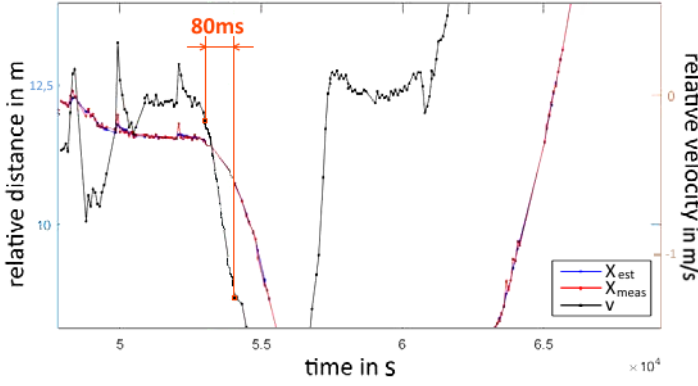


Fig. 4. Timing of sensor-based velocity measurement. X_{est} is the estimated long. distance to the front vehicle (kalman filter), X_{meas} the measured distance, V the calculated relative velocity based on distance over time. When distance drops, there are two measurement points for velocity that have a time distance of around 80ms, because this time is needed for calculation.

communicate obstructions that are beyond the line of sight of an individual vehicle or used to negotiate driving maneuvers between multiple vehicles [14]. 5G is a promising technology that can be used as radio based communication interface for V2X applications.

Since in this paper we aim to compare the performance of the 5G-based communication with sensor based systems, the amount of time for detection of the targets in the environment by the sensor such as LiDAR and Radar has to be considered. As a reference value for the velocity recognition time via LiDAR, a measurement from a test drive with the ACC system that is shipped with our test vehicle is shown in figure 4. In this case, the algorithm already classified the vehicle in front and followed the trajectory closely with a distance of 12m. As shown by the green dotted lines the processing time for the relative velocity with the tested LiDAR system is around 80ms.

The system architecture of a receiving vehicle for the cooperative emergency braking is shown in figure 5. The hardware components embedded in the vehicles are shown as grey colored components, whereas the white colored components present the software programs. The sending vehicle (not shown) had the same configuration, with BISSender and CAMSender accordingly. A 5G radio cell (5G-Cellular) or a device-to-device communication (5G-V2X) connects both vehicles. The 5G communication is accessed via the Radio Base-Band Unit (BBU).

The applications on the car PC's are interconnected via the Dominion framework [17]. This framework provides code generation features coupled with a shared memory (Dominion Data Core), where all registered Dominion applications can access and interchange data. Even applications from other car PC's (see the link between DisplayPC and AutomationPC) can access the shared memory via (UDP-) Ethernet connection.

In case of vehicle 1 the software program *BIS* (Brake Intervention System) accumulates and writes all relevant vehicle state information such as velocity, acceleration etc. in

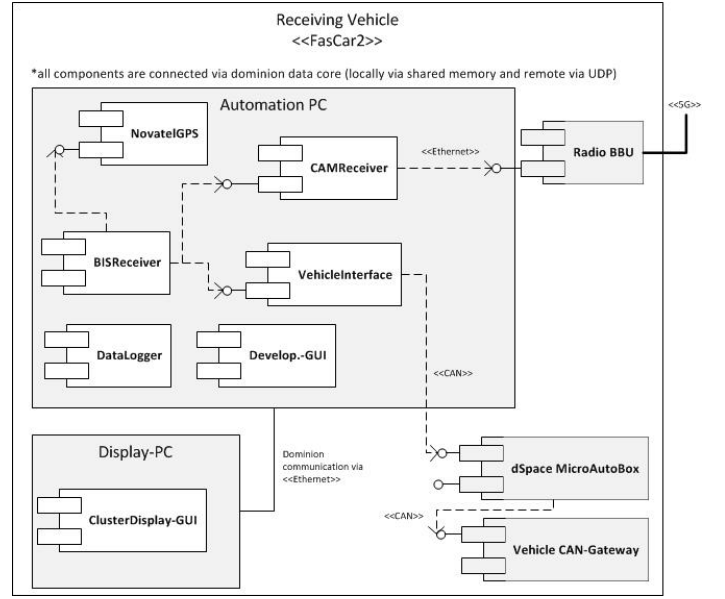


Fig. 5. Hardware and software architecture for the vehicle specific part of the system for 5G-V2X

Dominion shared memory. The software program *CAMSender* then encodes the information into an ETSI CAM message [16] with an additional container for automation specific data (25 bit) via ASN.1. The message packets are sent to the Radio BBU as UDP messages, that are then transferred to Radio BBU on vehicle 2 over 5G radio cell or device-to-device communication. The software program *CAMReceiver* then decodes the ETSI CAM message via ASN.1 and writes the information in Dominion shared memory. The decision about the emergency braking maneuver is made by *BISReceiver* based on the information obtained. The control input of brake pedal position is sent to *dSpace MicroAutoBox*, where the status of the actuators and plausibility of the control input is checked. Finally the control input is sent to vehicle actuators i.e. braking system via CAN for the realization of emergency braking maneuver.

