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A First Investigation of Congestion Control for LTE-V2X Mode 4

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***Abstract*—3GPP LTE-V2X is a recent new cellular technology allowing direct communications between vehicles and any other stations. Its Sidelink mode 4 allows the scheduler to be fully distributed and not requiring any support from cellular infrastructures, thus making this mode well fitted for V2X safety-related communications. Based on a Listen-before-Talk (LBT) strategy, the scheduler, however, remains subject to performance degradation under increased channel load, and thus requires wireless congestion control mechanisms. In this work, we focus on the interactions between the strategies used by the LTE-V2X Sidelink mode 4 for autonomous resource allocations - LBT and Semi-persistent scheduling (SPS) - and decentralized congestion control (DCC) mechanisms. Simulations under various scenarios showed counter-productive interactions leading to performance degradations, and strategies to mitigate them are suggested.**

I. INTRODUCTION

Cooperative intelligent transport systems (C-ITS) provides a framework for road users and traffic managers to share information, in the quest for a safer, greener and more comfortable travel. The term V2X defines the exchange of information between vehicles and any other type of stations, such as roadside units, infrastructure, pedestrians or other moving vehicles.

Today, two technologies are standardized for the V2X physical access layer, namely IEEE 802.11p[1] and 3GPP Long-Term-Evolution (LTE)-V2X. LTE-V2X uses the sidelink channel which is designed based on LTE uplink waveform. LTE-V2X made its debut in 3GPP Rel-14 specification, as an evolution of 3GPP Rel-12 Device-to-Device (D2D) functionalities.

Two sidelink modes dedicated to V2X were introduced in Rel-14: modes 3 and 4 support direct vehicular communications but differ on how stations' resources are allocated. In mode 3, vehicles are within the coverage of cellular network, and the stations' resources are selected, allocated and reserved by the eNodeB. In contrast, mode 4 was designed to work without the requirement of being under coverage of cellular network: resources are autonomously selected by the stations. Mode 4 defines an ad-hoc system, similar in concept to ITS-G5[2], and as such, one major challenge is to avoid collisions.

LTE-V2X Mode 4 resource scheduling uses a Listen-Before-Talk (LBT) type of algorithm in conjunction with a Semi-Persistent Scheduling (SPS) strategy as a way to announce resources utilization, and as such avoid simultaneous transmissions and thus collisions from other transmitters. However, Molina and Gozalvez showed in [1] the limited efficiency of the LBT-SPS mechanism under increased load, which emphasizes the need for controlling the congestion level of the LTE-V2X wireless channel.

Wireless congestion control represents a family of mechanisms adjusting communication parameter to control the congestion level on the vehicular wireless channel and guarantee reliable V2X communications. Known in Europe under the name Decentralized Congestion Control (DCC), possible parameters are, among others, adjusting the transmission rate, the transmission power, the modulation or the offloading to alternative channels, as described by Smely et al. [2]. However, the interaction between the LBT-SPS and DCC mechanisms have never been evaluated so far although being defined in US and EU Standards [3], [4].

In this paper, our focus is to analyze the impact of DCC mechanisms on the LTE-V2X mode 4. Our contributions are threefold: (i) we implement the LTE-V2X LBT-SPS scheduler on a network simulator (ns-3) and validate its performance, (ii) we evaluate its performance in conjunction with the ETSI DCC, (iii) we suggest modifications in the LTE-V2X mode 4 scheduler to better fit to safety-related traffic subject to DCC.

The rest of this paper is organized as follows. Section II proposes a brief overview of the state-of-art in LTE-V2X and DCC. Section III introduces the basic mechanisms of LTE-V2X mode 4, while Section IV describes the DCC and its application to LTE-V2X. Then, Section V introduces performance evaluation parameters and scenarios, while Section VI provides simulation results. Finally, Section VII discusses challenges of DCC and LTE-V2X, while Section IX concludes the paper.

II. BRIEF STATE-OF-ART OVERVIEW

A. *Cellular Device-to-Device*

In cellular networks, investigations on the potential capacity or resource allocations gains from Device-to-Device (D2D) communications have been observed since 2015 [5]–[8]. But these studies remained theoretical due to the lack of standards and protocols effectively describing D2D mechanisms for

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[1] Although widely known as “802.11p”, “IEEE 802.11-OCB” is a more technically correct terminology. OCB stands for "Outside the Context of a BSS".

[2] ITS-G5 defines a protocol stack for vehicular communications in an ad-hoc network to be used in the 5,9 GHz frequency band allocated in Europe. Its access layer is based on IEEE 802.11p standard. The ITS-G5 standard adds features for decentralized congestion control (DCC) to control the network load and avoid unstable behavior.

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LTE. Stemming from the early D2D protocol description from Rel.12, Gallo and Härri [9], [10] drew and evaluated the first sketches of what will later appear in the Rel-14 as LTE-V2X. With a full LTE-V2X specification published in the LTE Rel-14 in June 2017, several teams implemented and tested it via simulations [1], [11]–[13]. And although Molina and Gozalvez [1] showed limitations of the LTE-V2X scheduler under increased load, and Bazzi *et al.* [13] illustrated the impact of PHY and MAC parameters to such limitation, efficient wireless congestion control mechanisms have so far not been investigated. This is the objective of this paper.

