Performance Enhancement of C-V2X Mode 4 Utilizing Multiple Candidate Single-Subframe Resources

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Abstract—Prioritization of data streams in cellular vehicle-to-everything (C-V2X) may lead to unfavorable packet delays in low-priority streams. This paper studies allocating multiple candidate single-subframe resources (CSRs) per vehicle as a solution. It proposes a methodology to determine the number of CSRs for each vehicle based on the total number of neighboring vehicles, and to assign the multiple data streams among them for simultaneous transmission. The numerical results highlight the achievable delay gains of the proposed approach, and its negligible impact on packet collisions.

Index Terms—C-V2X Mode 4, medium access control, multiple candidate single-subframe resources, multi-priority data streams, vehicle-to-vehicle communication.

I. INTRODUCTION

In Release 14, the third generation partnership project (3GPP) introduced cellular vehicle-to-everything (C-V2X) Mode 4 to support vehicular communications without the support of cellular infrastructure. Therein, the medium access control (MAC) layer plays a crucial role in handling stringent, but varying, delay and reliability constraints of different V2X applications, and the variable delay constraints have necessitated the technologies to support multi-priority data streams [1]. It has been shown recently in [2], that in a setup with parallel multi-priority data streams, the competing technology IEEE 802.11p [3] outperforms C-V2X Mode 4 in terms of delay and priority management thanks to its enhanced distributed channel access (EDCA) mechanism. Thus, delay reduction is a pressing concern for C-V2X Mode 4 [4], specifically in avoiding stale packets in lower priority data streams.

Notable attention on enhancing the performance of C-V2X Mode 4 can be seen in the literature. Performance enhancement through variations in the transmit power is studied in [5]. In C-V2X Mode 4, vehicles use the semi-persistent scheduling (SPS) algorithm [6] in a distributed manner to sense the radio resources, termed candidate single-subframe resources (CSRs), utilized by other vehicles in a sensing window, and to select a CSR for its own transmission. To this end, [7] introduces a weighted power averaging methodology for sensing the CSRs in the sensing window. The authors of [8] show that re-selecting the CSR used for the previous transmission (reusing) more frequently, and using exponential sensing window sizes under high channel load levels can enhance performance. Authors stress several major enhancements, including subframe structure design, synchronization mechanism, resource pool configuration, and the SPS algorithm in [9]. Two resource selection methods for the reselection based on the information originally included in the control information are presented in [10]. As [5], [7], [8], [9], and [10] focus on a single data stream, they fail to capture the crucial aspect of priority management among different data streams. In this paper, we focus on multi-priority data streams, and study the possibility of enhancing the performance of C-V2X Mode 4 by exploiting its low channel utilization levels [2], through allocating multiple CSRs for each vehicle. Such parallel transmissions are practically possible thanks to the advancements in multiple-input multiple-output (MIMO) transmission technologies.

The proposed procedure leads to two fundamental problems:

- Number of CSRs per vehicle: We determine the number of CSRs allocated to each vehicle based on its number of neighbouring vehicles, in a distributed manner.
- Data stream allocation among the CSRs: Given the number of CSRs, we introduce a procedure for allocating the multi-priority data streams among the assigned CSRs.

We evaluate the performance of the proposed method using the discrete-time Markov chain (DTMC)-based models introduced in [2]. The results highlight significant reductions in the average delay, specially in the low priority data streams. In general, this is achieved through the allocation of separate CSRs for low priority data streams and allowing them more frequent transmission opportunities, opposed to making way to all higher priority queues as per the standard. The optimal allocation of the data streams among the multiple CSRs depends on the number of available CSRs per vehicle and the generation rates of each packet type. Increased packet collision is the tradeoff of allocating multiple CSRs as it creates more simultaneous transmission opportunities, and a higher chance of selection window overlap, as explained in [11]. However, the results show that these adverse effects are insignificant compared to the perceived benefits of delay and priority management.

