DSRC Versus LTE-V2X: Empirical Performance Analysis of Direct Vehicular Communication Technologies

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***Abstract*— Vehicle-to-Vehicle (V2V) communication systems have an eminence potential to improve road safety and optimize traffic flow by broadcasting Basic Safety Messages (BSMs). Dedicated Short-Range Communication (DSRC) and LTE Vehicle-to-Everything (V2X) are two candidate technologies to enable V2V communication. DSRC relies on the IEEE 802.11p standard for its PHY and MAC layer while LTE-V2X is based on 3GPP's Release 14 and operates in a distributed manner in the absence of cellular infrastructure. There has been considerable debate over the relative advantages and disadvantages of DSRC and LTE-V2X, aiming to answer the fundamental question of which technology is most effective in real-world scenarios for various road safety and traffic efficiency applications. In this paper, we present a comprehensive survey of these two technologies (i.e., DSRC and LTE-V2X) and related works. More specifically, we study the PHY and MAC layer of both technologies in the survey study and compare the PHY layer performance using a variety of field tests. First, we provide a summary of each technology and highlight the limitations of each in supporting V2X applications. Then, we examine their performance based on different metrics.**

***Index Terms*— Dedicated short range communication, LTE-vehicle to everything communication, vehicular ad hoc network, vehicular safety communication.**

I. INTRODUCTION

THE advent of the Vehicle-to-Everything (V2X) communication technologies has enabled the information exchange among traffic nodes; wherein, vehicles, infrastructure, and pedestrians can communicate crucial information, which can lead to a higher level of situational awareness among road users. In 1999, the United Federal Communications Commission (FCC) allocated 75 MHz on the 5.9 GHz band to Intelligent Transportation Systems (ITS) applications to enhance road safety, traffic flow efficiency, passenger infotainment, and manufacturer services [1], [2], [3]. The United States Department of Transportation (US-DOT) has developed a Connected Vehicle Reference Architecture (CVRA) to supervise the deployment of the V2X components. In CVRA, wireless communication technology is the essential component, which directly affects the implementation, performance, reliability, and inter-operation of the transportation applications. Currently, there are two wireless communication technologies to enable the V2X: 1) Dedicated Short Range Communication (DSRC) and 2) LTE-based Vehicle-to-Everything (V2X).

DSRC is a mature Radio Access Technology (RAT) which is developed for automotive and ITS applications via the short-range exchange of state information among the units. The exchanged safety information is known as Basic Safety Messages (BSM) that include vehicle speed, position, and heading information, etc. The DSRC system is based on a series of Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) International standards [4]. The IEEE 802.11p protocol specifies the physical, and the Medium Access Control (MAC) layers architecture of DSRC, which simplifies authentication, associated processes, and data transmission before sending data, and enables the vehicles to broadcast relevant security information directly to neighboring units. The DSRC uses IEEE 1609/Wireless Access in Vehicular Environments (WAVE) standard to define the network architecture and security protocols [5]. Also, developers employ the SAE J2735 standard to develop the application layer of the DSRC-based vehicular network [6], [7]. In addition to BSMs that are standardized and used in U.S., at European level Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) have been defined by European Telecommunications Standards Institute (ETSI) to support the implementation and deployment of Cooperative Intelligent Transport Systems (C-ITS) [8]

LTE-V2X is a competing alternative to DSRC that has been introduced by the 3rd Generation Partnership Project (3GPP) organization. The deployment of data-intensive applications along with the recent advancement in cellular network technology has motivated research communities to investigate LTE-V2X communication capabilities for V2X applications. LTE-V2X is based on 3GPP Release 14 and uses two different interfaces (namely *Uu* and PC5 interface) to enable the V2X communication. *Uu* interface exploits the existing Long Term Evolution (LTE) cellular infrastructure to exchange data among the vehicles, and *PC5* interface enables the vehicles to communicate using a sidelink. Two sidelink modes are

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available for the LTE based vehicular communication: modes 3 and 4. In mode 3, centralized resource management is implemented in the LTE base-stations, while in mode 4, radios can manage the resources independently. The PC5-mode 4 decentralized resource management technique makes this technology suitable for connected vehicle safety applications [1], [9], [10], [11]. The LTE-V2X is designed for a better link budget, compared to DSRC, and controlled Quality Of Service (QoS), which is based on the evolution of LTE, to address the demands for high reliability, high data rate/longer communication range and low latency in advanced vehicular applications [9], [11], [12], [13]. Furthermore, the PC5 interface has been enhanced in many aspects to support the rapid information exchanges in a high-speed vehicular network, and support advanced V2X services (e.g., automatic driving, vehicle platooning, sensor sharing) [14], [15].

DSRC was designed primarily to support the safety application using ITS band. To meet the high data traffic demands for in-vehicle internet access, Internet of Things (IoT), the allocated ITS band by FCC is not sufficient. On the other hand, the LTE-V2X *Uu* interface centralized nature (which is designed to support high-speed mobility environment) limits its ability to support low-latency V2V communications in the absence of cellular towers, and can jeopardize the effectiveness of safety applications. Compared to DSRC, LTE-V2X is relatively new, and its capabilities have not been examined to the same level as DSRC. The comparison between these technologies has not entirely been conducted, and there has been considerable debate over the relative advantages and disadvantages of using DSRC vs. LTE-V2X. Consequently, it is essential to explore the different aspects of these two existing RATs and compare their performances in a variety of scenarios. There're also studies emerging regarding the 5G New Radio (NR) V2X [16] which goes deep in theoretical aspect of NR-V2X and its differences with LTE-V2X.

In this article, we present a comprehensive comparison between two available solutions for a vehicular network–DSRC and LTE-V2X– using a detailed and extensive study on their physical and MAC layers architectures. We discuss how DSRC and LTE-V2X process data in the physical layer and compete for the medium in the MAC layer in the survey study. In addition to literature review, we conduct several test cases using five connectivity equipped test vehicles to evaluate the RATs reliability performances in a variety of real driving scenarios. To assess the RATs performances in terms of reliability, we accomplished various communication range tests. We also examine the capability of each RAT in transmitting data with different packet sizes. Furthermore, we conduct numerous field-tests that aim to examine the performance of the RATs in different Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) channel scenarios. We investigate each RAT with different radio configurations, including packet size, and spatial diversity, and utilized bandwidth, using different blocker vehicles.

Section II reviews the physical layer and MAC layer of DSRC and LTE-V2X, and discusses further improvements of next generation of V2X communication technologies. Section III reviews the different safety applications in Connected Vehicles (CVs) and their requirements on reliability, latency, and data rate. It also presents the advanced vehicular application of V2V communication and briefly explains the demands on the communication link. Section IV presents a comprehensive review of the existing performance analysis and comparison between DSRC and LTE-V2X in literature, and discusses the test parameters and metrics, test equipment specifications, and the test scenarios. In addition, this section presents a theoretical analysis of required LTE-V2X Signal to Interference Noise Ratio (SINR) at different Modulation and Coding Schemes (MCS) intended to support the empirical results. Section V presents and discusses the results of the field-test. Finally, Section VI concludes the article. Note that all the Cellular-based V2X experimental results conducted in this paper are based on LTE-V2X technology.

II. TECHNOLOGY OVERVIEW

To make roads safer, developing RATs that enable reliable and low latency vehicular communications has become of paramount importance. DSRC and LTE-V2X are two present-day technologies that are capable of supporting day-1 vehicular applications (that satisfy basic safety needs). In this section, we detail the DSRC and LTE-V2X RATs specification, protocol design in the physical and MAC layers.

A. Dedicated Short Range Communication –DSRC

DSRC is a Wireless Local Area Network (WLAN)-based communication protocol that enables Connected Vehicles (CVs) in ITS applications. This protocol operates based on the IEEE 802.11p standard, which is a part of the Wireless Access in Vehicular Environments (WAVE) protocol in the U.S. and uses the 75-MHz spectrum between 5.850 and 5.925 GHz [17], [18]. To fulfill the mobility requirement of a CV, compared to IEEE 802.11a, IEEE 802.11p has halved bandwidth (10 MHz), while it is doubled in time-domain [19], [20]. Due to the broadcast-based nature of IEEE 802.11p, DSRC does not return acknowledgement frames. Hence, to avoid large contention window sizes and high latency, the IEEE 802.11p contention-based MAC protocol benefits from a fixed contention window, instead of exponential back-off time [17], [21], [22].

