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Performance Comparison of IEEE 802.11p and LTE-V2X Through Field-Tests and Simulations

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***Abstract*—Vehicular communication is a key enabler in making Automated Vehicles (AVs) collaborate by sharing information, which complements on-board sensor information and facilitates precise vehicle control. This paper presents a tailored measurement campaign aimed at analyzing the performance of two vehicular communication technologies, namely IEEE 802.11p and LTE-V2X. Our study focuses on key metrics for cooperating AVs, such as end-to-end latency and packet delivery ratios. Additionally, we investigate the feasibility of channel coexistence, assessing the challenges associated with concurrent channel access. The results derived from field tests are correlated with simulations conducted on PLEXE and OpenCV2X, i.e., platforms used for simulating IEEE 802.11p and LTE-V2X, respectively. This combined methodology, comprising field tests and simulations, enables the attainment of replicable conclusions, which in turn enables better design choices.**

I. Introduction

Wireless vehicular communications can enable Automated Vehicles (AVs) to cooperate, aiming to enhance road safety by facilitating local communication between vehicles and surrounding infrastructure. The communicated information may include hazard messages, vehicle longitudinal and lateral control information such as position, speed, acceleration, and steering angle, as well as coordination messages for different types of maneuvers. Due to the safety-critical nature of locally cooperating AVs, information is required to be communicated with low latency and high reliability.

There are currently two main candidate technologies for achieving this local communication between cooperating vehicles: Dedicated Short Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) communications. Several studies in the literature conduct comparative performance evaluations between the DSRC technology IEEE 802.11p and the C-V2X technology LTE-V2X, aiming to discern the benefits and drawbacks of these technologies for collaborative AVs [1]–[3]. The IEEE 802.11p standard defines the underlying protocols for DSRC [4], enabling communication in vehicular environments. In the case of C-V2X, the 3GPP Release 14 defines two PC5 sidelink modes for LTE-V2X communications, i.e., Mode 3 and Mode 4 [5]. In Mode 3, an infrastructure manages the allocation of resource blocks, whereas in Mode 4, the vehicles themselves are responsible for managing the radio resources. When comparing IEEE 802.11p and LTE-V2X, the works in the literature conduct performance evaluation in terms of, e.g., Packet Delivery Ratio (PDR) [3], maximum achievable message periodicity [1], average message delay [6], throughput [7], etc. The results show that IEEE 802.11p outperforms LTE-V2X in terms of reliability, capacity, and vehicle density for ranges up to a few hundred meters, whereas LTE-V2X shows better performance when the communication range is longer [1] [3]. Therefore, to understand whether, for efficient local cooperation between Avs, long-range communication is more suitable than low latency and high reliability, a comprehensive comparative study of the performance metrics PDR and end-to-end latency for various modulation schemes and coding rates, packet sizes, and transmission powers is needed. This analysis of latency and reliability under different configurations is critical to ensuring that V2X communication technologies can fulfill safety-critical application requirements [8]. Additionally, while IEEE 802.11p and LTE-V2X have been tested and compared independently in the literature, e.g., [1]–[3], some works are considering the possibility of shared spectrum by these two technologies, e.g., [9], [10]. Nonetheless, the main problem with such an approach is that IEEE 802.11p and LTE-V2X are not interoperable due to the absence of a coordination mechanism for spectrum sharing. As a result, the adjacent-channel interference or the concurrent transmissions within the same channel have the potential to substantially degrade their performance [11].

It should also be noted that a majority of the comparative evaluations between IEEE 802.11p and LTE-V2X resort to simulation studies, e.g., [2], [3], [12]. However, all channel models needed for these types of simulations are always approximations of reality, and therefore it is necessary to complement them with measurements in a real environment. For instance, Segata *et al.* [13] carried out real-world measurements using the IEEE 802.11p technology to validate the simulations performed using PLEXE [14], which is an open-source platooning simulator that is developed as an extension of the VANETs simulator Veins [15]. Nevertheless, the current version of PLEXE does not facilitate the simulation of LTE-V2X Mode 4, which is essential for conducting the much-needed comparative evaluations.

