# Configuration of the C-V2X Mode 4 Sidelink PC5 Interface for Vehicular Communications

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***Abstract*— The 3GPP has released the C-V2X standard to support V2X (Vehicle-to-Everything) communications using the LTE sidelink PC5 interface. This standard includes two modes of operation, and this study focuses on the Mode 4. This mode does not require the support of the cellular infrastructure, and vehicles can autonomously select their sub-channels for their V2V transmissions. The adequate operation of C-V2X Mode 4 requires a careful configuration of its main parameters. This study analyzes the optimum configuration of the parameters that mostly influence the operation and performance of C-V2X or LTE-V Mode 4. This analysis is conducted for different channel loads and traffic conditions. The conclusions obtained are compared with existing studies taking into account the importance of using accurate models for adequately configuring the C-V2X Mode 4 interface.**

***Keywords*— Cellular V2X, C-V2X, LTE-V, LTE-V2X, PC5, V2V, vehicular networks, sidelink, semi-persistent scheduling, connected vehicles, automated vehicles, 5G V2X.**

## I. INTRODUCTION

The 3GPP published in Release 14 the C-V2X standard (also known as LTE-V or LTE-V2X) that uses the LTE PC5 interface for V2V (Vehicle-to-Vehicle) communications [1]. This standard has been designed to support cooperative traffic safety and efficiency applications, and includes two modes of operation. In C-V2X Mode 3, vehicles communicate directly between them, but the communications are managed by the cellular infrastructure that selects the sub-channels or radio resources for each V2V transmission. On the other hand, C-V2X Mode 4 does not require the support from the cellular infrastructure, and vehicles autonomously select the sub-channels or radio resources for their V2V transmission. To this aim, the 3GPP standard defines a distributed semi-persistent scheduling scheme that all vehicles must implement. C-V2X Mode 4 is highly relevant since it can support V2V safety applications in the absence of coverage from the cellular infrastructure. As a result, a careful configuration of C-V2X Mode 4 is necessary to increase its communications range and capacity. The 3GPP standard does not fix or recommend concrete values for all the parameters that can be configured in C-V2X Mode 4. These parameters can be configured by the cellular network if vehicles operating in Mode 4 are under cellular coverage. However, they would need to be pre-configured when vehicles are out of the cellular coverage. Standardization bodies such as ETSI are currently defining what should be the default configuration of C-V2X Mode 4 parameters [2]. Recent studies have also analyzed the configuration of some of the C-V2X Mode 4 parameters with sometimes differing conclusions [3-6]. The differences originate from the different modelling accuracy for some of the aspects that mostly influence the operation and performance of C-V2X Mode 4. This study complements existing studies by providing an independent analysis of C-V2X Mode 4 V2V communications, where we also identify and discuss the implementation and modeling aspects that have a major impact on the operation of C-V2X Mode 4, and that are at the origin of the differences observed in some of the studies published to date. To this aim, this study is conducted using a simulator that carefully implements the processes and models that mostly affect the operation and performance of C-V2X Mode 4. In particular, this study is conducted using the C-V2X Mode 4 simulator presented in [7][8]. The simulator is standard-compliant, and is configured following the 3GPP recommendations. This study also provides new insights compared to existing studies by analyzing the optimum configuration of C-V2X Mode 4 under different channel load levels and traffic patterns. As it is shown in this study, these two aspects have a significant influence on how to adequately configure the C-V2X Mode 4 standard.

## II. C-V2X MODE 4

### A. Physical Layer and Sub-channelization

C-V2X supports 10MHz and 20MHz channels, and uses SC-FDMA (Single-Carrier Frequency-Division Multiple Access). The channel is divided into 1ms sub-frames and into Resource Blocks (RBs) of 180kHz each. C-V2X defines a sub-channel as a group of RBs in the same sub-frame. The number of RBs per sub-channel can vary depending on the packet size and the utilized Modulation and Coding Scheme (MCS). Sub-channels are used to transmit data and control information. The data is transmitted in Transport Blocks (TBs) over Physical Sidelink Shared Channels (PSSCH). The control information is transmitted in Sidelink Control Information (SCI) messages (also referred to as SA or Scheduling Assignment) over Physical Sidelink Control Channels (PSCCH) [9]. A TB contains a full packet and it can occupy one or several sub-channels. This packet can be for example a beacon or Cooperative Awareness Message (CAM), or any other event driven message. Each TB has an SCI associated, and both must always be transmitted in the same sub-frame. The SCI occupies 2 RBs and includes information such as the MCS used to transmit the TB, the RBs that the TB occupies, and the