DSRC's proven performance in safety applications and the availability of DSRC devices have pushed major automakers toward deployment on their vehicle fleets [17], [23]. To address these concerns, in 2018, a new study group formed to develop the next generation of standards (such as the IEEE 802.11bd), which aim to improve in throughput and operational modes of next-generation DSRC technology. According to the IEEE Task Group 802.11bd (TGbd), backward compatibility will enable 802.11p and 802.11bd devices to communicate with each other in the same operational channel [22], [24].

1) DSRC Physical Layer: The implemented physical layer (referred to as PHY) architecture in the IEEE 802.11p standard is derived from IEEE 802.11a by reducing the sub-carrier spacing with a factor of two [17], [20], [25]. Due to the high-speed mobility nature of the vehicular network, the

TABLE I
SUMMARY OF ACRONYMS

Acronym	Term
BCC	Binary Convolutional Code
BLER	Block Error Rate
BSM	Basic Safety Message
BSW/LCW	Blind Spot Warning/Lane Change Warning
CAM	Cooperative Awareness Message
CAMP	Crash Avoidance Metrics Partnership
CBP	Channel Busy Percentage
CBR	Channel Busy Ration
CC	Conventional Code
CLW	Control Loss Warning
CR	Channel occupancy Ratio
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSR	Candidate Single sub-frame Resources
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
CVRA	Connected Vehicle Reference Architecture
DCF	Distributed Coordination Function
DMRS	Demodulation Reference Signal
DSRC	Dedicated Short-Range Communication
EDCA	Enhanced Distribution Channel Access
EEBL	Emergency Electronic Brake Lights
FCC	Federal Communications Commission
FCW	Forward Crash Warning
FEC	Forward Error Correction
HV	Host Vehicle
IMA	Intersection Movement Assist
ITS	Intelligent Transportation System
ITT	Inter-Transmit Time
LDPC	Low-Density Parity Check Code
LOS	Line of Sight
LTA	Left Turn Assist
LTE	Long Term Evolution
LTE-D2D	LTE Device-to-Device
MCS	Modulation and Coding Scheme
NLOS	Non Line of Sight
OBU	On-Board Unit
OCB	Outside the Context of a Basic Service Set
OFDM	Orthogonal Frequency Division Multiple Access
OLOS	Obstructed Line of Sight
PDR	Packet Delivery Rate
PER	Packet Error Rate
PSCCH	Physical Sidelink Control Channel
PSSCH	Physical Sidelink Shared Channel
QoS	Quality Of Service
RAT	Radio Access Technology
RB	Resource Block
RP	Radiation Power
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
RSU	Road Side Unit
SB-SPS	Sensing-Based Semi-Persistence Scheduling
SCI	Sidelink Control Information
SINR	Signal to Interference Noise Ratio
SS	Service Set
SUPRA	Stateful Utilization-based Power Adaptation
TB	Transmit Block
TC	Turbo Coding
US-DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VSCC	Vehicle Safety Consortium Communications
WAVE	Wireless Access in Vehicular Environment

lessened sub-carrier spacing of IEEE 802.11p makes the DSRC communication link delicate to the doppler spread effect shift error, while doubled symbol duration time enhances the link to multipath effect of the channel. Thus, there exists a trade-off between robustness of the link to the multi-path fading imposed inter symbol interference and relative doppler spread shift error [22]. Table II represents an overview of the delay and doppler spread measures of a V2V communication channel in a variety of channel scenarios [26], [27].

Table III represents the PHY layer specifications of the IEEE 802.11p communication link, in comparison with IEEE 802.11a [20]. The IEEE 802.11p offers eight possible combinations of Modulation and Coding Scheme (MCS) for the PHY layer. However, in practice, a data rate of 6 Mbps [7] is used for DSRC communication. Table IV presents a summary of MCS indexes and the corresponding coding rate and modulation [17].

2) DSRC MAC Layer: The Medium Access Control (MAC) layer architecture of IEEE 802.11p is based on the Outside the Context of a Basic Service Set (OCB) operation mode, where nodes can send and receive data, and control frames without the need for forming or being in a Service Set (SS) [19], [30]. The IEEE 802.11p incorporates the Distributed Coordination Function (DCF) in its radio resource allocation procedure. The DCF is a MAC technique, which employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol with a binary back-off algorithm. Compared to IEEE 802.11a, in an IEEE 802.11p based network, radio units compete for medium using the CSMA/CA protocol using a fixed back-off time and the contention window parameters [22]. As explained previously, exponential back-off time of contention window in IEEE 802.11a may result in a large latency in message transmission, which is not suitable for a vehicular network; hence, a fixed back-off time in CSMA/CA of DSRC enables us to limit the data transmission latency with the cost of network low scalability. The Enhanced Distribution Channel Access (EDCA) is a DCF based MAC technique that aims to address the scalability challenge in DSRC. In the EDCA approach, high-priority messages have a greater likelihood to be sent than the low-priority messages [19], [30].

In a CSMA/CA based MAC protocol, there are two significant effects that impact the packet collision rate and the system performance: *Hidden terminal effect* and *Capture effect*. In the *hidden terminal* scenario, two terminals might be out of the reciprocal sensing range of each other, and if they are both transmitting to the same destination using the same channel, packet collision will occur in the destination node. In a hidden terminal scenario, the *capture effect* happens if the power level of a signal, in the destination node, is sufficiently higher than the other signals. In this scenario, the message can be decoded correctly [17], [21]. In DSRC, the hidden terminal problem of CSMA/CA protocol may result in excessive packet collision rate and degrades the DSRC based network scalability [2], [31]. To improve the DSRC network scalability, in [32], authors represent an approach that controls the transmission power and rate of the DSRC message. Based on this principle, under an optimal protocol, the vehicles should adapt their transmitting rate and power in such a way that minimizes the tracking error for better safety performance [22], [33], [34].

Although, assessments on DSRC performance confirm its reliability for vehicular safety applications, the absence of a plan for the next generation of standard holds back industries

TABLE II

VEHICLULAR COMMUNICATION CHANNEL MODEL CHARACTERISTICS

V2C channel scenario	Pathloss Component	Mean RMS Delay Spread	Doppler Spread
Highway	1.8-1.9	40-400 ns	100 HZ (Up to 1 kHz)
Rural	1.8-1.9 (4 for 220 m break point and beyond)	20-60 ns	100 HZ (782 Hz [28])
Suburban	2-2.1 (4 for 100 m break point and beyond)	104 ns	Doppler shift is proportional to the relative velocity, but no Doppler spreading [29]
Urban	1.6-1.7	40-300 ns	30-350 Hz

TABLE III

COMPARISON OF THE IEEE 802.11P AND 802.11A PHY LAYER SPECIFICATIONS

Parameter	IEEE 802.11a	IEEE 802.11p	Changes
Sampling Frequency	20 MHz	10 MHz	Halved
Bit rate (Mbit/s)	6, 9, 12 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	Halved
Modulation mode	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM	None
Forward error coding	CC	CC	None
FFFT size (N_{FFT})	64 (3.2 μs)	64 (6.4 μs)	None (doubled)
Coding rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	None
Number of subcarrier	52	52	None
Symbol duration (T_s)	4 μs	8 μs	Doubled
Cyclic Prefix size (N_{cp})	16	16	None
Preamble duration	16 μs	32 μs	Doubled
Guard time	0.8 μs	1.6 μs	Doubled
Subcarrier spacing	312.50 kHz	156.25 kHz	Halved
Transmission power	Up to 24 dBm	23 dBm	-

TABLE IV

IEEE 802.11P MCSS AND THE CORRESPONDING CODING RATES, DATA RATES, AND PACKET DURATIONS

MCS (Mode)	Modulation	Coding rate	$R^{(11p)}$	t_{pk}
1	BPSK	1/2	3.0 Mbps	537μs
2	BPSK	3/4	4.5 Mbps	396μs
3	QPSK	1/2	6.0 Mbps	307μs
4	QPSK	3/4	9.0 Mbps	218μs
5	16-QAM	1/2	12.0 Mbps	173μs
6	16-QAM	3/4	18.0 Mbps	129μs
7	64-QAM	2/3	24.0 Mbps	107μs
8	64-QAM	3/4	27.0 Mbps	99μs

to rely on it for advanced vehicular applications. In 2018, the IEEE 802.11 Next Generation V2X study group was formed to work on the next generation of the standard of DSRC. In [17], [22], the authors presented a comprehensive review of the next version of DSRC technology and compared it with the current one. Table V highlights the improvements in DSRC PHY and MAC layer.