This paper evaluates the performance of IEEE 802.11p and LTE-V2X communications, focusing specifically on the metrics end-to-end latency and PDR for various modulation schemes and coding rates, packet sizes, transmission powers, and inter-vehicle distances. These metrics are essential to ensure the reliability and efficacy of vehicular communication systems in safety-critical applications [16]. To this end, field tests have been conducted in this study using two vehicles equipped with IEEE 802.11p and LTE-V2X devices. First, the field tests and evaluations are carried out using the two technologies independently to understand their performance in terms of the evaluation metrics and to establish a baseline. Then the evaluation is extended to analyze the feasibility of channel coexistence, examining the challenges associated with simultaneous spectrum access. For this purpose, additional measurements are carried out, where both technologies share not only the spectrum but also the same channel. These measurements, together with individual baselines, are used to analyze how performance is affected if channel access is not regulated. Finally, the field test scenarios are replicated in the PLEXE simulation framework. For this purpose, we have integrated the LTE-V2X Mode 4 simulator OpenCV2X [17] into PLEXE to enable a comparative evaluation under the same simulation scenarios and settings. The aim is to assess the validity of these simulators using real-world measurements in performing such comparative evaluations between IEEE 802.11p and LTE-V2X technologies.

The rest of the paper is organized as follows: Section II describes the state-of-the-art works analyzing the performance of IEEE 802.11p and LTE-V2X in simulation and real environments. Then, Section III details the setup of the field tests, and Section IV presents the simulation framework that integrates PLEXE and OpenCV2X and describes the simulation scenarios and settings. Next, Section V defines the key evaluation metrics considered in this paper. After that, Section VI first presents a comparative evaluation between the performance of IEEE 802.11p and LTE-V2X based on the measurement campaign, and then their performance while operating on the same channel is evaluated. Next, Section VII compares field tests and simulation results to validate the widely used simulation frameworks for such studies. Finally, Section VIII presents the conclusions that can be drawn from this study.

II. Related Works

Bazzi *et al.* [1] simulated and compared the performance of IEEE 802.11p and LTE-V2X on a highway scenario by varying the traffic conditions. They found that IEEE 802.11p is more robust than LTE-V2X in short-range communications, but for distances up to 500 meters, LTE-V2X demonstrates more reliable performance. Molina-Masegosa *et al.* also conducted a similar comparison in [3] by simulating periodic and aperiodic messages of different sizes, and the results show that LTE-V2X achieves better performance at low channel loads, but as the load increases, IEEE 802.11p maintains a higher packet delivery ratio, especially for aperiodic messages. In [12], Anwar *et al.* included the evolution of the standards, i.e., IEEE 802.11bd from IEEE 802.11p and 5G NR-V2X (Release 15) from LTE-V2X (Release 14), in their comparative evaluation. The authors report that both 802.11bd and 5G NR-V2X perform well in the case of messages with small sizes, with the latter achieving a higher range. However, for larger packets, 5G NR-V2X is the protocol to consider, especially for long-range communications.

Several studies carry out real-world measurements to compare 802.11p and LTE-V2X technologies. For instance, Wang *et al.* [6] measured the PDR and the average message delays of these technologies in two scenarios: first, a platoon formed by two vehicles, and in the second scenario, a car approaches another static vehicle. The authors concluded that LTE-V2X covered longer distances and that vehicle speed had no significant effect on performance in either of the technologies. Rayamajhi *et al.* [18] experimented with a scenario in which a moving vehicle acted as a transmitter and the receiver was placed in different static places. They compared the results for messages with different sizes and obtained similar performance in terms of reliability for both technologies, despite IEEE 802.11p having slightly higher packet loss. Moradi-Pari *et al.* conducted similar field tests comparing the PDR of IEEE 802.11p and LTE-V2X with line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios in [19]. They used two moving vehicles and created the NLOS scenario by inserting a blocking vehicle between them. With small packet sizes of 200 bytes, LTE-V2X was able to achieve longer ranges, but as the packet size increased, the range dropped out faster than IEEE 802.11p. From the literature study (both simulations and field tests), it can be concluded that IEEE 802.11p performs best for local communications even when the packet lengths and the channel loads increase. LTE-V2X performs best for longer ranges and when NLOS is available. The question is how long range is needed and when NLOS conditions are essential. To determine this, we need to evaluate how different settings, such as the coding and modulation scheme, the transmission power, and the packet size affect the performance in terms of packet latency.

There are already some approaches proposed for the cohabitation of IEEE 802.11p and LTE-V2X that have been tested in simulation environments. The simplest solution is to keep each protocol in a different channel. Ghafoor *et al.* elaborated on this idea and proposed a quality of service-aware relaying algorithm [9], wherein vehicles with both interfaces can relay messages from one protocol to another. Nonetheless, separating technologies into different channels reduces the available spectrum for vehicular communications. Bazzi *et al.* in [10] analyzed and compared the performance of IEEE 802.11p and LTE-V2X while sharing the same channel. The simulations showed that IEEE 802.11p was severely affected, while the effect on LTE-V2X was marginal. They were able to reduce the problem by defining the periodicity of the transmitted packets. In [20], the authors also proposed to insert an IEEE 802.11p preamble into LTE-V2X transmission in order to avoid collisions and allow co-channel coexistence. These approaches have been tested in simulation environments; yet, to the best of our knowledge, real-world measurements evaluating the coexistence of these two technologies using the same channel are missing in the literature, which this work aims to address.