B. Wireless Congestion Control

A holistic view of wireless congestion control challenges and solutions may be found in [2]. Without loss of generalities, although some studies tried to adjust the transmission power (e.g. [14]), most studies focused on adjusting the transmission rate [15]–[17], a more controllable variable. Adjusting the transmission rate notably became the official DCC mechanism by the ETSI [18]. Yet, Huang et al. [19] investigated the possibility of jointly adjusting transmission rate and power, a mechanisms, which later became the SAE standard for wireless congestion control in the US [20]. At the time of this study, and to the best of the authors' knowledge, no LTE-V2X studies have explicitly tested congestion control mechanisms for a LTE-V2X mode 4 network. This study aims to fill this gap, by evaluating the impact of one congestion control mechanism on a LTE-V2X mode 4 network.

III. LTE-V2X BASICS

A. LTE-V2X waveform

The sidelink waveform design is fairly similar to the earlier developed LTE uplink, re-using the same principles for the subframe organization. LTE-V2X is a synchronous network, where all the users shall have the same time reference, typically obtained from GNSS. Time is divided into subframes. Each LTE subframe has a length of 1 ms and contains 14 OFDM symbols. One LTE-V2X subframe comprises 4 demodulation reference symbols (DMRS) and 9 data symbols conveying the user's payload. The last symbol is not transmitted, and acts as a time guard to allow transmitters to return to receiver state before the next subframe. The first data symbol may not be available for use by the receiver as it might be used for AGC calibration purposes.

Frequency-wise, the LTE-V2X channel bandwidth is divided into a given number of subchannels. Each subchannel gathers a number of resource blocks (RB) (12 subcarriers). All subchannels have the same size. 3GPP LTE specification 36.213 [21] defines the following possible subchannel sizes: 4, 5, 6, 8, 9, 10, 12, 15, 16, 18, 20, 25, 30, 48, 50 RB, and the possible number of subchannels: 1, 3, 5, 10, 15 or 20 RB. One ITS station can use one or multiple subchannels to transmit its data. Two main physical channels are used in LTE-V2X:

- **Physical Sidelink Shared Channels (PSSCH) -** used to transmit data packets, known as transport blocks (TB).

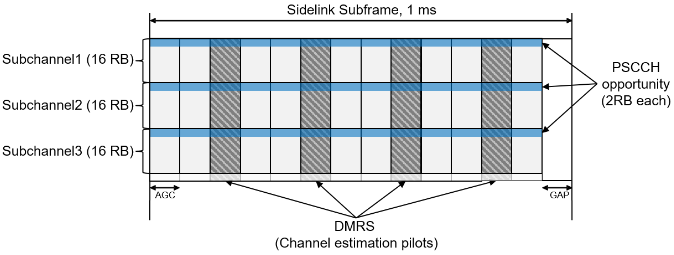


Fig. 1: Sidelink subframe, adjacent PSCCH-PSSCH, 3 subchannels

- **Physical Sidelink Control Channels (PSCCH) -** used to transmit the associated control message, known as sidelink control information (SCI).

The PSCCH SCI and its associated PSSCH TB are transmitted in the same subframe. The PSCCH always occupies two resource blocks. For PSSCH, the number of occupied RBs depends on the user's payload size, on the subchannels division, and on the modulation and coding scheme used (MCS). Two cases can be enabled for the location of PSCCH and PSSCH:

- **Adjacent PSCCH and PSSCH:** TB and its associated SCI are transmitted in adjacent RBs. The PSCCH always uses the first two RBs of each subchannel. The PSSCH uses the following RBs. If the PSSCH occupy more than one subchannel, it will be overlapping with the next PSCCH opportunities (that might or might not contain actual PSCCH messages). The present study focuses on this configuration, as shown in Fig. 1.
- **Nonadjacent PSCCH and PSSCH:** Subchannels are only used for PSSCH. PSCCH opportunities are grouped in a pool at one edge of the channel, such that they cannot overlap with PSSCH. This configuration is less spectrally efficient in case of low number of users per subframe, as some PSCCH opportunities RBs will be unoccupied.

B. SCI messages

The SCI contains the scheduling information for the PSSCH. In mode 4, SCI format 1 is used. It has a length of 32 bits, as shown in Fig. 2 and the following structure:

- **Priority:** indicates the message importance, such as high-priority Decentralized Environmental Notification Message (DENM), Cooperative Awareness Message (CAM) or other relayed messages.
- **Resource Reservation:** a field used only in mode 4, announcing resources to be used based on sensing decisions.
- **Frequency resource location:** a bit pattern used to define PSSCH physical RB resources.
- **Time Gap:** the number of subframes gap between the first and the optional second PSSCH transmission.
- **Modulation and Coding Scheme:** determines the MCS used for the PSSCH.
- **Retransmission Index:** indicates if the PSSCH refers to the first or the optional second transmission.
- **Reserved bits:** zero-valued padding bits.