B. LTE-Based V2X

TABLE V

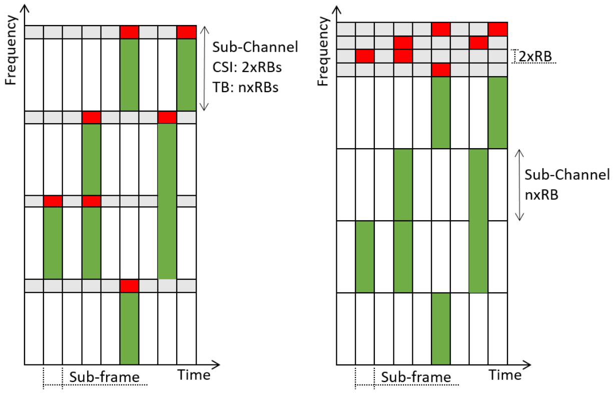
COMPARISON OF DSRC NEXT GENERATION (802.11P) AND 802.11G

Feature	802.11p	802.11bd
Radio bands of operation	5.9 GHz	5.9 GHz & 60 GHz
Channel coding	BCC	LDPC
Re-transmissions	none	congestion dependent
Countermeasures against Doppler shift	none	midambles
Sub-carrier spacing	156.25 kHz	312.5 kHz, 156.25 kHz, 78.125 kHz
Supported relative speeds	252 kmph	500 kmph
Spatial streams	1	multiple

The 3rd Generation Partnership Project organization (3GPP), by introducing the LTE sidelink in Rel. 12 for Device-to-Device (D2D) communication, endorsed LTE as an alternative solution for vehicular communication. 3GPP enhanced LTE-D2D in Rel. 13 and announced LTE-V2X in Rel. 14 especially for V2V application. The LTE-V2X orthogonal resources architecture enables higher multiplexing and results in higher reliability and capacity of the communication link, though the complexity of the hardware design and the requirement for fine synchronization among devices are concerns for LTE-V2X deployment [35]. The LTE-V2X standard includes two radio interfaces: 1) the cellular interface (referred to as *Uu*), which supports V2I communications, and 2) the PC5 interface, which supports V2V communications based on the direct LTE sidelink. Since the safety applications cannot rely on the accessibility of the cellular towers, *mode 4* has been adopted as the mode of choice for LTE-V2X in the United States [9], [36], [37].

1) LTE-V2X Physical Layer: To maintain the communication link quality in a variety of network topology and conditions, and also optimize the radio resource utilization efficiency, LTE-V2X uses a variable MCS in its PHY layer architecture. By allocating more Resource Blocks (RBs) (in time-domain and frequency-domain) to each radio unit under low-density network circumstances, LTE-V2X assures the communication link quality for more considerable distances. In contrast, in congested networks, by adopting the MCS with higher coding rates, the intended design of LTE-V2X enables more units to communicate data, while reducing the communication range [38], [39], [40].

Similar to DSRC, PC5 utilizes the ITS 5.9 GHz band to communicate vehicle information. The bandwidth of the link can be either 10 MHz or 20 MHz, with 1 μs sub-frame duration and 180 kHz bandwidth of each RB. In the LTE-V2X protocol architecture, a sub-channel is a group of the RBs in the same sub-frame. LTE-V2X transmits data in the form of Transport Blocks (TB)s over the Physical Sidelink Shared Channel (PSSCH) and exchanges the link control information in the form of Sidelink Control Information (SCI) blocks over the Physical Sidelink Control Channel (PSCCH). An SCI



(a) (b)

Fig. 1. LTE-V2X subchannelization; (a) Adjacent Physical Sidelink Shared Channel (PSSCH)+Physical Sidelink Control Channel (PSCCH), (b) NonadjacentPSSCH+PSCCH.

TABLE VI

INTRODUCED PC5 INTERFACE PHYSICAL LAYER SPECIFICATIONS IN 3GPP REL. 14 PROTOCOL

Feature	**3GPP Rel. 14 PSSCH+PSCCH**
Sampling Frequency	15.36 MHz
Modulation Mode	QPSK or 16QAM for TBs, and QPSK for SCI
Forward error coding	TC
FFFT size (N_{FFT})	1024
Coding rate	According to MCS
Number of subcarrier	$12 \times RB$
Symbol duration (T_s)	66.67 μs
Cyclic Prefix Size (N_{cp})	16 (4.7 μs)
Tone spacing	15 kHz
Transmission power	23 dBm

TABLE VII

LTE-V2X MODULATION AND CODING SCHEMES INDICES AND CORRESPONDING CODING RATE, DATA RATE, AND REQUIRED RBS

MCS index	**Modulation**	**Coding rate**	**Data rate**	n_{RB}
0	QPSK	0.131	1.15 Mbps	114
1	QPSK	0.169	1.49 Mbps	88
2	QPSK	0.207	1.82 Mbps	72
3	QPSK	0.266	2.34 Mbps	56
4	QPSK	0.324	2.85 Mbps	46
5	QPSK	0.407	3.59 Mbps	38
6	QPSK	0.484	4.26 Mbps	32
7	QPSK	0.573	5.05 Mbps	26
8	QPSK	0.645	5.68 Mbps	24
9	QPSK	0.731	6.44 Mbps	22
10	QPSK	0.804	7.08 Mbps	20
12	16-QAM	0.465	8.2 Mbps	16
13	16-QAM	0.532	9.37 Mbps	14
15	16-QAM	0.670	11.8 Mbps	12
17	16-QAM	0.744	13.12 Mbps	10
20	16-QAM	1.005	17.71 Mbps	8

consists of MCS, RBs, and resource reservation intervals information [19]. There are two possible schemes for LTE-V2X sub-channelization: *Adjacent PSSCH+PSCCH scheme* and *Nonadjacent PSSCH+PSCCH scheme* [9].

Figure 1 depicts the two possible sub-channelization schemes for LTE-V2X. In *Adjacent PSSCH+PSCCH scheme* (Figure 1-a), TBs and SCI are transmitted over the adjacent RBs. The SCI occupies the first two RBs of the sub-channel, and the TB occupies the following RBs in the same sub-channel. In the *Nonadjacent PSSCH+PSCCH scheme* (Figure 1-b), the channel is pooled into two parts, a reserved part consists of the RBs for SCI and another reserved part for TBs. Similar to the Adjacent PSSCH+PSCCH scheme, in the Nonadjacent PSSCH+PSCCH scheme, each SCI occupies two blocks in the reserved RBs. To improve the performance of the link to the high-speed mobility imposed doppler effect shift error, the LTE-V2X protocol assigns the third, sixth, ninth, and twelfth symbol of each sub-carrier per sub-frame to the Demodulation Reference Signals (DMRS) [9], [41], [42], [43].

Table VI represents the summary for 3GPP Rel. 14 protocol specifications in ITS application. Also, Table VII denotes the LTE-V2X MCS indices and equivalent data rates, respectively.

2) LTE-V2X MAC Layer: In the LTE-V2X mode 4, vehicles can access the channel in the absence of the cellular towers. In this communication mode, a vehicle uses a Sensing-Based Semi-Persistent Scheduling (Sensing-Based SPS) algorithm to transmit the TBs. In this technique, a vehicle senses the channel for one second (referred to as Sensing Window) and **reserves** the **selected** sub-channel for a number of consecutive re-selection counter-packet transmissions. The re-selection counter-packet is a random number, and after each transmission, the re-selection counter is decremented by one, and when it equals zero, new radio resources should be selected and reserved with a probability of $1 - P$. The parameter P is the probability of re-selection and each vehicle can set this parameter up between zero and 0.8. The re-selection counter is set randomly whenever the new resources must be reserved. In case the TB did not fit in the reserved sub-channel(s), the vehicle must compete over the medium again. The transmission rate can be one packet per 100 sub-frames (10 pps) or a multiple of it. To decrease the probability of packet collision, SPS includes the value of the re-selection counter packet and the packet transmission interval in SCI, which enables the other vehicles to estimate the time of the availability of the radio resources [9], [22].