III. Field Test Scenarios and Settings

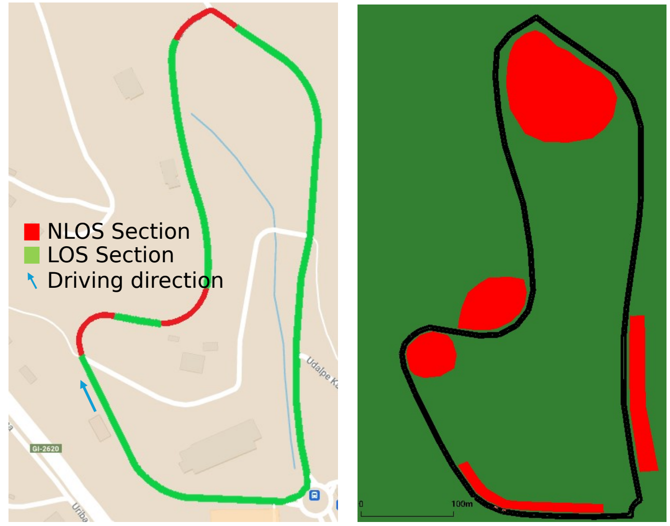
The field tests were performed with two primary objectives: *first*, to evaluate the performance of IEEE 802.11p and LTE-V2X in platooning scenarios with Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions for different coding and modulation schemes, transmission power and packet sizes. This allowed us to assess the efficacy of each technology under varying environmental conditions. The *second* objective is to evaluate the performance of these technologies when acting independently and when both technologies share the same channel and the spectrum allocation is not regulated. By determining how these two technologies influence each other in such scenarios, the implications of a possible channel cohabitation on overall performance are measured.

Taking these objectives into account, two platoon scenarios were defined:

- *Scenario 1*: the gaps between the vehicles were kept as short as possible (varying between 15 and 30 meters) to maintain a constant LOS condition.
- *Scenario 2*: the maintained gaps are between 60 to 90 meters, creating NLOS conditions in road curvatures.

The field tests were carried out at Mondragon Unibertsitatea in Spain, using commercial-off-the-shelf devices, e.g., MK5 On-Board Unit (OBU) to facilitate the communication of IEEE 802.11p and MK6C OBU for LTE-V2X Mode 4 measurements. Due to limited commercial hardware availability, IEEE 802.11bd and 5G NR-V2X were not included in the comparison. In our experiments, one vehicle acts as a transmitter, sending periodic beacons every 100 ms, and the other keeps acting as the receiver until the end of the experiment. For every sent and received frame, both devices record the position (altitude, longitude, and latitude) and speed of the vehicle, as well as the sequence number and transmission and reception times of the frames. The clock of each device is synchronized using the Global Navigation Satellite System (GNSS).

Fig. 1(a) depicts the route in which the field tests were carried out; the LOS segments are colored green, and the NLOS segments are colored red. Table I shows the different settings that have been tested; different test scenarios were generated by varying the packet size, Modulation and Coding Scheme (MCS), and transmission power for both the radio devices, i.e., MK5 OBU and MK6C OBU. The OBUs were configured to transmit in channel 184, centered at the 5.91 GHz frequency band with 10 MHz available bandwidth. Note that for each measurement, the vehicles complete three laps in the route in Fig. 1(a) to minimize the impact of different disturbances on the measurements, e.g., pedestrians crossing at a crosswalk or stopping the vehicles before a roundabout to yield to oncoming traffic.



(a) Field test scenario (Google 2023, Instituto Geográfico Nacional).
(b) Representation of the field test map in SUMO simulator.

Fig. 1. Road layout depicting the LOS (Scenario 1) and NLOS (Scenario 2) conditions in the field test and simulation environment.

TABLE I
Configuration parameters for field tests.