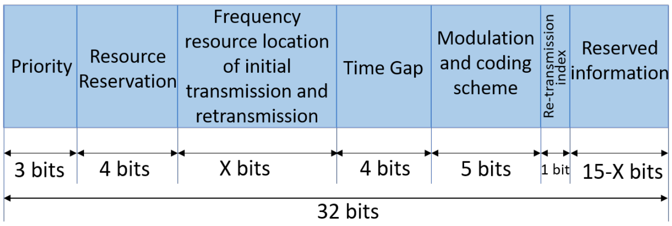


Fig. 2: SCI content

C. Semi-Persistent Scheduling

Semi-Persistent Scheduling (SPS) was introduced in LTE-V2X to avoid the need for frequent resource selection or reselection considering an a priori periodic transmission of safety-related messages (e.g. CAM), and also as a technique to reduce packet collisions in a synchronous network. The time interval between packets can be selected among the possible values: 20, 50, 100, 200, 300 ... 1000 ms, respectively corresponding to the following transmission rates: 50, 20, 10, 5, ... 1 Hz. When a vehicle selects a new resource, it will be reserved for a number of upcoming consecutive transmissions, given by the re-selection counter. It is uniformly randomly selected between 5 and 15 when the new resource is selected. The re-selection counter is decremented by one after each transmission. When it reaches zero, the vehicle decides to keep the same resource with probability P or to select new resource using the sensing-based resource selection mechanism with probability (1-P). The standard does not specify a fixed value of P, it can be any value from the range [0, 0.2, 0.4, 0.6, 0.8]. Transmitters also need to select a new resource if the previously reserved resource is too small. This procedure is represented in Fig. 3.

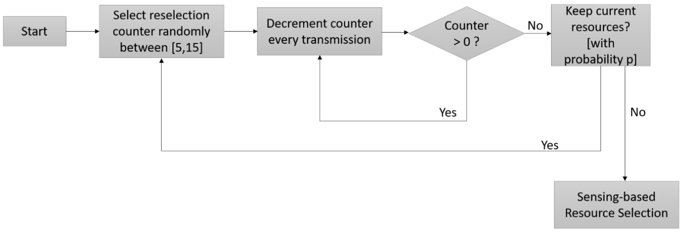
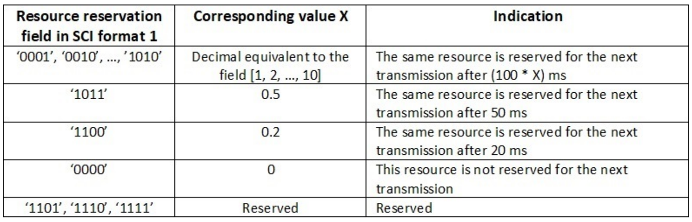


Fig. 3: LTE SPS flow chart

The station announces the reserved resource using the resource reservation field in the SCI. This field uses 4 bits to indicate the packet transmission interval. The SCI resource reservation field table (see Fig. 4) summarizes resource reservation field values and how it is interpreted by other vehicles.



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	This resource is not reserved for the next transmission
‘1101’, ‘1110’, ‘1111’	Reserved	Reserved

Fig. 4: SCI resource reservation field

D. Sensing-based resource selection

When a station decides to select a new resource for its transmission, it uses the sensing-based resource selection algorithm. It estimates which resources are in-use by others using the resource reservation field information included in the SCIs received. Decisions are also based on 2 measurements computed by the station itself:

- **Sidelink Reference Signal Received Power (S-RSRP)**: defined as the linear average over the power contributions (in [W]) of the resource elements that carry demodulation reference signals. The power per resource element is determined from the energy received during the useful part of the symbol, excluding the cyclic prefix.
- **Received Signal Strength Indicator (RSSI)**: comprises the linear average of the total received power (in [W]) observed only in the configured OFDM symbol and in the measurement bandwidth over N number of resource blocks, by the UE from all sources, including adjacent channel interference, thermal noise etc. To build this metric, a station considers the history in the last 1000 subframes, at the desired pace (for example 100 ms time interval).

In mode 4, radio resources are selected from a selection window, set between 20 ms and 100 ms, based on the above layers requirements. A shorter window provides a shorter latency but might increase the probability of collisions. The selection window is given by [n+T1, n+T2] where n is the time when the vehicle decides to select a new resource and T1 and T2 are selected by the vehicle with the limitation that T1 in [1,4] and T2 in [20,100]. Within the selection window, the vehicle identifies all the candidate resources. A candidate resource is a number of adjacent subchannels in which the packet to be transmitted can fit. When a message needs to be transmitted, the last 1000 ms of sensing history, referred to as the sensing window, are scanned to determine which resources are likely to be used by other stations. The sensing period and selection window are represented in Fig. 5.

