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ITS-G5 and C-V2X Link Level Performance Measurements

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Abstract

Safety-critical ITS applications, as for instance automated urban driving supported by collaborative perception requires a reliable V2X communication link to forward information about detected objects, i.e. vehicles, pedestrians and cyclists, to the automated vehicle. Reliability is given by a low packet error rate over a sufficient communication range and an acceptable latency in the end-to-end communication. The performance of ITS communication might be impaired by different effects, including congestion on the wireless channel, line-of-sight obstruction or fast-fading.

Currently, there are two competing wireless communication technologies proposed for V2X, namely WiFi-based ITS-G5 (or DSRC) and LTE-based Cellular-V2X. A field test using both communication technologies has been conducted in order to test the link level performance between a vehicle and a road-side unit. This paper describes the test setup, the executed experiments, discusses the results and gives first conclusions on the performance of both, ITS-G5 and C-V2X.

Keywords:

ITS-G5, DSRC, C-V2X, link-level performance tests, field tests

Introduction

V2X communication in urban environments might suffer from a sub-optimal performance. This performance drop can be quantified at link-level in terms of an increase of packet errors and an increase in the transmit latency. There are multiple reasons for an increase in packet errors. A blockage of the line-of-sight leads to a decrease in signal strength that causes an incorrect decoding of packets. Reflection and scattering processes lead to multipath propagation, which causes fading that also leads to insufficient signal for correct decoding. Packets are also dropped when channel estimation techniques cannot cope with a highly time variant channel. The concurrent access of many nodes to the same wireless medium leads to interference and packet collisions and also to an increase in the latency due to retransmissions or consecutive access attempts.

For this reason, it might be advantageous to have a supplementary communication technology for V2X in a separate communication channel to use in parallel to the main communication technology. In

Europe, there are currently two candidates for V2X communication being discussed: ITS-G5 and C-V2X.

ITS-G5 is the name of a communication technology standardized by ETSI for Europe and strongly based on IEEE802.11a working outside the context of a Basic Service Set (BSS) and half clocked, meaning that it uses 10MHz channel instead of 20 MHz channels. All data packets are transmitted in broadcast mode. In ITS-G5, the channel access method is the Distributed Coordination Function (DCF) which is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The transmitter senses the channel prior to transmission and only transmits if the channel is not used by another transmitter. If the channel is not idle, a back-off mechanism is performed to reduce the probability of packet collisions. However, in case of short packets and high-level modulation, the CSMA/CA introduces extra overhead in terms of access delay. Moreover, the CSMA/CA mechanism is known to fail at high network densities and thus the probability of packet collisions rises. On the other hand, the E2E delay in ITS-GS under CSMA/CA depends on the CSMA/CA parameters, i.e. Arbitration inter-frame spacing (AIFS), the back-off and sensing threshold.

At the receiver side, a capture effect is implemented. When the receiver is receiving a packet, it continuously monitors the signal strength of other incoming packets. This effect allows the receiver to stop decoding the packet if another packet is detected with higher signal strength. The capture effect mitigates the hidden node problem and improves the reception rate especially at short ranges [1].

Cellular-V2X (C-V2X) is derived from cellular LTE. It was first defined in Releases 14 of the 3GPP in 2017, originating from the device-to-device (D2D) communications of Release 12. Similarly, to the LTE uplink, LTE-V2X relies on single-carrier frequency-division multiple access (SC-FDMA) supporting 10 and 20 MHz channels. Each channel is divided into subframes of 1ms in length and Resource Blocks of 180kHz (12 sub-carriers of 15kHz). Data is transmitted in Transmit Blocks using QPSK or 16-QAM modulation with different possible coding rates. Besides various licensed frequency bands, C-V2X is also intended to operate in the unlicensed ITS band at 5.9GHz. In C-V2X system, each transmitter selects its resources based a semi-persistent scheduling (SPS) mechanism. This mechanism is sensing-based and used to select a sub-channel that is not occupied by another transmitter over a selection window. Neighbouring transmitters are notified that the selected sub-channel will be used in the next transmission to prevent them from using the same sub-channel. The SPS mechanism significantly improves the packet reception probability. However, the SPS mechanism has a fixed resources reselection window of either 20ms or 100ms.

Studies on the co-existence with 802.11-based technologies are currently ongoing. With the sidelink communication interface PC5, C-V2X allows a direct communication between peer nodes. Thereby, two modes are considered: Mode 3 and Mode 4. Mode 3 requires a connection to a base station (Uu link) for the exchange of control information; user data are exchanged via PC5 between peer nodes. Mode 4 allows the exchange of both user data and control information via PC5 between peer nodes. The evolution of C-V2X towards Release 16 based on 5G NR is currently ongoing.