Parameter	IEEE 802.11p	LTE-V2X
Channel	184	184
Bandwidth	10 MHz	10 MHz
Transmission Power	5, 20 dBm	5, 20 dBm
Transmission interval	100 ms	100 ms
MCS	QPSK 0.50 & 16QAM 0.75	QPSK 0.48 & 16QAM 0.75
Packet Size	200, 400, 1000 bytes	200, 400, 1000 bytes

IV. Simulation Environment

A. Simulator Architecture

In order to carry out the comparative evaluation of IEEE 802.11p and LTE-V2X, a complete simulation structure has been adopted in this study, as depicted in Fig. 2. In the following, the simulation framework together with its constituent elements is described:

- OMNeT++ [21]: a discrete-event and C++-based simulation framework primarily facilitating the development of network simulators. OMNeT++ is highly modular, enabling the integration of its constituent modules like Lego pieces.
- INET [22]: the INET framework is an open-source OMNeT++ model suite for wired, wireless, and mobile networks.
- SUMO [23]: an open-source, highly portable, and microscopic road traffic simulator, facilitating large-scale simulations.
- TraCI [24]: an Application Programming Interface (API) that couples SUMO and a network simulator by enabling the online control of multiple simulation objects.
- Veins [15]: Veins is an open-source VANET simulator that bidirectionally couples SUMO and OMNeT++ through TraCI.

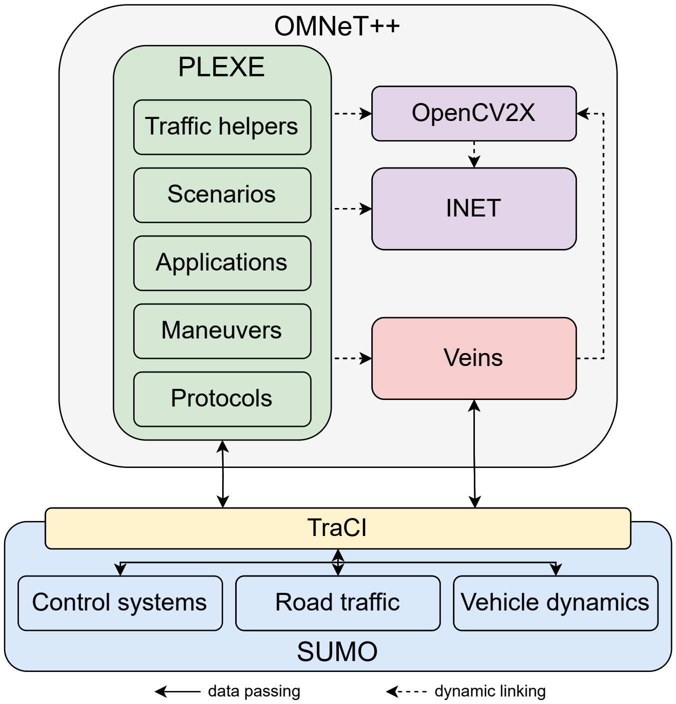


Fig. 2. Schematic representation of the simulation framework used for the performance comparison of IEEE 802.11p and LTE-V2X (adapted from [25]).

- PLEXE [14]: PLEXE is an extension of Veins, facilitating the simulation of platoons, different kinds of platooning maneuvers, state-of-the-art controllers, vehicle dynamics, engine models, mixed traffic scenarios, and more. The current version of PLEXE [25] also supports the simulation of multiple radio access technologies, e.g., IEEE 802.11p, cellular, and visible light communications. For the simulation of cellular communications, PLEXE integrates SimuLTE [26] (LTE-V2X Mode 3), which is an LTE user-plane simulator.
- OpenCV2X [17]: This is also an extension of SimuLTE, specifically tailored for LTE-V2X Mode 4 simulation.

The simulation part of this work uses PLEXE to simulate the IEEE 802.11p protocol stack. However, the current version of PLEXE does not support LTE-V2X Mode 4 simulations, which is required for the comparative evaluation of this study. On the other hand, OpenCV2X enables the LTE-V2X Mode 4 simulation. To this end, we integrated the OpenCV2X simulator into PLEXE, as depicted in Fig. 2, to enable the evaluation of IEEE 802.11p and LTE-V2X under the same simulation scenarios, settings, and channel conditions.

B. Simulation Scenarios and Settings

The field test route in Fig. 1(a) is recreated in SUMO, as depicted in Fig. 1(b). In order to simulate the LOS (Scenario 1) and NLOS (Scenario 2) conditions of the field tests in SUMO, obstacles are placed around the road curvatures to introduce shadowing effects, see the red segments in Fig. 1(b). Moreover, similarly to real-world field test scenarios, a platoon comprising two vehicles has been configured to drive through this road, maintaining inter-vehicle distances spanning from 15 to 30 meters for Scenario 1 (LOS) and 40 to 75 meters for Scenario 2 (LOS). In addition, speeds ranging between 30 and 60 km/h are used for both scenarios. Each scenario is evaluated with three distinct configurations from Table I: 1) a transmission power of 20 dBm paired with QPSK 0.5; 2) 5 dBm transmission power employing the same MCS; 3) a transmission power of 20 dBm coupled with 16QAM 0.75. Furthermore, like the field tests, data frames of 200 bytes are transmitted every 100 ms. In order to ensure statistical robustness, all simulation scenarios are repeated 100 times with different seeds.

