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An Explicit Reservation-Augmented Resource Allocation Scheme for C-V2X Sidelink Mode 4

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ABSTRACT In the autonomous sidelink resource scheduling for Cellular V2X (C-V2X), the standard sensing-based semi-persistent scheduling (SPS) algorithm relies on several mechanisms such as random resource selection, resource utilization pattern monitoring, and probabilistic reselection to minimize packet collisions and to cope with vehicular topology changes. Even so, the collision probability is still not negligible, and its performance is far from the projected requirements for low latency and high reliability applications for future C-V2X communication. In this article, we propose a reservation mechanism that supplements the standard SPS for C-V2X Sidelink Mode 4, which visibly improves the performance in face of congestion and in the fringe of the communication range. In particular, we demonstrate that the reservation achieves the best performance if made much earlier than actual use of the reserved resource at least by an average of one second.

INDEX TERMS Cellular V2X (C-V2X), sensing-based, semi-persistent scheduling (SPS), reservation, packet collision resolution.

I. INTRODUCTION

The cellular vehicle-to-everything (C-V2X) communication is expected to become one of the essential components of highly automated driving in the future. It will supplement the line-of-sight (LoS) sensors such as cameras, radars, and lidars for the non-LoS awareness that is essential for safer driving. It will also provide much larger sensing coverage than the LoS sensors do. Moreover, it will enable network-mediated operation such as remote driving in 5G V2X as defined in 3GPP Release 16 [1]. As the 5G V2X standards are still under development, however, we consider in this article the LTE-based C-V2X as specified in 3GPP Release 14 and 15 [2]–[4], where the periodic exchange of broadcast messages such as Basic Safety Messages (BSMs) [5] form the basis for many safety applications. Although further V2X use cases will be added in 5G that may not rely the periodic safety message broadcast, the periodic safety beacon exchanges will not be replaced as the foundation of the V2X-assisted driving safety [6].

There are two modes of transmit (Tx) resource allocation in C-V2X. In LTE Sidelink Mode 3, it is the base station (eNB) that allocates the resource for the vehicles in its coverage. In the case of LTE Sidelink Mode 4 [2], [3], vehicles directly communicate with each other without the mediation by the network infrastructure. Although Mode 3 in which the eNB assists resource allocation will be used together with Mode 4, vehicles will have turn to Mode 4 whenever they are not in the coverage of the cellular network or the coverage is only intermittent. For reliability, therefore, Mode 4 is considered the default mode, and it is also the focus of this article.

The biggest problem in the current autonomous resource scheduling algorithm for Mode 4, called the sensing-based semi-persistent scheduling (SB-SPS; henceforth SPS) [2], is that each vehicle may change the time-frequency resource as frequently as every second to avoid half-duplex collisions with other vehicles. In these resource reselection events, however, they do not explicitly announce their internal choice as to the location of the new resource to be used for the next

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second or so. Therefore, each vehicle must play a guessing game when they select the next resource to prevent the selections from different vehicles from converging on the same resource.

Although the sensing component in SPS helps reduce the packet collision probability significantly, the random resource selection without the explicit knowledge of other vehicles' choices inevitably leads to non-negligible collision probability. Due to the semi-persistent nature of the resource allocation in SPS, the collision event persists for a series of packets once it happens. Because the reliability and the latency requirements are extremely stringent, what small residual collision probability that the SPS algorithm leaves behind can still be critical in the envisioned C-V2X safety applications. In this article, we demonstrate how the remaining collision probability can be substantially reduced by changing the algorithm to explicitly announce each vehicle's intention for a newly selected resource, which we call "reservation." Moreover, the scheme selects the resource with a higher degree of freedom than SPS in terms of the location in the resource plane. Since the uncertainty of the resource locations chosen by neighbor vehicles is a main source of packet collisions in the distributed resource allocation algorithm defined in the standard, the explicit reservation can significantly contribute to resolving the performance issue of SPS.

Through the 3GPP-scripted simulation experiments, we show that the simple addition of the explicit reservation information leads to the absolute superior performance in terms of latency (Packet Inter-Reception time) and reliability (Packet Reception Ratio) [4]. Moreover, the proposed scheme degrades more gracefully than the standard SPS in face of increasing wireless channel congestion. Better yet, it turns out to help the message delivery to the fringe of the communication range where the signal power sensing-based SPS works less reliably. We call the proposed scheme Gapped Reservation-augmented SPS (GRaSPS), since we find that the explicit reservation-based scheme achieves the best performance if the reservation is made much earlier than actual use of the reserved resource, for instance, by a second.

The rest of the paper is organized as follows. Section II briefly summarizes the most relevant works that attempt to improve the performance of the SPS algorithm, including the few that introduce explicit reservation schemes. Section III first summarizes the core features of the SPS algorithm, and then introduces the proposed scheme to address the uncertainty aspect for reduced packet collision probability. Section IV conducts extensive simulation according to the methods and the parameters specified by 3GPP. It compares the performance of the SPS algorithm and the proposed modification. Finally, Section V concludes the paper.

II. RELATED WORK

The cellular V2X communication has been standardized by the 3rd Generation Partnership Project (3GPP) in Release 14 [7]. It focused on the communications for basic safety use cases. In Releases 15 and 16, the 3GPP has been working on 5G New Radio (NR)-based V2X that aims to enable advanced use cases in addition to the capabilities of LTE V2X. Due to the immaturity of the 5G V2X standards at the time of writing this article, however, we will refer to the LTE V2X as we discuss the resource allocation behavior of the SPS algorithm. Albeit relatively new, radio resource management for C-V2X is an actively studied topic recently. They are largely classified into network-controlled and autonomous approaches. As vehicles can be in locations where there is no infrastructure support, the latter is indispensable. The Sidelink Mode 4, as it is called, is the focus of this article. Below, we briefly summarize the previous work related with ours. For convenience, we classify them into two groups, depending on whether they use explicit reservation or not.

There are many works that illuminates the SPS behavior and proposes improvement without relying on explicit reservation.

Molina-Masegosa and Gozalvez [8] made two important observations about the SPS performance. They first found that among four different packet delivery error types, collisions dominate in the most safety-critical range. They also found that the merit of SPS resource selection diminishes as the transmitter-receiver distance increases. Being an evaluation study, however, this work falls short of providing a solution to reduce the collision problem. Our work in this article addresses the collision loss problem, and provides an explicit reservation scheme as a solution approach. Molina-Masegosa *et al.* [9] studied the impacts of the parameters to the SPS algorithm. They showed that the resource keeping probability should be regulated based on the traffic load to achieve the best packet delivery ratio, in a more mobile scenario than in a similar study by Bazzi *et al.* [10]. They also found the importance of the of the resource selection procedure in SPS, where the reserved resource by the previous packet is filtered out according to the Reference Signal Received Power (RSRP) of the previous packet. They found that this filtering is effective in filtering out the high-interference resources, which allows the Tx power to be raised to mitigate the effect of the hidden terminal problem. The reservation used by the SPS algorithm is for the immediate next packet [2], and that the filtering algorithm that respects the simple reservation information achieves a better performance provides a strong motivation for a more extended reservation in our work.

Molina-Masegosa and Gozalvez [11] noticed the differences in the BSM message sizes [4] as one source of poor performance in SPS. The resource allocated in alignment with the 300 bytes BSMs lets the next four BSM transmissions waste part of the allocated resource. As a solution to this problem, the authors suggested that a new resource reselection is performed for the 300 byte BSM for one transmission, and then another reselection for the subsequent four 190 bytes BSMs. The proposed scheme improves the packet delivery ratio. However, the scheme forces the reselections to be more frequent than when the resource keeping probability is 0. It could undermine the predictability aspect that is exploited by SPS to resolve collisions, and it may adversely affect the SPS performance. Later, Bazzi *et al.* [12] takes another approach that reorganizes the subframe structures to deal with the same problem, and solved it as a combinatorial optimization problem to maximize the number of vehicles that can be simultaneously allocated resource. As a result, the authors showed that higher system capacity can be achieved. However, changing the physical layer structure to adapt to the traffic model is not a general solution, especially when different packet size ratios may arise in the next generation of V2X communications. These two works show that a more generalized reservation feature in terms of the resource location and size is called for periodic traffic in C-V2X. Molina-Masegosa *et al.* [13] noticed that the SPS scheme is prone to the well-known hidden-terminal problem. To address this problem, they proposed a geo-based scheduling scheme that allows vehicles to autonomously select their radio resources based on the location and ordering of neighboring vehicles on the road. Although the geo-based algorithm may be one of few solutions to the hidden-terminal problem, its practical implementation is said to be hardly realistic [10]. It has other weaknesses as well, for instance when the number of resources is less than that required by the vehicles in the communication range it can lead to deterministic collisions. Hirai and Murase [14] made an interesting observation that the sensing-based SPS algorithm has shortcomings in identifying the candidate resources. They showed that the RSRP- and the Received Signal Strength Indicator (RSSI)-based candidate estimations fail to precisely identify the desirable resources under congestion or with dynamic topology change, leading to a worse performance in terms of reliable packet delivery than random scheduling. However, this work does not go so far as providing a solution to the observed problem. Bazzi *et al.* [15] considered and analyzed two benchmark algorithms that can be used to evaluate other resource allocation algorithms including SPS: random and geo-based. Although not realistic by themselves, these benchmarks can be used for fair comparison of various proposals, and for establishing the optimal performance that new proposals should strive for. Obviously, SPS does better than the random allocation, but worse than the geo-based allocation. The fact that SPS converges to the random allocation at the fringe of the communication range exposes the reliability of the received power-based resource selection in SPS. Our work shows that it can be overcome by including the explicit reservation information in every packet transmission.