The performance of these technologies has been analysed by simulations in recent publications. In [2],

authors evaluated the link level performance of ITS-G5 and C-V2X in mode 4 for different channel models through simulations. A packet size of 300 bytes, both QPSK $\frac{1}{2}$ and QPSK $\frac{3}{4}$ and different traffic densities were considered for the evaluation. The block error rate (BLER) results showed that C-V2X outperform ITS-G5 due to better channel coding. In [3], the CAM reception rate for platooning scenario showed that C-V2X performs better than ITS-G5. The authors in [4], compared the performance of the two systems and concluded that C-V2X is better in terms of packet error rate (PER). However, their simulations showed that in terms of latency, ITS-G5 has an advantage over C-V2X due to the larger resources access duration of C-V2X. Measurement-based evaluation of C-V2X and ITS-G5 is still scarce in literature as little work has been done so far. Our work is a step toward filling this gap. The authors in [5] compared the performance of the two systems through simulations with different network load, range and packet sizes. Their results showed that ITS-G5 can outperform C-V2X at low network load and short ranges due to the CSMA/CA mechanism at the transmitter side and the capture effect at the receiver side.

In the frame of this work, both ITS-G5 and C-V2X communication technologies have been evaluated in real world field tests to obtain statistical data in order to evaluate the link-level performance of these communication technologies. The following sections describe the test setup and the field tests and discuss the obtained results.

Test Setup

Test Tool

Communication units from the Australian manufacturer Cohda Wireless were used to evaluate the link-level communication performance of ITS-G5 and C-V2X. For ITS-G5, an MK5 on-board unit (OBU) was used. It incorporates a U-blox THEO-P1 module with NXP Semiconductors chipsets. The MK5 implements the full WAVE and ETSI V2X stack for the American and the European market. For C-V2X, Cohda's cellular V2X Evaluation Kit (EVK) MK6c was used. MK6c uses the MDM 9150 chipset developed by Qualcomm. Thanks to the development kit offered by both the MK5 and the MK6c, the user is able to configure different transmission parameters such as transmission power, modulation and coding schemes, payload length and update rate, which allow to test different applications and custom systems. It is important to mention that while the MK5 can be considered a commercial off-the-shelf product with the manufacturer stating that it is "proven ready for large-scale field trials, aftermarket deployments, or to serve as a reference design for automotive production", the MK6c EVK is still in a prototype phase and serves as "a preview of what is to come with the full MK6 OBU".

For the field tests, a test software has been developed to evaluate both communication technologies by generating test packets of variable length and variable update rate. The test packet contains a timestamp, the position, speed and heading of the transmitter and a set of dummy bytes for filling up the packets. The test packets can be either send towards the MK5, MK6c or both communication units.

On the communication units, the ETSI V2X stack including the geo-networking and transport layers is running. The packets are sent directly to the transport layer interface with a reserved transport protocol test port and transmitted by the geo-network layer in single-hop broadcast mode. On the communication units PHY layer parameters, such as the transmit power, the communication channel in the 5.9GHz frequency band and the modulation and coding scheme can be configured.

Test Parameters

The following table shows the test parameters used in the experiments. Transmit power and repetition rate are kept constant over all experiments. The same transmit power of 23dBm is chosen for both communication technologies in order to make the results comparable to each other. The repetition rate of 40 Hz was chosen to sample the wireless channel as often as possible without overloading the communication units. A similar modulation and coding scheme is chosen for both technologies in order to keep the results comparable for both ITS-G5 and C-V2X.

Table 1 - Test Parameters

| PARAMETER | ITS-G5 | C-V2X |
|-------------------|---|-------------------------------|
| TX power | 23dBm | 23dBm |
| Bandwidth | 10 MHz | 10 MHz |
| Modulation / Rate | QPSK, $r=1/2 = 6\text{Mbps}$ | MCS 5: QPSK, $r=0.411$ |
| Message length | 200 Byte, 800 Byte, 1000 Byte | 200 Byte, 800 Byte, 1000 Byte |
| Repetition rate | 40Hz | 40Hz |
| TX Channel | 180 (5895-5905 GHz), 182 (5905-5915 GHz), 184 (5915-5925 GHz) | 184 (5915-5925 GHz) |

Test Metrics

With the ability of logging a message counter, the position of TX and RX and the time of transmission and reception at either end we are able to evaluate the link-level performance in terms of packet error rate (PER) according to the distance and end-to-end delay.

