A Tutorial on the LTE-V2X Direct Communication

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ABSTRACT The concept of direct communications between vehicles and to/from vehicles and roadside infrastructure (vehicle to vehicle and vehicle to infrastructure – V2X) has been around for more than 20 years. With the specification of direct communication in the 3GPP, a new V2X technology has emerged with the global telecommunications specification efforts. This technology, formally known as PC5 Sidelink, but commonly called LTE-V2X (or sometimes C-V2X) is initially based on Release 14 of 3GPP, enabling those long-envisioned use cases to be delivered with a different, mainstreamed radio access technology. This paper summarizes how LTE-V2X works, describes the standard activities in different layers of LTE-V2X protocol stack for US deployment, and showcases the performance of LTE-V2X in variety of real-world driving scenarios.

INDEX TERMS Vehicle-to-everything (V2X), LTE-V2X, DSRC, V2X standardization, vehicle safety communication.

I. INTRODUCTION Vehicle-to-Everything (V2X) communication has enabled the information exchange between vehicles and other nodes and includes Vehicle-to-vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P). This information exchange will provide vehicles and other nodes with a more accurate knowledge of their surrounding environment and can significantly reduce the number of vehicle crashes, thereby reducing the number of associated fatalities [1]. There are collateral benefits of LTE-V2X to include increase the efficiency of traffic flow, reduce environmental impacts, and provide additional traveler information services [2].

To enable V2X communication, two main vehicular communication standards using the specially allocated 5.9 GHz unlicensed band have emerged in recent years: 1) Dedicated Short-Range Communications (DSRC) protocol and 2) Long-Term Evolution (LTE)-V2X. DSRC uses IEEE 802.11p based standards as the underlying wireless communication technology and IEEE 1609 WAVE standards for network layer and security protocols. LTE-V2X is a competing alternative to DSRC and uses the PC5 sidelink interface defined in 3GPP Release 14 and evolved in 3GPP Release 15 as the underlying wireless technology and IEEE 1609 WAVE standards for network layer and security protocols. Two PC5 sidelink modes are available for the LTE-V2X communication (modes 3 and 4). In mode 3, eNBs are needed for centralized resource management, while in mode 4, resource management can be done by the LTE-V2X radios autonomously.

Since PC5 sidelink mode 4 for the LTE-V2X communication enables resource management via the LTE-V2X radios autonomously, it is more suitable for V2X applications as it can operate out of the network coverage. LTE-V2X is designed to have a high link budget and Quality Of Service (QoS). It is also able to address the demands for reliability, high data rate, communication range, and low latency in safety vehicular applications [3], [4], [5]. Furthermore, the PC5 interface has been designed to support the information exchange in a high-speed vehicular network, and support V2X mobility applications [6], [7].

This paper presents an overview of the LTE-V2X that 3GPP developed in Release 14 along with application and security protocols.
deployment standards. The paper also presents field trial results to show the performance of the technology. Specifically, this paper covers several test cases using LTE-V2X-equipped test vehicles to examine performance in a variety of real-world driving scenarios. As part of the test scenarios, the capability of the Release 14 Radio Access Technology (RAT) is also examined in transmitting different packet sizes. Furthermore, results will be presented from field tests that have examined the performance of the RATs in different Line-Of-Sight (LOS) and Non-Line-Of Sight (NLOS) scenarios.

Section II provides an overview of LTE-V2X technology along with its protocol stack reference model. In Section III, LTE-V2X standards activities to enable interoperable US deployment are discussed. To showcase the performance and reliability of LTE-V2X, Section IV provides different field test results for LOS, NLOS, and congested environments. Finally, Section V provides some concluding remarks.

II. OVERVIEW OF LTE-V2X

LTE-V2X is defined in 3GPP Release 14 (and later refined in Release 15) for V2X communication to support cooperative traffic safety, traffic management, and telematics applications using two different LTE air interfaces (namely sidelink PC5 and Uu interface). PC5 enables vehicles and other road users to communicate between themselves and the infrastructure directly using a sidelink, while the Uu interface exploits the existing LTE cellular and emerging 5G infrastructure to exchange data.