Figure 2 demonstrates the utilized SB-SPS algorithm of resource selection in LTE-V2X MAC layer architecture. To **select** a sub-channel, a vehicle V makes a list, L_1, of Candidate Single sub-frame Resources (CSR) in a selection window $[T, T + n]$. The time T, in the selection window, corresponds to the time that the vehicle requires the radio resource to perform a transmission and n is the maximum tolerable latency (100ms for 10 pps). The list L_1 includes all the CSRs in the selection window except the ones that will be utilized. A CSR is recognized as utilized under two circumstances: (1) if another vehicle will use that resource at the same time as the vehicle V schedules for transmitting any of its re-selection counter-packets (the vehicle checks the received SCI in the last 1000 sub-frames), and (2), if the average measured Reference Signal Received Power (RSRP) of the CSR in last 10 transmission intervals is greater than a threshold, Th_{SPS}. The vehicle V will exclude a CSR from L_1 if it met both conditions. Moreover, due to the half-duplex transmission

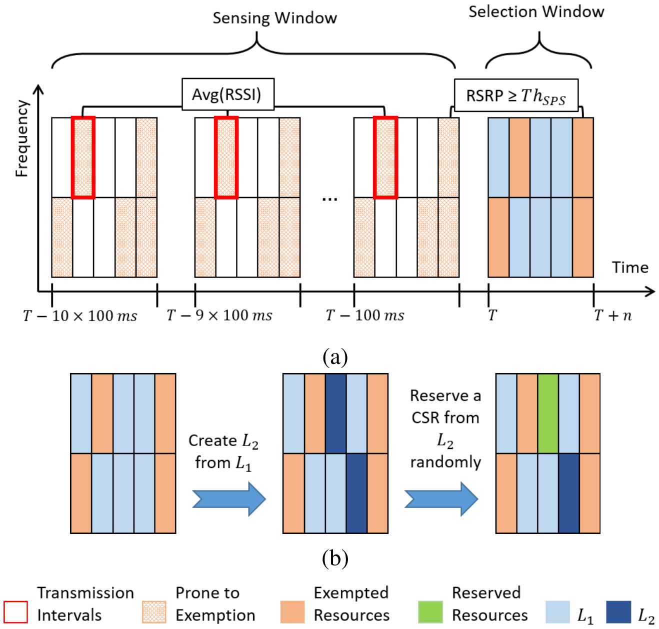


Fig. 2. Illustration of LTE-V2X radio resource selection algorithm.

mode, the vehicle V cannot receive any packet nor sense the channel during the transmission time; hence, it must exclude all the CSRs in sub-frames that had the transmission in last ten intervals. After excluding the utilized CSRs, the L_1 must comprise at least 20% of the selection window total CSRs. Otherwise, the vehicle V repeats the procedure with a $3dB$ increment in Th_{SPS}. Afterward, the vehicle V creates a subset of L_1, L_2, including exactly 20% of the selection window CSRs that have the lowest average Received Signal Strength Indicator (RSSI) over the last ten intervals. Finally, the vehicle V, randomly *reserves* one of the CSRs in L_2 for its next re-selection counter-packets transmissions [9], [44], [45], [46], [47]. The LTE-V2X re-transmission option enables a more efficient utilization of accessible RBs in locations with low cellular activity (e.g., in low congestion scenarios). This option aids LTE-V2X in maintaining reliability in the higher range of communication by transmitting a packet twice.

III. VEHICULAR APPLICATIONS

Broadcasting the BSM in a vehicular network enables vehicles to share information that can assist the driver to have enhanced perception about the current and future status of their surroundings and improve the driver situational awareness. In partnership with USDOT, the Crash Avoidance Metrics Partnership (CAMP) of Vehicle Safety Consortium Communications (VSCC) proposed more than 57 safety and non-safety applications for CVs, such as Emergency Electronic Brake Lights (EEBL), Forward Crash Warning (FCW), Blind Spot Warning/Lane Change Warning (BSW/LCW), Intersection Movement Assist (IMA), Left Turn Assist (LTA), and Control Loss Warning (CLW) [17], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61].

Although DSRC and LTE-V2X evaluations prove that the existing RATs can reliably fullfill the safety applications requirements, the dedicated spectrum by FCC is not sufficient to suit the high data traffic demands for advanced vehicular applications. Table VIII represents the requirements of general advanced V2X applications. As we can see in this table, the required quality of service for advanced vehicular application is much more stringent than the basic safety applications, and existing RATs fall short of supporting the requirements that are believed to be critical in enabling fully autonomous vehicles, such as variable payload, low latency, high link budget, and extremely high-reliability requirements [22]. However, moving toward advanced application is not just in favor of self-driving autonomous cars. Studies show that sensor-sharing-based safety application can serve human drivers and Vulnerable Road Users (VRUs) as well as driver-less cars [62], [63], [64].

TABLE VIII

QoS REQUIREMENTS OF ADVANCED V2X APPLICATIONS [22]

Use Case	**Max Latency** [ms]	**Payload** [Bytes]	**Reliability** (%)	**Data rate** [Mbps]	**Min. Range** [m]
Vehicle Platooning	10-500	50-6000	90-99.99	50-65	80-350
Advanced Driving	3-100	300-1200	90-99.999	10-50	360-500
Extended Sensors	3-100	1600	90-99.999	10-1000	50-1000
Remote Driving	5	-	99.999	UL:25 DL:1	-

IV. DSRC VS LTE-V2X

To assess the performance of DSRC and LTE-V2X, there exist a key measure: **reliability**. It indicates the maximum acceptable failure rate in packet reception in an Remote Vehicle (RV). The failure in packet reception may occur due to the different causes, such as packet collision, and low SINR of the signal in receiver. *Packet Error Rate* (PER) is a metric that is corresponding with reliability and specifies the failure rate of packet reception. The PER can be examined over a variety of the other parameters, such as vehicle speed and distance. The *effective communication range* is another measure that demonstrates the relationship between the PER, and can be alternatively expressed in terms of *Packet Delivery Ratio* (PDR), and communication range. The effective communication range expresses the maximum range of communication that provides a specified level of reliability. For safety applications, existing standards for minimum reliability, minimum communication range are restricting (see Table VIII).

A. Review on Simulation-Based Evaluation

DSRC was introduced in 1999, and several studies in literature have assessed its performance, using theoretical, simulation-based, and emulation-based methods. In [21], [65], [66], [67], [68], performance of DSRC is evaluated, considering the hidden terminal effect (capture effect is neglected). Compared to DSRC, LTE-V2X was introduced more than a decade later in 2015. LTE-V2X is a relatively new technology and its performance evaluation has not conducted fully yet, and industry standards are being developed. Some existing LTE-V2X performance studies are based on either theoretical or simulation-based analysis. References [44], [69], [70], [71] investigate the effect of MAC and PHY layer parameters on the performance of baseline LTE-V2X. References [72], [73], [74], [75] discuss the resource allocation protocol of LTE-V2X Uu and PC5 interfaces. In [76], authors present a system-level evaluation in terms of different types of transmission error, such as propagation errors, packet collision, and errors due to the half-duplex operation. In [9], authors develop a transmission error model using look-up tables from [77], that maps the Signal-to-Interference Noise Ratio (SINR) to the Block Error Rate (BLER). Reference [78] studies the impact of resource reservation periodicity and the number of available radio resources on the LTE-V2X performance. Some studies consider the LTE-V2X Uu communication interface for CV, while Uu interface dependency on infrastructure accessibility for packet delivery limits the spatial reliability of the communication link; therefore, in this article, we omit a thorough review of those studies.

