



HAL
open science

A Study of LTE-V2X Mode 4 Performances in a Multiapplication Context

Chourouk Ghodhbane, Mohamed Kassab, Sassi Maaloul, Hasnaa Aniss,
Marion Berbineau

► **To cite this version:**

Chourouk Ghodhbane, Mohamed Kassab, Sassi Maaloul, Hasnaa Aniss, Marion Berbineau. A Study of LTE-V2X Mode 4 Performances in a Multiapplication Context. *IEEE Access*, 2022, 10, pp63579-63591. 10.1109/ACCESS.2022.3182508 . hal-03745774

HAL Id: hal-03745774

<https://hal.science/hal-03745774>

Submitted on 4 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Received April 19, 2022, accepted May 19, 2022, date of publication June 13, 2022, date of current version June 20, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3182508

A Study of LTE-V2X Mode 4 Performances in a Multiapplication Context

CHOUROUK GHODHBANE¹, MOHAMED KASSAB¹, SASSI MAALOUL²,
HASNAË ANISS², AND MARION BERBINEAU³, (Member, IEEE)

¹ISIMM, University of Monastir, Monastir 5000, Tunisia

²COSYS-ERENA, Université Gustave Eiffel, 77454 Bordeaux, France

³COSYS, Université Gustave Eiffel, 77454 Villeneuve-d'Ascq, France

Corresponding authors: Chourouk Ghodhbane (choughchou@gmail.com) and Marion Berbineau (marion.berbineau@univ-eiffel.fr)

ABSTRACT With the growing importance of cooperative intelligent transport systems (C-ITS), 3GPP has standardized LTE-V2X (Long Term Evolution - Vehicle-to-everything) in Release 14 to address specifically vehicle-to-everything (V2X) connectivity. This standard introduces a mode 4, in which vehicles allocate radio resources autonomously without cellular infrastructure support for direct vehicle-to-vehicle (V2V) communications. However, as LTE-V2X is a recent technology (compared to WAVE and ITS-G5), it is not sufficiently evaluated in the literature. In this work, we propose an evaluation of LTE-V2X mode 4 performances considering the impact of the parameters of the sensing-based resource allocation mechanism, the traffic load and the Quality of service (QoS) mechanism. In addition, we propose a comparative study of LTE-V2X mode 4 with ITS-G5. Based on several simulation scenarios from 3GPP, we prove that the Sensing-based SPS mechanism parameters and the traffic load significantly impact the performance offered by LTE-V2X. In addition, we show that the QoS mechanism of LTE-V2X outperforms the ITS-G5 one in a realistic multi-application context.

INDEX TERMS ITS-G5, LTE-V2X, QoS, SPS, V2V.

I. INTRODUCTION

Cooperative intelligent transport systems (C-ITS) are attracting more and more attention in today's world. As a result, a set of applications dedicated to road safety were specified, such as obstacle detection, traffic management, such as track access control, and applications for entertainment, such as parking places availability. These applications are based on collaboration among vehicles and among vehicles and infrastructures by exploiting V2V (vehicle-to-vehicle) and V2I (vehicle-to-infrastructure) wireless communications. Thanks to C-ITS deployment, road users will benefit from increased safety, reduced congestion and user-friendly driving.

To set up the V2X communications required for C-ITS operation, several wireless communication technologies have been developed. Initially, two main technologies are derived from the IEEE 802.11p wireless standard and operate in the 5.9 GHz unlicensed band. The first one is the Wireless Access in Vehicular Environments (WAVE) technology [1], standardized in North America since 2010. The second one is

the Intelligent Transportation System ITS-G5 technology [2], standardized in 2012 by the European Telecommunications Standards Institute (ETSI). WAVE and ITS-G5 are mature technologies, but this notion of maturity must be considered with caution since the results of the deployment tests have shown technological limitations [3] such as limited radio range and especially limited data performance in terms of latency and traffic load resistance.

In parallel, an alternative derived from 4G cellular networks for V2X communication is proposed by 3GPP: the LTE-V2X. LTE-V2X introduces, particularly, the mode 4 developed explicitly for V2V communications based on the interface "PC5". In LTE-V2X mode 4, vehicles do not necessarily have to be located in the coverage area of the base station. An autonomous resource selection mechanism called Sensing-based SPS (Semi Persistent Scheduling) is implemented. Mode 4 imposes several technological challenges, putting aside the centralized management of LTE technology.

Several research works have been interested to performances offered by LTE-V2X mode 4. These works focus on evaluating the sensing-based SPS mechanism and the impact of its parameters on the performance provided by

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Jiang¹.

LTE-V2X ([4]–[7]). In addition, several works have been interested in comparing LTE-V2X and the IEEE802.11p type technologies (ITS-G5, WAVE) [8], [9]. Despite the number of works related to this issue, several shortcomings make that current knowledge of LTE-V2X performances remains partial. First, available evaluations focusing on applications based on periodic messages such as Cooperative Awareness Messages (CAM) and event-based applications using Decentralised Event Notification Messages (DENM) are not considered. Although event-based messages allow to develop advanced driver assistance applications. Second, the quality of service (QoS) mechanism of LTE-V2X mode 4 is not evaluated or even suggested for evaluation until now. Third, different works comparing LTE-V2X mode 4 and IEEE802.11p type technologies have proposed wildly divergent results and conclusions.

Based on this observation, we propose, in this paper, to extend the existing state of the art related to the evaluation of the LTE-V2X mode 4 performances by proposing:

- Realistic evaluation scenarios proposing a multi-application context that considers, in addition to CAM messages, event-based DENM messages
- The integration of the priority based medium access defined by the QoS mechanism to simulation scenarios
- an evaluation of the impact of traffic load, sensing-based SPS parameters and QoS priorities on performances offered to C-ITS applications
- a comparative study of LTE-V2X mode 4 with ITS-G5 based on clearly defined configurations that helps to clarify today confusion in performance comparisons of LTE-V2X and IEEE802.11p type technologies (ITS-G5, WAVE).

The structure of the document is the following. Section II introduces the LTE-V2X technology. In section III, we discuss briefly the related works. In Section IV, we summarize our simulation environment. Before conclusion and perspectives, in the sections V and VI, the main simulation results are presented.

II. LTE-V2X MODE 4

In 2017, 3GPP introduced the LTE-V2X to provide a viable alternative to the existing 802.11p technology. LTE-V2X was developed with multiple deployment scenarios in mind, leading to the following needs: operations with or without base station (eNB) coverage, autonomous operation on an unlicensed dedicated band or on a licensed band, and enhanced Device-to-Device (D2D) radio interface functionality to support low latency, high density and high speed. To answer these needs, LTE-V2X Release 14 was designed to introduce new Sidelink transmission modes 3 and 4. Within mode 3, also called “cellular-assisted”, the vehicles should be within the coverage area of the base station (Fig. 1) as the radio resources of the user equipment (UE) are allocated under the eNB station using control signaling on the Uu interface. Within mode 4, also known as “pure V2V Adhoc”, vehicles do not have to be within the base station coverage area (Fig. 2)

as an autonomous radio resource selection mechanism is implemented. In this mode, the unlicensed band in the 5.9 GHz band is targeted. Thus, LTE-V2X can operate both inside and outside network’s coverage. This mode is primarily used for V2V communications, as communication between vehicles cannot depend on cellular coverage. Later in this section, we will focus on mode 4.

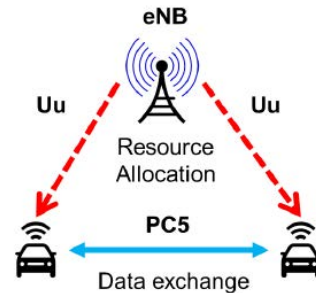


FIGURE 1. LTE-V2X mode 3 principle.

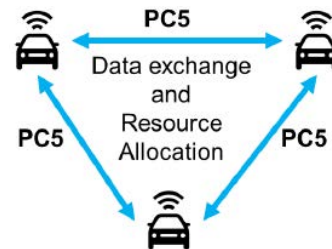


FIGURE 2. LTE-V2X mode 4 principle.