PC5 Mode 4 is germane to this safety communication and can operate without the cellular coverage since the UEs autonomously select, manage, and configure the communication resources.

Fig. 1 shows the protocol stack of the LTE-V2X. The access layer is defined by 3GPP Release 14, the network layer is defined by IEEE 1609.3, and the application layer is defined by regional standardization bodies. In the next section, we provide an overview of standardization of different layers as it applies for the US deployment.

III. LTE-V2X STANDARDS ACTIVITIES

There are many Standard Development Organizations (SDOs) working on the LTE-V2X standardization worldwide. In this section, we review standards activities of different LTE-V2X protocol stack layers for a US deployment.

A. 3RD GENERATION PARTNERSHIP PROJECT (3GPP)

In LTE-V2X communication, 3GPP defines the functionality of Layer 1 and Layer 2, while the upper layers and protocols are specified by other Standard Developing Organizations (SDOs) such as SAE (Society of Automotive Engineers). Here, we describe the physical layer and resource allocation for mode 4 defined in 3GPP Release 14.

1) PHYSICAL LAYER

LTE-V2X uses Single Carrier Frequency Division Multiple Access (SC-FDMA) and supports 10 MHz and 20 MHz channels. In the frequency domain, a channel is divided to 180 kHz Resource Blocks (RBs), each corresponding to 12 subcarriers of 15 kHz, and in the time domain the channel is divided into 1 ms subframes. Each subframe has 14 symbols with a normal cyclic prefix. In each subframe, nine symbols are used for data transmission and four of them (3rd, 6th, 9th, and 12th) are used to transmit Demodulation Reference Signals (DMRSs) to improve the performance of the link and combat the Doppler effect at high speed.

A subchannel consists of a group of adjacent RBs in the same subframe and the number of RBs per subchannel can vary and is pre-configured. Subchannels are the minimum units to use for transmission of data and control information. LTE-V2X exchanges the link control information in the form of Sidelink Control Information (SCI) blocks over the Physical Sidelink Control Channel (PSCCH) and transmits data in the form of Transmit Blocks (TBs) over the Physical Sidelink Shared Channel (PSSCH). Each TB has an associated SCI which occupies 2 RBs. SCI is transmitted in the same subframe that its associated TB is transmitted and includes information about the TB such as Modulation and Coding Scheme (MCS), ProSe Per-Packet Priority (PPPP) value, resource reservation interval, and an indication of RBs occupied by the TB. A TB contains a full ITS message packet and occupies one or several subchannels depending on the number of RBs in each subchannel, MCS, and the packet size. With Release 14, TBs can be transmitted using QPSK or 16-QAM, while the SCIs can only be transmitted using QPSK (as it includes critical information for the correct reception of the TB).

There are two possible sub-channelization schemes defined in Release 14: Adjacent PSSCH+PSCCH scheme and Non-adjacent PSSCH+PSCCH scheme [4] (see Fig. 2). In the Adjacent PSSCH+PSCCH scheme (Fig. 2(a)), the TB and its associated SCI are transmitted over adjacent RBs. In the Nonadjacent PSSCH+PSCCH scheme (Fig. 2(b)), the channel is divided into two parts, a reserved part for transmission of
FIGURE 2. LTE-V2X subchannelization. (a) Adjacent PSSCH+PSCCH. (b) Nonadjacent PSSCH+PSCCH.

SCIs and another reserved part for transmission of their associated TBs. It should be noted that Adjacent PSSCH+PSCCH scheme has been chosen for the US deployment.