The paper is organized as follows. The system model is presented in Section II. Section III studies the allocation of multiple CSRs to a vehicle. Section IV presents the numerical results and the discussion, and Section V concludes the paper.

II. SYSTEM MODEL

We consider a network where the target vehicle has \( N \) neighbouring vehicles, and \( N_{tot} = N + 1 \) is the total number of vehicles in the area of influence of the target vehicle. Each vehicle transmits decentralized environmental notification messages (DENM), high priority DENM (HPD), multi-hop DENM (MHD), and cooperative awareness messages (CAM). The priority order of serving these packets according to the standard is as follows: HPD > DENM > CAM > MHD. We use subscripts \( i \in I = \{H, D, C, M\} \) to
differentiate between the parameters for HPD, DENM, CAM, and MHD, respectively. The CAM packets are generated periodically with a generation interval $T_c$. Each HPD, DENM, and MHD are randomly generated at an average generation rate of $\lambda_m$, for $m \in \mathcal{C}$, based on events initiated by human activity or environmental conditions. Thus, the parameters related to packet generation can be written as $\mathcal{P} = \{\lambda_H, \lambda_D, \lambda_M, T_c\}$. The generated packets are queued separately, and transmitted according to their priority level, based on the SPS algorithm. For the simplicity of the study, we assume that packet generation rates are the same among all vehicles in the network [14]. Let $n_{CSR}$ denote the number of CSRs allocated to each vehicle such that $n_{CSR} \in \{1, 2, 3, 4\}$. To this end, CSRs are adjacent sub-channel sets within the subframe that are large enough to fit in the sidelink control information (SCI) and the transport block (TB) to be transmitted.

In [2], a similar setup is modeled using DTMCs for $n_{CSR} = 1$. For this overall model, $\mathcal{P}$, $N$, and $\Gamma$, which is called the selection window size in the SPS algorithm, act as the inputs, and we can obtain the respective values for the average delay, collision probability, and the channel utilization as outputs. When $n_{CSR} > 1$, multiple models run in parallel, and the inputs to each model depend on the packet types it handles. That is, for a particular model, $A \subset \mathcal{P}$, $N$, and $\Gamma$ act as inputs to the model, as illustrated in Fig. 1. The respective performance metrics, which are functions of $A$, act as the outputs of the model. We denote the average delay of the $l$-th data stream $d_{avg,l}(A)$, for each $l \in B$, the collision probability $P_{coll}(A)$, and the channel utilization $CU(A)$ as outputs, where $B \subset \mathcal{I}$ is the corresponding set of indices for $A$, e.g., $A = \{\lambda_H, T_c\} \rightarrow B = \{H, C\}$.

The overall model in [2] consists of four DTMCs that model the generation of each packet type, four DTMCs that model the queues of each packet type, and one DTMC that models the MAC layer operations of C-V2X Mode 4. We use an example scenario to elaborate further on each overall DTMC’s inputs, outputs, and internal structure. Consider an example where $n_{CSR} = 2$. HPD and DENM packets are handled through the first CSR, and the two remaining data streams are handled through the second, as illustrated in Fig. 2. With regards to the first CSR, $N$, $\Gamma$, and $A = \{\lambda_H, \lambda_D\}$ act as the inputs, and $d_{avg,H}(\lambda_H, \lambda_D)$, $d_{avg,D}(\lambda_H, \lambda_D)$, $P_{coll}(\lambda_H, \lambda_D)$, and $CU(\lambda_H, \lambda_D)$ act as the outputs. Furthermore, the two DTMCs model the generation of HPD and DENM packets, and two DTMCs model their device-level packet queues. The priority management is incorporated in the queue models such that a resultant queue is connected with the next DTMC that models the transmission of packets. The dependencies among these DTMCs are appropriately modelled.

Fig. 1. The DTMC based overall model for a given CSR based on the modeling techniques in [2].