A. RESOURCES GRID AND FRAME STRUCTURE

LTE-V2X can support both 10 and 20 MHz channel bandwidths (a two-dimensional resource grid represents a bandwidth). This study considers a 10 MHz channel bandwidth. The channel bandwidth in the resource grid is split into sub-channels in the frequency domain and into sub-frames in the time domain. In the frequency domain, the sub-carrier gap is set to 15 kHz, and the sub-carriers are used in sets of 12 (180 kHz) called Resource Block (RB). The 14 OFDM symbols, forming a TTI (Transmission Time Interval) in the time domain, constitute a subframe of 1 ms. In LTE-V2X, the sub-channel represents the minimum resource to be allocated in the frequency domain, which corresponds to a multiple of the 12 sub-carrier sets (RBs), while in the time domain, it is the TTI (a packet occupies one or more sub-channels in a TTI). The LTE specification [10] defines the numbers and sizes of possible sub-channels:

Number: [1, 3, 5, 10, 15, 20]

Size: [4, 5, 6, 8, 9, 10, 12, 15, 16, 18, 20, 25, 30, 48, 50] RB

A vehicle that would like to transmit a Transport Block (TB) includes a Decentralized Environmental Notification Message (DENM) or a CAM. An associated Sidelink Control Information (SCI) must also be transmitted, and the

other vehicles should receive the SCI correctly to ensure the transmitted TB decoding operation. The transmission of the SCI is usually carried out in the same sub-frame as its TB, and occupies the two first RBs of the primary sub-channel used. This method of occupying RBs called Adjacent PSCCH, PSSCH. The TB is transmitted in the RBs that follow the SCI, and according to its size, it may occupy the RBs of other sub-channels. Physical Sidelink Control Channel (PSCCH) and Physical Sidelink Shared Channel (PSSCH) are two physical channels introduced by LTE-V2X release 14. PSSCH is used to transmit Transport Blocks, while PSCCH is used to transmit the associated SCI.

B. SENSING-BASED SPS

LTE-V2X mode 4 uses the sensing-based SPS algorithm to organise resource allocation, which relies on listening to the channel before transmission to avoid selecting resources already in use, allowing for simultaneous transmissions and, thus, possible collisions. The Sensing-based SPS mechanism was developed in LTE-V2X to prevent the necessity to frequently select or re-select resources. When a station wants to get a new resource, it considers the resource reservation field information contained in the received SCI messages to determine, which other stations in the network already use the resources. The decisions are also based on the Sidelink Reference Signal Received Power (S-RSRP) and the Received Signal Strength Indicator (RSSI), self-calculated parameters at the station.

In LTE-V2X mode 4, the selection of radio resources is performed within a period, set in the interval [20...100] ms, according to the requirements of the previous layers, called the selection window. It is defined as $[n+T1, n+T2]$ where n is the instant at which the vehicle decides for a new resource allocation, $1 \leq T1 \leq 4$ and $20 \leq T2 \leq 100$ ($T1$ and $T2$ are selected by the vehicle). The vehicle determines a list of candidate resources (CRs) during the selection window. A CR is a set of adjacent sub-channels that the desired packet can be inserted into. When a packet is to be delivered, the most recent 1000 ms of the detection history, called the detection window, is scanned to identify any resources that others may take. The detection period and selection window are shown in Fig. 3. From the selection window, the station rejects resources that other stations will reuse and exceed a fixed RSRP threshold. After eliminating these resources, it must find that the set of candidate resources is equal to at least 20 % of the initial list of candidate resources. If this is not the case, the RSRP threshold will be raised by 3 dB. Then, the station identifies exactly the 20 % of candidate resources with the minimum average RSSI calculated during the detection period. Lastly, a resource is randomly selected from the set of resources considered in the preceding step.

Considering the random selection method permits to avoid situations where several stations choose the same resource with the lower RSSI. After the selection of a resource, it is booked for the n future transmissions, where n is randomly chosen from 5 to 15 while the new resource is selected

and called re-selection counter. After each transmission, this counter is decremented by one. Once it hits zero, the vehicle chooses whether to maintain the same resource with probability Kp (the *Keep probability*) or to start selecting a new resource using the sensing-based SPS with probability $(1-Kp)$. The value of Kp , is not fixed by the standard, it can be any value in the interval [0, 0.2, 0.4, 0.6, 0.8], and the station declares the reserved resource in the resource reservation field of the SCI shown in Table 1.

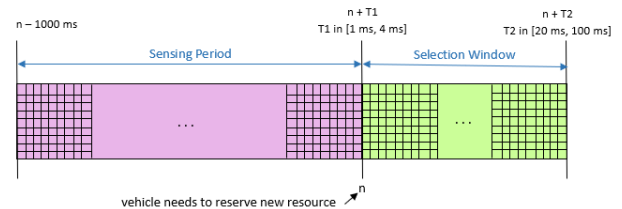


FIGURE 3. Sensing period and selection window.

C. QoS MANAGEMENT

In LTE-V2X mode 4, the QoS management is based on the Release 13 ProSe (Proximity-based Services) QoS mechanism using Per Packet ProSe Priority (PPPP). Direct ProSe discovery is the procedure used by the ProSe-enabled UE (user equipment) to discover other nearby ProSe-enabled UEs using direct E-UTRA radio signals via the PC5 interface. In 3GPP Rel-13, QoS is generally supported for ProSe one-to-many communications. Therefore, PPPP was introduced in TS 23.303, version 13.4.0 [11]. The PPPP is a scalar value (range of 8 possible values) associated with a protocol data unit, e.g. IP packet, that reflects the priority and latency of the V2X message for the sidelink. The PPPP enables packet prioritization. The application layer assigns a PPPP (indicated in the priority field of the SCI message) for each V2X message when it delegates it to the lower layer. The priority is assigned based on various criteria, such as the delay requirements of the service. The UE serves all packets associated with a N -valued PPPP before serving packets associated with an $N+1$ -valued PPPP (a lower number means a higher priority). The SCI message includes for the PSSCH the scheduling information. It is 32 bits long, as illustrated in Fig. 4. The Priority field reflects message's importance, like DENM and CAM messages standardized by the European standard ETSI. CAMs are short messages broadcast periodically by each vehicle to its neighbors to include information on the presence, position and kinematics. DENMs are also short messages but they are triggered by events and broadcast to alert road users of a hazardous event.

III. RELATED WORKS

A. LTE-V2X SENSING-BASED ALGORITHM EVALUATION

Most research on LTE-V2X performance evaluation have focused on evaluating the sensing-based SPS algorithm [4]–[7], studying its main parameters and their impact on LTE-V2X performance.

TABLE 1. Resource reservation SCI's field [13].

Resource reservation field in SCI format 1	Corresponding value X	Indication
'0001', '0010', ..., '1010'	Decimal equivalent to the field [1, 2, ..., 10]	The same resource is reserved for the next transmission after (100*X) ms
'1011'	0.5	The same resource is reserved for the next transmission after 50 ms
'1100'	0.2	The same resource is reserved for the next transmission after 20 ms
'0000'	0	The same resource is not reserved for the next transmission
'1101', '1110', '1111'	Reserved	Reserved

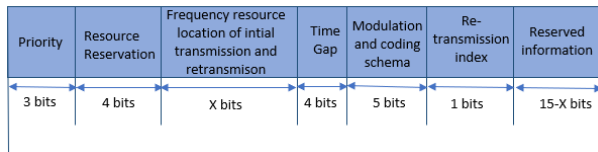


FIGURE 4. SCI message format [13].

Molina et al. showed in [4] that the Sensing-based SPS offers slightly better performances compared to a random resource allocation based on the Packet Delivery Ratio (PDR) at short and medium distances. Its gains decrease with the distances between vehicles. The inclusion of Hybrid Automatic Repeat reQuest (HARQ) almost cancels the benefits of sensing-based SPS compared to random allocation. In this paper, the authors have shown that at short and medium distances, the collisions cause the majority of errors. On the other hand, propagation errors dominate at longer distances.