TABLE II
ESTIMATED μ VALUES FOR NAKAGAMI DISTRIBUTION BASED ON THE DISTANCE BETWEEN RECEIVER AND TRANSMITTER [27].

Distance (in meters)	μ
From 0.0 to 5.5	4.07
From 5.5 to 13.9	2.44
From 13.9 to 35.5	3.08
From 35.5 to 90.5	1.52
From 90.5 to 230.7	0.74
From 230.7 to 588.0	0.84

In our simulations, the Nakagami fading model is used together with the dual-slope piecewise linear path loss model to account for the fading and path loss effects, respectively, as suggested by Cheng *et al.* in [27]. The authors in [27] report that the dual-slope piecewise linear path loss model can more accurately represent their field test measurements of IEEE 802.11p in the 5.9 GHz frequency band. Our simulations first calculate the average estimated power using the path loss exponents $\gamma_1 = 2.1$ and $\gamma_2 = 3.8$, and the critical distance $d_c = 100$ m; then the average estimated power is used in the Nakagami distribution. Moreover, the shaping parameter μ of the Nakagami distribution is automatically chosen in the simulations based on the distance bins in Table II. Note that the same channel models are used in Veins and OpenCV2X to ensure a fair comparison between the IEEE 802.11p and LTE-V2X Mode 4.

V. EVALUATION METRICS

In selecting metrics for evaluating the communication technologies for locally cooperating AVs, particular emphasis has been given to safety-critical applications requiring real-time control decisions. Achieving this entails enabling periodic information exchange characterized by low latency and high reliability. Hence, this paper concentrates on evaluating the Packet Delivery Ratio (PDR) and end-to-end latency for various modulation and coding schemes, packet sizes, transmission powers, and inter-vehicle distances.

- *PDR*: Calculated as the ratio of correctly received packets (N_{rx}) to the total number of transmitted packets (N_{tx}) expressed as a percentage, i.e., $PDR(\%) = \frac{N_{rx}}{N_{tx}} \times 100$. It serves as an indicator of the expected reliability offered by the two communication technologies.

- *End-to-end latency*: It is defined as the elapsed time between a message being transmitted and when the same message is received by the receiver. This metric also takes packet losses into account by adding the delay incurred since the lost packet is transmitted until the next periodic message is received. The end-to-end latency is plotted as a Cumulative Distribution Function (CDF), expressing the probability that the latency will be less than or equal to a value. For instance, if the CDF value at 60 ms latency is 0.4, it would imply that there is a 40% probability that the communication latency will be less than or equal to 60 ms.

VI. Evaluation of Field Test Results

A. Performance Evaluation of IEEE 802.11p and LTE-V2X when operating independently

Fig. 3 illustrates the CDF of the latency for IEEE 802.11p and LTE-V2X using different MCSs under Scenario 2, i.e., inter-vehicle gaps between 60 and 90 meters are maintained to generate NLOS conditions on the road curvatures, see Fig. 1(a). The first thing to notice in Fig. 3 is that LTE-V2X incurs significantly longer latency than IEEE 802.11p irrespective of the MCS. Moreover, when the MCS is changed from QPSK 0.50 to 16QAM 0.75, the latency of IEEE 802.11p is reduced by half. However, the latency of LTE-V2X does not vary despite the change in MCS because, while transmitting in Mode 4, it uses sensing-based Semi-Persistent Scheduling (SPS). In this mode, vehicles reserve the sub-channel in advance for a certain number of packets and it notifies the time during which the reserved sub-channel will remain busy [3]. The latency with LTE-V2X in this case arises from propagation delay, processing delay, and scheduling delay. Employing a higher MCS index reduces processing delay, but as the scheduling delay is substantially higher, the latency reduction is hardly discernible. Conversely, IEEE 802.11p uses Enhanced Distributed Channel Access (EDCA) based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), where the node senses the channel state and waits until the channel is found idle [4]. As the channel is not congested, channel access does not generate any additional delays, thus the latency is only compounded by propagation and processing delays, which can be reduced by adjusting the MCS.