2) RESOURCE ALLOCATION FOR PC5 MODE 4

In mode 4, a transmitter uses the Sensing-Based Semi-Persistent Scheduling (Sensing-Based SPS) algorithm (see Fig. 3) where the transmitter senses the channel for one second (referred to as Sensing Window) and reserves the selected subchannels (from Selection Window) for the transmission of its following Reselection Counter consecutive TBs. The Reselection Counter depends on the Resource Reservation Interval (RRI) and is a random number between 5 and 15 for the RRI greater than or equal to 100 ms. For RRI equal to 50 ms, the Reselection Counter is a random value between 10 and 30, and for RRI equal to 20 ms, the Reselection Counter is a random value between 25 and 75. After each transmission, the Reselection Counter is decremented by one and when it equals to zero, new subchannels must be selected and reserved with probability of $1 - P$, where $P$ is uniformly distributed between $[0, 0.8]$. In case that the TB does not fit in the reserved subchannels or the reserved subchannels does not satisfy the latency requirement of the TB, a new subchannel must be selected for transmission of the TB.

To decrease the probability of the packet collision, the RRI is included in the associated SCI when a TB is transmitted, which enables the other transceivers to know the occupied subchannels. Figure 3 illustrates the Sensing-Based SPS algorithm in the LTE-V2X MAC layer architecture. To select the subchannels for the TB transmission, the transmitter first makes a list ($L_1$) of Candidate Subframe Resources (CSRs) within the Selection Window $[T; T + n]$, where $T$ corresponds to the packet generation time and $n$ is the maximum tolerable latency, known as Packet Delay Budget (PDB). A CSR is a group of adjacent subchannels within the same subframe that the TB and its associated SCI fits. The $L_1$ list excludes the CSRs that are being utilized by other transmitters. A CSR is considered to be utilized under two conditions: 1) In the Sensing Window, the host transmitter has received an SCI indicating that a remote transmitter is going to use the CSR at the same time the host transmitter will need to transmit any of its following transmission, 2) If the average Reference Signal Received Power (RSRP) measured over the TB associated to the SCI is higher than a threshold. The threshold depends on the priority indicated in the received SCI and the priority of the packet to be transmitted. If the vehicle receives multiple SCIs from an interfering transmitter on a given CSR, it will use the latest received SCI to estimate the average RSRP. The transmitter excludes a CSR from the $L_1$ list, if above conditions are met. For example, in Fig. 3(a), the CSR distinguished with red star is not excluded from $L_1$ list as it does not meet the second condition. Then, the transmitter checks if the number of available CSRs in $L_1$ list is equal to or greater than 20% of all the CSRs within the Selection Window. If it is not the case, the RSRP threshold is increased by 3 dB until the process to determine the available CSRs in $L_1$ list is repeated until the number of available CSRs in the $L_1$ list is at least equal to 20% of the all the CSRs within the Selection Window.

After forming the $L_1$ list, the transmitter creates the $L_2$ list which is a subset of $L_1$ list and contains the CSRs with
the lowest average Received Signal Strength Indicator (RSSI) over the last ten intervals. The number of CSRs in \( L_2 \) list must be exactly 20% of the total number of CSRs in the Selection Window. Finally, the transmitter randomly selects and reserves one CSR from the \( L_2 \) list for the next Reselection Counter transmissions.

To increase the reliability and communication range, LTE-V2X can enable Hybrid Automatic Repeat Request (HARQ). To select and reserve the required CSR for HARQ retransmission, the SPS constitutes \( L_3 \) list which contains the CSR within [SF-15, SF+15] ms interval of \( L_2 \) list, where SF refers to the scheduled subframe for the packet transmission. The transmitter reserves a random CSR from \( L_3 \) list for redundant transmission and maintains it for the next Reselection Counter retransmissions.

## B. IEEE 1609 Working Group (IEEE 1609.3)

IEEE 1609.3 defines the services, operating at the network and transport layers, in support of high-rate, low latency communication between LTE-V2X devices. Generic Internet Protocol version 6 (IPv6) traffic is supported, as well as a specialized WAVE Short Message service. It provides data plane and management plane components corresponding to use of LTE-V2X as the underlying wireless communication technology [8]. It also describes the processing on transmit and receive for both Acknowledged Mode (AM) and Unacknowledged Mode (UM).