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resource reservation interval for the semi-persistent scheduling scheme. This interval refers to the periodicity used by vehicles to transmit their packets (in multiples of 100ms). The information on the SCI is critical, so the SCI must be correctly received to receive and decode the TB. Fig. 1 illustrates an example of C-V2X sub-channelization with 3 sub-channels. The figure differentiates the RBs used for TB and SCI transmissions.

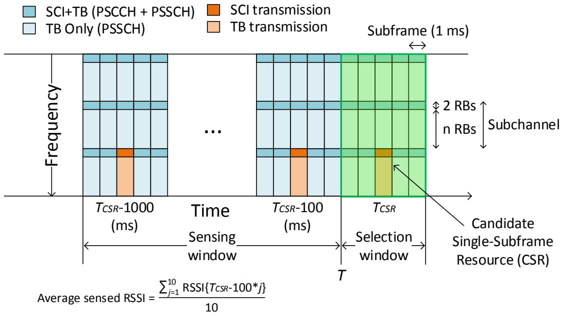

Fig. 1. C-V2X: sub-frames, sub-channels, Selection and Sensing windows.

### B. *Sensing-Based Semi-Persistent Scheduling*

Vehicles autonomously select their sub-channels in C-V2X Mode 4. Although C-V2X Mode 4 operates without cellular infrastructure support, the cellular network can configure the C-V2X Mode 4 configurable parameters when vehicles are under cellular coverage. When they are not, vehicles must utilize pre-configured values for these parameters. These parameters include the carrier frequency, synchronization references, number of sub-channels per sub-frame, and number of RBs per sub-channel, among others [10]. The 3GPP standard does not specify a concrete value for each parameter, but the default values are currently being discussed for example in [2]. Vehicles select their sub-channels using the sensing-based Semi-Persistent Scheduling (SPS) scheme specified in Release 14 [9][11]. Vehicles reserve the selected sub-channels for a number of consecutive packet transmissions equal to *Reselection Counter*. *Reselection Counter* is randomly set between 5 and 15 every time new sub-channels must be reserved, and whenever packets are transmitted every 100ms (i.e. vehicles transmit 10 packets per second or 10 pps). Vehicles include the value of *Reselection Counter* in the SCI. After each transmission, *Reselection Counter* is decremented by one. When it is equal to zero, new resources or sub-channels must be selected and reserved with probability (1-$P$). New resources must also be selected if a packet to be transmitted does not fit in the resources previously reserved. $P$ can be configured to any value between 0 and 0.8. Higher values of $P$ enable vehicles to maintain their selected resources for longer periods of time. The process followed by vehicles to select and reserve their resources or sub-channels is organized in three steps.

*Step 1*. Whenever a new resource must be selected, a vehicle $V$ can reserve resources between the time $T$ at which this new selection must be done, and the established maximum latency (equal or lower than 100ms [12]). This time period is referred to as Selection Window (Fig. 1). Within the Selection Window, $V$ identifies the Candidate Single-Subframe Resources (CSRs) to be reserved. A CSR is a group of adjacent sub-channels within the same sub-frame where the packet or SCI+TB to be transmitted fits.

*Step 2*. Vehicle $V$ has been sensing all packets transmitted within the Sensing Window that includes the last 1000 sub-frames before $T$ (Fig. 1). The vehicle creates then a list $L_1$ that includes all the CSRs in the Sensing Window except those that meet two conditions: (1) $V$ has correctly received in the Sensing Window an SCI from another vehicle indicating that it will utilize this CSR at the same time as $V$ will need it to transmit any of its next *Reselection Counter* packets; (2) $V$ measures an average Reference Signal Received Power (RSRP) over the RBs utilized to transmit the TB associated to the SCI received from the other vehicle higher than a given threshold. This RSRP threshold is a configurable parameter. The two conditions must be simultaneously met in order for $V$ to exclude a CSR. After Step 2 is executed, $L_1$ must include at least 20% of all CSRs in the Selection Window. If not, Step 2 is iteratively executed until the 20% target is met, and the RSRP threshold is increased by 3dB in each iteration.