The same authors [5] have shown that increasing the Keep probability (K_p) value reduces the PDR in situations where the channel overload, although the variation in K_p values is not deep. They also showed that changing the sensing window (SW) size from its standard value (1000 ms) to a non-standard exponential window or to a shorter window produces some improvement although the gains are very small. In addition, they found that the size of the selection list has no meaningful impact and that changing the RSRP threshold has no impact at low channel loads. In contrast, a low power threshold in the highest channel loads improves the PDR. Finally, they proved that reducing the transmit power in low loads decreases the PDR but has a negligible effect in high loads.

Bazzi et al. showed in [6] that mode 4 offers an Update Delay (UD) equal to the double or above compared to the random allocation. The authors concluded that a higher K_p improves the Packet Reception Ratio (PRR) at the risk of larger UD.

In [7], Nabil et al. found that the increase of the SPS resource reservation interval and the total of available sub-channels increases the PDR while the value of K_p has an insignificant effect for high network density. Consequently, the Sensing-based SPS parameters significantly impact the performances of LTE-V2X mode 4. Other researches present contradictory results, such as [6], that states the significant effect of K_p value on PRR or PDR performances, while the results of [5] and [7] show the opposite. The general

consensus of the recent works in this topic is that the sensing-based SPS algorithm, as it operates today, needs improvements to enhance its performance. Several researchers have started looking at possible improvements [12] and [13]. In addition to existing sensing-based SPS resource allocation mechanism, in [30], authors have provided a comprehensive overview of resource allocation (RA) schemes for IEEE 802.11p and LTE-V2X in various studies. They have analyzed the communication performance for these schemes. In the vehicular network based on LTE-V2X and more precisely in the context of an out-of-coverage scenario, they examined three studies that propose new RA schemes that aim at improving the communication performance offered by LTE-V2X and that are totally different from the main "sensing-based SPS" allocation strategy implemented in the 3GPP LTE-V2X mode 4. The authors consider here a continuous transmission of CAM messages with a period of 100 ms. They also suggested future research guidelines for resource allocation using machine learning, network slicing and context awareness.

In [31], the authors have focused on the fact that differences in message size is a source of poor performance in LTE-V2X. The approach proposed in this paper aims to reorganize the subframe structures to address this problem, and solve it as a combinatorial optimization problem to maximize the number of vehicles that can simultaneously allocate resources. For the evaluation, authors have implemented a model used by 3GPP during the LTE-V2X standardization process that considers periodically generated CAM messages with two sizes: 190 bytes and 300 bytes. The results have shown a growth system capacity. All these works have evaluated the Sensing-based SPS resource allocation mechanism. In particular, they have shown the significant effect of the sensing window and the keep probability on the performance offered by LTE-V2X. The results are obtained as a function of the transmitter-receiver distance in evaluation contexts characterized by periodic CAM traffic. In [31], the evaluation has the particularity to consider a variation of transmitted messages through the variation of size of CAM messages in comparison of other research works. However, the variation in CAM message size cannot lead to a multi-application C-ITS context. The definition of C-ITS context considering DENM based applications is required to evaluate the priority-based QoS mechanism of LTE-V2X mode 4.

In this paper, we propose to overcome the limitation of current works by considering a C-ITS context which includes

traffic based on periodic CAM messages and event-driven DENM messages. We consider the results of cited research to validate our scenarios configuration before progressing to more realistic evaluations in a multi-application context, which gives us the ability to evaluate the QoS mechanism of the LTE-V2X mode 4.

B. LTE-V2X MODE 4 COMPARISON WITH EXISTING VEHICULAR TECHNOLOGIES

The comparison of LTE-V2X mode 4 with existing vehicular communication technologies is an active research topic. Existing works cover comparison with ITS-G5, comparison with WAVE and comparison with IEEE802.11p.

The papers [8], [14], [15], [16] present comparisons of the LTE-V2X performance with that of ITS-G5. Cecchini *et al.* has shown in [14] that in a scenario characterized by a congested highway, the LTE-V2V mode 3 always outperforms ITS-G5 and LTE-V2V mode 4 regarding PRR, and that ITS-G5 provides better performance than LTE-V2V mode 4 for short communication distances. However, for distances between 350 and 400 m, LTE-V2V mode 4 outperforms slightly ITS-G5 and provides better reliability over very long communication distances. The authors also proved that in terms of UD, LTE-V2V mode 4 offers very low performance compared to mode 3 and ITS-G5.

Mannoni *et al.* has shown in [15] that in a disc-shaped static network of certain number of vehicles dependent on the network load, the LTE-V2X mode 4 performs better than ITS-G5 for low levels of vehicle density, while as congestion increases in terms of range, the performance difference narrows until finally, ITS-G5 surpasses LTE-V2X. In addition, the comparison of access time to resources shows an advantage to ITS-G5. The authors also proved that, ITS-G5 has a very less latency than LTE-V2X, and that the gap between the two technologies tends to reduce as the communication range increases until LTE-V2X eventually surpasses ITS-G5.

In [8], Roux *et al.* highlighted that in a Manhattan scenario, the LTE-V2X mode 4 always outperforms ITS-G5 in terms of PDR. Bazzi *et al.* evaluated in [16] the possibility that the two technologies LTE-V2X and ITS-G5 share the same channel considering the highway scenario defined by 3GPP [17], the same frequency channels. The simulation results showed that the ITS-G5 range is significantly degraded under channel coexistence whereas the effect on LTE-V2X is negligible. The principal cause of the significant effect of LTE-V2X interference on ITS-G5 is that LTE-V2X has the ability to estimate correctly the ITS-G5 stations channel usage. The negative impact of LTE-V2X signals on ITS-G5 is indeed decreased by varying the distance for various technology distributions.

The papers [18]–[20] compare the performance of LTE-V2X with that of IEEE 802.11p. Molina-Masegosa *et al.* highlighted in [18] that in the highway slow and fast scenarios described by the 3GPP Working Group in [17], the LTE-V2X mode 4 generally offers better performance, but IEEE 802.11p with 18 Mb/s data rate may be preferable in

case of higher channel load (50 packets/second). In [19], Molina-Masegosa *et al.* has shown that in a highway scenario, the LTE-V2X outperforms IEEE802.11p at low traffic density in terms of PDR but with increasing density, IEEE802.11p outperforms LTE-V2X at low communication distances. They also showed that IEEE802.11p has a very high packet loss percentage due to propagation conditions compared to LTE-V2X. Considering three simulation scenarios named Cologne, Bologna and Highway, Bazzi *et al.* proved that in terms of PRR, LTE-V2X mode 4 performs better than IEEE 802.11p [20]. In addition, LTE-V2V mode 4 offers lower UD than IEEE 802.11p in the highway scenario but a higher UD in the other two scenarios. Thus, authors proposed an enhancement of IEEE 802.11p by the PHY layer of LTE-V2X. The results with an enhanced PHY layer showed that, the performance in terms of PRR get to be similar to that of LTE-V2X, while providing a lower UD.

The papers [9], [21]–[23] highlight comparisons of the performance of LTE-V2X with that of WAVE. In [9], Nguyen *et al.* has shown that in the two highway and Manhattan scenarios described in [17], the LTE-V2X mode 4 provides a significant improvement regarding the communication range compared to WAVE. In the Manhattan scenario, the profit in terms of communication range decreases, although it is smaller in absolute value than in the highway case, it can also has a significant impact on urban transport security. Wang *et al.* has proven in [21] that in the freeway fast and urban slow scenarios described in [17], the LTE-sidelink works the same or better than multicast on short distances, but less well on long distances, and that LTE-sidelink mode 3 works better than mode 4 due to eNB central coordination. As long as, WAVE still works less well than LTE-multicast and LTE-sidelink. In the end, the authors found that LTE-sidelink and LTE-multicast can support higher vehicle densities than expected in the 3GPP scenario.

In [23], Shimizu *et al.* has shown that in a highway scenario, WAVE outperforms LTE-V2X in terms of Information Age (IA) and Inter-Packet Gap (IPG). In terms of Packet Error Rate (PER), the performance of WAVE and LTE-V2X are comparable, except for long distance V2V, LTE-V2X achieves better performance than WAVE. Shimizu *et al.* has proven in [22] that in a highway scenario, in a case of low vehicle density, both technologies are comparable or LTE-V2X offers a greater range of V2V communication, while in a case of high vehicle density, WAVE achieves higher performance than LTE-V2X. The authors also proved that WAVE achieves smaller end-to-end latency than LTE-V2X.