IV. MEASUREMENTS AND RESULTS

A. Simulations

In order to show the effectiveness of the 5G-based communication for cooperative emergency braking scenario in simulation, the Dominion simulation platform was used. The simulation platform includes software programs for the simulation of vehicle dynamics of the ego and target vehicles, software programs for the plausibility and feasibility of control inputs, environment representation and a scenario manager for the definition of the relevant scenario.

The cooperative emergency braking test case comprises a target vehicle(V1) driving on a straight road in a lane with an initial velocity of 50 km/h (see figure 6). The target vehicle is guided by the the underlying traffic simulation. Initially, a second vehicle(V2) is located 1.61m behind V1, drives with same velocity of 50 km/h and is guided by the automation

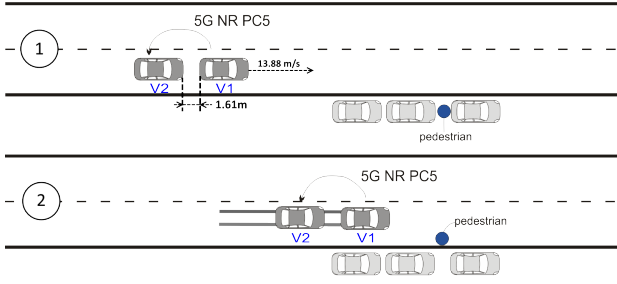


Fig. 6. 5G PC5 enhanced emergency brake simulation setup

system during the emergency braking scenario. Both vehicles are equipped with simulated 5G-V2x communication devices. The simulation of the message transfer between the vehicles with varying latency and package delivery rate (PDR) has been realized by a software program. For the emergency braking scenario presented here, an extended ETSI CAM message with some additional fields such as target velocity, target acceleration along with timing information was used. Initially V2 received CAM messages from V1 with a message rate of 10Hz. The occurrence of an unexpected obstacle (e.g.:pedestrian) triggers a critical situation for V1. V1 starts a collision avoidance maneuver as soon as possible. This critical situation is propagated to the surrounding vehicles and during that the CAM messages are sent with a message rate of 200Hz. Here it should be noted that the default message rate in ETSI standards is 1-10Hz, depending on the traffic situation. Since time and message reception is safety-critical in this setup, increased message rate was used to add redundancy in case messages are lost.

Delays of 0ms, 20ms and 100ms with different Packet Delivery Rates (PDR) of 90% and 100% are injected into the simulation environment. We obtain the speed of V1, V2, the relative velocity and the corresponding distance between the two vehicles against time as shown in figures 7-8. In table I, the final braking distance after the execution of the cooperative collision avoidance maneuver is summarized. By increasing the delay to 100ms and having 90% PDR a collision with the vehicle in front occurs (see distance -0.06m at 90% PDR and 100ms delay). In the test with 0 ms Delay and 100% PDR there is nearly a synchronized braking between the two vehicles as expected. From table I, it is clear that the delay influences the performance of the system more than the PDR.

TABLE I
DISTANCE BETWEEN CARS MEASUREMENTS AFTER COLLISION
AVOIDANCE BREAKING

PDR	Delay		
	0 ms	20 ms	100 ms
100 %	1.38 m	1.18 m	0.45 m
90 %	1.36 m	1.15 m	-0.06 m

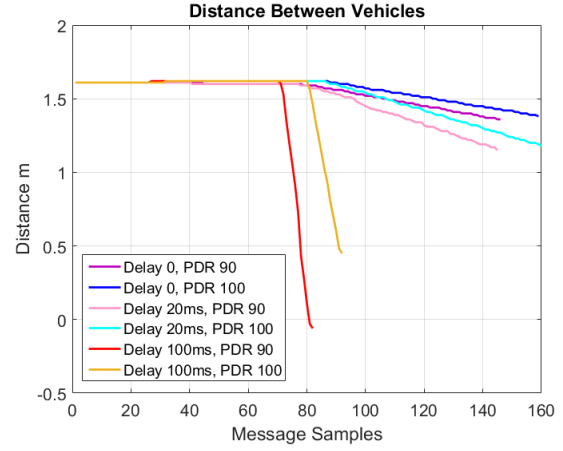


Fig. 7. Distance vs time for different delays and PDR.