*Step 3*. Vehicle $V$ creates a second list $L_2$ of CSRs. The total number of CSRs in $L_2$ must be equal to 20% of all CSRs in the selection window. $L_2$ includes the CSRs from $L_1$ (after Step 2) that experienced the lowest average RSSI (Received Signal Strength Indicator) over all its RBs. This RSSI value is averaged over all the previous $T_{CSR}$-100*$j$ sub-frames ($j \in$ N, $1 \leq j \leq 10$) when vehicles transmit 10pps (Fig. 1). Vehicle $V$ randomly chooses one of the CSRs in $L_2$, and reserves it for the next *Reselection Counter* transmissions.

The sensing-based SPS scheme can support also vehicles transmitting 20pps and 50pps. In this case, the following changes need to be applied to the scheduling: (1) the maximum tolerable latency is 50ms and 20ms for 20pps and 50pps, respectively, which reduces the Selection Window in Step 1; (2) the *Reselection Counter* is randomly selected between 10 and 30 for 20pps, and between 25 and 75 for 50pps; (3) in Step 3, the average RSSI is $T_{CSR}$-$T_{IPI}$*$j$, where $T_{IPI}$ is equal to 50 for 20pps and to 20 for 50pps. The variable $j$ takes values between 1 and 20 for 20pps, and between 1 and 50 for 50pps.

### C. *C-V2X Mode 4 parameters*

The operation and performance of C-V2X Mode 4 depend on a set of parameters that are analyzed in this study. This section discusses these parameters, and explains their relevance and influence on the operation and performance of C-V2X Mode 4.

*Probability P*. This is the probability that a vehicle maintains its previous CSRs when the *Reselection Counter* reaches zero. If $P$ is set equal to zero, a vehicle will need to execute the sensing-based SPS scheme to select new CSRs when the counter is equal to zero. Increasing $P$ produces two effects. First, increasing $P$ reduces the number of CSR selections per second since vehicles tend to use the same CSRs during longer periods of time. This can have a positive effect on the operation of the sensing-based SPS scheme since vehicles have a more stable sensing environment when they have to select their CSR. However, increasing $P$ can also produce a negative effect due to the mobility of vehicles. Let's suppose two vehicles that are moving in opposite directions, and that are transmitting in the same CSRs since they were out of their respective sensing ranges when they selected their CSRs. If these vehicles maintain their CSRs for long periods of time because $P$ is set to high values, they will interfere each other when they get in range. In addition, if two vehicles experience a packet collision, this collision will be recurrent and will happen for longer periods of time if $P$ is set to a high value, which can have a very negative effect on the traffic safety of these two vehicles.

*Sensing Window*. During the execution of Step 3 of the sensing-based SPS scheme, vehicles must compute the average RSSI experienced by all the CSRs over the last second (Sensing Window) previous to $T$. The Sensing Window was fixed in the standard to 1 second in order to support applications where vehicles transmit 1pps. However, during one second, most of the vehicles have probably changed their transmitting sub-channel, in particular if $P$ is set equal to 0. This can result in wrong estimations of the best CSRs. For example, it could result in that a CSR that has been freed before $T$ by another vehicle is discarded because the average RSSI value is high. Similarly, it could result in that CSRs that have not been used by any vehicle during a large portion of the Sensing Window, but have been selected by a vehicle just before $T$, are considered as candidate CSRs because the average RSSI over the Sensing Window is low. These examples illustrate possible risks of using long Sensing Windows where the RSSI is simply averaged. Alternative strategies that are analyzed in this study include using shorter Sensing Windows, or maintaining a one second Sensing Window but giving more importance to the more recent RSSI values when computing the average RSSI over the Sensing Window. It should though be noted that the use of shorter Sensing Windows entails the challenge to support applications requiring 1pps.