The PER is dominated by additive noise and packet collisions. In ITS-G5, the packet collision is caused by the well-known hidden node problem while in C-V2X mode 4, the packet collisions can be divided into resource-reselection collisions and persistent collisions. The packet error rate is defined as the number of lost packets over the complete number of transmitted packets. Usually, the PER is

measured over a predefined interval of time. In our case, a time window of one second has been chosen.

The End-to-End Latency performance metric is of high importance in V2X communication systems especially in safety-related applications (such as collision avoidance and platooning). The E2E delay is defined as the time required to successfully receive a packet and it includes both the transmission time and channel access delay, the (de)coding/(de)modulation and the time over the air.

Test Field

To evaluate both technologies, a field-test was executed at the shut-down airfield of Edemissen near Braunschweig. The test area is a classic airfield area with a 900m long runway cut out in a 150 m wide fieldstrip. On the southern side of the runways a thick forest exists. On the northern end, half of the runway is 40 m away from the forest while the other half is in open field area. There exists only few medium size buildings 80m away from the centre of the runway in the southern side.

Both the test vehicle and the sensor pole were equipped with the test setup: a host computer running the Hybrid COM test software was connected via Ethernet to an MK5 and an MK6c unit. Additionally, a uBlox LEA 4T GNSS receiver was attached to the host computer to provide timing and localization information. The test vehicle FasCarE had the V2X antennas placed on the roof of the vehicle 1m apart from each other. The antenna cables to the antennas were practically the same for ITS-G5 and C-V2X. At the sensor pole, the road-side unit (RSU) version of the MK5 was directly attached to the upper arm at a height of approx. 2,5m (see Figure 1). The MK5 RSU has the antennas directly attached to the radio unit. The C-V2X antenna was connected to the MK6c by a two-meter RF cable and placed on the sensor pole. It is important to mention, that although the output power of both the MK5 and MK6c was set to 23dBm, this was not validated in advance. The different configuration regarding RF cabling, antenna pattern and antenna gain make direct comparison of received power difficult.



Figure 1 Test vehicle used of the field-tests. DLR's FasCarE, an electric VW Golf, was equipped with both communication technologies and positioning equipment. Right: Close-up of the sensor pole unit used for the field-tests for hybrid communication

Results

End-to-End latency

The left plot in Figure 2 shows the end-to-end latency of both wireless technologies over time, the right plot a cumulative distribution function (CDF) of the end-to-end latency. On average, the latency for ITS-G5 is around 10 ms, while C-V2X has a larger latency of around 25 ms. The larger latency of the C-V2X is mainly due to the fixed resources re-selection window in the Semi-persistent Scheduling (SPS) mechanism. Also, the spread in the latency values is nearly twice as large for C-V2X than for ITS-G5. It can also be seen how for C-V2X the end-to-end latency is doubled in situations when the packet errors increase (compare with Figure 8). This can be due to packet retransmissions in HARQ.

Packet Error Rate

In Figure 3, the PER for ITS-G5 (blue) and C-V2X (red) is plotted over time along with the TX-RX distance (yellow). Since ITS-G5 and C-V2X are operating in different channels and only one Tx-Rx pair is operating in each channel, most packet errors are due to propagation errors associated with low SNR at large distances. Both technologies do not show important errors when the vehicle is moving away from the sensor pole in line-of-sight (LoS) up to a distance of 650m (700s and 1000s). While turning, the first important drops in both C-V2X and later in ITS-G5, occur. These could be related to the antenna pattern. The increased packet drops from 1100s on are due to a blockage of the LoS due to a small building and a forest. While driving away up to 1500s the PER for ITS-G5 is usually below that of C-V2X. This can be an indication that ITS-G5 is slightly more robust in these situations. On the way back, from 1630s on, the PER is more balanced between the technologies. This could also be related to the influence of the antenna pattern.

The high-speed pass in front of the sensor pole with 100km/h at 1770s does not lead to a noticeable increase in the PER. At LoS and short range the communication link with C-V2X is slightly more stable with 0% errors.