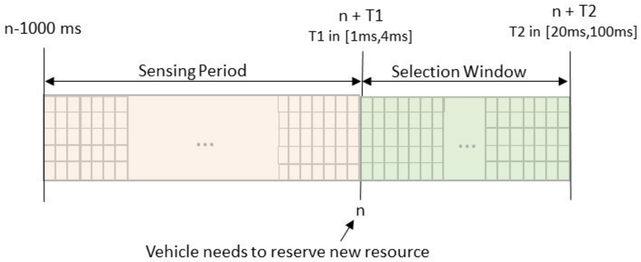


Fig. 5: Sensing period

The station excludes resources from the selection window that are going to be re-used by other users, and which measured RSRP is higher than a given threshold. After excluding these resources, the number of candidate resources must be at least 20% of the number of all candidate resources. If not, this step is re-iterated, with the RSRP threshold being increased by 3 dB. After that, the station extracts exactly the 20% candidate resources that have the lowest average RSSI measured in the sensing period. Finally, one resource is selected randomly from the resources considered in the previous step. Random selection is used to prevent situations where multiple stations select the same resource with the lowest RSSI. Once a resource is selected, it is reserved for the next n transmissions where n is given by the re-selection counter in the semi-persistent scheduling.

In LTE-V2X, stations have the possibility to send packets twice following the retransmission process to increase robustness, although at the expense of spectral efficiency. If retransmission is enabled, the station finds a second resource following the previously described procedure, in the time interval of [T-15ms, T+15ms] from the first resource. The vehicle indicates in the SCI if it is the first or second transmission using the retransmission index field, and the time interval between the original and the second transmissions in the time gap field.

IV. LTE-V2X DECENTRALIZED CONGESTION CONTROL

A. LTE-V2X Channel Load Metrics

In dense scenarios, a lot of LTE-V2X stations can be within a small geographical area, thus sharing resources is a challenge. To this end, Decentralized Congestion Control (DCC) is needed to coordinate the usage of the channel. All stations shall cooperate to keep the channel unsaturated, and resources are shared equally. The LTE-V2X standard defines two metrics to characterize the channel state and to allow stations to take necessary actions: the channel busy ratio (CBR) and the channel occupancy ratio (CR), shown in Fig. 6.

- **Channel busy ratio (CBR)**: defined as the portion of subchannels in the resource pool whose RSSI measured exceeds a pre-configured threshold. Such metric is sensed over the last 100 subframes. It provides an estimation on the total state of the channel.
- **Channel occupancy ratio (CR)**: calculated at subframe n, it is defined as the total number of subchannels used for its transmissions in subframes [n-a, n-1] and granted in subframes [n, n+b] divided by the total number of subchannels within [n-a, n+b]. a and b are determined by the station with the limitation of a+b+1 = 1000, a $\geq$ 500. The CR provides an indication on the channel utilization by the transmitter itself.

B. LTE-V2X Transmit Adaptation Mechanisms

CBR and CR measurements are updated after every subframe. The CBR range can be divided into up to 16 intervals. For each interval of CBR values, a CR limit is defined as a footprint that the transmitter should not exceed. When a LTE-V2X station decides to transmit a packet, it maps its CBR value to the correct interval to get the corresponding CR limit value. If its CR is higher than the CR limit, the station has to decrease its CR below that limit. The standard does not specify a particular technique to reduce the CR, and it is up to each implementation to decide which technique(s) to use among the following options:

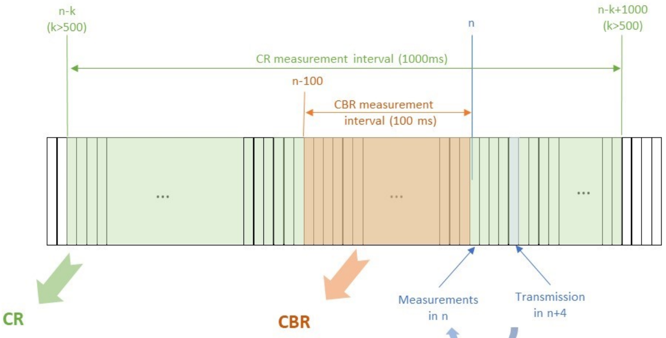


Fig. 6: CBR and CR calculations in DCC mechanisms

- **Drop packet retransmission**: if the retransmission feature is enabled, the LTE-V2X station can disable it. Note: this technique is not considered in this study as we assume the retransmission feature to be disabled.
- **Drop packet transmission**: the LTE-V2X station simply drops the packet transmission (including the retransmission if enabled). This is one of the simplest technique. As a reference, this technique is being used by 802.11p systems. Note: when doing such technique, from the LTE-V2X transmitter's perspective, the resource reservation for the subsequent transmissions is maintained even if one packet is dropped (as long as the re-selection counter has not reached 0).
- **Adapt the MCS**: the LTE-V2X station can reduce its CR by augmenting the MCS index used. This can reduce the number of subchannels used for the transmission. However, increasing the MCS reduces the robustness of the message, and thus reduces the range of the message. Note: this technique is not considered in this study as we assume the MCS index to be fixed at 7.
- **Adapt transmission power**: the LTE-V2X station can reduce its transmission power. Consequently, the overall CBR in the area will be reduced, and the value of CR limit might be increased. Note: this technique is not considered in this study as it notoriously complicated to fine-up (it can lead to oscillations), and would make sense only if all the stations are forced to use this technique.