*RSRP Threshold*. The C-V2X Mode 4 standard gives the option to modify the RSRP threshold used to decide if a given CSR is excluded in Step 2 of the sensing-based SPS scheme (provided its associated SCI has been correctly received). This threshold has been usually set in the evaluations conducted under the 3GPP working groups to a value sufficiently low so that a CSR is always excluded if its associated SCI is correctly received. It should though be remembered that Step 2 increases automatically the RSRP threshold if the percentage of excluded CSRs exceeds 80% of the Selection Window (e.g. when the channel load is high). However, setting the initial value of the RSRP threshold to a high value (e.g. because the channel load is high) would reduce the capability of Step 2 to exclude those CSRs whose SCI were correctly received. If these CSRs are not excluded, Step 3 could select them, and hence cause a packet collision.

*Transmit power*. The transmit power notably influences the communications range and the interference generated by vehicles. In principle, it would hence be reasonable to consider the possibility to reduce the transmission power of vehicles when the channel load is high, and increase it when it is not high. In fact, a low transmit power could reduce packet collisions. However, decreasing the transmit power reduces the communications range and the distance to the transmitter at which the hidden-terminal is more relevant.

*Size of* $L_2$. $L_2$ is the list of CSRs built by Step 3 of the sensing-based SPS algorithm considering the RSSI measurements over the Sensing Window. The CSR selected by a vehicle to transmit its packets is randomly chosen among the CSRs in $L_2$. The size of the list $L_2$ is defined as a percentage of the Selection Window, and this percentage is fixed by the 3GPP standard to 20%. Decreasing the size of $L_2$ could increase the packet collisions between nearby vehicles as there is less candidate CSRs, and nearby vehicles tend to exclude the same CSRs. So, if the size of $L_2$ is small, there is a risk that the two nearby vehicles have the same CSRs in $L_2$. This risk is reduced if we increase the size of $L_2$. However, a larger size of $L_2$ reduces the capacity of a vehicle to accurately select the most adequate CSR, since the CSR is finally selected randomly among all CSRs included in $L_2$.

## III. SIMULATION ENVIRONMENT

The analysis of the optimum configuration of C-V2X Mode 4 is conducted using VEINS, an open source framework for vehicular network simulations that integrates OMNeT++ and SUMO. We implemented in VEINS a C-V2X Mode 4 interface following the 3GPP specifications [12]. The developed C-V2X interface accurately implements the scheduling scheme described in section II, and takes into account the channel, traffic and mobility models in [12].

This study is conducted considering the Highway Slow scenario defined in [12] by the 3GPP. This scenario is a 5km highway segment with 6 lanes (3 lanes in each direction). The statistics have been extracted only from those vehicles that are in a road segment of 2km in the center of the scenario to avoid border effects. Following the 3GPP guidelines, the traffic density has been fixed to 120veh/km and the maximum vehicles' speed was set to 70km/h.

The implemented propagation model follows the 3GPP guidelines for evaluating C-V2X Mode 4. In particular, the simulator implements the WINNER+ B1 propagation model as in [12]. This model considers a log-distance pathloss to model the average propagation loss between transmitter and receiver at a given distance. It models the shadowing effect produced by the presence of surrounding obstacles using a log-normal random distribution with a standard deviation of 3dB. The shadowing correlation is modeled as specified in [12]. The PHY layer performance of C-V2X is modeled using the BLER (Block Error Rate)-SNR (Signal to Noise Ratio) curves in [13] that consider the fast fading effect. Following the 3GPP guidelines [12], we assume perfect time and frequency synchronization at sub-frame and sub-carrier levels and a noise figure of 9dB. Our simulator also implements the In-Band Emission model defined in [12].