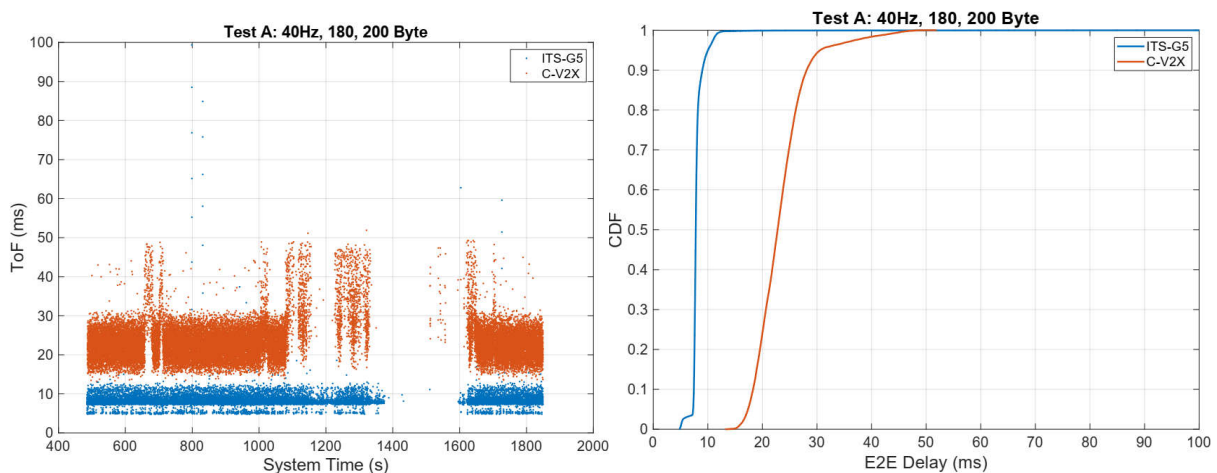


Figure 2 End-to-End latency for ITS-G5 (red) and C-V2X (blue) for the baseline experiment (40 Hz, 180/184, 200 Byte)

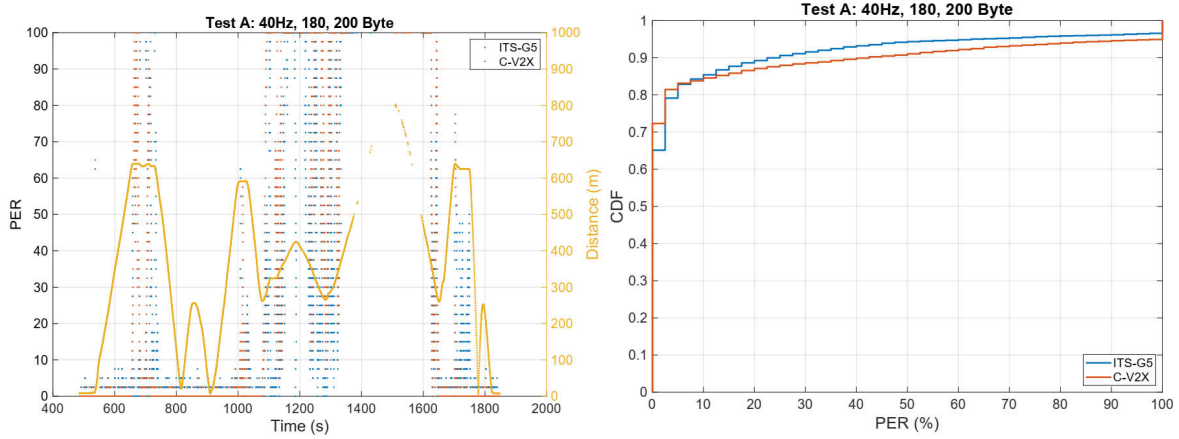


Figure 3 PER for ITS-G5 (red) and C-V2X (blue) for the baseline experiment (40 Hz, 180/184, 200 Byte). In yellow the distance between the vehicle and the RSU is shown.

Co-Channel Interference

In this section, the co- and in-channel interference between both technologies is investigated. The selected communication channel for ITS-G5 at the MK5 is changed from 180 (Test A) to 182 (Test B) and 184 (Test C), while the C-V2X channel is kept at 184.

End-to-End latency

In Figure 4, the E2E-latency over time for test A, B and C are shown for both technologies and the CDF curves for all three tests. To make the different tests statistically comparable using a CDF, an approximately identical section of the drive of around 200s has been cut out of each the tests.

While the delay of ITS-G5 is around 10ms, C-V2X is above 25ms. ITS-G5 does not show any significant difference in the E2E-delay when changing channel and being under the influence of additional communication traffic in the neighbour or even same channel. A clear increase in the E2E delay can be seen for C-V2X when changing from 182 to 184. More often retransmissions occur, independently of the distance, if traffic of ITS-G5 is present in the same channel (Test C).