There are resource allocation studies that propose some form of explicit reservation information to be shared among vehicles, which are more closely related with our work. He *et al.* [16] showed that by separating the control and the corresponding data payload in the time axis and by letting them carry the reservation information for each other in the chained manner, the packet collisions are reduced. However, the proposed reservation is for the immediate next control/data payload like SPS does. Our work in this article shows that not a single inter-packet time gap but a gap equivalent to a single packet burst achieves significantly better performance and has higher robustness against half-duplex packet collisions. Moreover, He *et al.* needs the data channel (PSSCH) to carry the reservation information so that cross-layer processing is required. Bonjorn *et al.* [17] proposed that each vehicle inform the others of its current resource Reselection Counter (RC) value in each packet and resolve any potential packet collision by forcibly changing the RC values of the vehicles that have the same RC value in the last resource reservation interval (RRI). This is because the collision in resource selection can only happen when the selection windows of the involved vehicles at least partially overlap. Through the proposed mechanism, the authors showed that the average collision rate is lowered. A deficiency in this work, however, is that the resource utilization of 25% considered in the work is rather low to be considered congestion. Moreover, dynamically changing the RC counter value can become increasingly difficult when there are many contending vehicles because there are a limited number of RC values to choose from. Moreover, if there are multiple RRIs [2], it may trigger unnecessary RC changes because some may not overlap in the selection windows. Unlike this indirect approach, our work does not publicize the RC value, but instead directly pinpoints the intended resource location for the upcoming reselection. Even if the selection windows partially or totally overlap, it is acceptable in our approach if their specified resources are different. Even if there is conflict between reservations, there is time for the latter to change before the actual reselection. Along this line, Jeon *et al.* [18] proposed to broadcast the reselected resource location immediately before the reselection. However, our investigation in this article shows that a more aggressive approach by publicizing the reservation even earlier achieves much higher performance in both packet reception rate (PRR) and packet inter-reception rate (PIR), especially under congestion.

III. RESERVATION-AUGMENTED SPS

In this section, we tackle the high packet collision probability problem of SPS, and reveal that the root cause is the lack of an explicit scheduling information shared between vehicles. The information sharing by a vehicle as to the next resource to use is relatively straightforward. However, the performance improvement it can bring to the standard SPS is significant towards the stringent latency and reliability requirements set forth by C-V2X applications. Below, we introduce the standard SPS algorithm operation, analyze its collision probability, and then discuss the proposed enhancement.

A. SENSING-BASED SPS

The resource scheduling in C-V2X is done over a two-dimensional space, where the two axes are time and frequency. The wireless resource grid is divided into subchannels in frequency and subframes in time. On the frequency axis, the granularity of resource allocation is a subchannel.

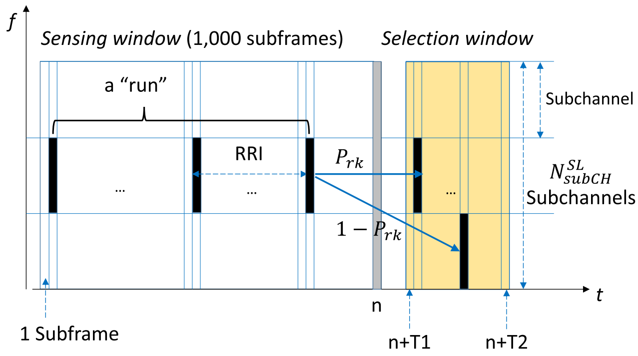


FIGURE 1. Structures for the Sensing-based SPS in LTE-V2X Sidelink Mode4.

Each block in the wireless resource grid (*e.g.*, small shaded boxes in Fig. 1 is defined by one or more subchannels (*e.g.* one in case of a small packet such as BSM) and a single subframe, which we will simply call a "resource."

SPS fits well with the periodic nature and the predictable sizes of the safety messages such as BSMs transmitted by a vehicle. In SPS, a group of packets evenly spaced on the time axis are allocated the same subchannel(s) together. This contrasts to the dynamic scheduling (DS) where each packet requires a separate signaling for resource allocation. For convenience, we will call this short burst of packets from the same vehicle using the same subchannel(s) in SPS by a "packet run" or simply a "run" in this article. For instance, a vehicle can be allowed to transmit for an average of one second [5] within which BSMs are spaced 100 ms before another attempt to obtain resources for the next run is made. The space between BSMs are called the Resource Reservation Interval (RRI), whose typical values are 20 ms, 50 ms, and 100 ms, where longer intervals are also allowed [2].

Priority	RRI	Frequency resource location	Time gap	MCS	ReTx index	Reserved
3 bits	4 bits	X bits	4 bits	5 bits	1 bit	15-X bits
32 bits						

FIGURE 2. SCI Format 1 as per 3GPP TS 36.213 [2].

To determine which resource a host vehicle V can use for the next run, it relies on sensing the resource use by neighboring vehicles in the recent past. Each vehicle monitors 1,000 subframes (= 1 s) in the immediate past called the sensing window to identify the resources that have been used by other vehicles. Whether used or not is determined by the RRI field in the Sidelink Channel Information (SCI) of the received packet (Fig. 2). The 'reservation' in the term RRI is simply an indication whether or not the next packet will follow on the same subchannel in the given interval. The 3GPP TS 36.213 [2] standard uses a 4-bit codepoint in the SCI for the indicator. For instance, '1010' indicates another packet will follow in 100 ms on the same subchannel, whereas '0000' indicates none. It must not be confused with the term 'reservation' used in this article that refers to an explicit and more free time-frequency coordinate on the resource plane, so that the reserved resource can be located after multiple other packets and on a different subchannel.

In SPS, if the reserved resource by the immediately previous packet by other vehicle in the RRI field has a higher RSRP than a preset threshold and it falls in the selection window of the host vehicle, it is excluded from the pool of available resource [2]. Even if not, it is excluded if the average RSSI of the previous resources in the sensing window in the multiple of RRIs back is over a threshold. Finally, the whole subframes used by V itself in the sensing window are also projected to the selection window to be excluded as unselectable. This is because these subframes could not be sensed by V due to the half-duplex transmission, and there might be other vehicles that were transmitting there that may keep transmitting in the selection window.

After excluding the resources reserved through the RRI field, the remaining resources are called the candidate set S_A. If S_A is less than 20% of the entire selection window resources, then more candidate resources are identified by raising the RSRP threshold by 3 dB, and repeating the filtering process. Then in Step 3, SPS sorts S_A in the order of increasing RSSI values, of which it picks only 20% of the selection window resources with the lowest RSSI values to get another set S_B. The higher layer randomly selects one resource from S_B. The number of times that the selected subchannel is used without further signaling is also randomly selected in range $[C_1, C_2]$ and is called the Reselection Counter (RC) [3]. The range of the random number depends on the RRI. It is $[C_1, C_2] = [5, 15]$ if RRI is 100 ms or higher, in [10, 30] if RRI is 50 ms, and in [25, 75] if RRI is 20 ms. Notice that each run is designed to last for only one second on average.

Each packet transmitted in a run decrements RC by one. When RC reaches 0, the next run should be scheduled, which is called the resource reselection. With the resource-keeping probability P_k ($0 \leq P_k \leq 0.8$) that upper layers configure [3], however, the SPS can decide to keep using the same resource for the next run (see Fig. 1). With $1 - P_k$, a different resource is chosen from S_B according to the filtering procedure discussed above. There are two reasons why SPS keeps reselecting resources every second, even though keeping the same resource would increase the predictability and hence lowers the packet collision probability. With only a few choices of RRIs [2], half-duplex transmission, and multiple packets transmitted in a single run, the transmissions from different vehicles can collide in multiple packets on end, if the vehicles happened to choose the same resource. The packet collisions can also occur when new vehicles join the group of vehicles that are already coordinating the resource use through SPS. Therefore, the run is designed to last only a second on average so that any colliding resource selections from different vehicles can part from the other in a second at most.