All vehicles in the scenario transmit their beacons (also referred to as CAMs or BSMs) in a dedicated channel of 10MHz bandwidth in the 5.9GHz frequency band. Beacons are generated following the traffic model described in [12]. This model defines that beacons are periodically generated. One out of five beacons contains 300 bytes of data, and is referred to as LF (Low Frequency). The other four have 190 bytes, and are referred to as HF (High Frequency). LFs are transmitted in this study using MCS 7, and hence fit in 20 RBs [9] (22 RBs including the SCI). HFs are transmitted using MCS 9, and hence fit into 10 RBs (12 RBs including the SCI). The 10MHz channel is divided into 50 RBs per sub-frame that are used for V2V communications. The channel is divided into 4 sub-channels of 12 RBs each (10 RBs for the TB and 2 RBs for the SCI). As a result, LFs need 2 sub-channels to be transmitted, while HFs fit into one sub-channel. In addition to this traffic model defined in 3GPP, we also consider a traffic model where all beacons have 190 bytes of data (HFs)[1]. For clarity, this simplified traffic model will be used by default to analyze and explain the optimum configuration of the C-V2X Mode 4 parameters. However, this paper will also present the results of the analysis for the 3GPP traffic model when the conclusions regarding the optimum configuration of C-V2X Mode 4 differ with respect to the simplified traffic model.

This study analyzes scenarios in which vehicles transmit 10 or 50 beacons or packets per second (pps), which correspond to beacon transmission intervals equal to 100ms and 20ms. By default, a transmission power of 23dBm is considered following 3GPP guidelines [12]. By default, the probability $P$ of selecting new resources is set to $P$=0, i.e. all vehicles always select new resources when their *Reselection Counter* goes down to 0. Similarly, the default RSRP threshold used in Step 2 is set equal to -120dBm, which is sufficiently low to guarantee that a CSR is always excluded if its associated SCI is correctly received.

## IV. C-V2X MODE 4 CONFIGURATION

### A. *Probability P*

Fig. 2 shows the impact of the probability $P$ of maintaining the selected resources or sub-channels on the Packet Delivery Ratio (PDR) as a function of the distance between transmitter and receiver. Fig. 2 shows that the PDR improves if we augment $P$ to 0.6 when vehicles transmit 10pps. This is the case because augmenting $P$ reduces the number of resource reservations, and hence provides a more stable sensing environment that benefits the operation of the sensing-based SPS scheme. As a result, vehicles tend to select resources that are less prone to suffer packet collisions. However, Fig. 2 shows that when the channel load increases[2], augmenting $P$ can reduce the PDR. An increase of the channel load reduces the communication range. In this case, if vehicles select a resource and maintain it for a long time, it is highly probable that due to their mobility they will get in range with vehicles that were previously not under their sensing range, and hence were not taken into account for the resource selection by the sensing-based SPS scheme. In this case, if vehicles maintain their resources for longer, they will experience packet collisions with these vehicles that enter into their sensing range after the resource has been reserved. [4] and [5] conclude that augmenting $P$ increases the PDR as we have shown for 10pps. However, vehicles move at lower speeds in [4] and seem to be static in [5]. In addition, these studies do not consider the effect of increasing the channel load on their analysis, so the negative effects of augmenting $P$ when vehicles move at higher speeds and the channel load increases are not detected.

Fig. 3 shows the effect of $P$ on the PDR with the 3GPP traffic model that includes HF and LF packets. The comparison of Fig. 2 and 3 shows that the effect of $P$ on the PDR varies with the traffic patterns. When vehicles generate packets of different sizes, and these packets require a different number of sub-channels, the number of reselections increases and the effectiveness of the sensing-based SPS scheme decreases. The number of reselections increases because larger LF packets cannot be transmitted with the number of sub-channels reserved for smaller HF packets. Augmenting $P$ decreases reselections, and improves the PDR independently of the channel load (Fig. 3). [3] uses the same traffic model and sub-channels configuration than Fig. 3, but does not find a significant effect of $P$ on the average PDR. However, their analysis is based on average PDR, and hence does not capture the evolution of the PDR with the distance.

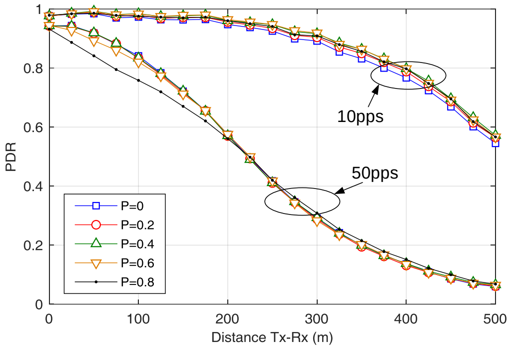

Fig. 2. Effect of $P$ on the PDR.