## C. Society of Automotive Engineers (SAE) International

SAE International; SAE is a US based SDO. Of the many standards that SAE develops, there are a family of technical committees under the general area of V2X communications. These technical committees define the message sets, profiles, minimum performance criteria, and other parameters and guidelines for V2X technology. Many of the standards in SAE are independent of the underlying radio access technology and pertain to upper parts of the communication stack, but the C-V2X technical committee is focused on configuration parameters and minimum performance of LTE-V2X. The C-V2X technical committee has published three RAT-specific standards that are essential for deployment of LTE-V2X technology: 1) SAE J3161, 2) SAE J3161/1, and 3) SAE J3161/1A.

1) SAE J3161

SAE J3161 provides a reference system architecture based on LTE-V2X technology and addresses the on-board system needs for ensuring the exchange of V2V, V2I, and I2V communications in the LTE band 47 using UARFCN 55140 with a 20 MHz channel width (which corresponds to 5905-5925 MHz). It also describes features unique to LTE-V2X (Mode 4) that can be used by current and future application standards and provides the desired interoperability and data integrity to support the performance of the envisioned safety and mobility applications [9].

In SAE J3161, the V2X traffic is divided into different traffic families based on the priority and direction of the message [9]. The V2X messages are divided into safety and mobility services where safety service messages are those that are used in safety applications and mobility service messages address other ITS functions. Table 1 describes the different traffic families defined in SAE J3161 [9].

As indicated in Table 1, safety services have lower PPPP value (higher priority) than mobility services. Between the safety applications, Critical V2V, V2I, and I2V traffics contains the messages (e.g., critical Basic Safety Message (BSM), Road Safety Message (RSM)) that have higher priority than essential V2V, V2I, and I2V traffic (e.g., BSM, MAP).

Table 2 describes PSSCH transmission parameters for different relative speeds and CBR levels defined in [9]. As indicated in Table 2, for speeds higher than 120 kmph lower MCS indexes are allowed to combat the Doppler effect while for speeds lower than 120 kmph higher MCS values are allowed to get higher spectral efficiency. In SAE J3161 [9], the 20 MHz channel is divided to 10 subchannels where each sub-channel contains 10 PRBs. The document provides a guidance in showing how to select the MCS and number of PRBs for a given packet size.

The document also provides a solution to overcome repetitive packet collisions.

2) SAE J3161/1

SAE J3161/1 addresses the exchange of BSM among V2V applications. The standard aims to provide the minimum radio performance, interoperability, and data integrity needed for the parts to communicate with one another [10].

3) SAE J3161/1A

SAE J3161/1A is a recommended practice document that provides vehicle-level data collection, data analysis, and procedures that may be used to verify that an instrument under test satisfies the vehicle-level requirements specified in SAE J3161/1. The OmniAir Consortium uses this standard as the basis for certification testing, verifying device conformance and interoperability. Two categories of test procedures are defined in the SAE J3161/1A. The first consists of a set of data collection and validation procedures that rely on the transmitted BSMs and the second consists of a set of data collection and validation procedures that test the Radio Frequency (RF) performance requirements [11].

4) SAE J3161/2

As it is mentioned earlier in this article, an LTE-V2X reference system architecture and common design elements for 20 MHz safety channel (e.g., LTE band 47 using UARFCN 55140 with a 20 MHz channel width corresponding to 5905-5925 MHz) is provided in SAE J3161. Additionally, the deployment profile and radio parameters for 10 MHz...
TABLE 1 Different Traffic Families [9]

| Traffic Families | Safety Services | Mobility Services |
|------------------|-----------------|------------------|
| Critical V2V     | Critical V2I - 12V | V2I - 12V |
| Essential V2V    | Essential V2I - 12V | V2I - 12V |
| Traffic Direction|                  |                  |
| Minimum PPPP     | 2               | 100              |
| Minimum PDB (ms) | 3               | 500              |