All these recently detailed papers have compared the performance of LTE-V2X technology with other existing vehicular communication technologies. They have shown a significant gap between the performances offered by the different technologies in terms of several metrics such as PDR, PRR, *etc.* But it is not yet clear if this gap is in favor of which technology exactly, as we have shown that some papers highlight quite the opposite results. Thus, this paper, will

present a new comparative study of LTE-V2X with ITS-G5 in a multi-flow context. We have considered ITS-G5 because it is today the most mature technology in terms of deployment among the IEEE 802.11p type technologies.

IV. SIMULATION CONTEXT

In this section, the simulation context chosen in our performance evaluation is described. We have considered in this study the network simulation and the OpenCV2X [24] simulation platform. OpenCV2X is an open source implementation of LTE-V2X mode 4 based on an extended version of the SimuLTE simulator, originally developed to simulate cellular networks based on LTE technology. This framework incorporates the SUMO road traffic simulator and the OMNeT++ network simulator and integrates the Vanetza framework, which delivers the ITS-G5 implementation.

A. SIMULATION SCENARIO

We consider a simulation scenario that models a highway use case. It is based on a reference scenario considered by the 3GPP working group and defined in [17]. It is modeled by a highway of 5 km with 6 lanes in total, 3 lanes per direction, each 4 m wide, as shown in Fig. 5. We vary the network load characteristics in terms of the number of vehicles, speed and inter-vehicle distance (see Table 2).

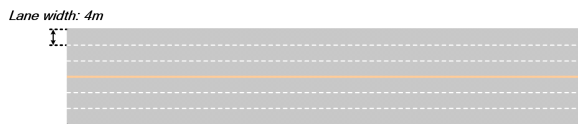


FIGURE 5. 3GPP highway scenario.

In addition, we propose an evaluation context that considers a set of applications associated to different QoS priorities: applications based on DENM messages and one application based on CAM messages. Table 3 summarizes application characteristics.

B. SIMULATOR CONFIGURATION

Regarding the radio configuration of LTE-V2X, we considered a bandwidth of 10 MHz and a carrier frequency of 5.9 GHz with a resource grid of 48 RBs partitioned into 3 sub-channels in the frequency domain (see Table 4).

For the radio configuration of ITS-G5, we considered a carrier frequency at 5.890 GHz with a transmission power of 12 mW (see Table 5). 3 iterations of each experiment have been conducted for all results presented in the following sections. The results showed very low variance with 99% confidence intervals.

V. LTE-V2X MODE 4 PERFORMANCE EVALUATION

In this section, we evaluate the performances offered by the LTE-V2X mode 4 considering the network load, the parameters of the Sensing-based SPS mechanism and the QoS priorities.

A. NETWORK LOAD

To understand the influence of the network load on LTE-V2X mode 4 performances, we evaluate the Percentage of Packet Delivery (PPD), and the Percentage of Packet Loss (PPL) within the fast, slow and congested highway scenarios. PPD and PPL are shown as a function of the distance between transmitter and receiver.

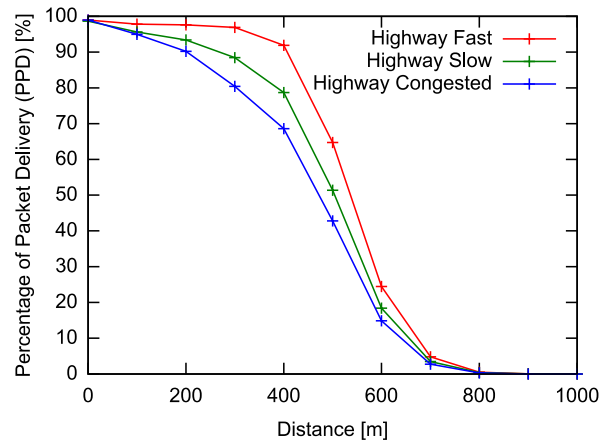


FIGURE 6. Percentage of Packet delivery (PPD) as a function of transmitter-receiver distance.

Fig. 6 shows the Percentage of Packet Delivery (PPD) as a function of the distance for the three scenarios. With the Fast highway scenario, which represents the lowest network load compared to the other scenarios, we obtain the best PPD values and, therefore, the best data delivery performance. Considering a transmitter-receiver distance higher than 500 meters, the data delivery performances decrease considerably independently of the network load. These results show that the transmitter-receiver distance remains the predominant parameter with respect to the data transmission efficiency.

To better understand the previous results, we have determined the cause of each TB transmission loss that can be classified as:

- 1) Half-Duplex: The reception of the TB fails because the receiver was transmitting in the same sub-frame.
- 2) Propagation: This type of error excludes those quantified in 1). The reception of the TB fails because it has not been received with sufficient SNR to decode it correctly.
- 3) Interference: This type of error excludes those quantified in 1) and 2). The reception of a TB fails because it has not been received with sufficient SINR to correctly decode it because of the interference/collisions from other vehicles.

Fig. 7 presents the percentage of packet loss due to each cause as a function of the transmitter-receiver distance for the three scenarios. We can observe that with short transmitter-receiver distances, the main cause of packet loss is interference for all scenarios. As the distance increases, the propagation becomes the main cause of packet loss. For the

TABLE 2. 3GPP highway evaluation scenarios.

Parameter	Highway Fast	Highway Slow	Highway Congested
Road	2 km	2 km	2 km
Number of vehicles	126	246	320
Maximum speed	38.89 m/s	19.44 m/s	15.1 m/s
Acceleration	2.6 m/s ²	2.6 m/s ²	2.6 m/s ²
Deceleration	4.5 m/s ²	4.5 m/s ²	4.5 m/s ²
Inter-vehicle distance	50 m	20 m	10 m
Probability of insertion	0.5	0.5	0.5
Simulation duration	512 s	512 s	512 s

TABLE 3. Data flow parameters for LTE-V2X evaluation.

Flow	Priority	Message size	Inter-packet delay	Repetition interval	Diffusion area
App1 DENM	0	124 bytes	0.1 s	1 s	1 km
App2 DENM	1	124 bytes	0.1 s	1 s	1 km
App3 DENM	5	124 bytes	0.1 s	1 s	1 km
App4 DENM	7	124 bytes	0.1 s	1 s	1 km
CAM	7	141 bytes	[0.1 ; 1] s	-	-

TABLE 4. LTE-V2X radio configuration.

Bandwidth	10 MHz
Carrier frequency	5.9 GHz
Number of sub-channels	3
Subchannel size	16 RBs
Sensing Window	1000 ms
Keep Probability	0.4
RSRP	-128 dBm
Message transmission rate	10 Hz
Transmission power	23 dBm
MCS (Modulation and Coding Schema)	[7,9]

TABLE 5. ITS-G5 radio configuration.

Carrier frequency	5.890 GHz
Data rate	6 Mbps
Transmission power	12 mW

three scenarios with great distances (beyond 600 meters), the losses are mainly caused by interference. The influence of the network load on the results obtained becomes more and more insignificant as the distance increases, which justifies the results of Fig. 6. On the other hand, the results of Fig. 7 show that the difference in network load for the three scenarios significantly impacts the percentage of packet loss due to interference. At a distance of 500 meters, the percentage of packet loss increases from a value of 7 % with the Fast Highway scenario (low network load) to a value of 36 % with the Congested Highway scenario (high network load). These results show that interference remains a significant factor in data loss, especially with increasing network load.

We show by these results that the sensing-based SPS mechanism used by LTE-V2X mode 4 to manage channels significantly loses efficiency with the increase of network load. Further improvements of the sensing-based SPS should be investigated.

B. INFLUENCE OF SENSING-BASED SPS PARAMETERS

As presented in section II, Sensing-based SPS mechanism operations are based on two configurable parameters: keep probability (Kp) and sensing window (SW). To better understand the influence of these parameters we evaluate their impact on packet loss. We evaluate the percentage of packet loss (PPL) due to interference within the congested highway scenario considering different values of these parameters.