In [79], the author studies the Bit Error Rate (BER) at the PHY layer in one realistic intersection, using ray tracing. References [80], [81] use the Manhattan grid scenario to simulate and compare the end-to-end latency, packet delivery rate (PDR), and throughput of two RATs. Reference [22], [82], [83], [84] use analytical models for RATs comparison in terms of PDR, and [85] represents a comprehensive comparison between DSRC and LTE-V2X. [45] focuses on PC5 interface of LTE-V2X to compare the direct communications protocol. References [86], [87] consider a non-congested scenario to compare the performance of broadcast transmissions. In [1], an overview of the applications and use cases of V2X communication is presented. Also, it discusses a link-level performance comparison of LTE-V2X and DSRC, which demonstrates that LTE-V2X out-performs DSRC in most of the vehicular scenarios (e.g., highway and urban scenarios). The [88] shows that LTE-V2X outperforms DSRC when 802.11p is configured with the default 6 Mbps data rate, while, 18 Mbps configured DSRC outperforms LTE-V2X.

In addition, the performance of LTE-V2X and IEEE 802.11p was compared in [89] based on link level simulation under typical road topologies and traffic models. In simulation, the system level performance of LTE V2X outperforms IEEE 802.11p by using the efficient sensing and SPS resource allocation scheme, etc. [89]. In [90], based on the standardized ETSI CAMs, periodic and aperiodic messages of variable and constant size were tested under different possible configurations and scenarios of LTE-V2X and IEEE 802.11p. The road traffic simulator Simulation of Urban MObility (SUMO) and the network simulator Objective Modular Network Testbed in C++ (OMNET++) were integrated and used. Results show that when aperiodic messages of variable size are transmitted, due to inefficiencies in the LTE-V2X sensing-based semi-persistent scheduling, IEEE 802.11p performs better when coping with variations in the message size and time interval except very-low channel load situations. In [91], ITS-G5 (European standard for vehicular communications based on IEEE 802.11p) and LTE-V2X were compared using a vehicular and networking simulation platform under different use cases. Main goal of [91] is to ensure to select an adequate technology based on service performance requirements. Reference [92] compared the scalability performance of IEEE 802.11p-based DSRC and 3GPP Rel-14 LTE-V2X PC5 mode 4 in simulation. Results show performance of 10-MHz bandwidth DSRC is comparable with 20-MHz bandwidth LTE-V2X with hybrid automatic repeat request (HARQ) retransmission, and LTE-V2X semi-persistent scheduling mechanism can cause consecutive packet loss issue.

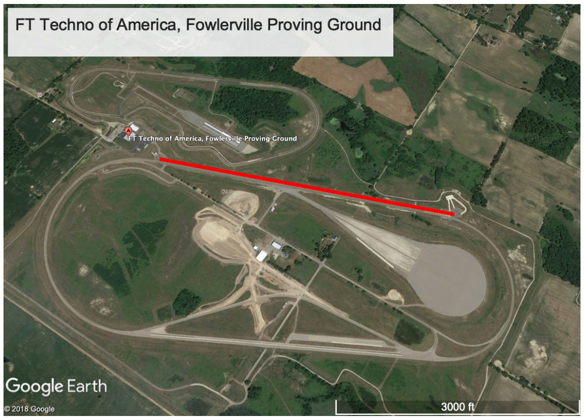


Fig. 3. FT Techno of America, Fowlerville Proving Ground, Michigan, USA. Authors employed the Road A to conduct the field-tests.

The software-based analysis has benefits, such as low cost, short deployment cycle, and flexible parameters setting. But scenarios of Line of Sight (LOS), Non-LOS (NLOS) and Obstructed-LOS (OLOS) have been difficult for the industry to simulate accurately and typically the results lead to overly optimistic performance estimates. Hence, it is essential to conduct a series of field-test to accomplish a relatively comprehensive comparison between the LTE-V2X and DSRC performance.

B. Experimental Test Setup and Scenario Design

Here, we aim to design a number of test scenarios to empirically evaluate the performance of RATs in question. To perform the field-tests, we used the Fowlerville Proving Ground in Michigan, from November 2019 till March 2020. The employed test track road is four lanes wide, and 4,500 ft. (1,370m) in length (see Figure 3).

Figure 4 shows the employed vehicles for creating different channel scenarios. To create the LOS and NLOS scenarios, in this field-test we employed two connectivity equipped sedans (approximate dimensions: Length 192in, Width 73in, Height 57in) which can broadcast and receive the BSM. The blocking vehicles in NLOS scenarios include a regular sedan (approximate dimensions: Length 192in, Width 73in, Height 57in), an SUV (approximate dimensions: Length 196in, Width 78in, Height 67in), and a truck (approximate dimensions: Length 270in, Width 94in, Height 90in). Figure 5 shows the antenna placement for no diversity testing (Figure 5-a) and diversity testing (Figure 5-b).

1) Test Parameters: In Section II, we presented a comprehensive review on the PHY and MAC layer architecture of

TABLE IX
THE LTE-V2X AND DSRC PARAMETER SETTING IN THE FIELD TESTS

	DSRC	**LTE-V2X**
Sampling Frequency, F_e	10 MHz	15.36 MHz
Tone Spacing, δf	156.25 kHz	15 kHz
FFT Size, N_{FFT}	64	1024
Symbol Duration, T_s	$8\mu s$	$66.67\mu s$
Number of data subcarrier, N_u	48	12xRB
Cyclic Prefix Size, N_{cp}	16	72
Modulation	QPSK	QPSK/16QPSK
Forward Error Correction	CC	TC
Coding Rate, R_c	1/2	from MCS
Transmission power	20 dBm	20 dBm

DSRC and LTE-V2X. There are some adjustments in RATs that may affect the performance directly or indirectly, such as the adopted MCS, spatial diversity and re-transmission options, the utilized bandwidth, and the message size. The **MCS** index determines the coding rate and data rate in the PHY layer of a RAT. **Spatial diversity** is a communication link enhancement technique to the channel-imposed multipath interference. In the LTE-V2X radio front-end, the spatial diversity is mandatory, while in DSRC, spatial diversity can be either enabled or disabled. The **re-transmission** (referred to as blind HARQ) is an optional feature of LTE-V2X, which enables the radio unit to broadcast a packet twice with different coding and ensure lower failure rate of packet reception (i.e., PER) at higher communication ranges. In this communication technique, the receiver uses the two transmissions jointly to determine the sent message. However, the IEEE 802.11p does not support the re-transmission; this feature is supposed to be included in the Next-Generation V2X (NGV) as well. The next effective parameter on the radio performance is the **bandwidth**. Obviously, additional resources in the frequency domain can enhance radio performance. The LTE-V2X higher bandwidth utilization enables it to adopt lower MCS indices and gains the link reliability in higher communication ranges. Finally, the **packet size** is another parameter that impacts the RATs performances. Large packet sizes makes access to the medium more challenging (e.g., in a congested network).

Table IX represents the active LTE-V2X and DSRC units setting in the field-tests, which are fixed during the tests. Other than the fixed parameters, we will modify the following parameters to study their impact on RAT performance in different test scenarios:

- Spatial Diversity
- Bandwidth
- Packet size

2) Test Scenario – Communication Range Test: Figure 4 represents the four cases of the effective communication range test. The effective communication range is the maximum range of communication at which the radio maintains a certain level of reliability. The objective of this experiment is to measure the PER and reliability of communication link, under LOS/NLOS situations, in terms of the distance between Host Vehicle (HV) and Remote Vehicle (RV). In LOS scenario, HV and RV can transfer the data through open space (Figure 4-a). In NLOS scenarios, we incorporate a blocker vehicle to study the impact of the blocker type and size on the performance of each RAT. The blocking vehicle may either prevent the LOS or attenuate the LOS signal (OLOS). Compared to LOS, in both NLOS and OLOS scenarios, the received signal has significantly lower power level, which results in higher PER at a specified distance between HV and RV. In the communication range test, the blocker vehicle can be either a sedan (similar to HV and RV), an SUV (which mainly emulates the OLOS case), or a large truck (to mimic the NLOS case). All the vehicles were moving in varying distances, including 2 test vehicles approaching toward and departing from each other. Using the recorded sent and received messages in continuously varying distances, the PDR are obtained by comparing the sending messages number and receiving messages number of 2 test vehicles and averaged by multiple runs for each system setting.