Packet Error Rate

Similarly, Figure 5 shows the PER for these tests. When changing the channel of ITS-G5 to 182 and 184 an important increase in the PER floor independent of the distance can be observed. Hence, the C-V2X packets on the adjacent- and in-channel, collide with the ITS-G5 packets, causing errors in the decoding process. However, contrary to what would be expected, this PER floor is higher for channel 182 (Test B with approx. 20%) than for 184 (Test B with approx. 12%). This could be explained with returning packet collisions due to the periodic transmission time and the random initialization instant. C-V2X, on the other hand, has a very low PER of nearly 0% when ITS-G5 is on 182, and it increases to 5% when ITS-G5 changes to 184. The behaviour in non-LoS is similar than in Test A, with C-V2X showing packet errors and losing communication earlier than ITS-G5. It has to be mentioned, that the authors did not test the out-of-band emission and the compliance with the spectral mask for C-V2X.

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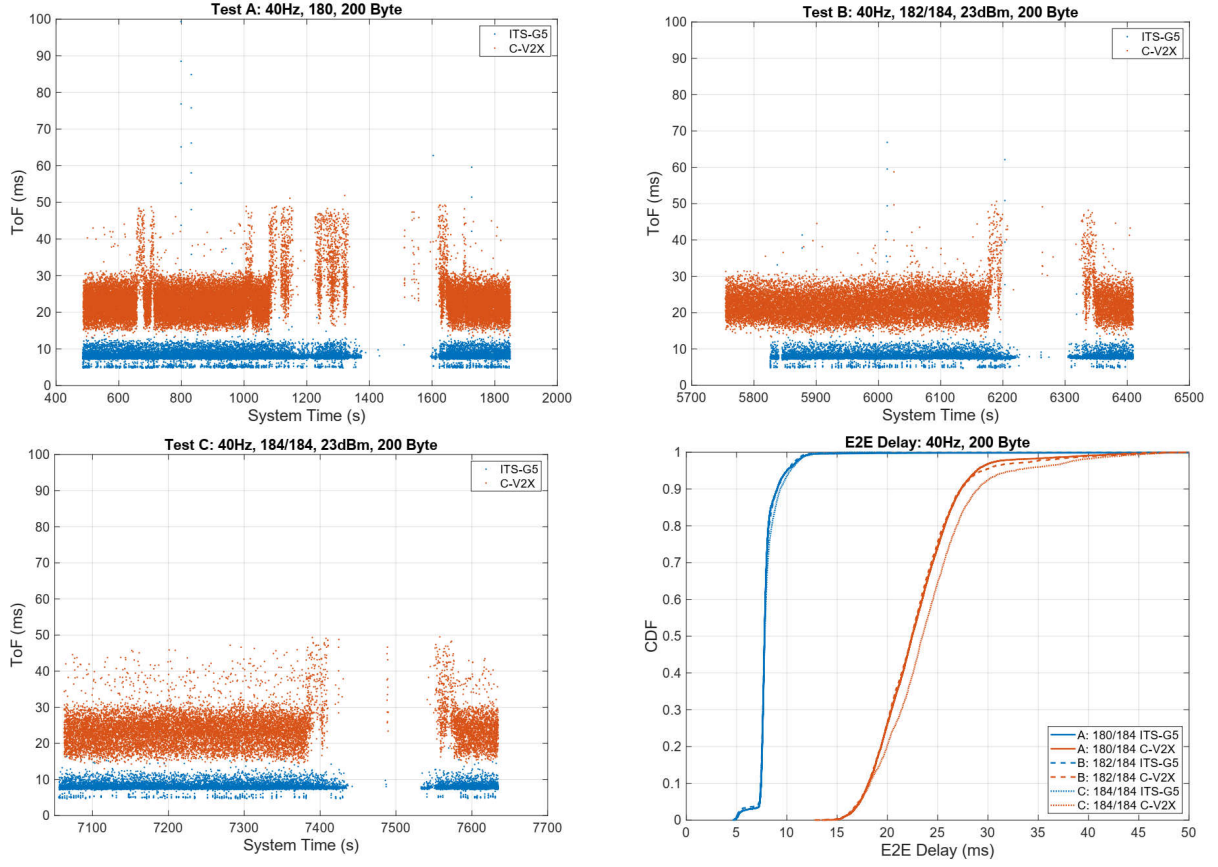


Figure 4 End-to-End latency for ITS-G5 (red) and C-V2X (blue) for the experiments A, B and C.