V. PERFORMANCE EVALUATION

A. Simulation assumptions

We evaluate the performance of the LTE-V2X on a safety-related ITS 10-MHz channel, and considering Cooperative Awareness Messages (CAM). We assess the impact on DCC considering the communication parameters indicated on Table I. At the time of this study, there was no official "profile" set for physical layer parameters provided by regulators. For example, the ETSI ITS specification is still in a drafting stage [22]. Therefore, we have used the set of parameters we thought would make most sense. This set of parameters is fully allowed and compliant with LTE-V2X Rel-14.

The CAM size is set to 190 Bytes, a value which is aligned with the published studies so far [1], [11], although arguably

Parameter	Value
Standard version	LTE-V2X Rel-14
Adjacency of PSSCH-PSCCH	enabled
Number of subchannels	3
Channel size	50 RB
Subchannel size	16 RB
MCS index	7 (≈ IEEE 802.11p QPSK $\frac{1}{2}$)
HARQ retransmissions	disabled
transmission power	23 dBm
Noise Figure	5 dB
RSRP threshold (init)	-110 dBm
Message Size	1480 bits (190 bytes)
Message Tx rate	max 10 Hz
Number of Subchannels/msg	1
PSSCH size	12 RB
Channel Throughput	4.5 Mbps

TABLE I: LTE-V2X communication parameters

optimistic for real life scenarios, as shown for example in [23], where the average CAM sizes is typically measured around 350 Bytes, with a very diverse set of CAM sizes. Nevertheless, such value was used also to allow comparisons with other studies. For all the simulation results presented in this this study, the vehicles' movements have been simulated in SUMO (Simulation of Urban MObility), according to the mobility scenario described in Table II. Realistic traffic patterns were considered with the Krauss car following model, targeting a maximum speed yet adjusting its speed depending on the surrounding traffic congestion. NS3 has been used as simulation platform to perform the evaluations. The propagation path loss model is based on WINNER B1. In particular LOS components have been considered for slow and fast highway scenarios.

Scenario	Fast Highway	Slow Highway
Number of lanes	3 lanes x 2 directions	3 lanes x 2 directions
Length of the road	2000 m	600 m
Max vehicle speed	70, 140, 250 km/h	50 km/h
Min inter-vehicle spacing	2.5 sec	2.5 sec
Avg. number of vehicles	245, 123, 70	100, 200 250

TABLE II: LTE-V2X mobility parameters

Finally, the DCC mechanism used in this work is "packet drop" (i.e. Tx Rate Control, TRC). At the time of this study, there was no official CR limit table provided by regulators. For example, the ETSI ITS specification is still in a drafting stage [3]. Therefore we used the CR limit table from 3GPP RAN1 working group contribution [4], as depicted in Table III.

CBR measured	CR limit
CBR $\leq$ 0.650	no limit
0.650 < CBR < 0.675	1.6e-3
0.675 < CBR < 0.700	1.5e-3
0.700 < CBR < 0.725	1.4e-3
0.725 < CBR < 0.750	1.3e-3
0.750 < CBR < 0.800	1.2e-3
0.800 < CBR < 0.825	1.1e-3
0.825 < CBR < 0.850	1.0e-3
0.850 < CBR < 0.875	0.9e-3
0.875 < CBR	0.8e-3

TABLE III: LTE-V2X DCC parameters

1) Fast highway scenario: We consider a highway of 6 lanes, with 3 lanes in each direction. The whole length of the highway is 2000 m long. All the cars move with the same speed. We considered 3 different target speeds: 70 km/h, 140 km/h and 250 km/h, leading respectively to 245, 123 and 70 vehicles in average (based a minimum inter-vehicle spacing of 2.5 seconds). The CAM Tx rate is aligned with CAM generation triggering conditions, based on change in location, that means 5 Hz for 70 km/h and 10 Hz for 140 km/h and above.

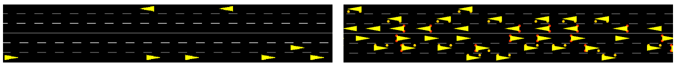

(a) fast highway (b) slow highway

Fig. 7: SUMO simulation examples

2) Slow highway scenario: This set of simulations is designed to test the performance of LTE-V2X mode 4 under heavy traffic load, where the DCC mechanism is stressed. To this end, the channel needs to be close to saturation. In this scenario, we simulate the vehicles' movements in a 600 m long highway road, composed of 3 lanes in each direction. To reach a dense network, the maximum speed is reduced to 50 km/h in order to also reduce the inter-vehicle spacing. Simulations were conducted for 100, 200 and 250 vehicles on average. This scenario essentially tends to simulate a moving traffic jam. The CAM Tx rate is set to 10Hz to ease comparison with other LTE-V2X studies [4].

VI. SIMULATION RESULTS

1) Fast highway scenario: Figure 8 presents the Packet Delivery Ratio (PDR) against the transmitter-to-receiver distance (Distance Tx-Rx) in case of sensing-based resource selection and for 3 different speeds.