TABLE 2 PSSCH Transmission Parameters for Different Speeds and CBR Levels Defined in [9]

| Pre-configuration Parameter | CBR | Speed | Comment |
|-----------------------------|-----|-------|---------|
| minMCS-PSSCH-r14            | 0.65| < 0.65| Minimum/MAXimum MCS index that should be used. |
| maxMCS-PSSCH-r14            | 0   | 0     | Minimum/MAXimum number of subchannels which may be used for transmissions of a packet. |
| minSubChannel-NumberPSSCH-r14| 1   | 1     | Indicates the number of allowed HARQ retransmissions. |
| maxSubChannel-NumberPSSCH-r14| 10  | 10    |         |
| allowedRtxNumberPSSCH-r14   | n1  | n1    |         |
| maxTxPower-r14              | 20  | dBm   | Maximum allowed transmission power. |

channel (e.g., LTE band 47 using UARFCN 54990 with a 10 MHz channel width corresponding to 5895-5905 MHz) are needed to be defined to enable current and future applications (e.g., truck platooning, public sector applications, see-through video, short voice). SAE J3161/2 is a work-in-progress in SAE which is going to describe deployment profile and radio parameters for 10 MHz channel (5895-5905 MHz) based on LTE-V2X (mode 4) to support future application standards.

IV. FIELD TRIALS RESULTS

The V2X applications require frequent and reliable connectivity to a large number of surrounding devices. LTE-V2X Release 14 was specifically designed to support large numbers of vehicles sharing a channel to send periodic messages. V2X safety applications depend upon these periodic messages to be able to do their threat assessment from other vehicles. The reliability of these messages under different field conditions and road geometries such as LOS, NLOS and channel congestion is what determines the performance of the V2X applications.

Several field trials have been conducted to assess the performance of LTE-V2X technology and to demonstrate V2X applications. Before examining the results from these field trials, it is important to understand the KPI used to assess the performance of the LTE-V2X technology. Here, five important KPIs are described:

1) Packet Error Rate (PER) — PER is the ratio of the packets not successfully received by the receiver to the number of packets sent by the transmitter. The common application of this KPI in the field, is to plot the PER vs distance between transmitter and receiver to show the distance at which reliable communication is maintained.

2) Communication Range — Reliable communication range is defined as the maximum distance at which PER remains below 10%.

3) Inter-packet Gap (IPG) — IPG is the time between two successively received packets at the receiver from the same transmitter. It is typically measured in milliseconds (ms). This KPI is used to assess successively missed packets at the receiver from a particular transmitter. V2X applications depend upon the periodic reception of the information and too many missed packets in a row from a vehicle can affect the capability of applications to track that vehicle accurately.

4) Channel Busy Ratio (CBR) — CBR is a metric that tracks the LTE-V2X channel utilization and is defined as the amount of subchannels in the previous 100 subframes that experience an average RSSI higher than a preconfigured threshold.

5) Information Age (IA) — IA is a metric used when looking at safety messages and is an indicator of the freshness of the information received. IA represents the time interval, expressed in milliseconds, between the current time at a receiver and the timestamp, applied by the transmitter, corresponding to the data (e.g., position, speed, heading) contained in the most recently received safety message from the transmitter.

LTE-V2X performance has been characterized by many stakeholders (Original Equipment Manufacturers (OEMs), government entities, solution providers) in many parts of the world. In the sections below, we will review selected published results from the comprehensive testing undertaken by Crash Avoidance Metrics Partnership, LLC (CAMP) C-V2X Consortium (Ford, GM, Hyundai, Nissan and Qualcomm) [11].

A. TEST SCENARIOS

We examine results showing LTE-V2X performance under different road geometries, confederate tests on public roads with real world traffic conditions, and performance under congestion. We will start out by stating the high level configuration and setup followed by the results arranged by road geometries and road conditions. Additional details about the test geometry are provided as part of the results.

1) CONTROLLED FIELD TESTING

Tests conducted at the FT Techno of America (FTTA), Fowlerville Proving Ground in Michigan. Tests were conducted with up to 10 V2X units covering the following test geometries:

- V2V
2) MIXED TRAFFIC TESTING
Platoon of 4 vehicles driving on city and state roads in rural and urban environments.

3) CONGESTION TESTING
Offered channel loads representing 260 vehicles in 300 m, emulating 5 lanes of bumper-to-bumper traffic a real-world scenario alongside fast moving High-Occupancy Vehicle (HOV) lane.