![Diagram of DTMC based overall model for a given CSR based on the modeling techniques in [2].](image1)

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III. ALLOCATION OF MULTIPLE CSRS TO A VEHICLE

Allocating multiple CSRs to a vehicle leads to two key fundamental questions. Firstly, we need to ascertain a plausible value for $n_{CSR}$. We assume $n_{CSR} \leq 4$ for simplicity, i.e., we assume that multiple CSRs are not allocated to a single data stream. Secondly, given $n_{CSR}$, we need to decide how the four parallel data streams should be allocated among the $n_{CSR}$. In this section, we find solutions to these two questions based on the average delay and present an algorithm for the multiple CSRs allocation for a vehicle.

A. Determining the Number of CSRs

It is rather intuitive that $n_{CSR}$ is inversely proportional to $N$. Also, $N$ has a direct impact on the length of the selection window $\Gamma$, which is defined as the maximum latency in ms [15] between consecutive transmission opportunities by the MAC layer, and should be set as 20 ms, 50 ms, or 100 ms according to [16]. Increasing $\Gamma$ increases the time gap between two successive MAC layer transmission opportunities, which in turn leads to more radio resources for the network. Thus, $CSR_{tot}$ is proportional to $\Gamma$, where $CSR_{tot}$ denotes the total number of available CSRs in the selection window for resource re-selection. According to the 3GPP C-V2X standard [15], [17] single-carrier frequency-division multiple access (SC-FDMA) is considered for the sidelink, using a 10 MHz channel. Fifty resource blocks (RB) are allocated for this bandwidth per each slot (half-subframe), and hence, one subframe contains 100 RBs. A CSR requires at least 4 RBs to transmit a 100 byte payload, using 64 QAM modulation. Therefore, each 1 ms subframe can hold up to 25 CSRs, and hence, the largest selection window of 100 ms can hold up to 2500 CSRs ($CSR_{tot} = 2500$). Furthermore, $CSR_{tot}$ is 1250 and 500 for selection window sizes 50 ms and 20 ms, respectively. In this calculation, we have assumed the LTE frame structure, which consists of two slots of 0.5 ms in a 1 ms subframe [17]. The standard allows allocating 80% of these CSRs to the neighbouring users. Thus, $N_{tot}^\text{max} = 0.8 \times CSR_{tot}/n_{CSR}$, where $N_{tot}^\text{max}$ is the maximum number...
of users that can be supported simultaneously with a given $\Gamma$. With larger $\Gamma$ values, the system can support more users, but with a tradeoff of a higher delay between transmission opportunities, and serving the application layer. For a given $N_{tot}$, we need to obtain $n_{CSR}$, and then appropriately set $\Gamma$ values for each of these CSRs.

To this end, we resort to allocating the same $\Gamma$ value across the multiple CSRs allocated to a vehicle. This allocation can be justified as follows. Although different $\Gamma$ values are allocated across the multiple CSRs, the number of simultaneous users the overall system can support is constrained by the shortest $\Gamma$ value currently being used in the system. For example, consider the proposed scenario where a vehicle uses 2 CSRs, and we allocate $\Gamma=20$ ms ($N_{tot}^{max}=400$) for the first CSR and $\Gamma=50$ ms ($N_{tot}^{max}=1000$) for the second. It is not hard to see that the overall system can only support 400 users. Thus, allocating different $\Gamma$ values across multiple CSRs is counterproductive and only leads to higher delay values at the MAC layer.

The relationship between $n_{CSR}$ and $N_{tot}^{max}$ for the three values of $\Gamma$ is tabulated in Table I. We prefer shorter $\Gamma$ values to reduce the average delay [2], and higher values for $n_{CSR}$ to exploit higher degrees of freedom (resources) for the allocation of the parallel data streams. Fig. 3 illustrates the selection of $n_{CSR}$ and $\Gamma$, when $N_{tot}$ increases from 1 to 2000. The methodology associated with allocating multiple CSRs is presented using the solid red arrows, and the dashed blue arrows show the equivalent transitions when the vehicle uses a single CSR according to the standard. The values inside the rectangles of the pyramidal shapes depict the value of $\Gamma$, and the values inside the green-colored rectangles depict the maximum supported value of $N_{tot}$ for each multiple CSR configuration.