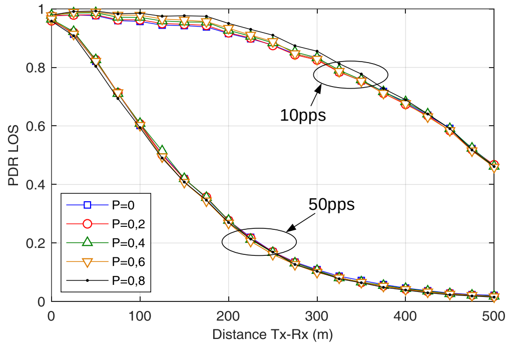

Fig. 3. Effect of $P$ on the PDR when HF and LF packets require a different number of sub-channels.

The previous analysis has shown that augmenting $P$ does not always increase the PDR. It is also important to analyze the effect of $P$ on the Packet Inter-Reception (PIR) time. Augmenting $P$ increases the time between resource reselections. This can be beneficial if the sensing-based SPS scheme results in that vehicles avoid selecting resources experiencing packet collisions. On the other hand, if two vehicles experience packet collisions, these collisions will be maintained for a longer period of time if $P$ is high. These effects are illustrated in Fig. 4 that represents a CDF (Cumulative Distribution Function) of the PIR for different values of $P$. The figure corresponds to the scenario where vehicles transmit 10pps and all the packets have the same size. Fig. 4 shows that for the majority of transmissions, augmenting $P$ reduces the PIR. However, large values of $P$ significantly increase the PIR for the vehicles that experience persistent collisions, although such collisions are certainly less probable in Fig. 4. It should also be noted that, following the observations in Fig. 2, an increase in the channel load reduces the benefits of augmenting $P$ on the PIR since the channel load increases the probability of packet collisions.

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[1] From the resource management point of view, using a single beacon size is equivalent to increasing the MCS of the longer packets so that both long and short beacons use the same number of sub-channels.

[2] A similar trend would be observed if we augment the traffic density.

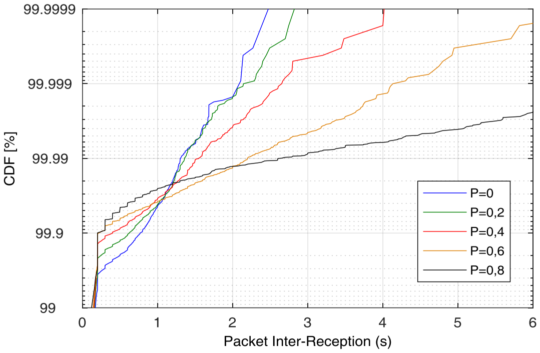

Fig. 4. CDF of the PIR for 10pps and packets of equal size.