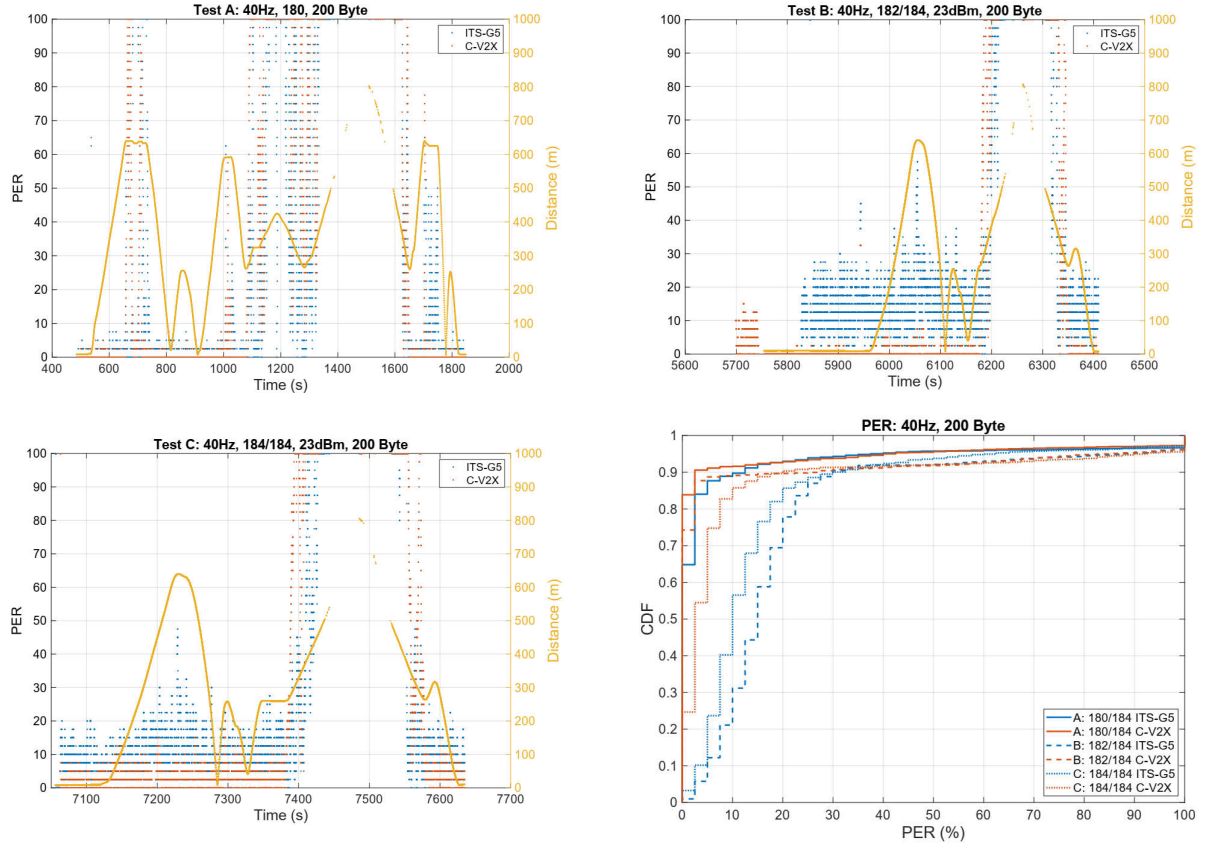


Figure 5 PER for ITS-G5 (red) and C-V2X (blue) for experiments A, B, and C. In yellow the distance between the vehicle and the RSU is shown.

Packet Length

In Test D, the packet length has been increased from 200 Byte in Test A to 800 Byte and in Test E to 1000 Byte while keeping ITS-G5 on channel 180 and C-V2X in channel 184. This length of messages could correspond with the actual length of a MAPEM or collaborative perception message (CPM). Next, the E2E-delay and the PER are analysed for Test D and Test E in comparison to Test A.

End-to-End latency

A clear increase in the E2E-delay for ITS-G5 can be seen in Figure 6 when the length of the messages is increased. The minimum delay of the messages increases from 5 to 8 and 9ms for 800 and 1000 Byte, respectively. This can be explained with the longer coding and decoding and transmission of longer messages. However, 40% of the longer messages need more than 20ms and 30ms. For C-V2X the E2E-delay increases smoothly from 25ms to 40ms and 45ms (1 sigma). The characteristic increase in the E2E delay caused by the HARQ retransmissions at low SNR situations of Test A are not recognized in Test D and E.