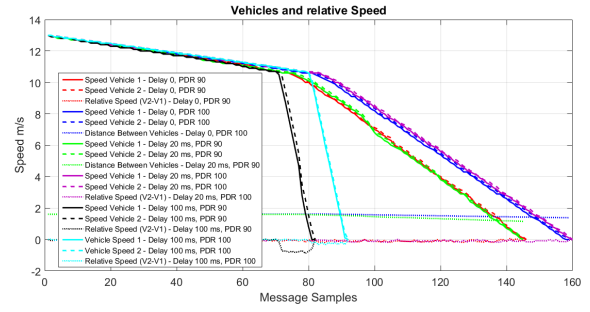


Fig. 8. Velocity vs time for different delays and PDR.

B. Field Test

The objectives of the test drive were to investigate the latency and reliability of the 5G communication in a critical scenario. In the examined scenario, the automation system of one vehicle heavily relied on fast and constant traffic situation updates based on 5G communication to avoid a potential collision with a vulnerable road user (VRU).

1) *Test Setup:* The test drives were executed at a former airport located at the Bundeswehr University of Munich. From the start point, vehicle 1 (V1, right vehicle) and vehicle 2 (V2, left vehicle) accelerated up to 50 km/h (see figure 10). As soon as V1 reached the rear of the first sight obscuration the pedestrian started to cross the track. The driver of V1 manually triggered an emergency brake. The brake pressure information as well as the velocity and the acceleration of V1 was transmitted to V2. In the trials the 5G-V2X communication was used (direct link).The Radio communication setup parameters are summarized in Table II.

2) *Methods:* The one-trip time (OTT), the experienced user throughput (EUT) and the Packet Delivery Rate (PDR) for the communication layer as well as the latencies and packet losses within the automation system were measured to backtrace the complete communication chain and identify major issues in the system. All values are evaluated at the application layer. Other key performance indicators (KPI) were not examined. The

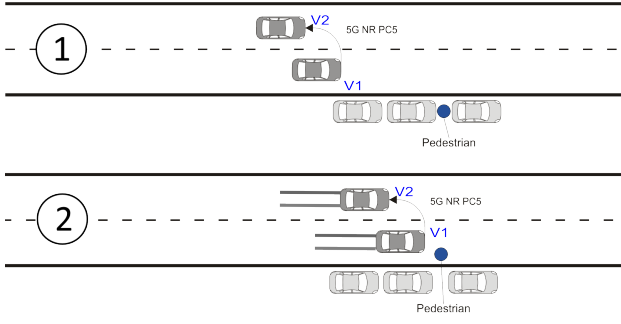


Fig. 9. Parallel driving scenario that was used for the trials in munich.



Fig. 10. Scene taken from the test drive in munich. Left: FASCarE that sends an emergency brake signal to the FASCar2. Right: FASCar2 receives that message and triggers the brake immediately.

traffic volume density for example, is related to the amount of devices connected to the network, the maximum data volume of each of them and the range of the network [15]. This KPI is difficult to evaluate because of the sheer mass of devices that are necessary to produce a realistic traffic scenario, were this KPI could be objectively evaluated.

The OTT is the time span measured between the send time t_1 and the receive time t_2 of the transmission of a data packet from device to device. If a packet was not received, the latency measurement was skipped. Lost packets are separately considered in the PDR calculation.

TABLE II
5G COMMUNICATION PARAMETERS

Carrier Frequency	2.6 GHz
Bandwidth	10 MHz
MCS	QPSK, 1/3
TTI length	0.5ms
FFT size	256
CP length	64
Inter-carrier Spacing	60 KHz
Number of symbols	17
Pilot spacing/Distribution	4 pilot symbols [1 6 12 17]
Waveform	P-OFDM
Transmit Power	8 dBm
Reception mode	Receive Diversity

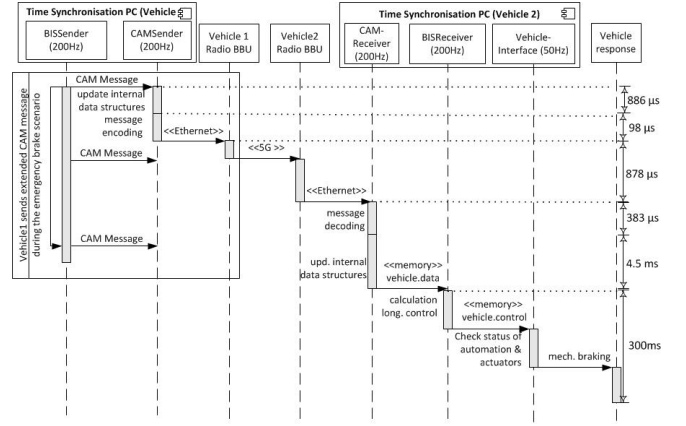


Fig. 11. Communication diagram depicting the flow of information for the vehicle specific part of the system

$$T_{OTT} = \frac{1}{n} \sum_{i=0}^n (t_{i1} - t_{i2}), n \in \mathbb{N} \quad (1)$$