Fig. 8 presents the percentage of packet loss (PPL) as a function of the sensing window (SW) size. Results show that the increase of the sensing window size leads to a decrease the percentage of packet loss. Indeed, increasing the size of the sensing window gives more historical information that forms the basis for the selection process of the Candidate Single-Subframe Resources (CSR), which increases the efficiency of this process to avoid contention channel access.

However, the increasing the SW size is not always the optimal solution as the impact of SW size varies according to the traffic load. For example, when the traffic load is low, most of the CSRs are available, and the probability that two vehicles select the same resource remains low in this case choosing a high SW size increases the data transmission delays, as the sender has to wait for the duration of the SW before sending the data.

Fig. 9 presents the percentage of packet loss (PPL) as a function of the keep probability value. Results show that

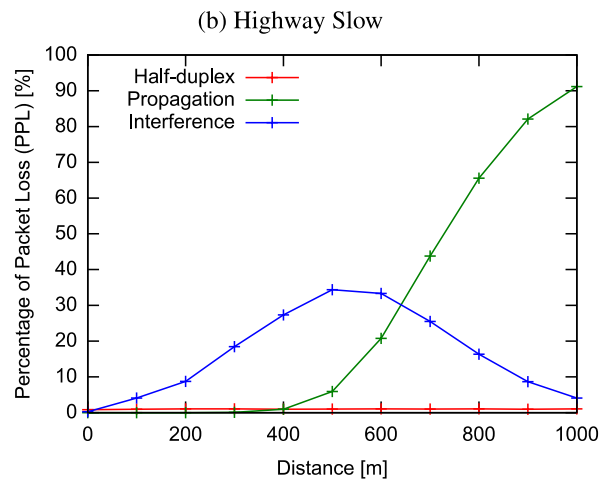
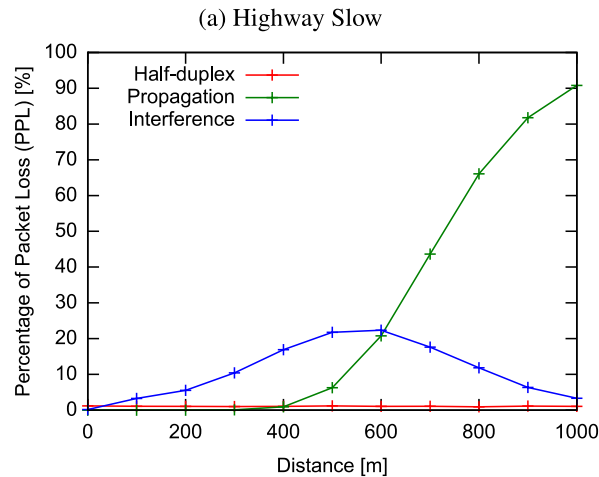
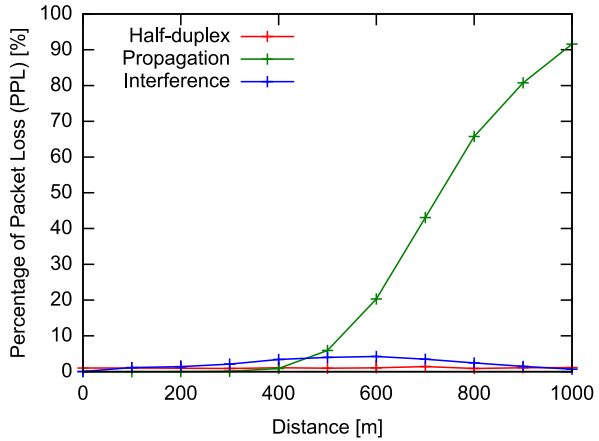


FIGURE 7. Percentage of Packet Loss (PPL) as a function of transmitter-receiver distance.

greater values of keep probability improve data delivery performances. In addition, a high value of K_p increases the stability of resource reservations and it offers a more stable sensing environment, which benefits the sensing-based SPS operations independently of the channel load.

As for SW size, the increasing of the k_p value is not necessarily an optimal choice. A first counterexample is a vehicle

generating a traffic with variable packet size that requires different number of sub-channels. If the K_p is equal to 1, from one transmission to another, the vehicle may find itself in a situation of underestimating the resource needs. This leads to a resource re-selection, while old resource remains reserved until the next SCI informs the other vehicles that the resource is available. A second counterexample is a vehicular context with a high variability of vehicles' neighborhood. With a K_p is equal to 1, a vehicle selects resources almost permanently. When the vehicle change its range zone where the resources are reserved by another vehicles, which leads to collisions. Thus, a high K_p value results in a performance loss in these two cases.

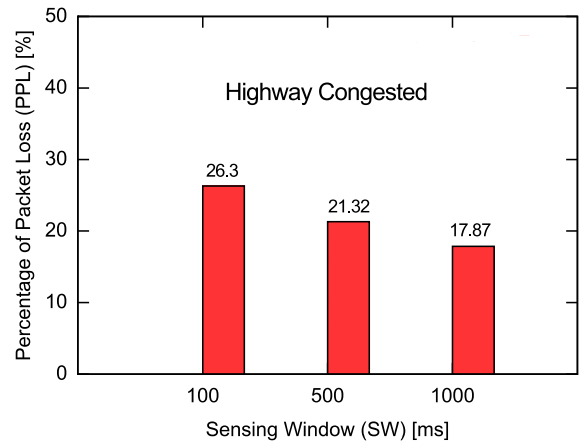


FIGURE 8. Percentage of Packet Loss (PPL) due to interference as a function of SW value.

C. IMPACT OF QoS PRIORITIES

The QoS management of LTE V2X mode 4 is based on the Per Packet ProSe Priority (PPPP) mechanism (c.f. subsection II-C. PPPP proposes 8 priorities to prioritize access to the radio channel. As presented in section IV, we consider the PPPP priorities in our scenarios that implement 5 applications having different priorities (c.f. Table 3). To understand the influence of these priorities, We evaluate the amount of total number of well received messages DENM messages and the number of these messages for each application. Then, we present the percentage of well received messages (from the total) for each application. We perform this evaluation in fast, slow, and congested highway scenarios as shown in Fig. 10.

Obtained results highlight the effectiveness of the PPPP mechanism to offer differentiated services based on assigned priorities. App1 with the highest priority has the highest percentage of received DENMs compared to other applications. In addition, a high priority for an application guarantees the performances even in highly congested conditions (for App1 in Fig. 10) although there is a slight drop in the percentage of received message for the application. On the other side, we show an increase of the percentage of received messages for App4 (with the lowest priority) while the network load increases.

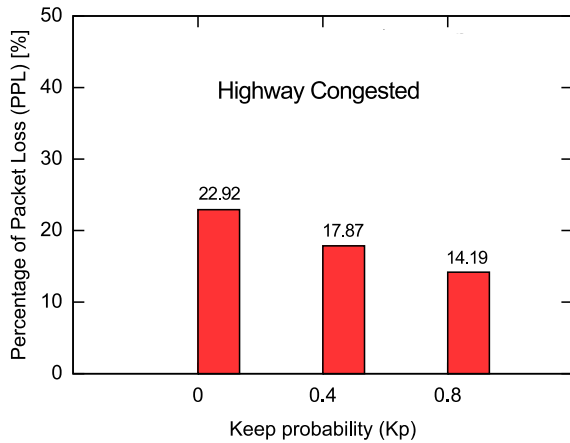


FIGURE 9. Percentage of Packet Loss (PPL) due to interference as a function of Kp value.

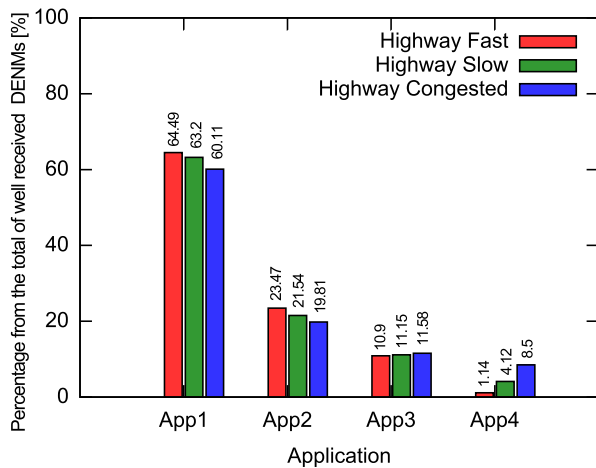


FIGURE 10. Percentage per application of well Received DENMs with LTE-V2X.