B. TEST RESULTS
Here, we describe the results for the field test and emulation test scenarios conducted by CAMP C-V2X Consortium.

1) CONTROLLED FIELD TESTING
Table 3 describes the high level test setup and parameters. Two payloads of 365 and 1400 bytes have been tested in 20 MHz bandwidth. The transmit power is 20 dBm in the test scenarios and transmission rate is 10 Hz. The LTE-V2X modem dynamically picks the MCS and number of sub-channels to use depending upon the size of the message to be transmitted. For the US deployment, the mapping of packet size to MCS and number of sub-channels is specified in SAE J3161/1 [10]. The controlled field test track length is approximately 1400 meters. For each controlled field tests the moving vehicle completed 10 loops of the test track length in order to collect enough data samples for each test. Table 4 describes the modem parameters used for the different packet sizes.

The packet size of 365 bytes represents the maximum size of the BSM with a full certificate attached. BSM is the safety message used by vehicle safety applications in the US and is expected to make up the most of the traffic on the channel. Every fifth BSM will have a full certificate attached. The other four BSM’s will have a certificate digest attached and will be smaller in size. The smaller messages will use a lower Modulation and Coding Scheme (MCS) and the range achieved will be larger compared to the 365 bytes message results shown below. The results for the 1400 bytes message shows the expected performance of the larger messages.

V2V LOS: The setup for the Vehicle-to-Vehicle Line of Sight (V2V LOS) experiment is shown in Fig. 4. Vehicle #31 was the moving vehicle and vehicles #101 and #12 were the stationary vehicles of interest placed at the opposite ends of the test track. The other vehicles are stationary and were also transmitting and receiving messages during the test.

Figure 5 shows the results for the V2V LOS communication range test for both approaching and separating scenarios.
V2V NLOS with Same Lane Blocking: The setup for the Vehicle-to-Vehicle Non-Line of Sight (V2V NLOS) with same lane blocking experiment is shown in Fig. 6. Vehicle #31 was the moving vehicle and vehicles #101 and #12 were the stationary vehicles of interest placed at the opposite ends of the track. Vehicle #101 had a single 26 ft U-Haul truck as the blocker, whilst vehicle #12 had a 26 ft U-Haul and 5 additional vehicles preceding the U-Haul as the blockers. The other vehicles were stationary and were also transmitting receiving messages as well. It should be noted that this is a heavy blocking scenario with approximately 15 ft between the U-Haul and the stationary vehicles. Typically, vehicles maintain 1 to 2 s headway in heavy traffic and much greater than 2 s headway in free flow traffic at 60 mph that would translate to 88 to 176 ft. The range under those circumstances would be greater than the scenario noted below.

Fig. 7 shows the results for the communication range of V2V NLOS with same lane blocking test for both approaching and separating scenarios for Tx/Rx pair of vehicles #31/#12. The communication range was found to be 180 meters for 1400 bytes packets and 200 meters for 365 bytes packets. The difference between the approaching and separating geometries results can be attributed to the radiation pattern of the antenna used for this test.

V2V NLOS with Intersection: The setup to emulate the V2V NLOS with intersection experiment is shown in Fig. 8. Vehicle #31 was the stationary vehicle with two 26 ft U-Haul trucks as blockers, one on each side. Vehicle #101 was the moving vehicles driving perpendicular to vehicle #31 and the blockers. As shown in Fig. 9, the communication range for the V2V NLOS with intersection was found to be 370 meters for 1400 bytes packets and 440 meters for 365 bytes packets for Tx/Rx pair of vehicles #31/#12.

V2V with High Speed at Opposite Direction: The setup to emulate the V2V with high speed at opposite direction is shown in Fig. 10. Vehicle #12 and #31 started at opposite ends of the track and drove toward each other at speeds of 70 mph and 80 mph in successive runs. Other vehicles shown in the test were stationary but were transmitting and receiving LTE-V2X messages. As shown in Fig. 11, the communication range for V2V with high speed at opposite direction was found to be 800 meters for 1400 bytes packets and 1000 meters for 365 bytes packets for Tx/Rx pair of vehicles #31/#12.