B. PACKET COLLISION PROBABILITY IN SPS

In the resource selection, a packet collision can happen if two or more vehicles select the same resource. The fact that the SPS algorithm chooses the bottom 20% of the candidate resources in the order of the RSSI can render the selections from different vehicles to focus on a relatively small set of candidates if the wireless resource utilization (*i.e.*, CBR) is high. Although the random selection from the candidate pool S_B helps reduce the collisions, the probability may not be so small as the number of vehicles increases that reselect the resource closely in time.

To analyze the collision probability of SPS as the function of CBR, we will use some simplifying assumptions. We assume that all vehicles are beaconing at 10 Hz, namely $RRI = 100$ ms. We set $T_1 = 1$ and $T_2 = 100$, leading to the maximum selection window width allowed by the current standard. Then we have RRI subframes in the selection window. Then the total number of resources in the window is $RRI \times N_{subCH}$, where N_{subCH} is the number of subchannels on the sidelink band. Among the resources in the selection window, the usable fraction R is upperbounded by

$$R = RRI \times N_{subCH} \times (1 - CBR) \tag{1}$$

when the same resource usage pattern is repeated in the selection window and CBR is defined by the fraction of used resources in the sensing window. Now, we will assume that the vehicles choose from R instead of S_B. Note that the assumption better approximates the SPS behavior when the CBR is not high. However, the analysis in this section will be used to illustrate only the macro-dynamics of SPS. More realistic and detailed dynamics will be explored through simulations in Section IV.

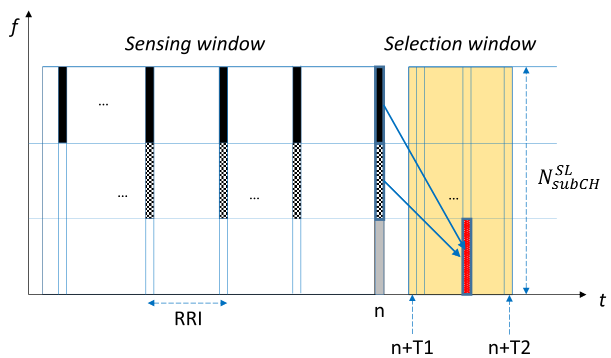


FIGURE 3. **Two vehicles reselecting in the same subframe leading to the half-duplex packet collision in their next run.**

Among the vehicles transmitting in the same subframe n (see Fig. 3), those that should reselect the resource because they have reached $RC = 0$ is given by

$$V_0 = CBR \times N_{subCH}/C_{avg} \tag{2}$$

where $C_{avg} = (C_1 + C_2)/2$ is the average length of the packet runs. For instance, if $RRI = 100$ ms, $C_1 = 5$ and $C_2 = 15$ [3], and we would have $C_{avg} = 10$. Denoting the probability of choosing a particular resource in the selection window by $p = 1/R$, the packet collision probability $P_{col,0}$ with vehicles transmitting in the same subframe n is given by

$$P_{col,0} = 1 - (1 - p)^{V_0 - 1}. \tag{3}$$

In $P_{col,0}$, 0 denotes the time gap between two reselecting vehicles as they are on the same subframe. Note that the collision arises because these vehicles cannot sense each other, namely the half-duplex condition. In this section, we do not model the losses caused by the hidden terminal problem because it is highly complicated by many parameters in the V2X communications such as traffic density, Tx power, Rx sensitivity, modulation and channel coding (MCS) level, packet size, and propagation model, among others. Moreover, the most safety-critical ranges in V2X applications are shorter than the full communication ranges so that the hidden terminal problem is of secondary importance than the collisions within the safety-critical distances. Therefore, we note that the analysis in this section will be missing the impacts of the hidden terminals especially at the fringe of the communication range. However, in Section IV the hidden terminal losses will be accounted for in the simulation.

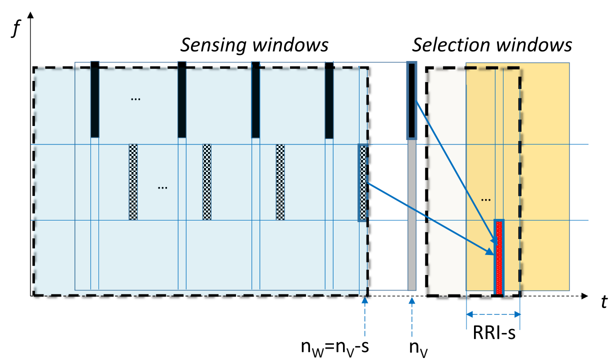


FIGURE 4. **Collision between two vehicles *V* and *W* selecting on different subframes with time gap *s*.**

Unfortunately, the packet collisions in SPS are not limited to the half-duplex cases. As long as there is an overlap in their sensing windows, vehicles can be involved in a packet collision (see Fig. 4). However, the reselecting vehicles with the time gap of more than one RRI in their sensing windows will not be in such relation because the latter reselecting vehicle can see at least one packet (and its reservation in the SCI) from the other vehicle in its sensing window hence avoid choosing it. Even if the packet from a vehicle is not decoded, which happens with a small probability [8], the increased average RSSI will help other vehicles avoid the resource. Therefore, let us simplify the analysis by considering only the cases where the reselection instants of two vehicles, say n_v and n_w in Fig. 4, are less than one RRI apart. The overlapping resource pool that the vehicles reaching the reselection instant in exactly s $(0 < s < RRI)$ subframes apart have is

$$R \times (RRI - s)/RRI. \tag{4}$$

Each vehicle chooses a resource in the pool with the probability p_s, where

$$p_s = \{R \times (RRI - s)/RRI\}^{-1}. \quad (5)$$

Then the probability that at least one neighbor with $RC = 0$ exactly s subframes ago reselected the same resource as the host vehicle in the overlapping resource pool is

$$P_{col,s} = 1 - (1 - p_s)^{V_0}. \quad (6)$$

because there are V_0 vehicles on average that reach $RC = 0$ in each subframe.

Considering $\forall_s, 0 \leq s < RRI$, namely all contending vehicles modeled in Eq. (3) and Eq. (6), the probability of the packet collision with at least one vehicle with an overlapping resource pool is

$$\begin{aligned} P_{col} &= 1 - \prod_{s=0}^{RRI-1} (1 - P_{col,s}) \\ &\approx 1 - \prod_{s=0}^{RRI-1} (1 - p_s)^{V_0}. \end{aligned} \quad (7)$$

The approximation in the last step is because there is one less contending vehicles in subframe n where the host vehicle has reached $RC = 0$. Below, we compare this collision probability with those in the proposed scheme, which we discuss below. Last but not least, we note that under the semi-persistent scheduling, the packet collision event modeled above is not limited to a loss of a single packet. Instead, it can persist over multiple packet runs especially when P_k is set high, potentially causing the vehicles involved to be "invisible" to neighbor vehicles during the successive packet losses [19].

C. PROPOSAL: RESERVATION-AUGMENTED SPS

The main objective of our proposal is to enhance SPS with an additional reservation mechanism that has three contrasting features to SPS.

- Explicit: the location is explictly specified by a time-frequency coordinate
- Early: the reservation can be made for a far location in future, much ealier than its real use
- Repeated: the reserving information is repeated many times for reliability

The first feature of our proposal is that each vehicle explicitly informs other vehicles of the reselected resource location. By using a time-frequency coordinate of the resource to use, we can reserve for the packet transmission at an arbitrary time in future and at a different subchannel if necessary. In contrast, the standard SPS algorithm specifies only the time gap between the current packet and the next, so the reservation is limited to the current channel, and to the next packet. Due to the first limitation, SPS reservation cannot specify any information as to the next resource location upon reselection because a different subchannel can be selected. The second feature that falls out from the first is that our reservation can be made much earlier. The SPS reservation is only for the immediate next packet, and even that is absent when a packet run ends. However, the proposed reservation can be made many packets before the actual transmission on the reserved resource. It lets neighbor vehicles make an informed decision when it is their turn to reserve or select a resource. The third feature is enabled by the second feature. Since the reservation information appears in each packet before the actual transmission using the reserved resource, an earlier reservation means a larger number of announcements. It improves the reliability of the reservation information as conveyed to neighbors.

For the convenience of discussion, we will call the proposed scheme by Gapped Reservation-augmented SPS (GRaSPS). We will also include in our discussion an intermediate form called Reservation-augmented SPS (RaSPS) that lies between SPS and GRaSPS, in order to put GRaSPS into perspective in the spectrum of the reservation time horizon. We settle for GRaSPS after exploring the ideal reservation instant that most reduces the collision probability in the resource reselection based on the SPS procedure. The reason that we call the proposed schemes the augmentations of SPS instead of replacements is that except that they proclaim their choice of the resource in the upcoming selection window, they still rely on SPS for the sensing and the actual resource selection steps. In our proposal, a vehicle additionally takes into account the explicit reservations of other vehicles when they exclude unusable resources from the candidate resource pool when executing the SPS algorithm.