The PPPP mechanism manages the transmission according to the priority order. Thereby, the packets with the highest priorities will be at the front of the queue and they will be the first to suffer from the collisions generated by the network load. Then, the lower priority packages will benefit from occasional reduction of the queue size (and consequently of less network load) following the collisions to be successfully transmitted.

VI. PERFORMANCE COMPARISON OF LTE-V2X AND ITS-G5

As a second part of evaluation, we propose comparing performances offered by LTE-V2X and ITS-G5 to C-ITS applications. We focus this comparison on the QoS mechanisms proposed by both technologies as at the best of our knowledge this comparison has not been proposed yet in the literature. We consider the packet reception ratio (PRR) and the inter-packet gap (IPG) as performance indicators.

A. QoS MANAGEMENT IN ITS-G5

EDCA (Enhanced Distributed Channel Access) is the QoS mechanism proposed by ITS-G5. It is defined in the IEEE802.11e standard [25] for IEEE 802.11 technologies. EDCA is based on four priorities that correspond to distinct Access Categories (AC), each one corresponds to a class of traffic and is associated with an independent queue. These access categories are:

- AC-VO: for voice traffic.
- AC-VI: for video traffic.
- AC-BE: for “Best Effort” traffic.
- AC-BK: for Background traffic.

EDCA mechanism specifies a set of parameters for each AC: an AIFSN (Arbitration InterFrame Space Number), a minimum and maximum CW (content window size) and a TXOP (transmission opportunity). The lowest priority is associated with the access category AC3 and the highest priority is assigned to AC0. A node triggers the start of transmission because the transmission medium is not occupied for a period greater or equal than AIFS[AC]. When the transmission medium is busy during the AIFS[AC] interval, the node randomly chooses a back-off time between $[0, CW[AC]]$, where the initial value is CW_{min} . Thereafter, the interval size will be doubled in case of transmission failure. This will be repeated until the CW_{max} value is reached. At this point, by studying the technical reports [26], [27] related to IEEE 802.11, we found that the configuration of the EDCA parameters have changed over time since it was standardized in 2003. Most of the works in the literature dealing with QoS management in ITS-G5 and also the OpenCV2X simulator are considering the old configuration (defined in the IEEE 802.11p standard) [28]. Table 6 summarizes this old configuration. Today, ETSI is adopting a new configuration parameters for ITS-G5, defined in version 1.3.1 (01-2020) [29]. Table 7 summarizes the newest configuration.

Before comparing ITS-G5 and LTE-V2X, we propose to evaluate the performance of ITS-G5 considering these two configurations to understand the difference. For this, we consider the same evaluation performed in section V-C with traffic load generated by applications presented in Table 3. The priorities of the EDCA mechanism are assigned as following:

- AC-VO for App1
- AC-VI for App2
- AC-BE for App3
- AC-BK for App4 and CAM traffic

As in section V-C, we evaluate the Percentage per application of the well received DENM messages in fast, slow, and congested highway scenarios.

Fig. 11 and Fig. 12 present the Percentage per application of the well received DENM messages obtained with the old and the recent version of the EDCA configuration, respectively. The results show that the AC-VI priority traffic has a higher percentage of received DENMs compared to the AC-VO priority traffic with the old version (Fig. 11). This is

TABLE 6. Old EDCA configuration [28].

Type of traffic	Access category	AIFSN	CWmin	CWmax	Txop
VoIP	AC-VO (AC0)	2	7	15	3.264 ms
Vidéo	AC-VI (AC1)	2	15	31	6.016 ms
Best effort	AC-BE (AC2)	3	31	1023	0
Background	AC-BK (AC3)	7	31	1023	0

TABLE 7. Recent EDCA configuration [29].

Type of traffic	Access category	AIFSN	CWmin	CWmax	Txop
VoIP	AC-VO (AC0)	2	3	7	0
Video	AC-VI (AC1)	3	7	15	0
Best effort	AC-BE (AC2)	6	15	1023	0
Background	AC-BK (AC3)	9	15	1023	0

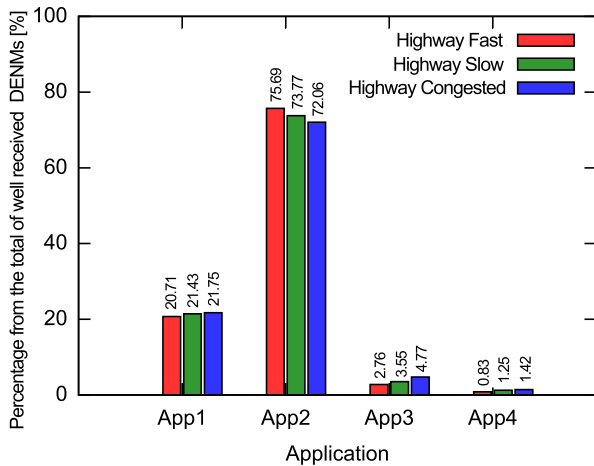


FIGURE 11. Percentage per application of well Received DENMs with ITS-G5 – Old EDCA configuration.

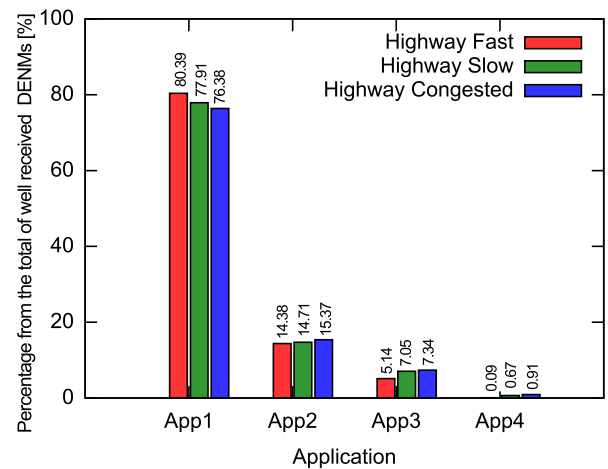


FIGURE 12. Percentage per application of well Received DENMs with ITS-G5 – Recent EDCA configuration.

TABLE 8. 3GPP highway evaluation reduced scenario.

Parameter	Highway congested
Road	600 m
Number of vehicles	320
Maximum speed	15.1 m/s
Acceleration	2.6 m/s ²
Deceleration	4.5 m/s ²
Inter-vehicle distance	3.5 m
Probability of insertion	0.5
Simulation duration	512 s

because the AC-VI priority has a higher TXOP than AC-VO priority. Hence, the applications with the AC-VI priority have a chance to send more packets despite the fact that the

AC-VO has a higher priority than the AC-VI. This problem is solved with the latest version, where the AC-VO has a higher percentage of received DENMs than other traffic as seen in Fig. 12.

B. PPPP AND EDCA COMPARISON

As we have seen in the previous subsection, a simple modification in the settings of the QoS management mechanism EDCA in the same scenario and under the same conditions leads to a significant difference in the obtained results. In the following, we consider the latest EDCA configuration version to progress to a more attractive comparison between two different QoS management mechanisms: the EDCA of ITS-G5 technology versus the PPPP of LTE-V2X technology. For the comparison, we considered a reduced version of the congested highway scenario (see Table 8) because the range of ITS-G5 technology is generally limited, unlike

TABLE 9. Traffic set 1.

Flow	Priority	Message size	Inter-packet delay	Repetition interval	Diffusion area
CAM	7	141 bytes	[0.1 ; 1] s	-	-

TABLE 10. Traffic set 2.

Flow	Priority	Message size	Inter-packet delay	Repetition interval	Diffusion area
App1 DENM	5	124 bytes	0.1 s	1 s	500 km
App2 DENM	5	124 bytes	0.1 s	1 s	500 Km
App3 DENM	5	124 bytes	0.1 s	1 s	500 Km
App4 DENM	5	124 bytes	0.1 s	1 s	500 Km
CAM	5	141 bytes	[0.1 ; 1] s	-	-

TABLE 11. Traffic set 3.