## B. *Sensing Window*

The Sensing Window has been defined in 3GPP equal to 1 second. [4] analyzed the effect of reducing and increasing the Sensing Window for scenarios with 10pps, and found gains if the Sensing Window was reduced to 0.1 seconds. In [6], the authors found that higher gains were also possible by exponentially weighting the RSSI values in order to give higher priority to the more recent measures. However, [6] does not exactly implement the C-V2X mode 4 standard[3], and hence the use of an exponential Sensing Window still needs to be validated with a standard-compliant C-V2X mode 4 implementation. In this study, we have analyzed the effect of the Sensing Window by comparing the PDR obtained with the standard implementation (RSSI is averaged over 1 second), shorter (0.1 and 0.5 seconds) Sensing Windows (still computing average RSSI values), and with an exponential Sensing Window of 1 second. Similar PDR values have been observed for all configurations when vehicles transmit 10pps. Small differences are though observed when vehicles transmit 50pps and the channel load increases (Fig. 5). In this scenario, the exponential Sensing Window outperforms the standard one. Gains are also observed when shortening the Sensing Window. However, this option should be carefully considered if vehicles transmit fewer packets per second (e.g. 1pps). The gains observed in our evaluations with the exponential Sensing Window are significantly smaller compared to those observed in [6]. This is due to the fact that [6] does not implement the standardized Step 2 of the sensing-based SPS scheme, and this step has a significantly higher impact on the operation of SPS than Step 3. This is actually observed in Fig. 6 that compares the PDR obtained with the standardized sensing-based SPS scheme to that obtained when only Step 2 or Step 3 of the scheme are implemented. No significant differences are observed when vehicles transmit 10pps because the channel load is low, most of the CSRs are available, and both steps can easily detect the CSRs with higher probability to suffer packet collisions. On the other hand, when vehicles transmit at 50pps, the channel load increases and there are more CSRs occupied. In this case, it is important to exclude the CSRs that are used by nearby vehicles since they will generate more interference. This is achieved by Step 2 that monitors the reception of SCIs. Since SCIs are transmitted with a robust MCS, the probability to correctly receive them is high, and Step 2 can exclude CSRs that can experience higher interference levels. Adding Step 3 actually does not show much improvement since Step 2 is already capable enough to eliminate these CSRs. In fact, only considering Step 3 of the sensing-based scheme reduces the PDR since the accuracy in the estimation of occupied CSRs is lower with Step 3 than with Step 2 (Fig. 6).

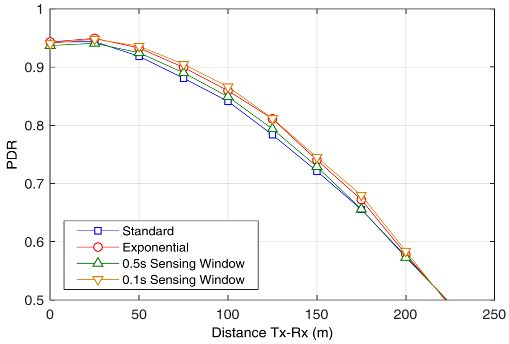

Fig. 5. Effect of the Sensing Window on the PDR with 50pps.

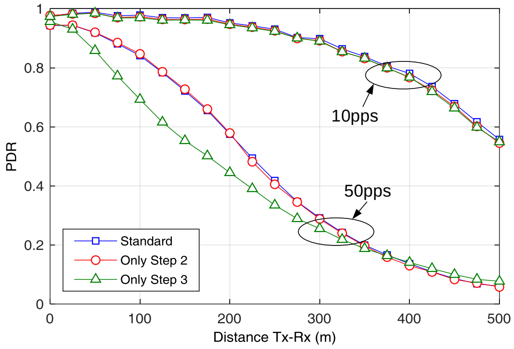

Fig. 6. Comparison of the PDR for different configurations of the sensing-based SPS scheme.

## C. *RSRP Threshold*

The previous section has illustrated the importance of Step 2 of the sensing-based SPS scheme. One key parameter in Step 2 is the RSRP threshold that is used to exclude CSRs. Simulations reported in 3GPP working group documents usually set up this threshold to a low value to make sure a CSR is excluded if the reception of an SCI indicated that another vehicle was planning to utilize it. [4] evaluated the impact of the initial RSRP threshold, and found that it did not have a major impact on the performance. However, the study only analyzed initial RSRP threshold values up to -90dBm. In Fig. 7, we analyze the effect of the initial RSRP threshold for a larger range of possible values (from -120dBm to -40dBm), and considering scenarios with low and high channel load levels (varying the number of packets transmitted per second per vehicle). Similarly to the conclusions reported in [4], Fig. 7 shows that the initial RSRP threshold value does not have an impact on the PDR when the channel load is low (10pps). However, the initial RSRP threshold has a clear and significant impact on the PDR when the channel load increases (50pps). In this case, we observe that the PDR increases with the lowest values of the RSRP threshold, and a significant degradation is observed when it increases to -80dBm. When the initial RSPR threshold value is increased, Step 3 is more active in excluding CSRs from the $L_1$ list. As shown in the previous section, Step 3 achieves the same results as Step 2 when the load is low. However, when the load increases, Step 3 is less effective than

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[3] Instead of implementing the standardized Step 2 of the sensing-based SPS scheme, [6] implements for Step 2 the Step 3 defined in the standard but averaging RSRP values instead of RSSI ones. The exponential Sensing Window is then applied to the modified Step 2 and Step 3.