For the subsequent discussion, let $z_v(k)$ and $a_v(k)$ respectively denote the subframe indices of the last and the first packet in the k^{th} packet run of vehicle V, or V_k. Assume that V_k and W_j are the current packet runs of vehicles V and W, respectively. At the end of these runs V_k and W_j, the standard SPS algorithm executed at V and W will internally determine the resource to use for the next runs V_{k+1} and W_{j+1}, respectively. To understand how our proposed scheme changes the packet collision dynamics, we consider three cases.

1) PACKET COLLISION BETWEEN VEHICLES WITH $0 < |z_V(k) - z_W(j)| < RRI$

Here, we have partially overlapping selection windows, as depicted in Fig. 4. Recollect that SPS cannot prevent the collision if V and W internally choose the same resource in the overlapping area of their selection windows. However, the explicit reservation can resolve the collisions of this type. If a vehicle V receives a transmission from W with the reservation for resource r that it has decided on, V will change the resource to $r' \neq r$ in S_B and also announce it when it transmits its BSMs.

As to when to announce the reservation information, we consider two variants in this article. First, in what we call Reservation-augmented SPS (RaSPS), a vehicle V announces it when $RC = \theta \geq 0$, where θ represents how early the announcement is to be made before the RC expires. In RaSPS, the reservation is made relatively close to the actual reselection instant. Namely, we limit $\theta < C_1$, so that the reservation for the run V_k is made in the immediately preceding run V_{k-1}. After a resource to reserve is determined in V_{k-1}, it is repeatedly announced throughout the subsequent transmissions at $RC \leq \theta$ until V_{k-1} ends. As we will discuss in Section III-D, the announcements are piggybacked in each packet transmission.

Unless the vehicles have a completely overlapping selection window (i.e., $s = 0$), one vehicle can receive the reservation information from the vehicle that has reached $RC = \theta$ in an earlier subframe. It can avoid the collision by choosing a different resource. Under the perfect channel assumption, therefore, the non-half-duplex collisions would be completely eliminated by RaSPS. The only remaining collisions would be caused by the half-duplex condition $s = 0$, whose probability is Eq. (3). Therefore, the performance improvement of RaSPS over SPS comes mainly from the difference between Eq. (7) and Eq. (3). Under an imperfect channel, on the other hand, the number of announcement repetitions $\theta + 1$ will also contribute to the reduction of packet collisions in RaSPS.

An imperfect channel affects the collision-suppressing performance of RaSPS but not that of SPS because SPS does not announce reservation information for the next run. If some of the reservation announcements are lost in RaSPS, some packet collisions may not be prevented due to the lack of reservation information. Suppose we have an imperfect channel where the probability of receiving each reservation announcement is denoted P_{rx}. We consider a few P_{rx} values, from perfect reception ($P_{rx} = 1.0$) to fair condition ($P_{rx} = 0.8$) to relatively poor reception ($P_{rx} = 0.5$). In particular, the last amounts to the measured channel quality at the Tx-Rx distance of 600 meters in the worst (shadowing) condition [20]. The collision probability in face of the channel loss and non-half-duplex condition is given by

$$P'_{col,s} = (1 - P_{rx}) \times P_{col,s}, \quad (s > 0) \tag{8}$$

because we assume that collisions can only occur when the packets are not already lost by propagation-induced errors [13]. Substituting $P'_{col,s}$ for $P_{col,s}$ in Eq. (7) for $s > 0$, the collision probability of RaSPS with $\theta = 0$ and that of SPS are shown in Fig. 5. Here we assume $N_{subCH} = 2$, $RRI = 100$ ms, $T_1 = 1$, and $T_2 = 100$. We observe that with perfect reception of the reservation information, the improvement in collision probability is close to two orders of magnitudes. We can also see that even with very poor channel at $P_{rx} = 0.5$, the collision probability is visibly lower than in SPS.

We can expect that the performance improvement over SPS to grow if we increase θ. Fig. 6 shows the impact of making the reservation announced earlier. Consequently, we have $(1 - P_{rx})^\theta$ for $1 \leq \theta < C_1$ in Eq. (8). Even for the worst channel condition considered in Fig. 5, $P_{rx} = 0.5$, we observe that larger θ does reduce the collision probability, due to the reservation information being delivered with an increasingly higher probability. Indeed, this result is the main motivation to explore even earlier

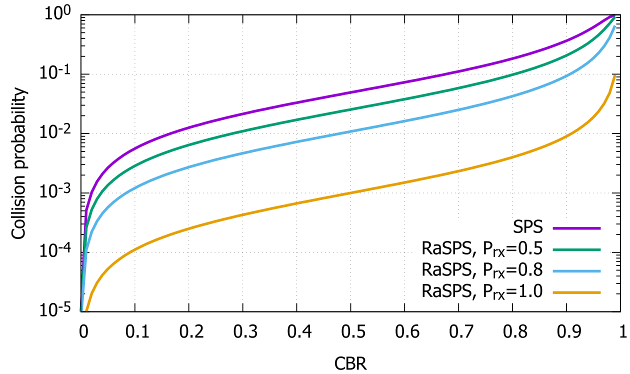


FIGURE 5. Packet collision probability, with varying delivery probability P_{rx}; $\theta = 0$.

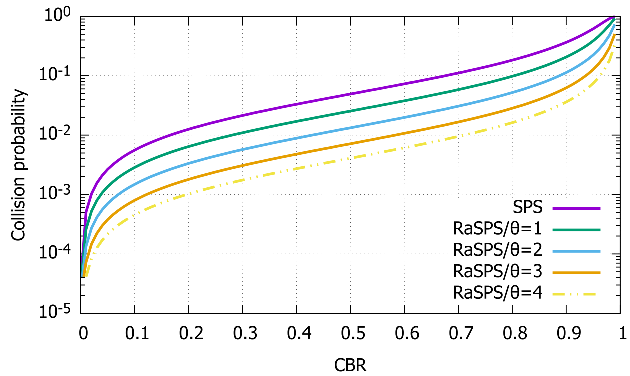


FIGURE 6. Packet collision probability under different early announcement timing $\theta \geq 1$; $P_{rx} = 0.5$.

announcements ($\theta \geq C_1$) below, which we call Gapped Reservation-augmented SPS (GRaSPS).

Note that there is no adverse impacts in reliability and latency by using an early announcement. In the proposed scheme, we add a pointer to a resource location in the future in the SCI of each packet. Namely, in RaSPS, all the packets in packet run $V(k)$ point to $a_v(k+1)$. There are on average $(C_1 + C_2)/2$ pointers toward $a_v(k+1)$, which makes it robust to losses. In fact, the earlier the announcement, the more robust it becomes. But as we lose more of these pointers, the RaSPS performance will converge to that of SPS that provides no explicit information as to the scheduled location of the next run. As to the latency, the time lag between the reservation and the real resource use does not cause additional delays. We do not delay the actual transmission of packets for the sake of the proposed reservation because the selection of the next resource to use for the next run is made earlier than SPS that performs it at the end of a run.

2) PACKET COLLISION BETWEEN VEHICLES WITH $z_v(k) = z_w(j)$ BUT $a_v(k) \neq a_w(j)$

Here, V and W are completely overlapped in their selection windows as their runs end at the same subframe, namely $z_v(k) = z_w(j) = n$. Fig. 7 further elaborates this half-duplex condition. If the reservation is announced at $RC = 0$, the vehicles cannot eliminate the possibility of a packet

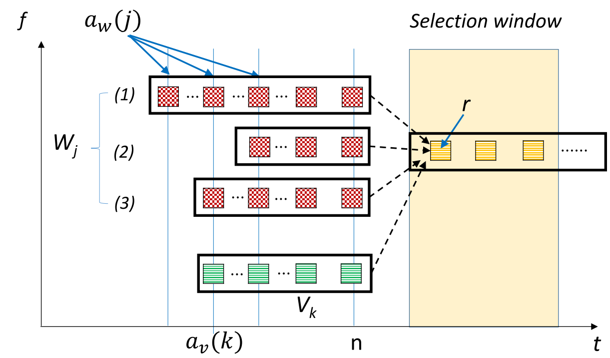


FIGURE 7. **Half-duplex situations; *n* is the current subframe.**

collision. In fact, an earlier announcement of reservation at $RC = \theta < C_1$ cannot resolve the issue either, because their runs span at least C_1 packets — their announcements will all coincide. Therefore, we need a reservation scheme with a better collision resolving capability, i.e., GRaSPS.

Given $z_v(k) = z_w(j)$, it is highly likely that we will have $a_v(k) \neq a_w(j)$ (depicted by the subcases (1) and (2) for W_j in Fig. 7). For instance, the probability that two arbitrary runs have an identical length is only 1/11 when $C_1 = 5$ and $C_2 = 15$. The probability is even lower at 1/21 and 1/51, respectively, for the other standard RRIs of 50 ms and 20 ms [2]. If we have $a_v(k) \neq a_w(j)$, we can let one vehicle hear the other at the beginning of a run by allowing $\theta \geq C_1$. One straightforward way to determine the announcement instant irrespective of various packet run lengths is to announce the reservation for V_{k+1} at the beginning of V_k or at the end of V_{k-1}. For a higher collision resolving capability, we take the latter approach in this article because it can further deal with the case $a_v(k) = a_w(j)$ as we discuss later. We call the scheme Gapped Reservation-augmented SPS, because there is a gap of one run (V_k) between the first announcement of the reservation and the first packet transmission as per the reservation. Because each packet run spans one second on average [3], the GRaSPS reservation is made approximately one second before an actual transmission starts.