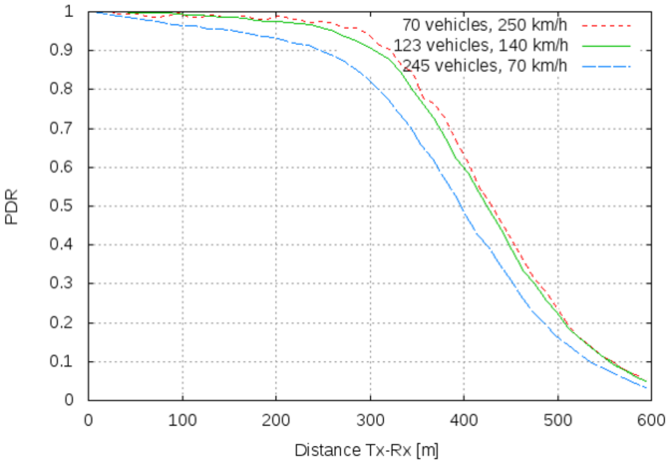


Fig. 8: PDR vs Distance Tx-Rx for 70, 123, 245 vehicles (speed = 250, 140, 70 km/h) in fast highway scenario

One can see that for 250 km/h and 140 km/h (when vehicles move fast), PDR is over 90% for a range of 300 m. For distances bigger than 300 m, we start to have signal regression due to propagation path loss. This validates the choice of MCS 7 as an upper bound for the MCS index, to cover correctly any speed value. The PDR decreases progressively for distances bigger than 300 meters. In this scenario, the performance of LTE-V2X is limited more by the propagation path losses than by packets collisions. The channel is not heavily congested.

For a low speed of 70 km/h, the system starts to impact interferences. Since vehicles are moving with a relatively slow speed, we will have a denser network (reduced inter-distance). In this situation, we can observe the PDR to start decreasing noticeably already for small distances.

2) Slow highway scenario: Figure 9 presents the Packet Delivery Ratio (PDR) against the transmitter-to-receiver distance (Distance Tx-Rx) for respectively 100 and 200 vehicles, considering sensing-based and random resource selections.

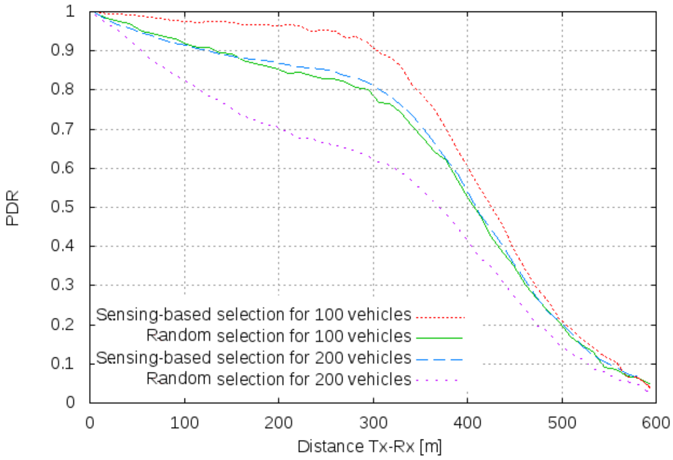


Fig. 9: PDR vs Distance Tx-Rx for 100 and 200 vehicles in slow highway scenario

We can see that the sensing-based resource selection provides significant improvement in terms of packet reception rate. When the sensing-based resource selection is used for 100 vehicles, the PDR is $\geq$ 90% until approximately 300 meters of distance, then it starts to decrease steeply. For 200 vehicles, the PDR is $\geq$ 90% until approximately 125 meters, and then it decreases progressively as the $\geq$ 80% PDR mark is passed at approximately 300 meters, then starts to decrease more steeply. For both cases, when resources are selected randomly, the system is performing much worse: the PDR is decreasing fast even for small distances and this due to collisions since resources are selected randomly and no resource selection mechanism is used.

For the case of 200 vehicles and with the sensing-based approach enabled, we investigate the reasons behind packet losses. Fig. 10 shows the percentage of packets correctly received, packets lost due to collisions and packets lost due to propagation path loss. We can see that for small distances, the only reason of losing packets is collisions. At 300 meters, we start to have decoding errors due to the propagation path loss, until it becomes by far the main reason of packet lost for big distances. We can see that collisions still occur when sensing-based resource selection is used, and it can affect more than 10% of the messages if the number of stations in the area is significant. An explanation will be provided in the next section.