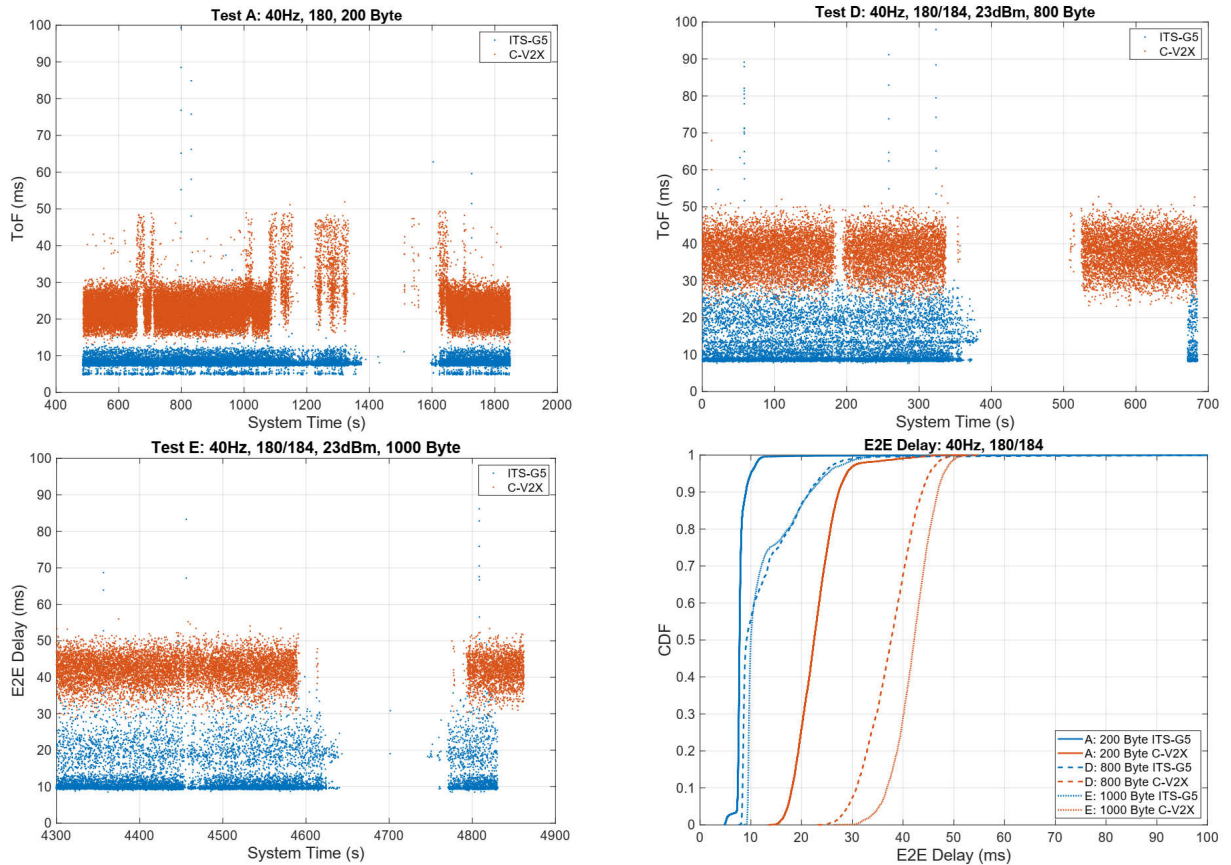


Figure 6 End-to-End latency for ITS-G5 (red) and C-V2X (blue) for the experiments A, D and E.

Packet Error Rate

The PER is shown in Figure 7. For both communication technologies the PER floor increases for larger messages. This can be explained with the increased probability of bit errors leading to a wrong decoding of the message due to insufficient SNR. Longer messages are also stronger affected by a

suboptimal channel estimation in time-variant environments. For long messages C-V2X showed a soon and sharp increase up to 100% PER when moving in the non-LoS section at 3450s and 4590s, in Test D and E, respectively. Looking at the CDF curve, for C-V2X the PER clearly increases from almost 0% (1 sigma) to 10% and 13% (1 sigma) for 800 and 1000 Byte, respectively.