Step 2 in excluding the CSRs that are more likely to experience high interference levels. So if we increase the initial RSRP threshold value, and hence depend on the effectiveness of Step 3 to exclude the adequate CSRs, the performance is degraded as observed in Fig. 7.

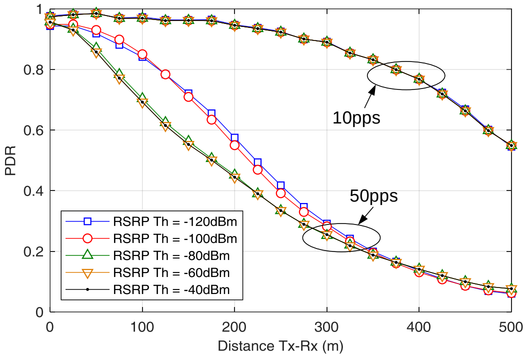

Fig. 7. Impact of the initial RSRP threshold value on the PDR.

### D. *Transmit Power*

Fig. 8 shows the impact of the transmit power on the PDR as a function of the distance between transmitter and receiver. The figure shows that, independently of the channel load, the higher transmit powers evaluated in this study improve the PDR. Reducing the transmit power reduces the interference range, but also the distance at which the hidden terminal problem becomes more relevant. In addition, Step 2 is capable to exclude the CSRs experiencing higher interference levels, and considers as candidate resources those used by vehicles farther away. So, reducing in addition the transmit power does not improve the CSR selection process, and reduces instead the communications range, which explains the lower PDR values observed in Fig. 8.

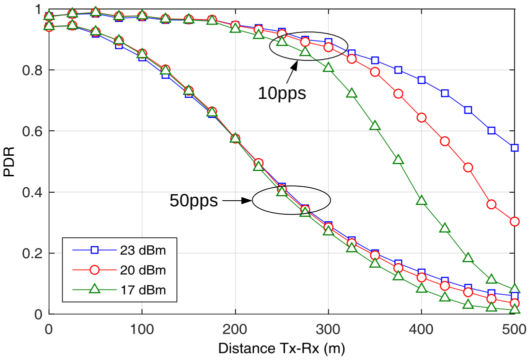

Fig. 8. Effect of the transmit power on the PDR.

### E. *Size of the $L_2$ list*

The size of the $L_2$ list is established to be equal to 20% of the Selection Window in the 3GPP standard. We have analyzed the impact of changing this size to 10% and 30% of the CSRs, and have found no significant impact when vehicles transmit 10pps and 50pps. When vehicles transmit 10pps, the channel load in our scenario is low, and there are always more than 30% of the CSRs that are unoccupied. In this case, increasing or reducing the size of $L_2$ is irrelevant. When the channel load increases, if we decrease the size of $L_2$ to 10%, vehicles can more accurately select the CSR since the effect of the final random selection is smaller. However, if we reduce the size of $L_2$, it is more probable that two close vehicles will have an overlapping $L_2$, so the packet collision probability between these two vehicles increases. The opposite effects are observed if we increase the size of $L_2$ to 30%, which explains why decreasing or increasing the size of $L_2$ does not have any significant effect.

## V. CONCLUSIONS

This paper has evaluated the configuration of C-V2X Mode 4 under different channel load and traffic scenarios, and has identified those factors that are more relevant for an adequate configuration of the standard. The evaluation has been conducted following the 3GPP standard and guidelines, and the conclusions of our analysis have been compared with related studies. This study has shown the operating conditions for which increasing the probability $P$ can improve the performance of C-V2X Mode 4. The study has also shown that although some improvements can be obtained using an exponential Sensing Window under high channel load levels, the gains are small since the effectiveness of the sensing-based scheme is mainly due to Step 2 of the algorithm and not to Step 3. The conducted analysis has also shown the benefits obtained using a low RSRP threshold in Step 2 and a high transmit power (within the standard limits). The results and conclusions presented in this paper are important for the community since they contribute to a better understanding of C-V2X Mode 4 and to its adequate configuration.

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