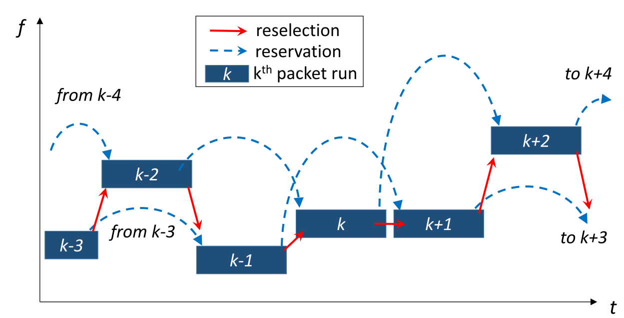


FIGURE 8. **Early reservation for the second next packet run of a vehicle in GRaSPS (repeated announcements are not depicted for readability).**

Fig. 8 illustrates the operation of GRaSPS. In the figure, only the packet run $k + 1$ keeps the same resource as k, but all others reselect other resources than the previous one. At the end of each packet run, it makes the reservation for the second next run, not the immediately following run. In the very beginning, therefore, a vehicle should choose the starting resource location and the RC value of the first packet run by using the traditional SPS, and at the same time choose the starting resource location of the next run and start to announce it.

3) PACKET COLLISION BETWEEN VEHICLES $z_v(k) = z_w(j)$, $a_v(k) = a_w(j)$ BUT WITH $z_v(k-1) \neq z_w(j-1)$

Here, we have $|V_k| = |W_j|$ (subcase (3) in Fig. 7). If we have $z_v(k-1) \neq z_w(j-1)$, however, GRaSPS can resolve the collision. Since there are $RRI = 100$ subframes where the $z_v(k-1)$ and $z_w(j-1)$ can coincide, $z_v(k-1) = z_w(j-1)$ occurs with the probability of only 1/100. Namely, GRaSPS can resolve 99% of the potential packet collisions between V_{k+1} and W_{j+1} even if V_k and W_j completely coincide and are in the half-duplex relation.

We could conceive of pulling the reservation instant to an even earlier time than GRaSPS does, to progressively elide more collision cases. However, it would reduce the flexibility of GRaSPS to cope with the vehicle topology change. For example, if new vehicles merge with the ongoing traffic, they may not have heard the reservation information by the vehicles in the ongoing traffic. If the vehicles from different groups adhere to their previously scheduled reservations, collisions could persist as long as the widened time gap between the announcement and the actual resource use. Moreover, a longer reservation horizon may raise the possibility of wasting usable resources if passing vehicles in the opposite lane or in the intersection announce their reservation. Because they will soon go out of the communication range, their reservations left behind would deprive the qualified vehicles of their chances to use them. Furthermore, only with the gap of approximately one second, GRaSPS already leaves only a small fraction of unresolved cases. Even those remaining cases do not all lead to collisions because the SPS random resource selection from S_B still works, so only a subset of reselections not under the protection of GRaSPS will suffer an actual collision. Finally, there would be an added signaling cost in terms of the number of bits in the announcement to encode the widened time gap between the announcement and the reserved resource. Therefore, we do not consider pulling the reservation instant further in the time axis than GRaSPS.

D. RESERVATION SIGNALING

To point to a starting resource in the second next run, we need to specify its time-frequency coordinate. Here, we compute the number of bits needed to specify the reservation information, which is the signaling cost of the proposed scheme. In GRaSPS, suppose we are at $n = z_v(k-1)$ to announce a reservation for $V(k+1)$. We need two pieces of information to specify the starting location, namely the subchannel number of the first packet in $V(k+1)$ and the time gap to it. For a more practical illustration, we will assume the baseline assumptions from 3GPP TR 36.885 [4] Annex A.2. Namely, the sidelink is allocated a 10 MHz band with

50 physical resource blocks (PRBs). The modulation and target coding rate are QPSK and 0.5, respectively. Although the message set dictionary SAE J2735 states that four 190-byte BSMs with digested and a single 300-byte BSM with the full security credential to be iterated [5], we will assume constant 300-byte packets as in many previous work [10], [14], [15], [27], to focus more on the impacts of the explicit reservation. As to the inefficiency that the varying message sizes may cause on the resource use, the readers are referred to Molina-Masegosa and Gozalvez [11].

For a 2,400-bit transport block size (TBS) that accommodates the 300-byte BSM, the TBS index of $I_{TBS} = 7$ that can carry 2,472 bits produces the coding rate of 0.55, close to the target. With $I_{TBS} = 7$, the number of required PRBs is 20 for the payload. Since we need 2 more PRBs for the Sidelink Control Information (SCI), a single BSM needs 22 PRBs. Since we have 50 PRBs, we can have two subchannels, so $N^{SL}_{subCH} = 2$ [11]. We assume that the SCI and TB of a single message are adjacent, but the alternative non-adjacent configuration would not affect the proposed scheme. According to the 3GPP TS 36.212, the subchannel number is coded by $2 (= \lceil \log_2(N^{SL}_{subCH}(N^{SL}_{subCH}+1)/2) \rceil)$ bits [21]. As for the time gap, it reaches the maximum when $|V(k)| = C_2 = 15$ and $a_v(k) - z_v(k-1) = a_v(k+1) - z_v(k) = T_2 - T_1$. It is approximately 1,600 subframes, which we can code in $\lceil \log_2 1600 \rceil = 11$ bits. Thus the total number of bits for the baseline configuration is 2+11=13 bits, although if we use a larger number of subchannels, it can further increase.

One way to accommodate the reservation information bits is to utilize the undefined (''Reserved'') bits in the SCI transmitted on Physical Sidelink Control Channel (PSCCH). The SCI Format 1 [21] has the structure shown in Fig. 2. The third field, Frequency resource location of initial transmission and retransmission, is $X = \lceil \log_2(N^{SL}_{subCH}(N^{SL}_{subCH}+1)/2) \rceil = 2$ bits. Therefore, we have $15 - X = 13$ bits available. Therefore, the baseline configuration discussed above would exactly fit in the SCI Format I. As the reserved bits are utilized, the number of resource blocks (RBs) used for the SCI remain the same.

However, there can be more subchannels in other configurations, or the resource allocation unit on the time axis can be smaller than a subframe. Then the reservation information would not be accommodated in the Reserved field of the current SCI Format 1. As to the increased signaling bits required by GRaSPS, it is worthwhile to note that in 5G V2X, the SCI is split into two stages so that the second stage will be carried in the Physical Sidelink Shared Channel (PSSCH) instead [22], which will allow for more room in the SCI so that we can utilize more bits to specify explicitly reservation information. For instance, a recent proposal in the 3GPP Radio Access Network Working Group 1 (RAN1) is to move the RRI and the MCS fields among others to the SCI stage 2, making room for other new fields [23]. In particular, the SCI stage 1 newly includes the number of bits to point to a future reserved transmission on PSCCH, with $\lceil \log_2(N^{SL}_{subCH}(N^{SL}_{subCH}+1)/2) \rceil$ bits for the frequency coordinate and 7-10 bits for the time gap. Such provision could be easily leveraged by GRaSPS.

Alternatively, we could consider piggybacking the reservation bits in the payload part at the cost of increased cross-layer signaling. For example, the BSM Part II that carries optional information and is less frequently transmitted than Part I [5], could accommodate them. As for the cross-layer signaling, ETSI TS 103 574 allows the access layer to talk to the congestion control management entity (CCME) that in turn can talk to either the networking and transport layers or the facilities layer [24]. In effect, the CCME can serve as the cross-layer signaling channel. Then, one could let the facilities layer extract the proposed reservation information, and through the CCME, hand it over to the access layer. But this is left as a topic to be further explored as we track the development of the related standards.