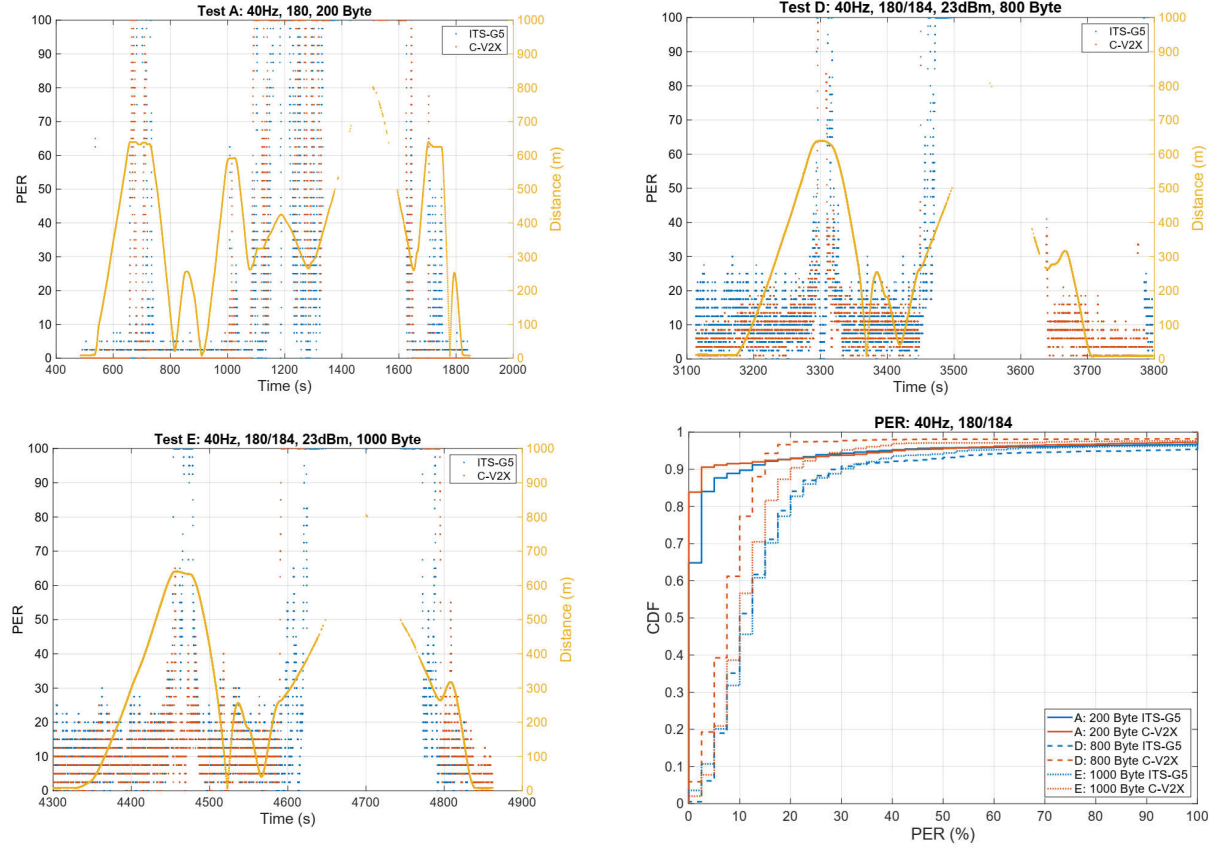


Figure 7 PER for ITS-G5 (red) and C-V2X (blue) for experiments A, D, and E. In yellow, the distance between the vehicle and the RSU is shown.

Conclusions

This paper describes the field tests that have been executed for assessing the link-level performance of ITS-G5 and C-V2X communication. In general, the link-level communication performance without congestion, i.e. interference from other nodes, is in general similar for both technologies. However, we can state the following conclusions from the field test evaluation:

- The E2E-delay is considerably lower for ITS-G5 than for C-V2X using the MK5 and MK6c communication units from Cohda Wireless. For delay sensitive applications it is advisable to switch towards ITS-G5 when using MK5 units.
- At LoS conditions with good SNR long messages were transmitted less reliably (up to 13% PER) than short messages. It is advisable to invest effort in keeping the V2X payloads short or even split payload on two consecutive messages.
- In all tests, an influence of the antenna pattern was experienced when turning the vehicle. This can

lead to important increases of the PER at low SNR regions.

- ITS-G5 suffered stronger (up to 20% PER in LoS) when C-V2X communication was taking place on the adjacent or the same channel. To minimize interference between both technologies we advise to separate both technologies at least 20 MHz apart from each other.

Acknowledgment

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