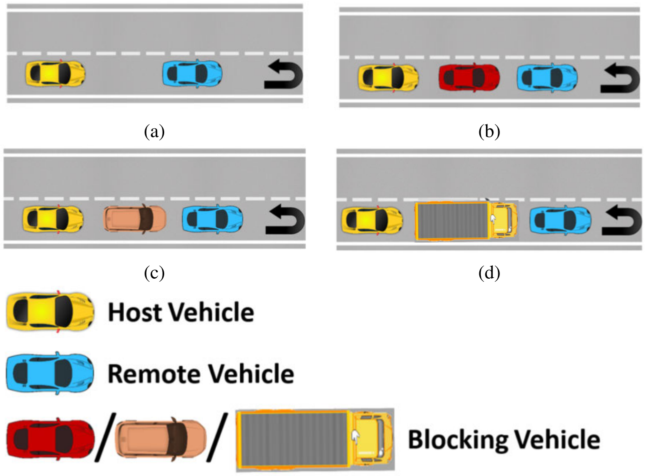


Fig. 4. Communication Range test scenarios: (a) LOS test, (b) NLOS test scenario using a sedan as the blocker, (c) NLOS test considering an SUV as the blocker, (d) NLOS test scenario including a large truck as the blocking vehicle.

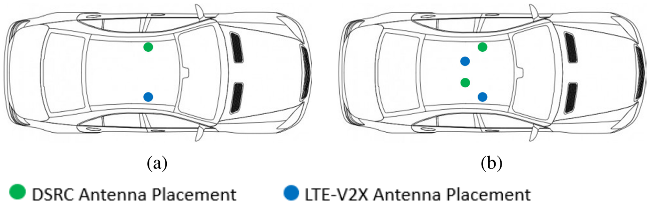


Fig. 5. Antenna placement: (a) primary antenna placement (no diversity), (b) antenna placement for diversity.

C. Theoretical Analysis of Packet Size Variations

V2X by design employs different message sizes based on the use case, message information, and security profile implementation. This paper studies three buckets of payload sizes (which are well known to be associated with different applications). We targeted 200-byte packets. This category accounts for 80 percent of messages every minute (8 out of 10 messages) [7] in normal operation (no critical event is happening) and is used for basic vehicular safety applications such as intersection collision avoidance and rear-end collision

TABLE X

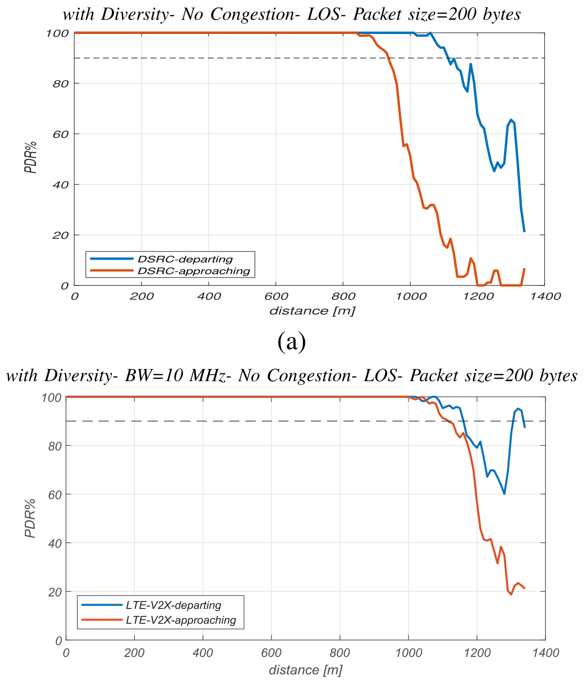
CV2X ON 20MHz CHANNEL-LOW SPEED (<120KMH) [93]

Packet Size	**<=193**	**194-233**	**234-277**	**278-389**	**390-421**	**422-597**	**598-775**	**776-1063**	**1064-1239**	**1240-1479**	**1480-2124**
MCS	5	6	7	11	7	11	11	11	6	7	11
RB	18	18	18	18	27	27	36	48	96	96	96
Transport Block Size	193	233	277	389	421	597	775	1063	1239	1479	2124

avoidance, etc. The second category is 360-byte messages. This category represents 20 percent of normal operation as well as critical event situations (e.g., hard braking, ABS engagement, traction control engagement, and stability control engagement). The third category is 1400-byte messages. This category represents Road Side Unit (RSU) messages about Signal Phase and Timing (SPaT) and MAP as well as coordinated driving and AD use cases such as maneuver sharing and sensor data sharing. It is important to understand and compare how each technology limitation would impact the underlying application and use case. As it was noted above, LTE-V2X uses adaptive MCS while DSRC uses fixed coding rate (QPSK, coding rate) for various packet sizes. Table X shows the optimized and standardized MCS selection for different payloads. In Table X, all transport block sizes and packet sizes are in bytes. It lists the mapping between packet size and MCS & RB pairs for 20 MHz bandwidth at low speeds [93]. Since LTE-V2X MSC selection is payload size dependent, it is expected that the performance of the technology varies under different payload condition and the performance could be theoretically measured. For example, for a 200-byte packet, MCS6 (QPSK and 0.54-rate) and 18 PRBs for PSSCH +2 PRBs for PSCCH (i.e., 2 sub-channel) will be used. For 20 dBm Tx power, the power spectral density is reasonably high as a result of narrow banding (only 2 sub-channels are used and the power density should be calculated over this given frequency). For the 360-byte packet, MCS11 (16QAM and 0.45-rate) and 18 PRBs for PSSCH +2 PRBs for PSCCH (i.e., 2 sub-channels) will be used. Required SINR is slightly higher (arround 2dB) than 200-byte as a result of higher MCS. For 20 dBm Tx power, the power spectral density for PSSCH stays the same as the 200-byte packet. For the 1400-byte packet, MCS7 (QPSK and 0.64-rate) and 96 PRBs for PSSCH +2 PRBs for PSCCH (i.e., 10 sub-channels) will be used. Required SINR (Shannon bound) is higher than a 360-byte case and of course 200-byte messages. For 20 dBm Tx power, the power spectral density for PSSCH is significantly lower than 360-byte and 200-byte as a result of wider band (10 sub-channel are used and the power density should be calculated over this given 20MHz frequency band). Theoretically, the 1400-byte packet requires higher Tx power at the transmitter or Rx power at the receiver compared to the 360-byte case and 200-byte case.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments are conducted to investigate and compare DSRC and LTE-V2X, in terms of effective communication range. The presented test-setup and field-test design in Section IV-C enable us to compare the RATs performances under different combinations of the radio parameters and scenarios. Accordingly, in the conducted field-tests, we explore the effect of spatial diversity, radio acquired bandwidth, and the packet size on the RATs performances, under a variety of the scenarios. Furthermore, employing different blockers, in type and size, allows us to assess the LTE-V2X and DSRC PHY layer architecture design efficiency when the communication link quality is degraded due to the absence of LOS signal.



(a)

(b)

Fig. 6. Approaching vs. Departing - PDR over communication range: (a) receive percentage of DSRC radio, (b) receive percentage of LTE-V2X.

A. Effective Communication Range Assessment and Comparison in LOS Scenario

In the first test scenario, we aim to study the reliability of DSRC and LTE-V2X based vehicular networks, using an effective communication range measure in the LOS scenario (see Figure 4-a). Usually, the minimum tolerable reliability is a part of the vehicular applications QoS. As the presented investigation is application-independent, the effective communication range is defined as the maximum range that the RATs preserve the PDR higher than 90%.

Figure 6 demonstrates the PDR over the distance between the HV and RV when the radio is either DSRC or LTE-V2X. As shown in Figure 4-a, in a communication range test, the RV starts moving away from the HV toward the end of a test track, so-called departing, and when it gets to

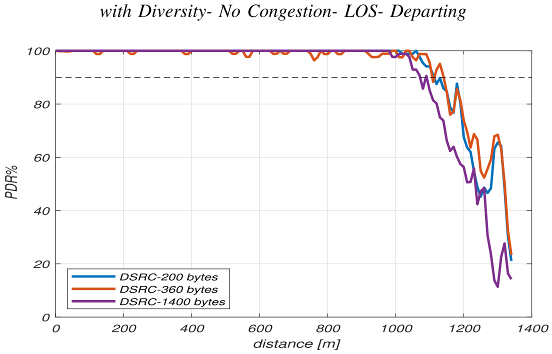


Fig. 7. DSRC performances in terms of PDR vs. range over various packet size (200 bytes, 360 bytes, and 1400 bytes).

