A study of LTE-V2X mode 4 performances in a multi-application context

CHOUROUK GHODHBANE¹, MOHAMED KASSAB², SASSI MAALOUL³, HASNAA ANISS³, AND MARION BERBINEAU⁴, (Member, IEEE)

¹ISMM, University of Monastir, Tunisia
²ISMM, University of Monastir, Tunisia (e-mail: mohamed.kassab@gmail.com)
³COSYS-ERENA, Université Gustave Eiffel, Bordeaux, France
⁴COSYS, Université Gustave Eiffel, Villeneuve d’Ascq, France

Corresponding author: Chourouk GHODHBANE (e-mail: choughchou@gmail.com).

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 WA VE 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 sensing-based resource allocation mechanism parameters, 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 on the performance offered by LTE-V2X. In addition, we show that the QoS mechanism of LTE-V2X outperforms the ITS-G5 one in realistic multi-application context.

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

I. INTRODUCTION

C ooperative intelligent transport systems (C-ITS) are attracting more and more attention in today’s world. A set of applications dedicated to road safety were specified, such as obstacle detection, applications dedicated to 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 operating in the 5.9 GHz unlicensed band. The first one is the Wireless Access in Vehicular Environments (WA VE) 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). WA VE 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 as it puts aside the centralized management of LTE technology.
Several research work have been interested to performances offered by LTE-V2X mode 4. These work are focused on the evaluation of the sensing-based SPS mechanism and the impact of its parameters on the performance offered by LTE-V2X ([4] [5] [6] [7]). In addition, several work have been interested on the comparison of 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 work 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 the 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.

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 at 15 kHz, and the sub-carriers are used in sets of 12 (180 kHz) called Resource Block (RB). Thus, 14 OFDM symbols forming a TTI (Transmission Time Interval) in the time domain is 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:

![FIGURE 1. LTE-V2X mode 3 principle](image1)

![FIGURE 2. LTE-V2X mode 4 principle](image2)
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 makes the decision for a new resource allocation, \(1 ≤ T1 ≥ 4\) and \(20 ≤ T2 ≥ 100\) (T1 and T2 are selected by the vehicle). During the selection window, a list of candidate resources (CRs) is determined by the vehicle. 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 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 \(p\) or to start selecting a new resource using the sensing-based SPS with probability \((1-p)\). The value of \(p\), 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.

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 PCS interface. In 3GPP Rel-13, QoS is generally supported for ProSe one-to-many communications. Therefore, PPP was introduced in TS 23.303, version 13.4.0 [11]. The PPP 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 PPP 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 an 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 neighbours 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.

| Resource reservation field in SCI format | 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 |
| ‘1101’                                 | 0.5                   | The same resource is reserved for the next transmission after 10 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 |

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

**FIGURE 4.** SCI message format [13]

### III. RELATED WORKS

#### A. LTE-V2X SENSING-BASED ALGORITHM EVALUATION

Most of the reseach work 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.

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 decreases 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, but propagation errors dominate at longer distances.

The same authors have showed in [5] that increasing the Keep probability (Kp) value reduces the PDR in situations where the channel overload, although the variation in Kp 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 Kp 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 Kp has an insignificant effect for high network density. Consequently, the Sensing-based SPS parameters have a significant impact on the performances of LTE-V2X mode 4. Other researches present contradictory results, such as [6], that states the significant effect of Kp 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 performances. 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 DSRC 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 of these work 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 enable the evaluation of 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 researches to validate the configuration of our scenarios 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 VEHICLE TECHNOLOGIES

The comparison of LTE-V2X mode 4 with existing vehicular communication technologies is an active researched topic. Existing works cover comparison with ITS-G5, comparison with WAVE and comparison with IEEE802.11p. The papers [14], [15], [8], [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-V2X 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], [19], [20] present comparisons of 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 showed also that IEEE802.11p has a very high percentage of packet loss 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], [22], [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 also LTE-sidelink. In the end, the authors found that LTE-sidelink and LTE-multicast are able to support more 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 LTEV2X 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 favour 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 mode 4 of LTE-V2X based on an extended version of the SimuLTE simulator, which is used 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 model 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](image)

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](image)

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.
### 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       | 2.6m/s²     | 2.6m/s²      | 2.6m/s²           |
| Deceleration       | 4.5m/s²     | 4.5m/s²      | 4.5m/s²           |
| 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

| Parameter                  | Value          |
|----------------------------|----------------|
| Carrier frequency          | 5.9 GHz        |
| Number of sub-channels     | 2              |
| 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

| Parameter               | Value          |
|-------------------------|----------------|
| Carrier frequency       | 5.890 GHz      |
| Data rate               | 6 Mbps         |
| Transmission power      | 12 mW          |

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 correctly decode it.

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 as a result 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 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 figure 6. On the other hand, the results of Fig. 7 show that the difference in network load for the three scenarios has a significant impact on 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 channel significantly loses efficiency with the increase of network load. Further improvements of the sensing-based SPS must be studied.