The EUT is described by the relation of the expected size of a packet L and the expected latency for the transmission T_{OTT} .

$$T_h = \frac{L}{T_{OTT}}, \text{ where } L = \frac{1}{n} \sum_{i=0}^n (l_i), n \in \mathbb{N} \quad (2)$$

The PDR was determined by a comparison of each data packet y_i in the set of transmitted packets A to the set of received packets B . This comparison was related to the amount of transmitted packets in one test driver.

$$PDR = \frac{1}{n} \sum_{i=0}^n x_i, x_i = \begin{cases} 0 & y_i \notin A \cap B \\ 1 & y_i \in A \cap B \end{cases}, n \in \mathbb{N} \quad (3)$$

3) *Results:* Figure 11 shows a simplified communication diagram depicting the flow of information between the software programs (running on different Car PC's). In case of critical situations such as emergency braking, the amount of time required for the detection of emergency braking by front vehicle or in this case the message transfer plays an important role. Therefore a detailed analysis of the time required for each of the task based on the vehicle tests is depicted. The timing information shows that the amount of time before V2 starts to brake is of the order of few milliseconds, thus showing a considerable improvement over the sensor based systems.

The latency measurements in figure 11 base on $n = 850$ packets, that were evaluated around the point in time, where an emergency brake was triggered (see figure 12). The frequency of packets was raised from 10 Hz up to 200 Hz as soon as the brake pedal pressure of V1 exceeded a predefined threshold. The most time consuming operation is the transmission of the decoded data from the CAMReceiver to the BISReceiver via shared memory with a mean value of 4.5ms. The mean complete transmission time is around 6.6ms. Figure 12 shows the resulting velocity trend of both vehicles. We have to note

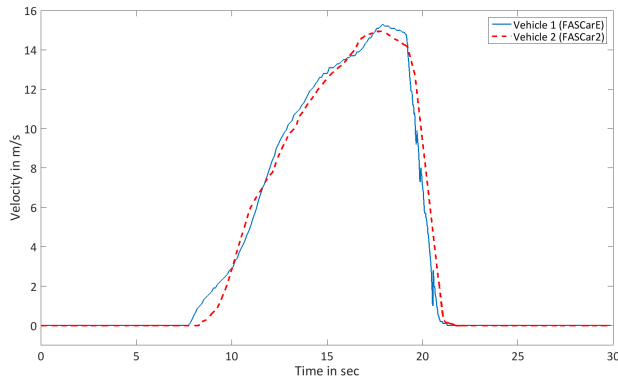


Fig. 12. Velocity trend showing the emergency brake of V1 and V2 in the 5G-V2X test driver.

that a reaction time of around $100ms$ is depicted for V2. This is related to the additional time the mechanical parts of the brakes need to react. Comparing the electrical communication delay to a sensor-based emergency brake recognition system ($> 80ms$), that uses visual or radar sensors to measure the velocity of surrounding vehicles over time, a much faster reaction time for an automated vehicle is possible when 5G communication is available. In the shown scenario, were both vehicles move with $50 km/h$, V2 could apply the brake $1m$ earlier.

For the calculation of the EUT, the OTT between CAM-Sender and CAMReceiver is used. The envelopes for the transmission via 5G are not considered. The calculation is based on a mean packet size of $50 Bytes$ and a mean OTT of $0.878ms$ (see figure 11), resulting in an EUT of $455.58 Kbps$ on average for the 5G-V2X test drive.

For the PDR, 3 packets got lost from EmergencyBrake-Sender to CAMSender, 3 packets between CAMSender and CAMReceiver via 5G and 226 packets between CAMReceiver and EmergencyBrakeReceiver. The high amount of lost packets between CAMReceiver and EmergencyBrakeReceiver is explainable via the high decoding and transmission time relative to the high sample rate of $200 Hz$. If the decoder takes more than $5ms$ (see the mean and std. for CAM decoding in figure 11), a packet will be dropped by the CAMReceiver and not passed to the EmergencyBrakeReceiver. For the 5G-V2X communication a PDR of 0.9965 was calculated ($n=850$, $x=847$).

V. CONCLUSION

We examined first trials with V2X communication via 5G D2D and used it for cooperative automated driving in a critical traffic scenario. Therefore the technique was extensively tested on a test track in munich in December 2016. Beforehand, the impact of latencies and packet delivery rates in safety critical scenarios was evaluated via traffic simulations. We showed that ultra low latency allowed for almost synchronized braking between two vehicles, thereby allowing them to drive with smaller distances between them. This findings are especially important for future projects that will utilize 5G for platoon-

ing scenarios where more cooperation between vehicles and drivers is necessary and decreased safety distances between the vehicles can reduce fuel consumption and optimize the traffic flow.

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