### Table I

| $n_{CSR}$ | $\Gamma=20$ ms | $\Gamma\geq50$ ms | $\Gamma=100$ ms |
|-----------|----------------|-----------------|---------------|
| 1         | 400            | 1000            | 2000          |
| 2         | 200            | 500             | 1000          |
| 3         | 134            | 334             | 667           |
| 4         | 100            | 250             | 500           |

**Fig. 3.** The process of selecting $n_{CSR}$ and $\Gamma$ with $N_{tot}$.

#### B. Allocating the Multi-Priority Data Streams Among the CSRs

Having established $n_{CSR}$ and an appropriate value for $\Gamma$ for a given $N_{tot}$, we now face the problem of allocating the multi-priority data streams among the CSRs. We present the grouping options using Table II. Let $n_G$ denote the index of the grouping option. If $n_{CSR}=1$, we simply allocate all data streams to the single CSR, as per the current standard, and we call this grouping option $n_G=1$. The grouping is again trivial if there are 4 CSRs, as we can allocate a separate CSR for each data stream. Thus, we get $n_G=15$. The number of groups for the 2 and 3 CSR scenarios is based on the Stirling number of the second kind, thus there are 7 and 6 grouping options for each scenario, respectively.

### Table II

| $n_{CSR}$ | $n_G$ | Generation Parameters for CSRs |
|-----------|-------|--------------------------------|
| 1 CSR     |       | CSRI                           |
| 2 CSRs    |       | CSRI                           |
| 3 CSRs    |       | CSRI                           |
| 4 CSRs    |       | CSRI                           |

We select the best grouping option $n_{CSR}^*$ for a given $n_{CSR}$ with respect to the average delay. Let $D_{ng,l}$ be the average delay of the $l$-th data stream for grouping option $n_G$. These delay values can be calculated using the DTMC models by appropriately setting the parameter combinations tabulated in Table II for $A$, as explained in reference to Fig. 2. For example, the resulting average delay values for grouping option $n_G=2$ are $D_{2,C} = d_{avg,c}(T_C)$ and $D_{2,m} = d_{avg,m}(\lambda_H, \lambda_D, \lambda_M)$ for $m \in I \setminus \{C\}$. The sum average delay for grouping option $n_G$ is written as

$$\Delta D_{ng} = \sum_{l \in I} w_l D_{ng,l},$$

where $w_l$, for $l \in I$, denotes a weight for each data stream of interest. We set $w_H > w_D > w_C > w_M$ such that the priority management in the standard [1] is incorporated in our selection, and we select the sum average delay minimizing grouping option as the best one for a given $n_{CSR}$. Our approach to allocating multiple CSRs to a vehicle is formally presented through Algorithm 1. Each vehicle needs to determine the number of their neighbouring vehicles to utilize the proposed algorithm. Due to the utilization of DTMCs in the analysis, the number of neighbors needs to be fixed at a given analysis point to guarantee convergence. Therefore, we have made the assumption that $N_{tot}$ is fixed for all vehicles in the region of interest. This also implies that we have assumed an ideal sensing process at each vehicle.

### IV. Numerical Results and Discussion

This section presents numerical results that highlight the performance of using multiple CSRs by the vehicles according to Algorithm 1. The reference packet formats of HPD, DENM, CAM, and MHD are set according to [18] and [19]. HPD and DENM packets are retransmitted at fixed intervals for added reliability [20] as per the standard, and for the results, we have set the number of repetitions to 8 and 5 times, respectively. The candidate values for $\lambda_m$, where $m \in I \setminus \{C\}$, are set by being consistent with the example use case scenarios in [21] and $T_C$ is set between 100 ms and 1 s according to standard [18]. We set $w_H = 0.4$, $w_D = 0.3$, $w_C = 0.2$, and $w_M = 0.1$ to extend the priority management in the standard [1] into the grouping methodology. The DTMC models have already been validated in [2] through simulations.