Fig. 4 shows the CDF of latency in Scenario 2, with varying transmission powers while keeping the MCS and packet size constant. A decrease in the transmission power of IEEE 802.11p results in the PDR dropping from 94% to 66%. LTE-V2X instead maintains a consistent PDR even at 5 dB transmission power. Throughout the measurements, distances are kept between 60 to 90 meters, which implies that the PDR reduction with IEEE 802.11p occurs in the NLOS situations in Fig. 1(a). On the other hand, LTE-V2X offers a broader coverage, ensuring high reliability even in NLOS scenarios. Additionally, in applications where LOS communication is guaranteed, it is advisable to maintain lower transmission power levels to minimize channel interference, effectively reducing the range without compromising performance.

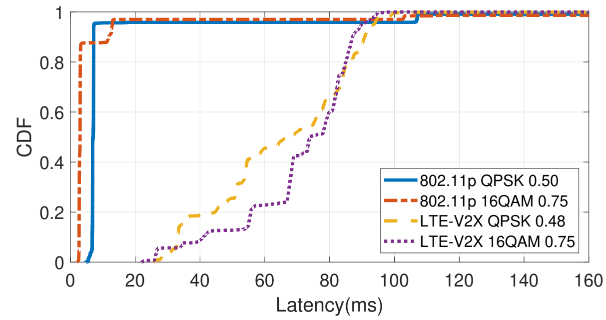


Fig. 3. CDF of latency with different MCSs under Scenario 2 (NLOS). The transmission power is set to 20 dBm and the packet size to 400 bytes.

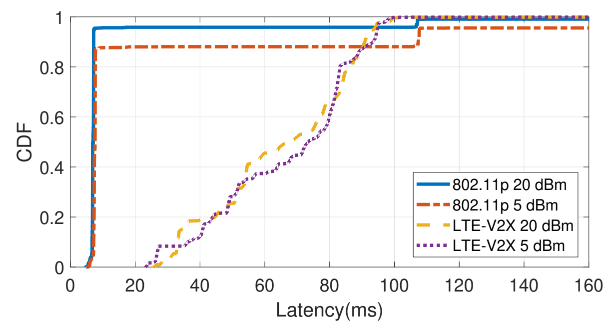


Fig. 4. CDF of latency with different transmission powers under Scenario 2 (NLOS). The MCS and coding rate are set to QPSK 0.50, and the packet size is 400 bytes.

Fig. 5 depicts the CDF of latency with IEEE 802.11p and LTE-V2X with varying packet sizes under Scenario 1, i.e., the inter-vehicle gaps are between 15 and 30 meters, generating LOS conditions. In this experiment, the LOS condition is considered to understand the impact of packet sizes while the other factors remain constant. The results in Fig. 5 demonstrate that IEEE 802.11p exhibits a consistently low latency of around 4 ms with both packet sizes, whereas, the average latency of LTE-V2X increases from 62.60 ms to 77.39 ms. This difference is mainly due to the underlying channel access methods with IEEE 802.11p and LTE-V2X. As mentioned above, IEEE 802.11p uses EDCA, wherein a node only transmits when the channel is sensed to be idle. On the other hand, LTE-V2X Mode 4 schedules the messages with SPS; however, the challenge arises when a packet exceeds the capacity of the selected sub-channel, necessitating the scheduling process to repeat. Therefore, with a packet size of 1000 bytes, the device is constantly rescheduling, which diminishes the efficiency of SPS and increases the latency for all transmitted messages.

The results above show that IEEE 802.11p consistently maintains communication latency below 10 ms across all instances. On the other hand, the latency with LTE-V2X fluctuates between 20 and 100 ms. This variability in latency with LTE-V2X can pose safety risks in applications that require low and/or consistent latency, e.g., emergency braking in a platoon. Our results also show that LTE-V2X offers

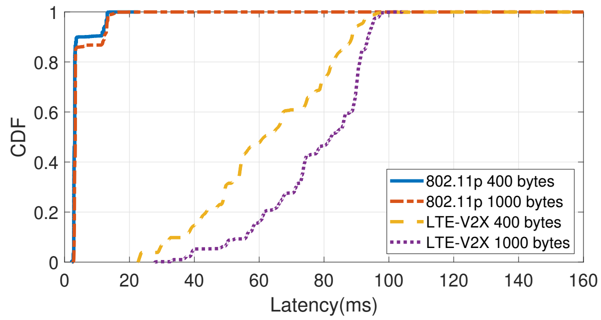


Fig. 5. CDF of latency with different packet sizes under Scenario 1. The MCS is set to 16QAM 0.75, and the transmission power is 20 dBm.