Flow	Priority	Message size	Inter-packet delay	Repetition interval	Diffusion area
App1 DENM	0	124 bytes	0.1 s	1 s	500 Km
App2 DENM	1	124 bytes	0.1 s	1 s	500 Km
App3 DENM	5	124 bytes	0.1 s	1 s	500 Km
App4 DENM	7	124 bytes	0.1 s	1 s	500 Km
CAM	7	141 bytes	[0.1 ; 1] s	-	-

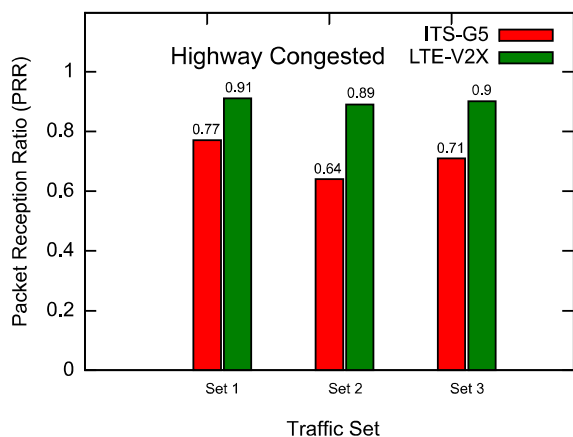


FIGURE 13. Packet Reception Ratio (PRR) as a function of the traffic sets.

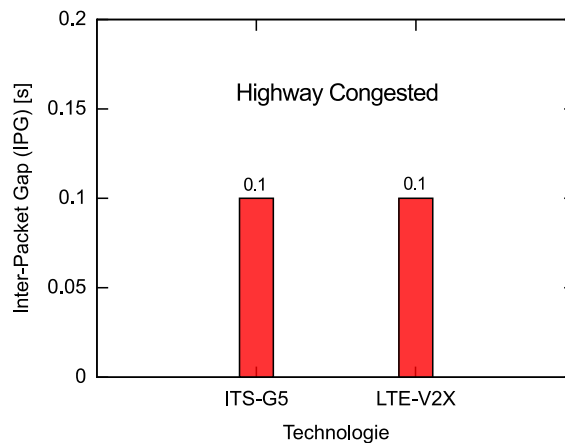


FIGURE 14. Inter-Packet Gap (IPG) as a function of technologies. (Traffic set 1.)

LTE-V2X. We simulated three sets of traffic presented in Table 9, Table 10, and Table 11. The goal of this comparison is to show the difference of the QoS mechanism defined by ITS-G5 and LTE-V2X and also to evaluate the influence of the type of traffic on the gap between the two technologies. The first traffic set is an uniform CAM traffic. The second set consists of multiples flows based on CAM and DENM messages, all with the same priority. The set consists of a mixture of CAM and DENM traffics with different priorities.

Fig. 13 illustrates the Packet Reception Ratio (PRR) obtained with LTE-V2X and ITS-G5 as a function of the traffic sets. The PRR results show that LTE-V2X outperforms ITS-G5 for all traffic sets with a very interesting difference

(e.g. with traffic set 2 case, ITS-G5 offers a PRR equal to 0.64 while LTE-V2X reaches 0.89). Fig. 14, Fig. 15 and Fig. 16 present the Inter-Packet Gap (IPG) obtained with LTE-V2X and ITS-G5 with the traffic set 1, 2 and 3 respectively. In the case of traffic set 1, both technologies offer the same inter-packet time (IPG). However, the results for set 2 and set 3 are different. In the case of single-priority multi-flows traffic (traffic set 2), LTE-V2X has the ability to guarantee the same IPG for the different flows since they have the same priority, which is not the case with ITS-G5. On the other side, the IPGs offered by ITS-G5 is slightly lower than the one of LTE-V2X. In the case of multi-flows traffic with different priorities (traffic set 3), LTE-V2X provides lower

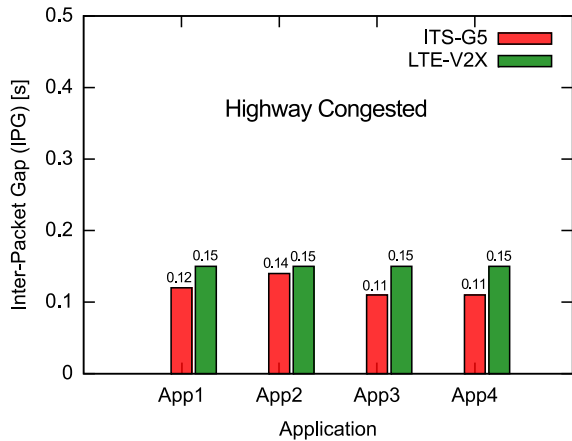


FIGURE 15. Inter-Packet Gap (IPG) as a function of applications. (Traffic set 2.)

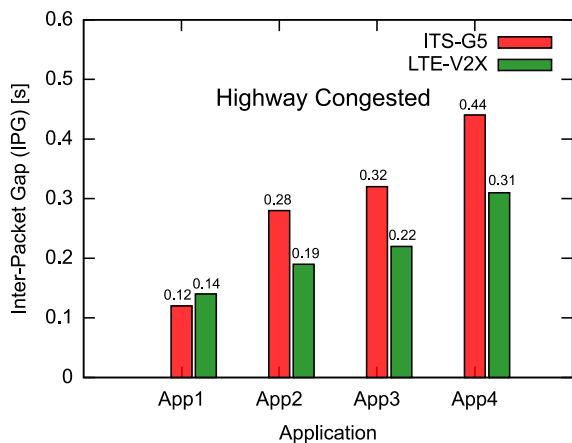


FIGURE 16. Inter-Packet Gap (IPG) as a function of applications. (Traffic set 3.)

inter-packet time than ITS-G5 with an average difference of 75 milliseconds.

The comparison of LTE-V2X and ITS-G5, presented in this section in terms of PRR and IPG, gives an advantage to LTE-V2X with a significant gain over ITS-G5 in the case of multi-flow traffic with different priorities, which means that the QoS mechanism of LTE-V2X outperforms the QoS mechanism of ITS-G5.

VII. CONCLUSION

In this work, the performance of LTE-V2X technology was evaluated, in addition to a comparative study of LTE-V2X with ITS-G5 using different metrics. The results show that, on the one hand, an increase in network load degrades the performance of LTE-V2X, and the interference errors depend on the sensing window (SW) and keep probability (Kp) settings. On the other hand, the comparison of LTE-V2X and ITS-G5 gives an advantage to LTE-V2X with a significant gain over ITS-G5. Finally, our evaluations proves that the QoS mechanism of LTE-V2X outperforms the QoS mechanism of ITS-G5. As a continuity of this work, we are defining a set of evaluation scenarios implementing real world C-ITS applications associated to their performance requirements in

a context of real world vehicular contexts (actual road maps and vehicular traffics). The goal is to shows the ability of these applications to fulfill their role of in the communication conditions currently offered by the technologies. In addition, we also studying the effect of coupling the sensing-based SPS mechanism with the DCC (Decentralized Congestion Control) mechanism proposed for the ITS-G5.