Algorithm 1 Multiple CSR Allocation for C-V2X Mode 4

1: procedure $n_{CSR} \& \Gamma$ ALLOCATION ($N_{tot}, \lambda_H, \lambda_D, \lambda_M, T_C$)
2: \hspace{1cm} $\Gamma = 0, n_{CSR} = 0$  \hspace{1cm} $\triangleright$ Initialization
3: \hspace{1cm} if $0 < N_{tot} \leq 100$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 4, \Gamma = 20$ ms
4: \hspace{1cm} else if $100 < N_{tot} \leq 134$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 3, \Gamma = 20$ ms
5: \hspace{1cm} else if $134 < N_{tot} < 200$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 2, \Gamma = 20$ ms
6: \hspace{1cm} else if $200 < N_{tot} < 400$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 1, \Gamma = 20$ ms
7: \hspace{1cm} else if $400 < N_{tot} < 500$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 2, \Gamma = 50$ ms
8: \hspace{1cm} else if $500 < N_{tot} < 1000$ \hspace{1cm} \hspace{1cm} $n_{CSR} = 1, \Gamma = 50$ ms
9: \hspace{1cm} end if
10: BestGroup($n_{CSR}, \Gamma, \lambda_H, \lambda_D, \lambda_M, T_C$)
11: end procedure

12: function BestGroup($n_{CSR}, \Gamma, \lambda_H, \lambda_D, \lambda_M, T_C$)
13: \hspace{1cm} $n_{G}^* = 0$  \hspace{1cm} $\triangleright$ Initialization
14: \hspace{1cm} if ($n_{CSR} = 1$) \hspace{1cm} \hspace{1cm} $n_{G}^* = 1$
15: \hspace{1cm} else if ($n_{CSR} = 2$) \hspace{1cm} \hspace{1cm} $n_{G}^* = \arg \min_{k \in \{2, 8\}} \Delta D_k$
16: \hspace{1cm} else if ($n_{CSR} = 3$) \hspace{1cm} \hspace{1cm} $n_{G}^* = \arg \min_{k \in \{9, 14\}} \Delta D_k$
17: \hspace{1cm} else if ($n_{CSR} = 4$) \hspace{1cm} \hspace{1cm} $n_{G}^* = 15$
18: \hspace{1cm} end if
19: \hspace{1cm} Return $n_{G}^*$
20: end function

A. Average Delay

Firstly, we present the results on the average delay. In this paper, we focus on the average delay between the generation and the transmission of a packet. It captures the queuing delay, which is the time a packet waits in the queue, and the access delay, which is the time a vehicle waits before accessing the radio resources. Fig 4 illustrates the average delay behavior of CAM and MHD packets with $N_{tot}$ for $\lambda_M = \lambda_D = 1, \lambda_M = 10$ packets/s and $T_C = 100$ ms. As shown in this figure, the average delay is mainly sensitive to $\Gamma$, exhibiting a step-wise increase when $\Gamma$ switches from a shorter to a longer value, and constant with respect to $N_{tot}$ for fixed $\Gamma$. It was noticed that delay gains for HPD and DENM were negligibly small due to their higher priority levels, thus omitted in the results. The higher priority packets are served first regardless of the number of CSRs, and hence, the gains are insignificant. It can be seen that the average delay values can be maintained below 100 ms thanks to the utilization of multiple CSRs. Further results on the average delay reduction percentages for all four data streams relative to using a single CSR as per the standard, are tabulated in Table III. In Table III, the average delay reduction is given compared to the delay when one CSR is used as in [2]. Therefore, in the range $[200, 400]$, where only one CSR is used, there is no difference in average delay.