E. COMPLEXITY AND CONVERGENCE TIME

GRaSPS uses the reservation information of other vehicles to determine the location of the resource to use for its second next packet run. Given $|\mathcal{T}|$ neighbor vehicles, a host vehicle V has to remember the reservations for the next and the second next packet runs, $a_w(j+1)$ and $a_w(j+2)$, for each neighbor $W \in \mathcal{T}$. This is because a neighbor W announces only $a_w(j+2)$ at the end of the packet run j, but their immediate next resource location, $a_w(j+1)$, must also be remembered from the previous announcement made at the end of run $j-1$. For each announcement c from a neighbor $W \in \mathcal{T}$, the host vehicle V should

1) Find the reservation information for W, i.e., $a_w(j+1)$ and $a_w(j+2)$
2) If $c > a_w(j+2)$, set $a_w(j+1) \leftarrow a_w(j+2)$ and $a_w(j+2) \leftarrow c$

After vehicle V executes Step 2), vehicle W will begin to use $a_w(j+1)$ for the next beacon transmission. Step 1) requires a search. But with the large temporary vehicle ID size (e.g. 32 bits [5]), a hash table can reduce the average complexity to $O(1)$. In the worst case, the complexity will be upper-bounded by $O(|\mathcal{T}|)$, e.g. with a simple list. Step 2) is $O(1)$. Therefore, each RRI, GRaSPS performs $O(|\mathcal{T}|)$ computations in addition to SPS in the worst case.

As to the convergence time, suppose a vehicle U joins the vehicle traffic $\mathcal{T}$, where $\mathcal{T}$ has already converged in terms of resource allocations. Suppose U is using a resource $a_u(k)$ in its current packet run $U(k)$, and reserved $a_u(k+1)$ and $a_u(k+2)$ for the next and the second next runs. Let us further assume that there is a vehicle in $\mathcal{T}$ that is currently using $a_u(k)$. All U can hear is the second-next reservations from vehicles in $\mathcal{T}$, so U cannot change its decision on $a_u(k)$ or $a_u(k+1)$. Any collisions on the current run using $a_u(k)$ cannot be resolved as in SPS. The largest non-coordinated packet transmissions can persist until the end of the current packet run $U(k)$. The average length of the packet run is $(C_1 + C_2)/2$, which is one second on average. However, this is no worse than SPS. For $a_u(k+1)$, we can rely on the reselection procedure in SPS to mitigate collisions

Algorithm 1 Reselection With Reservation in GRaSPS

```
1:  procedure GRaSPS (RRI, C1, C2, N_subCH, P_k)
2:      txSubCH ← random(1, N_subCH)          ▷ Initialize SPS parameters
3:      txSubFR ← random(1, RRI)
4:      RC ← random(C1, C2)
5:      t ← 0                                 ▷ This is the current time
6:      RsvTxSubCH ← random(1, N_subCH)
7:
8:      RsvTxSubFR ← txSubFR + RRI × RC + random(1, RRI)
9:      RsvRC ← random(C1, C2)                ▷ Initialize Rsv parameters
10:     ——————————————
11:     while True do
12:         if t == txSubFR then              ▷ It is time to transmit
13:             txPacket(txSubCH)             ▷ On the specified subchannel(s)
14:             if RC ≠ 0 then                ▷ Continue the current run
15:                 txSubFR ← txSubFR + RRI   ▷ Schedule next Tx
16:                 RC ← RC − 1
17:             else▷ RC = 0: time to switch to reserved run
18:                 RC ← RsvRC
19:                 txSubCH ← RsvTxSubCH
20:                 txSubFR ← RsvTxSubFR
21:
22:                 RsvRC ← random(C1, C2)    ▷ Reserve another
23:                 if random(0, 1) < P_k then    ▷ Inherit current resource
24:                     RsvTxSubFR ← txSubFR + RRI × (RC + 1)
25:                     RsvTxSubCh ← txSubCH
26:                 else    ▷ Must move from current location
27:                     call select_ resource_for_Rsv( )
28:                                           ▷ Reselect RsvTxSubCH,RsvTxSubFR using SPS after excluding already reserved resources
29:         else
30:             call sensing_update( )        ▷ Sense and update resource map
31:         t ← t + 1                         ▷ Push time
```

with any other vehicle that reserved the same resource, based on the average RSSI. This is because the proposed scheme is not a replacement of SPS, but an augmentation of SPS. From $a_u(k+2)$ and on, GRaSPS handles the reservation. In summary, it takes two seconds on average until GRaSPS to integrate a new vehicle in the resource coordination of existing traffic, relying only on SPS for the latter half of the two-second period.

The GRaSPS algorithm is described in Algorithm 1. The changes from the standard SPS appear in lines 7 – 9 and the lines 18 – 28. The former randomly initialize the location (*RsvTxSubCH* and *RsvTxSubFR*) and the length (*RsvRC*) of the reserved run $k+1$. In the latter, when the current run k reaches its end with $RC = 0$, lines 18 – 20 put to use the reserved parameters for $k+1$ that were created at the end of the previous run $k-1$. Finally, since we are at the end of run k, another reservation is made for $k+2$ in lines 22 – 28. It will be put to use when the now starting run $k+1$ ends, through the code in lines 18 – 20. In line 23, it is determined whether the next run will contiguously follow the current one, whose probability is P_k. If not, line 27 selects a new resource. Specifically, it excludes all reserved resources from the selection window and then those sensed busy. To exclude the latter, we follow the standard SPS procedure.

IV. SIMULATION EXPERIMENTS

In this section, we conduct simulation experiments to evaluate the performance of the two reservation schemes, in comparison with the standard SPS algorithm. For a more realistic assessment, we use a similar setting to the urban scenario prescribed in the Annex A of 3GPP TR 36.885 [4]. The urban topology is shown in Fig. 9, and the other simulation configurations are summarized in Table 1.

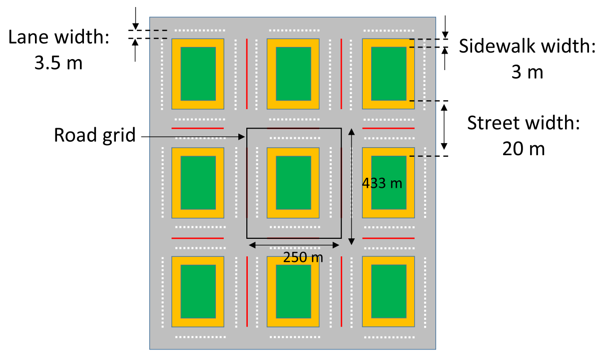


FIGURE 9. Simulated urban topology, populated with ρ vehicles [4].

Additionally, we model the link level performance such as the block error rate (BLER) by using the performance evaluation guidelines in a 3GPP RAN1 WG contribution [25]. Specifically, we tabulated the BLER curves presented in the contribution to estimate the BLER for each received packet. Also, we vary the vehicle density more flexibly for the simulated topology. According to the Annex A of 3GPP TR 36.885 [4], the vehicles should be spaced by the distance covered in 2.5 seconds at the given speed v. However, for $v = 15$ km/h and 60 km/h that the standard specifies, the average inter-vehicle gaps are approximately 10 and 40 meters, respectively, which create severe traffic jam in the intersections as vehicles move according to the SUMO-generated trajectories [26]. Therefore, we reduce the number of vehicles in the simulated area (ρ) so that the traffic jam situation where some vehicles are not moving at all is avoided. Although scaled down, the road with $v = 15$ km/h is more congested condition than with $v = 60$ km/h. When each vehicle encoun-

TABLE 1. Simulation parameters.

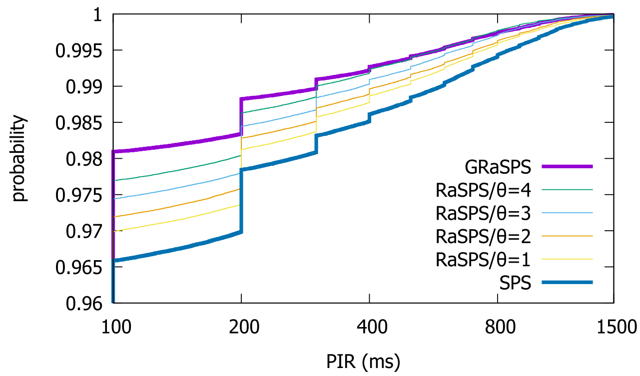
	Parameter	Assumption
PHY	Carrier frequency	PC5 based V2V: 5.9 GHz
	Bandwidth	PC5 based V2V: 10 MHz
	No. of subchannels	2
	Antenna height	1.5 m
	Antenna gain	3 dBi
	Maximum Tx power	23 dBm
	Noise figure	9 dB
	Pathloss model	WINNER+ B1 Manhattan grid
	Shadowing distribution	Log-normal
	Shadowing std. dev.	3 dB for LOS, 4dB for NLOS
	Decorrelation distance	10 m
Road	Number of lanes	2 in each direction (4 in total)
	Lane width	3.5 m
	Road grid size	433-meter × 250 m
	Simulation area size	1299-meter × 750 m
	Absolute vehicle speed (v)	15 km/h, 60 km/h
	No. of vehicles in the simulated area (ρ)	15 km/h: 120 – 420 60 km/h: 60 – 120
C-V2X	No. of subchannels	2
	Packet Tx frequency	10 Hz
	Packet size	300 bytes
	MCS	7 (QPSK 0.5), 9 (QPSK 0.7)
	C_1, C_2	5, 15, resp.
	T_1, T_2	1, 100, resp.
	P_k	0, 0.4, 0.8
	RRI	100 ms

ters an intersection, it either makes a turn or goes straight with 50% probability each. For the turn, again it applies the equal probability to left and right turns. On the boundary roads, vehicles move in the clockwise direction. Finally, we omit the results for MCS 9, because it produces the identical qualitative results as MCS 7, only with lower packet delivery performances. We use 300 bytes as the BSM size as used in other works in the literature [10], [14], [15], [27]. Note that two different beacon sizes, such as prescribed by 3GPP TR 36.885 [4], more reselections may be necessary in case the resource allocation is only based on the smaller size, which could impact the performance [9]. Alternatively, one workaround to allow different beacon sizes if the SCI size can be further increased as in NR V2X [23] could be specifying the number of consecutive subchannels that the packet should occupy by using additional $\lceil \log_2 N^{SL}_{subCH} \rceil$ bits in the SCI. In fact, how to accommodate different packet sizes may have more than a few potential solutions. In this article, therefore, to focus more on the performance impact of the reservation on the performance of SPS, we use the identical packet size. The performance analysis of the proposed reservation scheme under the differing packet sizes is left for a future work.