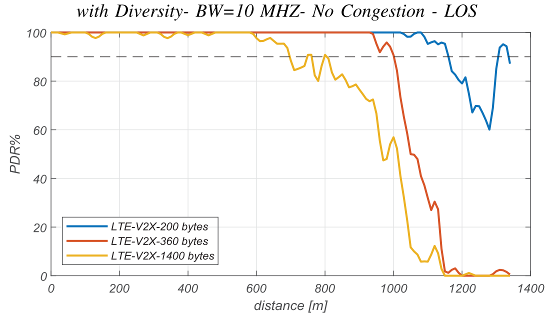
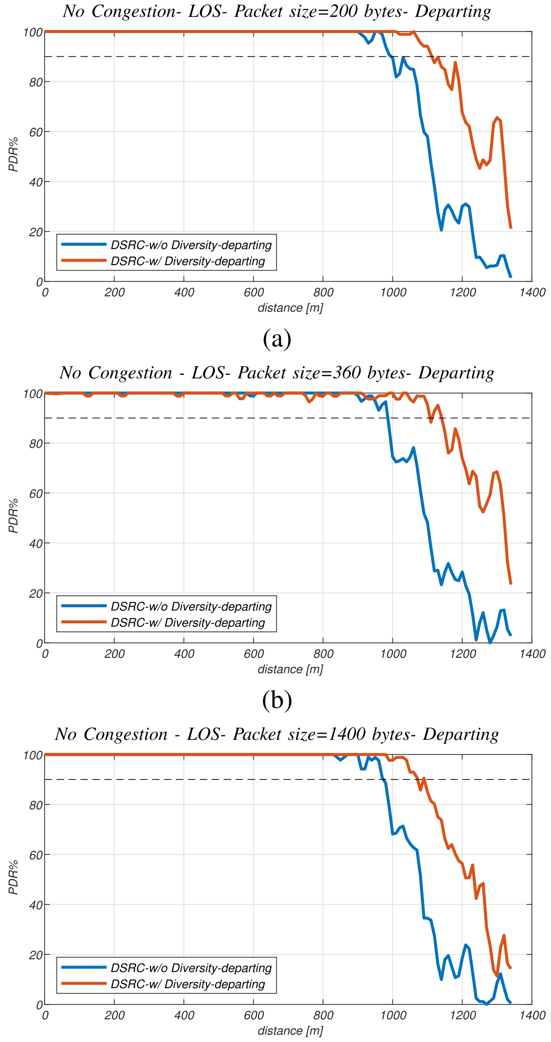


Fig. 8. LTE-V2X performances in terms of PDR vs. range over various packet size (200 bytes, 360 bytes, and 1400 bytes).



(a)

(b)

(c)

Fig. 9. Impact of spatial diversity on DSRC radio performance: (a) PDR vs. range, when RV departs from HV, when the packet size is 200 bytes, (b) PDR vs. range, when RV departs from HV, when the packet size is 360 bytes, (c) PDR vs. range, when RV departs from HV, when the packet size is 1400 bytes.

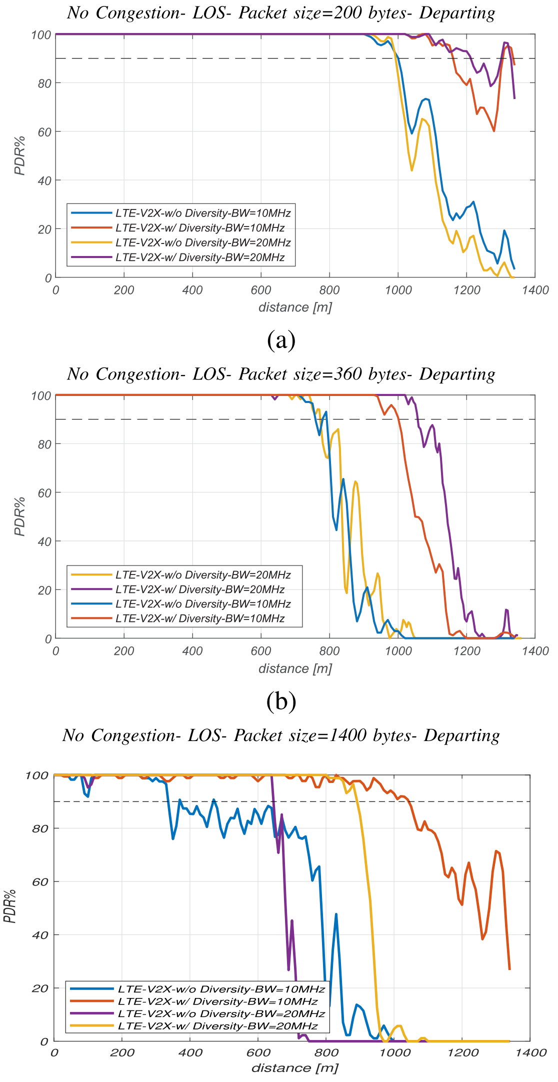
the end of the track, it moves toward the HV, referred to as approaching. In this experiment, both DSRC and LTE-V2X radio units utilize the 10 MHz bandwidth, the spatial diversity is enabled for both technologies, and the packet size is set to 200 bytes. As we observe, for an existing departing RV within the communication range, the RATs can maintain the link quality for larger distances. In the approaching scenario, the effective communication ranges of DSRC and LTE-V2X are 930m and 1110 m, respectively. When the RV departs from HV, the effective communication ranges of DSRC and LTE-V2X extends to 1120 m and 1170 m, respectively.

To study the impact of the packet size on the RATs scalability, we repeat the range test by setting the packet size to 200 bytes (representing a BSM without a security certificate), 360 bytes (representing a BSM with security certificate), or 1400 bytes (representing a MAP message or an advanced application message such as sensor data sharing). Figure 7 demonstrates the impact of the packet size on the DSRC effective communication range. As we observe, the DSRC performance in broadcasting a 200-byte packet and a 360-byte packet are very similar (effective communication range is measured as 1100 m), while its measured effective broadcasting range of a 1400-byte packet is more limited.

Figure 8 presents the LTE-V2X PDR over the communication range for different packet sizes. The LTE-V2X effective communication ranges are 1170 m, 1010 m, and 700 m, when the packet size is set to 200 bytes, 360 bytes, and 1400 bytes, respectively. According to Figure 7 and Figure 8, the larger packet size degrades the RATs performances. We observed that DSRC maintains a reliable communication link for larger distances when the packet size is large.

Figure 9 demonstrates how the spatial diversity technique in the receiver enhances the DSRC radio performance related to different transmitted packet sizes. According to the field test results, enabling spatial diversity in DSRC radio units extends the measured effective communication range up to 130 m, 170 m, and 280 m, when the packet sizes are 200 bytes, 360 bytes, and 1400 bytes, respectively.