Firstly, while focusing on less critical scenarios such as roadwork warnings and safety function out of normal condition warnings, where the packet generation rates are considerably lower ($\lambda_D = 0.1$ packets/s), we can observe clear gains of utilizing multiple CSRs at each vehicle. The maximum average delay reduction percentage for CAM is 54.7%, which is around 30 ms, and for MHD, it is 50.4%, which is around 48.9 ms. We can expect the gains for MHD to increase further at higher $\lambda_M$ values. For example, if $\lambda_M = 10$, the gain is 69.2% which is 236 ms. While focusing on more critical scenarios, such as emergency electronic brake lights and warnings from emergency vehicles that have higher packet generation rates ($\lambda_D = 1$), we can observe very high gains for both CAM and MHD, i.e., a maximum delay reduction percentage of 77.4% (85 ms) and 80.7% (334 ms), respectively. This can also be observed in the range $N_{tot} \in [400, 500]$ in Fig 4. Thus, the multiple CSR configurations can contribute considerably by alleviating the issue of state packets in low-priority queues. In general, the results show that the proposed method works favorably for both less critical and critical scenarios when considering the average delay. Furthermore, it is useful when more frequent location updates are required, which is achieved using CAM. This can be seen by comparing the gains for $T_C = 100$ ms with $T_C = 500$ ms. Thus, the multiple CSR configuration will be ideal for applications that require high CAM rates, which is 10 Hz according to the standard [21].

Moreover, based on the $n_{G}^*$ values, we can provide the following insights on allocating the multiple CSRs among the data streams. For 2 CSR configurations, it can be observed that allocating the periodic and event-triggered traffic for separate CSRs performs better when the CAM rate is high. On the other hand, better delay-wise performance can be obtained by allocating a separate CSR for MHD when the CAM rate is low. This eliminates the necessity of MHD packets waiting until all higher-priority queues are empty. For 3 CSR configurations, better delay-wise performance can be obtained by allocating a CSR each for CAM and MHD streams, and the other CSR for HPD and DENM streams, given that the CAM rate is high. As the system considers both HPD and DENM packets to have relatively higher priority and hence transmit with minimum delay, allocating a CSR each for CAM and MHD streams, and the other CSR for HPD and DENM streams, can be grouped with the data stream having the lowest generation rate. In our results, we observe that the grouping was with DENM as it...
has a lower effective rate compared to HPD due to the lower number of packet repetitions.

Besides, we compare the proposed solution with the random allocation of multi-priority data streams among CSRs. Also, with first-come-first-serve allocation, where the system serves the packet based on their priorities, the same as the single CSR case, and the only difference is the number of CSRs allocated for a vehicle is changed, as explained in Section III-A. In Fig. 4, the proposed multiple CSR allocation shows a higher delay gain compared to first-come-first-serve and random allocation when \( N_{\text{tot}} \geq 400 \), for both CAM and MHD packets. At \( N_{\text{tot}} < 400 \) the average delay of the proposed method overlaps with the first-come-first-serve and random allocation, except when \( 100 \leq N_{\text{tot}} < 134 \), where the proposed allocation exhibits better delay performance. The random allocation of three CSRs in \( 100 \leq N_{\text{tot}} < 134 \) leads to HPD and DENM getting separate CSRs, and MHD and CAM sharing the remaining CSR. This results in higher delay values for the two low-priority packet types.

### B. Collision Probability and Channel Utilization

Although favorable in terms of delay, using multiple CSRs may lead to a tradeoff in terms of higher packet collisions. The variation of per CSR collision probability for the single and multiple CSR configurations is illustrated in Fig. 5. The collision probability derivation per vehicle is a trivial extension to [2], and can be obtained by following similar lines and taking the sum of collision probabilities on each CSR. The collision probability increases exponentially with \( N_{\text{tot}} \). We can also observe that \( \Gamma \) has a significant impact on the collision probability as the collision probability reduces significantly when the value of \( \Gamma \) increases at \( N_{\text{tot}} = 400 \) in Fig. 5. This is thanks to the availability of more radio resources at higher \( \Gamma \) values [2].