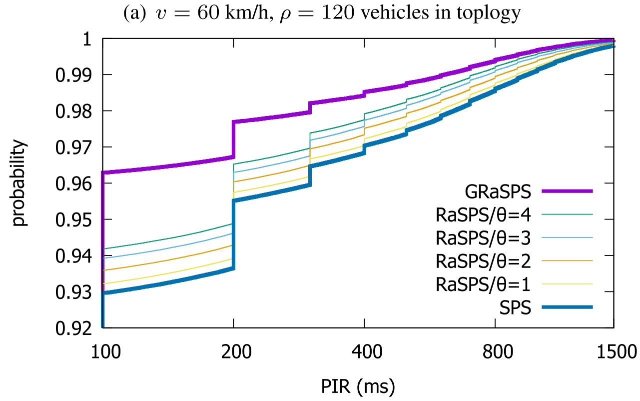
For performance metrics we use Packet Reception Ratio (PRR) and Packet Inter-Reception time (PIR). They are defined in 3GPP TS 36.885 as follows [4]:

- Packet Inter-Reception (PIR): PIR is the time elapsed between two successive successful receptions of two different packets transmitted from vehicle V to W.
- Packet Reception Ratio (PRR): For each transmitted packet, PRR is calculated by X/Y, where Y is the number of vehicles that are located in the range (a, b) from the transmitter, and X is the number of vehicles with successful reception among Y.

PIR is also known as Inter-Packet Gap (IPG) or Update Delay (UD) in the literature. It is more associated with latency. For PRR, it is recommended that $a = 0$, $b =$ baseline of 320 meters for freeway and 150 meters for urban. Optionally, $b = 50$ meters for urban with $v = 15$ km/h. PRR is more associated with reliability. In this article, we use $b = 150$ meters for both vehicle speeds. The values of a and b are only defined for PRR in the recommended simulation configurations [4], but we will apply it to both PRR and PIR below.



(a) $v = 60$ km/h, $\rho = 120$ vehicles in toplogy



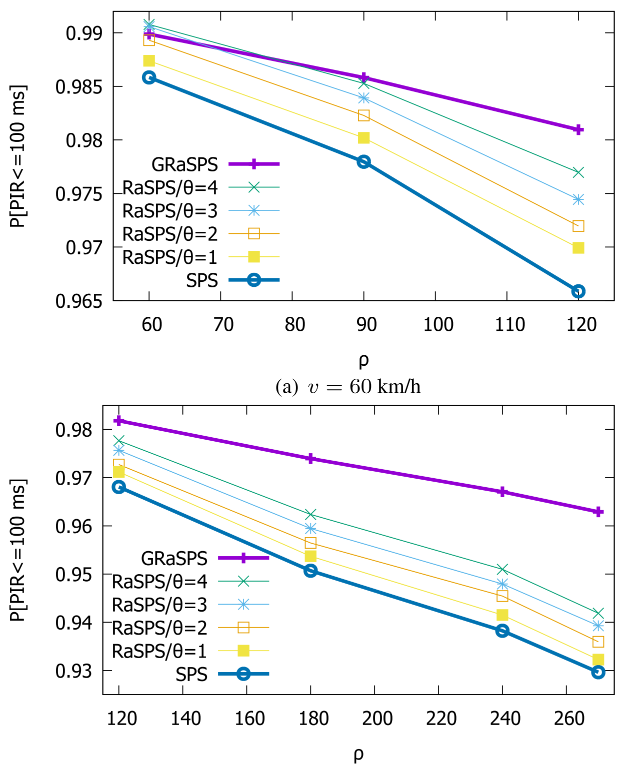
(b) $v = 15$ km/h, $\rho = 270$ vehicles

FIGURE 10. Packet Inter-Reception (PIR) times distributions.

A. PACKET INTER-RECEPTION TIME (PIR)

Fig. 10 shows the PIR distributions of the explicit reservation schemes as compared to the original SPS algorithm. Fig. 10(a) is a less congested situation than Fig. 10(b), as the higher vehicle speed corresponds to a less congested road according to the 2.5 second inter-vehicle distance configuration guideline in 3GPP TR 36.885 [4]. The figure presents the results for two high ρ values among those in Table 1, where the resource contention is more severe. It proves that the earlier the reservation instant the better the PIR performance. In particular, GRaSPS consistently outperforms RaSPS and SPS. In Fig. 10(a), more than 98% of the packets under GRaSPS arrive within 100 ms at the neighbor vehicles in the 150-meter range. In contrast, even those arriving in double the PIR (= 200 ms) is less than 98% in the original SPS algorithm. The RaSPS scheme lies in between, with larger

θ's achieving better PIR. The result for a more congested road condition in Fig. 10(b) shows that the gap at 100 ms between GRaSPS and SPS grows even larger to more than 3%, proving the efficacy of the proposed scheme. Although the differences in the PIR may seem small, achieving the lowest PIR with very high reliability above the 90% range is deemed crucial in the safety-oriented C-V2X.

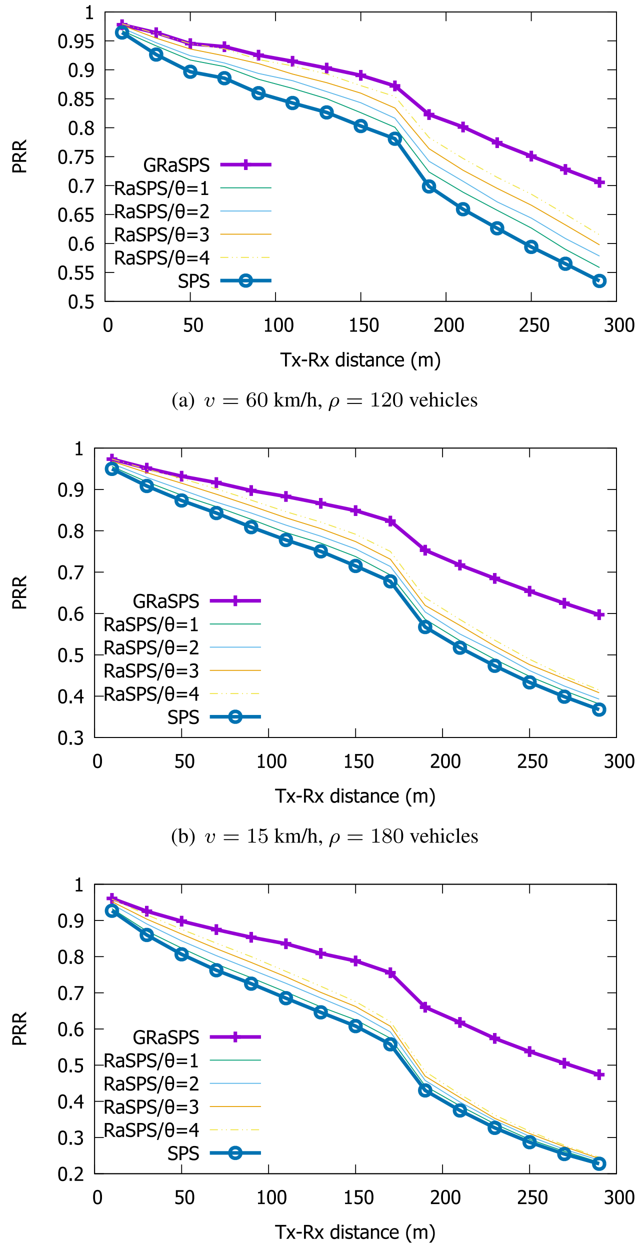


(a) $v = 60$ km/h

(b) $v = 15$ km/h

FIGURE 11. Fraction of PIR times ≤ 100 ms.