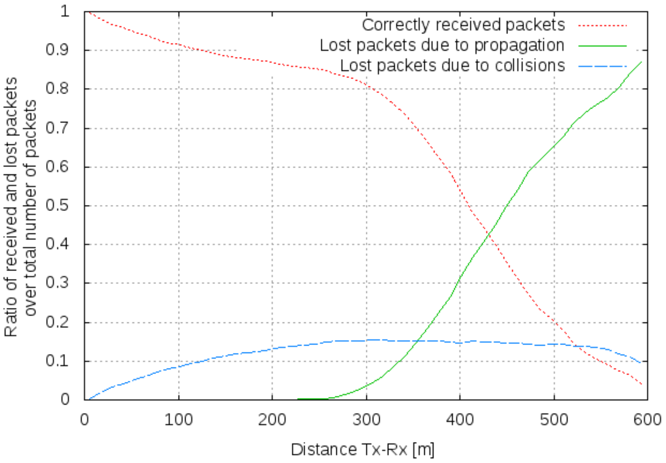


Fig. 10: Ratio of received and lost packets over number of sent packets for 200 vehicles in slow highway scenario

In our configuration, the channel bandwidth is divided into 3 subchannels and the selection window is 100 ms. When a station selects a new resource, it has to select 1 out of 300 available resources. We then investigate the system's performance when 250 vehicles are in the same area, which is getting very close to the 300 resources, thus requiring to enable DCC, for the two following configurations:

- Resources are selected using sensing-based resource selection but without DCC algorithm
- Resources are selected using sensing-based resource selection and with DCC algorithm

Figure 11 shows the value of the CBR, as measured locally by a random vehicle over time. We can see that when the DCC is not applied, the measured CBR reaches up to 75% and the channel can be considered saturated. When the DCC is applied, the measured CBR is reduced and keeps oscillating around 60% ± 3%. This confirms that the DCC is functioning correctly.

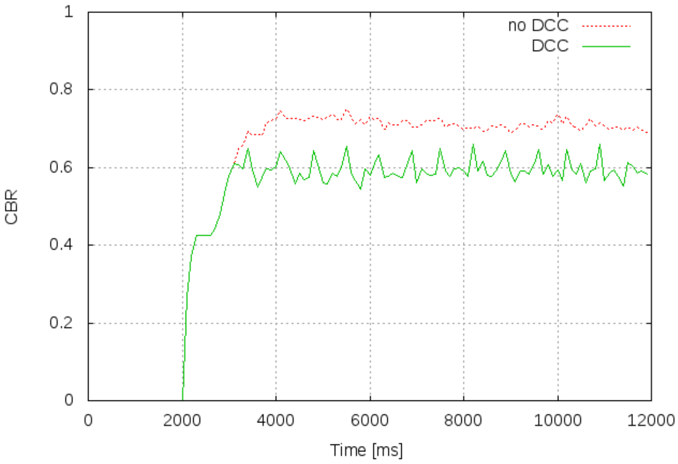


Fig. 11: CBR vs time for 250 vehicles in slow highway scenario

Figure 12 shows the PDR vs distance between transmitter and receiver for 250 vehicles for 2 use cases: with and without DCC. We can see that there is a drop in PDR when DCC is enabled, compared to DCC disabled, even though DCC reduces the number of transmitted packets (a packet dropped is considered not transmitted). In this configuration, vehicles will have to select one resource from the 20% of

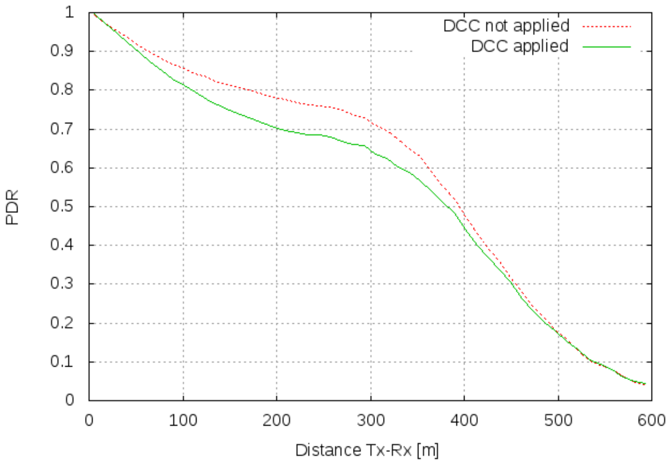


Fig. 12: PDR vs Distance Tx-Rx for 250 vehicles in slow highway scenario

available resources (20% of 300 resources) that experienced the lowest RSSI. Since the number of vehicles is high in a small geographical area, one vehicle is more likely to select an already reserved resource by another vehicles. Once a collision takes place, it occurs for a number of transmissions given by the re-selection counter.

VII. CHALLENGES OF DCC ON LTE-V2X

In the previous part, we showed the performance of LTE-V2X algorithms under slow and fast highway. The sensing-based resource selection algorithm always provided better packet delivery rate compared to a random resource selection.

When the channel is congested, with many users in the same area, DCC must be applied. Dropping packet transmission will decrease the packet delivery rate and the total number of transmitted and received packets will be decreased, which is good from a pure CBR and CR limit compliance perspective. However, we noticed in Fig. 12 that when the DCC is enabled, the overall performance of the system is degraded. We investigate this phenomenon in this section.

When a first vehicle decides to select a new resource, it sets a selection window. The sensing-based resource selection selects one resource from this selection window. The other vehicles will not know about the selected resource until the packet is transmitted and decoded correctly. In the meantime, if a second vehicle decides to select a new resource, it can unfortunately select the same resource already selected by the first vehicle. This is depicted on Fig. 13.