### 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.
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 in 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. 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 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 greater values of keep probability improve data delivery performances. In addition, a high value of Kp increases the stability of resource reservations and offers a more stable sensing environment, which benefits to the operations of the sensing-based SPS independently of the channel load. As for SW size, the increasing of the kp 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 Kp 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 Kp 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, in these two cases a high Kp value results in a loss of performance.
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 implements 5 applications having different priorities (c.f. Table 3).

To understand the influence of these priorities, we evaluate the percentage for each application from the totally well received messages in fast, slow, and congested highway scenarios as shown in figure 10.

Obtained results highlight the effectiveness of the PPPP mechanism to offer differentiated service 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 a very acceptable performances even in highly congested conditions (for App1 in figure 10) although there is a slight drop in the percentage of received message for the application. On the another side, we show an increase of the percentage of received messages for App4 (with the lowest priority) while the network load increases. 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 a comparison of 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 corresponding to a class of traffic and associated to 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 CWmin. Thereafter, the interval size will be doubled in case of transmission failure. This will be repeated until the CWmax 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.

Fig. 11 and Fig. 12 present the Percentage of Received DENM messages as a function of applications 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 due to the fact that 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.

![Figure 11. Percentage of Received DENMs Type as a function of applications (with the default configuration of EDCA)](image)

![Figure 12. Percentage of Received DENMs Type as a function of applications (with the recent configuration of EDCA)](image)

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 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 multiple 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 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
TABLE 6. The default configuration of EDCA [28]

| Type of traffic | Access category | AIFS/N | CWmin | CWmax | Txop |
|-----------------|-----------------|--------|-------|-------|------|
| VoIP            | AC-VO (AC0)     | 2      | 7     | 15    | 3.264 ms |
| Video           | 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. The recent configuration of EDCA [29]

| Type of traffic | Access category | AIFS/N | 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    |

Parameter | Highway congested
---|---
Road | 600 m
Number of vehicles | 320
Maximum speed | 15.1 m/s
Acceleration | 2.6 m/s²
Deceleration | 4.5 m/s²
Inter-vehicle distance | 3.5 m
Probability of insertion | 0.5
Simulation duration | 512 s

TABLE 8. 3GPP highway evaluation reduced scenario

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)

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.
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   | 7        | 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 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)

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CHOUROUK GHODHBANE obtained her 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 focuses on wireless technologies and vehicular communication.

DR MOHAMED KASSAB is an assistant professor at University of Monastir, Tunisia, and an associate researcher at University Gustave Eiffel, France. He received his PhD in computer sciences from IMT Atlantique, France, in 2008. He also received his Engineer degree and MSc. in computer sciences from ENSI, Tunisia, in 2003 and 2004, respectively. He is broadly interested in problems related to mobility management, QoS and security in wireless technologies. His works are mainly related to the optimization of wireless technologies for Internet of Things and intelligent transport system use cases.

DR SASSI MAALOUL received his master’s degree in Electronic and Telecommunication from the National School of Engineer, University of Monastir, in 2009, and his PhD degree in Information and Communication Technologies from the Higher School of Communication of Tunis, University of Carthage, Tunisia, in 2016. Since 2020, he has been with the University Gustave Eiffel as a postdoctoral researcher. His work mainly focuses on C-ITS services, vehicular networks and QoS management in heterogeneous wireless access networks.

DR HASNAA ANISS received her PhD degree in Electromagnetism in 2001 from Blaise Pascal University, Clermont-Ferrand, France. Between 2004 and 2006, she was an assistant researcher at the Research Laboratory Téléc in Underground Communications at Quebec University in Abitibi-Temiscamingue (LRTCS-UQAT). Her major field of study was electromagnetic propagation. In 2006, she became a professor in the applied sciences department at UQAT. Her major fields of interest are confined propagation and cross-layer optimization for ad hoc networks. She was 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), 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 such as SCORE@F and Co-Drive. Recently, she was involved in SCOOP@F, C-roads, C-roads platform, Intercom and Indid, especially in specifications on C-ITS-S for France and at 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.
DR MARION BERBINEAU received her Engineer degree from Polytech'Lille former EUDIL in Informatics, Electronics, Automatics, and her PhD degree in Electronics from the University of Lille, France, in 1986 and 1989, respectively. Dr Berbineau has been a Research Director at Université Gustave Eiffel (previously Ifsttar and Inrets) since 2000. She was director of the Leost laboratory from 2000 to 2013 and then deputy director of the COSYS department from 2013 to 2017. In addition to research activities and supervision of PhD students, she coordinates railway research at Université Gustave Eiffel. She is pole leader of the Intelligent Mobility pole of Eurnex (European Railway Research Network of Excellence). Her current interests are wireless communications for connected and automatic vehicles (trains and cars) (radio propagation, channel characterization and modelling, MCM, MIMO, ITS-G5, GSM-R, LTE, 5G NR). She has participated in many European and national research projects since 1990. She is currently the project leader of the Emulradio4Rail project in the framework of Shift2Rail IP2 and is involved in several other projects (X2RAIL3, X2RAIL4, X2RAIL5). She is an IEEE member and is on the reserve list of the Scientific Council of the Shift2Rail program.