REFERENCES

- [1] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, Dec. 2016.
- [2] R. F. Atallah, M. J. Khabbaz, and C. M. Assi, "Vehicular networking: A survey on spectrum access technologies and persisting challenges," *Veh. Commun.*, vol. 2, no. 3, pp. 125–149, Jul. 2015.
- [3] D. Eckhoff, N. Sofra, and R. German, "A performance study of cooperative awareness in ETSI ITS G5 and IEEE WAVE," in *Proc. 10th Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, Mar. 2013, pp. 196–200.
- [4] R. Molina-Masegosa and J. Gozalvez, "System level evaluation of LTE-V2V mode 4 communications and its distributed scheduling," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5.
- [5] R. Molina-Masegosa, J. Gozalvez, and M. Sepulcre, "Configuration of the C-V2X mode 4 sidelink PC5 interface for vehicular communication," in *Proc. 14th Int. Conf. Mobile Ad-Hoc Sensor Netw. (MSN)*, Dec. 2018, pp. 43–44.
- [6] A. Bazzi, G. Cecchini, A. Zanella, and B. M. Masini, "Study of the impact of PHY and MAC parameters in 3GPP C-V2V mode 4," *IEEE Access*, vol. 6, pp. 71685–71698, 2018.
- [7] A. Nabil, K. Kaur, C. Dietrich, and V. Marojevic, "Performance analysis of sensing-based semi-persistent scheduling in C-V2X networks," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–5.
- [8] P. Roux, S. Sesia, V. Mannoni, and E. Perraud, "System level analysis for ITS-G5 and LTE-V2X performance comparison," in *Proc. IEEE 16th Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS)*, Nov. 2019, pp. 1–9.
- [9] T. V. Nguyen, P. Shailesh, B. Sudhir, G. Kapil, L. Jiang, Z. Wu, D. Malladi, and J. Li, "A comparison of cellular vehicle-to-everything and dedicated short range communication," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2017, pp. 101–108.
- [10] *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures*, document 3GPP TS 36.213, Version 14.2.0, Apr. 2014.
- [11] *Universal Mobile Telecommunications System (UMTS); LTE; Proximity-based Services (ProSe); Stage2*, document 3GPP TS 23.303, Version 13.4.0, Jul. 2016.
- [12] Y. Jeon, S. Kuk, and H. Kim, "Reducing message collisions in sensing-based semi-persistent scheduling (SPS) by using reselection lookaheads in cellular V2X," *Sensors*, vol. 18, no. 12, p. 4388, Dec. 2018.
- [13] A. Mansouri, V. Martinez, and J. Harri, "A first investigation of congestion control for LTE-V2X mode 4," in *Proc. 15th Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, Jan. 2019, pp. 56–63.
- [14] G. Cecchini, A. Bazzi, B. M. Masini, and A. Zanella, "Performance comparison between IEEE 802.11p and LTE-V2V in-coverage and out-of-coverage for cooperative awareness," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2017, pp. 109–114.
- [15] V. Mannoni, V. Berg, S. Sesia, and E. Perraud, "A comparison of the V2X communication systems: ITS-G5 and C-V2X," in *Proc. IEEE 89th Veh. Technol. Conf. (VTC-Spring)*, Apr. 2019, pp. 1–5.
- [16] A. Bazzi, A. Zanella, I. Sarris, and V. Martinez, "Co-channel coexistence: Let ITS-G5 and sidelink C-V2X make peace," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Nov. 2020, pp. 1–4.
- [17] *Technical Specification Group Radio Access Network; Study on LTE-Based V2X Services*, document 3GPP TR 36.885, Version 14.0.0, Jul. 2016.
- [18] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications," *IEEE Veh. Technol. Mag.*, vol. 12, no. 4, pp. 30–39, Dec. 2017.
- [19] R. Molina-Masegosa, J. Gozalvez, and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An evaluation with periodic and aperiodic messages of constant and variable size," *IEEE Access*, vol. 8, pp. 121526–121548, 2020.

- [20] A. Bazzi, G. Cecchini, M. Menarini, B. M. Masini, and A. Zanella, "Survey and perspectives of vehicular Wi-Fi versus sidelink cellular-V2X in the 5G era," *Future Internet*, vol. 11, no. 6, p. 122, May 2019.
- [21] M. Wang, M. Winbjork, Z. Zhang, R. Blasco, H. Do, S. Sorrentino, M. Belleschi, and Y. Zang, "Comparison of LTE and DSRC-based connectivity for intelligent transportation systems," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5.
- [22] T. Shimizu, H. Lu, J. Kenney, and S. Nakamura, "Comparison of DSRC and LTE-V2X PC5 mode 4 performance in high vehicle density scenarios," in *Proc. 26th ITS World Congr.*, 2019, pp. 1–7.
- [23] T. Shimizu, B. Cheng, H. Lu, and J. Kenney, "Comparative analysis of DSRC and LTE-V2X PC5 mode 4 with SAE congestion control," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2020, pp. 1–8.
- [24] B. McCarthy and A. O'Driscoll, "OpenCV2X mode 4: A simulation extension for cellular vehicular communication networks," in *Proc. IEEE 24th Int. Workshop Comput. Aided Modeling Design Commun. Links Netw. (CAMAD)*, Sep. 2019, pp. 1–6.
- [25] H. Wu, X. Wang, Q. Zhang, and X. Shen, "IEEE 802.11e enhanced distributed channel access (EDCA) throughput analysis," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2006, pp. 223–228.
- [26] *Intelligent Transport Systems (ITS); European Profile Standard for the Physical and Medium Access Control Layer of Intelligent Transport Systems Operating in the 5 GHz Frequency Band*, Standard ETSI ES 202 663, Version 1.1.0, Jan. 2010.
- [27] *Intelligent Transport Systems (ITS); ITS-G5 Access Layer Specification for Intelligent Transport Systems Operating in the 5 GHz Frequency Band*, Standard ETSI EN 302 663, Version 1.3.0, May 2019.
- [28] A. Perez, "L'intégration du Wi-Fi dans les réseaux de télécoms," Collection: Réseaux et Télécommun., ISTE Group, May 2018, p. 270.
- [29] *Intelligent Transport Systems (ITS); ITS-G5 Access Layer Specification for Intelligent Transport Systems Operating in the 5 GHz Frequency Band*, Standard ETSI EN 302 663, Version 1.3.1, Jan. 2020.
- [30] M. Noor-A-Rahim, Z. Liu, H. Lee, G. G. M. N. Ali, D. Pesch, and P. Xiao, "A survey on resource allocation in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 2, pp. 701–721, Feb. 2022.
- [31] A. Bazzi, A. Zanella, and B. M. Masini, "Optimizing the resource allocation of periodic messages with different sizes in LTE-V2V," *IEEE Access*, vol. 7, pp. 43820–43830, 2019.



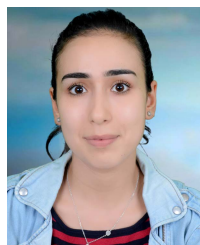
QoS management in heterogeneous wireless access networks.



involved in research work in underground communications and especially communications in underground mines. Since 2010, as a research engineer at IFSTTAR (French Institute of Science and Technology for Transport, Development and Networks) and now at Université Gustave Eiffel (created in 2020), her fields of interest concern the evaluation of C-ITS systems. She is participating in European FOT on C-ITS, such as Drive-C2X and national projects (SCORE@F and Co-Drive). Recently, she was involved in SCOOP@F, C-roads, C-roads platform, Intercor and Idid, especially in specifications on C-ITS-S for France, and the European level (harmonization of ITS-G5 and hybrid communications for European interoperability) and evaluation of those systems. She is also involved in many scientific conference committees. Her research interests include confined propagation and cross-layer optimization for ad hoc networks.



from 2013 to 2017. She is currently the Pole Leader of the Intelligent Mobility Pole of European Railway Research Network of Excellence (Eurnex). In addition to research activities and supervision of Ph.D. students, she coordinates railway research at Université Gustave Eiffel. She has participated in many European and national research projects, since 1990. She is also the Project Leader of the Emulradio4Rail Project in the framework of Shift2Rail IP2 and involved in several other projects, such as X2RAIL3, X2RAIL4, and X2RAIL5. Her current research interests include wireless communications for connected and automatic vehicles (trains and cars) (radio propagation, channel characterization, and modeling, MCM, MIMO, ITS-G5, GSM-R, LTE, and 5G NR). She is on the Reserve List of the Scientific Council of the Shift2Rail Program.



CHOUROUK GHODHBAE received the master's degree in computer science, specialty software engineering from the Higher Institute of Computer Science and Mathematics, University of Monastir, Tunisia, in 2021. Her research interests include wireless technologies and vehicular communication.



MOHAMED KASSAB received the Engineering and M.Sc. degrees in computer sciences from ENSI, Tunisia, in 2003 and 2004, respectively, and the Ph.D. degree in computer sciences from IMT Atlantique, France, in 2008. He is currently an Assistant Professor at the University of Monastir, Tunisia, and an Associate Researcher at Université Gustave Eiffel, France. His works are mainly related to the optimization of wireless technologies for the Internet of Things and intelligent transport system use cases. His research interests include problems related to mobility management, QoS, and security in wireless technologies.

...