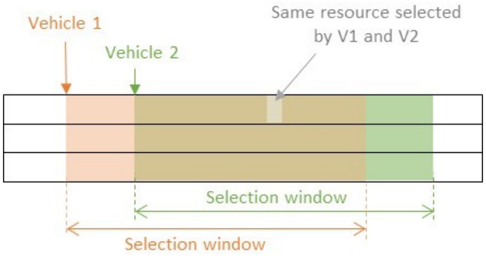


Fig. 13: Same resources selected by two vehicles

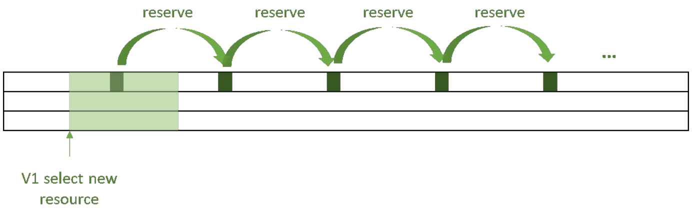


Fig. 14: Resource reservation in LTE-V2X SPS

When such kind of collision occurs, it cannot be detected by transmitters due to half duplex. Such collisions can last for a large number of consecutive transmissions. As the re-selection counter is uniformly selected between 5 and 15, this means that such collisions last in average 1 second (if transmitting at 10 Hz), which is a relatively long time for safety related messages.

The LTE-V2X standard does not specify a particular DCC technique. It is up to the implementation to decide what to do in order to reduce its CR. In our simulations, we adopted the packet dropping technique. Results have showed that using this technique, the CBR may be reduced and as such, the channel remain less saturated. However, this technique will also cause a decrease in the PDR even if the total number of transmitted packets has dropped, which is indeed neither expected nor desired. One reason behind this behavior is due to the way LTE stations treat the reservation field placed in their SCI messages. The reservation field indicates to other vehicles when the resource will be used next time. If the vehicle decides not to reserve the resource for the next time, this field is set to zero. The important point is to notice is that the resource reservation is in fact done only for the next transmission, as depicted in Fig. 14.

When a packet is dropped due to DCC mechanism, the reservation series continues at the transmitter's side, but the message is not sent. On the one hand, receiving stations not finding a reservation being placed might decide to start using the same resource. The incompatibility of a semi-persistent scheduling scheme with a packet-drop DCC mechanism becomes clear. If the DCC allows a vehicle to resume packet transmission, it will not start a new reservation process but simply transmit, which will clearly lead to packet collisions with other stations, which opportunistically took the slot made available by DCC, as shown in Fig. 15.

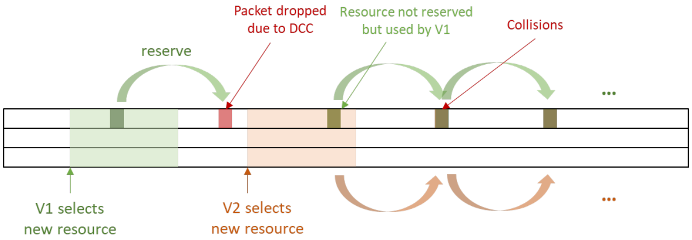


Fig. 15: Collisions due to packet drop (DCC mechanism)

On the other hand, when a station decides to drop a packet, if its resource was already reserved, the other stations will not consider this resource as a free candidate resource, and no other transmission will occur on the same resource during the subframe when packet drop is performed. This shows the potential waste of resource generated by DCC.

VIII. LTE-V2X ENHANCEMENTS FOR CONGESTION CONTROL

In this section, we provide some ideas for potential improvement of the LTE-V2X system, which we will investigate in future work.

First, Fig. 11 showed some CBR oscillations, which are mostly due to abrupt changes in CR limits kicking in when the CBR exceeds a threshold.It would be required to have a CR limit table with more entries and an additional rule that would avoid CR limit to change by more than one row at a time.

Secondly, we have clearly shown that packet-drop is not a suitable technique for LTE-V2X mode 4 congestion control, due to the semi-persistent scheduling with reservations. Dropping the packet causes the resource to be sensed free and thus available for use by the surrounding nodes, leading to collisions when the station resumes its series of reserved transmissions. Therefore one suggestion would be to force a station to perform a new resource reservation process whenever a packet is dropped, by resetting its re-selection counter to zero.

Finally, different techniques for congestion control are required, as packet drop has been shown not to be satisfactory. Other techniques, such as transmission power or MCS adaptations, could be studied.

IX. CONCLUSION

We presented in this paper a first study on the impact of wireless congestion control on LTE-V2X sidelink Rel-14 mode 4. It includes a detailed analysis of semi-persistent scheduling (SPS) in conjunction with sensing-based resource selection used as a distributed resource scheduling, as well as the ETSI Decentralized Congestion control (DCC) as wireless congestion control mechanism. We first showed that the sensing-based resource selection helps to increase the system performances compared to a random scheduling. However, degradations have been confirmed in case of channel congestion, requiring DCC to mitigate them. Yet, our study showed that DCC led worse performance than no congestion control at all. Future work will investigate strategies to improve the interaction between DCC and LTE-V2X.

X. ACKNOWLEDGEMENTS

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