V2I LOS: The setup for the Vehicle-to-Infrastructure Line of Sight (V2I LOS) test is the same as the V2V LOS setup (see Fig. 4). As shown in Fig. 12, the communication range for V2I LOS was found to be greater than the available test track length of 1400 m for both 365 and 1400 bytes packets.

V2I NLOS: The setup to emulate the Vehicle-to-Infrastructure Non-Line of Sight (V2I NLOS) scenario is shown in Fig. 13. In this experiment, a 26 ft U-Haul is leading the moving Vehicle #31 as it drives toward the RSU. Once near the RSU, vehicle #31 switched places with the the U-Haul as it drove away. As shown in Fig. 14, the communication range for V2I NLOS is 710 meters for the 1400 bytes packets and 1160 meters for the 365 bytes packets.
2) MIXED TRAFFIC FIELD TESTING

For the mixed traffic field testing, CAMP test teams drove two different platoons of four LTE-V2X equipped vehicles each on complementing routes. The “East Route” represents urban and dense urban characteristics including underpasses, short tunnels and downtown Detroit with medium to heavy traffic. The “West Route” represents semi-rural and rural conditions with light to medium traffic. The goal of this experiment is to gauge the performance of the LTE-V2X radio under different road geometries and traffic conditions. Figure 15 shows the routes driven by the platoons.

The result for the mixed traffic field testing is provided in Table 5. During this experiment, The PER between the vehicles remained at or below 0.05% except for one case where one vehicle got left behind around the corner in NLOS condition. IPG remained at or around 100 ms between the vehicles. The figure below shows the results between the leading vehicle and the last vehicle in the platoon.

3) CONGESTION FIELD TESTING

Traffic congestion is typical in many large cities and can result in many 100’s of vehicles on a section of the road. On an 8 lane highway, with bumper to bumper traffic, we can have approximately 1280 vehicles (assuming average car length of 5 m and 1 m spacing between cars) on 1 km section of the road. Large number of cars will lead to greater RF congestion and we need to be sure the technology can continue to work and provide safety benefits under such conditions as well. Even in such heavy congestion, there can be High Occupancy Vehicles (HOV) lanes or adjacent roadways with free flowing traffic where the technology needs to continue to function. In this

| TABLE 5 V2V Mixed Traffic Testing Results |
|-------------------------------------------|
|                                           |
| East Route                                |
| Total Sent BSM                           | 5880 | 56115 |
| Total Received BSM                       | 58976 | 56101 |
| Failure Count                            | 4    | 14    |
| PER(%)                                    | 0.007 | 0.025 |
| Average IPG(ms)                           | 100.3 | 97.4  |
|                                           |
| West Route                                |
| Total Sent BSM                           | 74417 | 87987 |
| Total Received BSM                       | 74395 | 86915 |
| Failure Count                            | 1072  |
| PER(%)                                    | 0.029 | 1.22  |
| Average IPG(ms)                           | 100.0 | 101.2 |
CAMP undertook a comprehensive evaluation of C-V2X performance under different levels of RF congestion (representing congested roadway scenarios) by varying the density of the LTE-V2X radios and the track length. Alongside the congesting units, there were 8 vehicles under test and two RSU’s placed along the track. Depending upon the test, the vehicles under test were either stationary or moving.

**Congestion Field Test Setup:** The congestion field test is performed with up to 60 devices (50 congestion generation LTE-V2X radios, 8 LTE-V2X equipped vehicles, and 2 RSUs) at FTTA test track in Michigan. The testing involved 50 congesting LTE-V2X units that was set up on 25 mobile pods. Each pod could hold two LTE-V2X units. The LTE-V2X radios on a single pod were set ten feet apart horizontally to represent vehicles in adjacent lanes. Each radio was capable to generate 1x, 2x, or 5x of representative BSM traffic profile. The mobile pods were either placed 12.5 m, 25 m, and 50 m apart representing 300 m, 600 m, and 1200 m track lengths, respectively. Only the units setup on the pods were enabled to generate 1x, 2x, and 5x BSM traffic profiles while the 8 vehicles under the test were never in emulation mode. The high-level test setup is shown in Fig. 16.