In addition to the spatial diversity, in a LTE-V2X radio, the utilized bandwidth can be adjusted; hence, it is important to examine the influence of bandwidth, as well as spatial diversity, on the LTE-V2X broadcasting performance. Figure 10 illustrates the effect of spatial diversity and utilized bandwidth on the LTE-V2X radio effective communication range. Similar to DSRC, utilization of spatial diversity reinforces the communication link lessening the impact of channel imposed error; consequently, it increases the rate of successful data



(a)

(b)

(c)

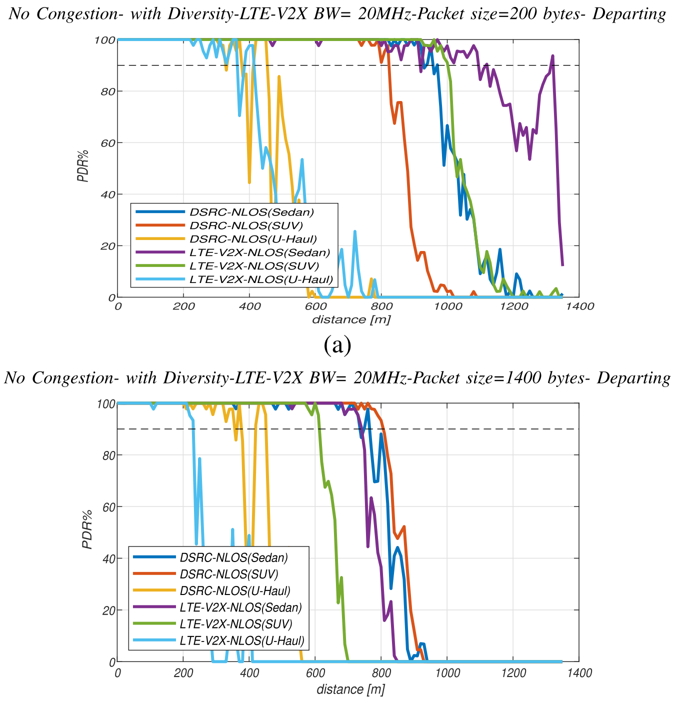
Fig. 10. Impact of the spatial diversity feature in LTE-V2X radio receiver and the incorporated bandwidth by the LTE-V2X on its performance: (a) PDR vs. range, when the packet size is 200 bytes, (b) PDR vs. range, when the packet size is 360 bytes, (c) PDR vs. range, when the packet size is 1400 bytes.

transmission over a LTE-V2X based vehicular communication link. Besides, a wider bandwidth enables the LTE-V2X to adopt lower MCS indices in the PHY layer, which results in a lower coding rate and lower modulation rate. Considering a certain SINR, incorporating lower modulation rates in radio PHY layer results in a lower BER, and enhances the communication link quality. Table XI represents the measured effective communication range corresponding to the different radio parameter configurations.

TABLE XI

LTE-V2X MEASURED EFFECTIVE COMMUNICATION RANGE IN A NON CONGESTED SCENARIO (IN METER)(SEE FIGURE 10)

Packet size (bytes)	Without Diversity		With Diversity	
	BW = 10 MHz	BW = 20 MH	BW = 10 MHz	BW = 20 MHz
200	990m	980m	1110m	1200m
360	750m	650m	1040m	1060m
1400	330m	640m	1000m	960m



(a)

(b)

Fig. 11. DSRC and LTE-V2X performance in a variety of NLOS scenarios: (a) PDR vs. range, when the spatial diversity is enabled on both DSRC and LTE-V2X, LTE-V2X utilizes 20 MHz bandwidth, and the packet size is set to 200 bytes, (b) PDR vs. range, when the spatial diversity is enabled on both DSRC and LTE-V2X, LTE-V2X utilizes 20 MHz bandwidth, and the packet size is set to 1400 bytes.

TABLE XII

DSRC AND LTE-V2X EFFECTIVE COMMUNICATION RANGE IN VARIOUS CHANNEL SCENARIOS

Scenario	DSRC		LTE-V2X	
	200 bytes	1400 bytes	200 bytes	1400 bytes
LOS	1025m	1020m	1150m	885m*
NLOS-Sedan	880m	755m	905m	685m
NLOS-SUV	765m	755m	950m	570m
NLOS-Large truck	270m	275m	335m	205m

*this presented effective communication range is according to 20 MHz bandwidth of the LTE-V2X radio unit.

B. Packet Delivery Rate Assessment and Comparison in NLOS Scenario

Other than the LOS scenario, we need to study the consequence of the different blocking vehicles on the quality of the channel and the RATs performances. The blocking vehicle may either prevent the LOS communication link, referred to as NLOS, or just attenuate the LOS signal (OLOS). Compared to LOS, in both NLOS and OLOS scenarios, the received signal has significantly lower the power level, which results in higher PER and lower PDR at a specified distance between HV and RV. Here, the blocker vehicle can be either a sedan (the same vehicle as to the employed HV and RV), an SUV (which mainly emulates the OLOS case), or a large truck (to mimic the NLOS case) (Figure 4).

Figure 11 demonstrates the impact of a blocker vehicle on the DSRC and LTE-V2X communication links. As expected, the presented results show that the SUV blocker degrades radio performance more significantly than the sedan vehicle. Furthermore, compared to the LOS link, when the blocking vehicle is a large truck, the measured effective communication range drops down to about 30% of this measure in the LOS scenario. Comparing the Figure 11-a and Figure 11-b, we observe that changing the transmitted packet size alters the influence of the different blocking vehicles on the radio functionality. When the packet size is 1400 bytes, the sedan blocker has minor influences on the RATs effective communication range, while the large truck shrinks this measure by a factor of 1/3, approximately. This feature will allow the radios to enhance the communication link quality in both none-congested and congested networks (see Section II). Table XII summarizes the measured DSRC and LTE-V2X effective communication of DSRC and LTE-V2X is different channel scenarios. Note that results in Table XII are average of departing and approaching, and results in Table XI are departing only. Referring to SAE J3161/1 LTE-V2X PC5 pre-configuration requirements [93], for the communication range test with blockage, only 20MHz LTE-V2X was tested.

There're other existing studies that tested V2X technologies [94], [95], [96]. In [94], an initial baseline tests comparing DSRC and LTE-V2X were conducted at a test track, and variations in reliability were observed for different receiver locations at the test track. Reference [95] presented a vision of LTE-V2X research, field testing, and development in China. Among them, the one has the most similar system settings is Crash Avoidance Metrics Partners LLC (CAMP) communication range testing for LTE-V2X (20MHz bandwidth) in 2019 [96] and we observed consistency when compared with CAMP communication range testing results: V2V LOS 1400 bytes scenario (Table XII: 885m, CAMP: 840m), V2V NLOS 1400 bytes scenario (Table XII: 205m, CAMP: 200m).

VI. CONCLUSION

This article presents a comprehensive comparison between the two available solutions for a vehicular network, the DSRC and the LTE-V2X. We presented a detailed and extensive technology overview on the DSRC and LTE-V2X PHY and MAC layers architectures. We offered tables and schematics that explain how DSRC and LTE-V2X process data in the PHY layer and reserve the medium for broadcasting purposes. Next, we discussed the current vehicular safety applications and declared how the future advanced application QoS outlines the requirements of the forthcoming DSRC and LTE-V2X. We reviewed the literature that offers an assessment or comparison among these two RATs performances and discussed the importance of an emulation-based comparison between these two technologies to address the debates in industry and academia. Accordingly, we developed a test setup and a series of field tests that evaluate the RATs performances in a variety of realistic driving scenarios. Using the communication range test, we assessed the RATs, in terms of reliability, when the HV and RV either move towards each other or when they get farther apart. Besides that, we evaluated the capability of each RAT in transmitting data with different packet sizes. Moreover, we observed how the different configuration of the RATs can enhance their performances. The spatial diversity enables both technologies to extend their range 200m-300m, and utilizing narrow banding (fewer sub-channels in use) allows the LTE-V2X to stretch its effective communication range up to 1200 m for smaller packet sizes. Then, we conducted several field tests that aim to examine the performance of the RATs in different channel scenarios. We investigated each RAT with different radio configurations, including packet size, and spatial diversity in the receiver, and utilized bandwidth, using diverse types of blocker vehicles. In conclusion, enabling spatial diversity allows both technologies to improve their effective communication range in all driving scenarios that have been tested in the work. Also, based on range analysis, LTE-V2X delivers longer range for smaller packet sizes (around 200 bytes) while DSRC provides longer range in larger packet sizes (around 1400 bytes). For BSMs with full security profile (around 360 bytes which LTE-V2X uses MCS 11), both technologies deliver similar performance. Note that this study has not considered congestion scenarios or interference scenarios and has no experiments and comparisons in the scalability of DSRC and LTE-V2X technologies in this paper. Future studies should be focused on performance analysis under congested scenarios as well as application assessment under congested scenarios. When involving 5G technology and more bandwidth-demanding applications, it will be necessary to test and compare the maximum throughputs among multiple V2X technologies.

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