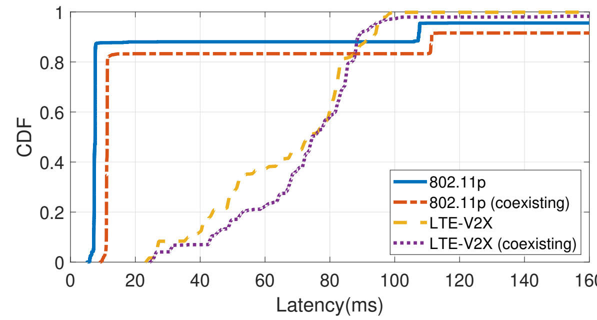


Fig. 6. CDF of latency with IEEE 802.11p and LTE-V2X working independently or sharing the channel under Scenario 2. The MCS is set to QPSK 0.5, transmission power is 5 dBm, and the packet size is 400 bytes.

broader coverage and effectively minimizes packet losses in NLOS environments. Nonetheless, this may present challenges in congested traffic scenarios, where a single transmitter could interfere with distant vehicles.

B. Evaluation of the coexistence of IEEE 802.11p and LTE-V2X

Fig. 6 illustrates a challenging scenario, in which a longer packet size of 400 bytes, low transmission power of 5 dBm, and longer inter-vehicle distances (NLOS with Scenario 2) are considered in the measurements. Under these configurations, the plots in Fig. 6 compare the performance of the two technologies when they operate independently and when they transmit on the same channel. The latency of IEEE 802.11p increases from 7 ms to 11 ms (without considering lost packets) when both communication technologies are accessing the same channel, while LTE-V2X experiences a smaller degradation. The PDR with IEEE 802.11p is also reduced from 67% to 52%, and LTE-V2X goes from almost no packet losses to a PDR of 89% (these results are not presented here for brevity). It is important to note that in a more realistic urban context with a higher density of vehicles, performance degradation would be even more pronounced due to increased channel congestion. The adverse impact on IEEE 802.11p is because its channel sensing mechanism, i.e., EDCA, becomes less effective in detecting opportunities for transmission when the channel is persistently occupied. In contrast, LTE-V2X demonstrates an ability to reserve periodic sub-channels, even if this results in some overlaps with other transmissions. These observations reveal that channel coexistence between IEEE 802.11p and LTE-V2X results in deteriorated performance for IEEE 802.11p, even with a single transmitter. Additionally, the increase of latency with only one of the communication technologies, i.e., IEEE 802.11p, implies that fair channel access is not guaranteed and LTE-V2X protocol obtains a higher priority over IEEE 802.11p.

VII. Validation of the Simulation Framework

In this section, the simulation results using the simulation framework and simulation settings described in Section IV are presented using the same evaluation metrics as in the previous section, i.e., PDR and end-to-end latency, for various MCSs and communication ranges. A hundred simulation runs are carried out with different seeds to compare the simulation results with the field test results.

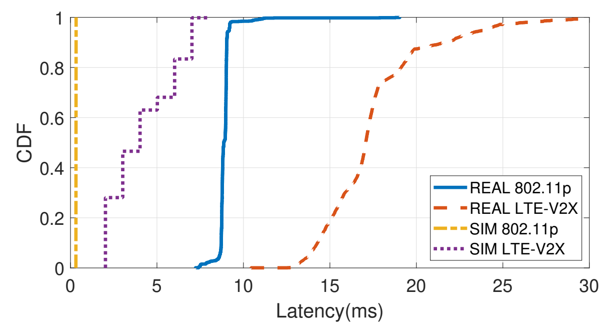


Fig. 7. CDF of latency with simulation and field test results under Scenario 1. The MCS is set to QPSK 0.50, the transmission power is 20 dBm, and the packet size is 200 bytes.

Fig. 7 presents the CDF of latency with real-world measurements and simulations under Scenario 1 (LOS). The results show that IEEE 802.11p demonstrates very consistent latency both in simulations and real-world measurements. On the other hand, LTE-V2X demonstrates longer and inconsistent latency, similar to the results in Section VI-A. As explained before, the SPS process implies allocating a random sub-channel up to 100 ms in advance, generating an additional inconsistent delay to the latency. Note that there is an absolute difference of around 8 ms between the simulated and measurement results. The main reason behind this difference is that in real scenarios, the hardware incurs an additional small processing delay, while the simulated latency only considers an ideal scenario.