**Congestion Field Test Background:** The tests are conducted using the Congestion Control (CC) algorithm specified in SAE J3161/1 [10]. The LTE-V2X units used in the test had the option to either enable congestion control mechanism or to disable it. With congestion control disabled, every vehicle transmits a BSM once every 100 m. Each transmission takes 2 sub-channels. The 20 MHz channel used for the test has 10 sub-channels available in every 1 ms time slot. Hence looking a 100 ms time frequency grid there are 500 non-overlapping BSM transmissions that can be possible. With HARQ enabled, 250 unique equipped vehicles can ideally fill up the channel in non-overlapping fashion at 100 ms transmission cadence. Hence with the 50 units in 1x, 2x and 5x BSM traffic profile mode and 8 equipped vehicles in non emulated mode resulted in 24%, 44% and 104% of available channel capacity.
Congestion Control Algorithm: The premise of CC algorithm is that in a congested environment, vehicles are moving slowly and their movement is less dynamic and hence they do not need to transmit their information at the 100 ms cadence [10]. However, there might be vehicles in an HOV lane, neighboring lane or adjacent roadway that are moving at faster speeds and hence would benefit from more frequent transmission. The standard allows for more frequent transmission based on tracking error, PER estimates, and critical events. Please refer to the standard for more details [10].

At a high level, with congestion control enabled, each vehicle will adjust its BSM transmission interval based on number of vehicles in 100 meters radius. If \( N_s(t) \) is the number of vehicles within 100 m radius, then the Maximum Inter Transmit Time (ITT) can be calculated as follows:

\[
Max_{ITT}(t) = \begin{cases} 
100 \text{ ms} & N_s(t) \leq 25, \\
\frac{100 \text{ ms} \times N_s(t)}{25} & 25 < N_s(t) < 150, \\
600 \text{ ms} & 150 \leq N_s(t).
\end{cases}
\]  

In 2x and 5x emulation mode, the \( N_s(t) \) was adjusted accordingly.

TABLE 6 Congestion Testing Results KPI Summary (Maximum PER and Maximum 95 Percentile IA in 300 Meter Range is Used in This Table)

| Test Scenarios       | CC OFF PER | IA | CC OFF PER | IA |
|----------------------|------------|----|------------|----|
| 5X emulation, 20 mph, 1200m | 30% | 1.1s | <10% | 400 ms |
| 5X emulation, 20 mph, 600m  | 70% | 2.1s | <10% | 900 ms |
| 5X emulation, 80 mph, 600m  | 40% | 1.5s | 10% | 600 ms |
| 5X emulation, 20 mph, 300m  | 70% | 3s  | 10% | 1 s   |
| 5X emulation, 80 mph, 300m  | 80% | 4s  | 10% | 1 s   |

Congestion Test Results: Results from 32 tests with different combinations of vehicle densities, track length, congestion control enabled/disabled, speed, critical event scenarios are documented in [12]. A video of how the tests were executed can be found at CAMP website [13].

A very high level summary of the results is shown in the Table 6. The results show that with congestion control enabled, for vehicles within 300 meters, the PER remains at or below 10% and 95% of IA remains at or below 1 s.

V. CONCLUSION

We presented an exhaustive overview of the LTE-V2X that 3GPP developed in Release 14 along with the application and deployment standards for US deployment. We described some functionalists of Layer 1 and Layer 2 along with radio profile and application layer standardization by SAE. We also presented extensive field trial results to showcase the maturity and performance of the LTE-V2X technology. Emulation and field test results show that the LTE-V2X is a reliable technology to enable safety and mobility applications. The results show that the V2V communication range for BSM can be as high as 1100 meters and the V2I communication in LOS scenario can be at least 1400 meters. Also, we presented that with congestion control enabled, for vehicles within 300 meters, the PER remains at or below 10% and 95% of IA remains at or below 1 s.
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