When comparing the collision probabilities of the two configurations, it can be seen that utilizing multiple CSRs lead to higher collision probability values in \( 0 < N_{\text{tot}} \leq 200 \) and \( 400 < N_{\text{tot}} \leq 500 \). This is due to the higher number of overlaps in the selection windows when multiple CSRs are used, as explained in [11]. Therefore, there is a clear tradeoff of using multiple CSRs. However, it can be seen from Fig. 5 that the maximum increase in collision probability is approximately 0.6% (at \( N_{\text{tot}} = 99 \)) when compared to a single CSR and the first-come-first-serve allocations, which are relatively insignificant compared to the gains achieved on delay and priority management.

We already saw that the average delay increases with \( \Gamma \), and in Section III, we showed that each \( \Gamma \) has its respective \( N_{\text{tot}}^{\max} \). We can increase the \( N_{\text{tot}}^{\max} \) threshold levels further if the standard allows allocating a higher percentage of available CSRs to the users, \( i.e., \) increasing the 80% parameter in the SPS algorithm stated in Section III. In that case, allocating multiple CSRs may be even more favorable regarding the average delay. However, we can observe from Fig. 5 that this change leads to an exponential increase in the collision probability. Therefore, fine-tuning \( N_{\text{tot}}^{\max} \) needs to be done after carefully studying the QoS requirements of the applications. The behavior of channel utilization with \( N_{\text{tot}} \) is shown in Fig. 6. The figure clearly shows how the channel utilization has been exploited in the ranges of \( 0 < N_{\text{tot}} \leq 200 \) and \( 400 < N_{\text{tot}} \leq 500 \) to achieve the initial objectives. The sharp discontinuities in Fig. 4, Fig. 5, and Fig. 6 are due to the change in \( \Gamma \) values at these values of \( N_{\text{tot}} \). The reasons for these changes are elaborated in detail in [2] and [11].

We end the discussion by providing some insights on some implications of the proposed method. Firstly, let us focus on the SPS algorithm. According to the current standard in the SPS algorithm, each vehicle can track the CSRs used by itself and the neighboring vehicles within the sensing window. These identified CSRs are excluded when selecting a CSR for the subsequent transmission. Using multiple CSRs at each vehicle will not bring about significant changes to how the SPS algorithm tracks CSRs used by neighboring vehicles. However, the SPS algorithm needs to be slightly modified to identify and exclude the CSRs used within the target vehicle to minimize internal collisions. The authors note that the proposed method may also cause changes in the hardware setup as the parallel transmission is required, but with the developments in multi-antenna technologies, handling the hardware implications seems practically feasible. Extensive details on hardware implications are beyond the scope of this paper.

### V. Conclusion

This paper has focused on a vehicular network that utilizes C-V2X Mode 4 for communication and supports multi-priority data streams to fulfill varying quality-of-service constraints of ITS use cases. It has proposed increasing the channel utilization of the network through allocating multiple CSRs at each vehicle and has studied its achievable performance gains at the MAC layer. The proposed method has led to two fundamental questions: how many CSRs should be allocated to each vehicle and how the multi-priority data streams should be allocated among them. The number of CSRs at each vehicle has been ascertained as a function of the total number of neighboring vehicles for the target vehicle, and a procedure has been introduced for allocating the multi-priority data streams among CSRs based on the average delay in the network. The results have shown that using multiple CSRs at each vehicle can lead to significant gains in the network in terms of average delay. In particular, the average delay of lower priority data streams can be improved significantly by...
allocating them separate CSRs, which ameliorates the risk of stale packets. An increase in the collision probability can be observed as a tradeoff, but the performance loss is almost insignificant compared to the delay gains.

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