Table III presents the PDRs with IEEE 802.11p and LTE-V2X using simulation studies and field tests for various inter-vehicle gaps and MCSs. The results of 100 simulation runs demonstrate that the PDRs with simulations do not exhibit any major deviations from the field test results. LTE-V2X exhibits no significant packet losses in any of the considered scenarios. In the case of IEEE 802.11p, the packet losses are very low with shorter inter-vehicle gaps; however, with longer inter-

TABLE III
PACKET DELIVERY RATIOS IN SIMULATIONS AND FIELD TESTS WITH IEEE 802.11P AND LTE-V2X FOR VARIOUS MCSS AND INTER-VEHICLE GAPS.

Technology	Gaps	MCS	PDR (real)	PDR (simulation)
802.11p	15-30 m	20 dBm QPSK 0.5	100%	100%
802.11p	15-30 m	5 dBm QPSK 0.5	100%	96%
802.11p	15-30 m	20 dBm 16QAM 0.75	100%	100%
802.11p	40-75 m	20 dBm QPSK 0.5	99%	92%
802.11p	40-75 m	5 dBm QPSK 0.5	61%	79%
802.11p	40-75 m	20 dBm 16QAM 0.75	85%	84%
LTE-V2X	15-30 m	20 dBm QPSK 0.48	100%	100%
LTE-V2X	15-30 m	5 dBm QPSK 0.48	100%	100%
LTE-V2X	15-30 m	20 dBm 16QAM 0.75	100%	100%
LTE-V2X	40-75 m	20 dBm QPSK 0.48	100%	100%
LTE-V2X	40-75 m	5 dBm QPSK 0.48	96%	100%
LTE-V2X	40-75 m	20 dBm 16QAM 0.75	100%	100%

vehicle gaps, low transmission power, or higher MCS index, the packet losses in both real and simulated environments increase considerably.

The results in this section indicate that the simulations are consistent with the field tests, validating the fact that simulation frameworks such as PLEXE and OpenCV2X can be used to study the performance of IEEE 802.11p and LTE-V2X technologies. Further, in the scenarios in which field tests are not feasible due to issues such as costs, scalability, etc., simulation studies present a viable alternative. Nevertheless, simulating the coexistence of IEEE 802.11p and LTE-V2X on the same channel using the simulation framework in Fig. 2 is not yet feasible. The rationale is that Veins and OpenCV2X have independent implementations for the PHY and MAC layers; thus, although both vehicular communication technologies can be used within the same scenario, they will not share the same channel manager and therefore will not affect the performance of one another.

VIII. CONCLUSIONS

This paper presents a performance comparison of the IEEE 802.11p and LTE-V2X communication technologies in terms of end-to-end latency and Packet Delivery Ratio (PDR) under various modulation and coding schemes, transmission powers, packet sizes, and communication ranges. Moreover, the feasibility of these two technologies in sharing the same communication channel is evaluated. To this end, real-world measurements have been carried out using commercial-off-the-shelf devices. Further, the field test results are correlated with simulation results obtained from the PLEXE and OpenCV2X simulation frameworks.

The field-test results indicate that IEEE 802.11p maintains a significantly lower and more consistent latency than LTE-V2X. While IEEE 802.11p and LTE-V2X experience similar PDRs in short-range communications, LTE-V2X facilitates wider coverage than IEEE 802.11p, even in NLOS scenarios. However, the broader coverage with LTE-V2X, while beneficial in sparse road and data traffic scenarios, may inadvertently escalate communication interference over longer distances in dense traffic scenarios. In general, our field test results reveal that IEEE 802.11p is better suited for safety-critical applications for automated vehicles which communicate to enable local collaboration. It also shows that IEEE 802.11p does not cope well when required to coexist with LTE-V2X. Moreover, the real-world measurements show high consistency with the simulation results demonstrating that the PLEXE and OpendCV2X frameworks are viable options for carrying out such performance comparisons and studying complex cooperative automated vehicle applications.

Furthermore, in situations where short inter-vehicle gaps and LOS are ensured, reducing the transmission power for both, IEEE 802.11p and LTE-V2X, can minimize interference with vehicles that are distant from the transmitter. Additionally, a higher MCS index in such scenarios could further contribute to latency reduction, improving the reliability of the system.

The experimental results with IEEE 802.11p and LTE-V2X sharing the same channel demonstrate higher interference experienced by the vehicles. Moreover, IEEE 802.11p experiences higher latency and PDRs during the simultaneous usage of the same channel by the two technologies due to unfair channel access by LTE-V2X, resulting in a detrimental impact solely on IEEE 802.11p performance. Addressing such disparities in channel access is also important to establish fair and efficient communication protocols within vehicular networks.

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