Fig. 11 shows the performance of the compared schemes in terms of the fraction of PIR values no larger than the 100 ms RRI keeping the original information update rate, as we vary the vehicle density ρ. The PIR under 100 ms can occur upon a reselection, because the resource is chosen from the selection window whose right edge is $T_2 = 100$ ms. We observe in both cases that as ρ increases, the PIR value decreases for all schemes due to increases congestion. However, in all cases, the use of explicit reservation helps improve the PIR. Especially under heavier congestion the impact of explicit reservation is more conspicuous. We notice that the gap in the PIR between GRaSPS and RaSPS schemes in Fig. 11(b) is wider than in Fig. 11(a). Moreover, the PIR drop due to the increase of ρ is also much steeper with the original SPS. In Fig. 11(a), SPS drops by 2% where GRaSPS drops by 1%. In Fig. 11(b), the drop is nearly 4% with SPS, whereas GRaSPS drops by only 2%. We can conclude that the GRaSPS clearly outperforms SPS and leads to a more graceful degradation of PIR times in face of severe congestion. This is because the collisions are more likely under higher channel congestion, which GRaSPS is effective to mitigate.



(a) $v = 60$ km/h, $\rho = 120$ vehicles

(b) $v = 15$ km/h, $\rho = 180$ vehicles

(c) $v = 15$ km/h, $\rho = 270$ vehicles

FIGURE 12. PRR as a function of communication distance.

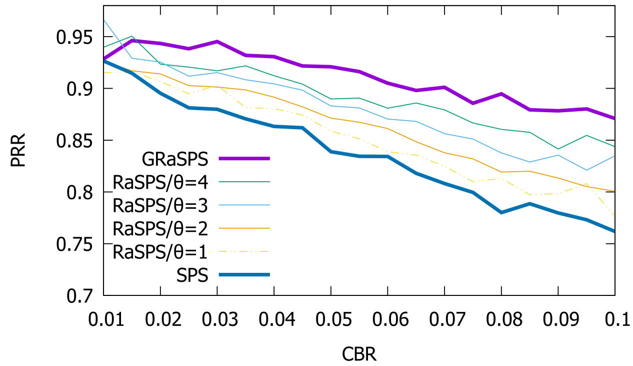
B. PACKET RECEPTION RATIO (PRR)

Fig. 12 shows the Packet Reception Ratio (PRR) of the compared schemes as functions of the Tx-Rx distance. Here, we do not limit the range for PRR computation to $b = 150$ meters, but starting from the transmitter, use 20-meter bins for each of which we compute PRR. Again, we observe that making explicit reservations consistently achieves better PRR. In particular GRaSPS is much more robust than SPS. As the Tx-Rx distance increases, the performance difference between SPS and GRaSPS grows. This implies that the resource selection based on the RSRP and the RSSI in SPS becomes less reliable to identify the used resource against unused ones, as the distance from the transmitter to the receiver grows. In contrast, the explicit reservation information, if decoded, could not be more clear indication as to the resource location to be used. Since the reservation information is announced repeatedly, it can be more reliably delivered to remote vehicles at the fringe of the communication range. It helps the remote vehicle to exclude the used locations from its selection window with an improved accuracy than in SPS.

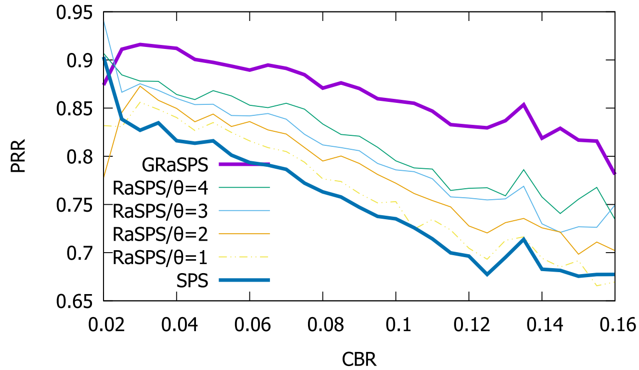
Another interesting observation in Fig. 12 is that the RaSPS performance deviates significantly from GRaSPS and moves towards SPS as the congestion level rises. This is because RaSPS cannot resolve the half-duplex collisions for which $z_v(k) = z_w(j)$ as discussed in Section III-C2 and III-C3. As Eq. (2) shows, the rise of CBR leads to a larger V_0 that should reselect. The rise of the congestion level also means that the candidate set will become less diverse for different vehicles. It exacerbates the half-duplex collision problem, so RaSPS converges to SPS under heavy congestion. It tells us that an explicit resource reservation scheme must be able to resolve the half-duplex collisions to operate effectively under congestion.

To corroborate the robustness of GRaSPS against the half-duplex collisions that are aggravated by the increased congestion level, we plot the PRR as a function of the CBR respectively experienced and sensed by each vehicle in Fig. 13. For this experiment, we use the case of $v = 15$ km/h to force higher CBR values, and $b = 150$ meters to compute the PRR. Despite some unstable data points at the extremities in the graphs due to the sparsity of data samples with the very low or very high CBR values that the vehicles experience, we again confirm that GRaSPS consistently outperforms RaSPS and SPS. In Fig. 13(a) where $\rho = 180$, the PRR difference between GRaSPS and SPS can be as large as 10%. In Fig. 13(b) and (c) with higher ρ values, the difference can increase to 20 to 30%. Also, we observe in Fig. 13 also that RaSPS increasingly converges to SPS as congestion worsens. We can confirm that the capability of GRaSPS to resolve most half-duplex collisions gives the clear performance advantage against the other two resource allocation schemes.

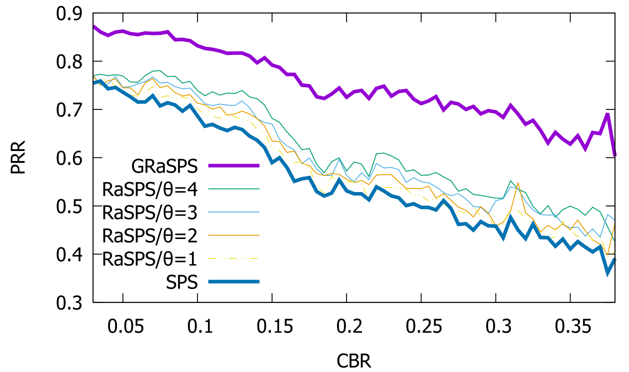
So far, we have assumed $P_k = 0$. We now relax the assumption to evaluate the impact of larger resource keeping probabilities on PRR under SPS and GRaSPS. Because we have confirmed in previous experiments that RaSPS is inferior to GRaSPS, we omit it in this experiment. Recollect that in the standard, $P_k = 0.8$ is the maximum allowed resource keeping probability [3]. As above, the PRR distribution is for the Tx-Rx distances of no more than 150 meters [4]. Fig. 14 shows the complementary cumulative distribution function (CCDF) of the PRR (i.e. $Prob[PRR > x]$) under two more standard P_k values, 0.4 and 0.8, along with $P_k = 0$. For this experiment, we use two traffic densities: $\rho = 120$ ($v = 60$ km/h) and $\rho = 270$ ($v = 15$ km/h). In the figure, we first observe that the larger resource keeping probabilities increases the fraction of packets with higher PRR.



(a) $v = 15$ km/h, $\rho = 180$ vehicles



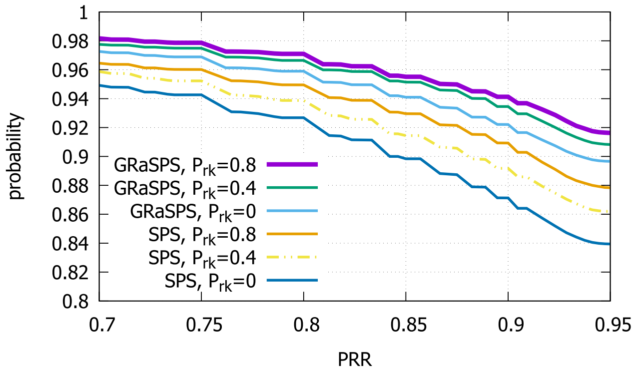
(b) $v = 15$ km/h, $\rho = 270$ vehicles



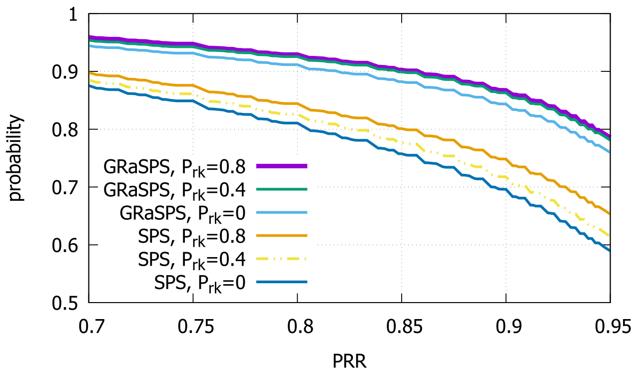
(c) $v = 15$ km/h, $\rho = 420$ vehicles

FIGURE 13. PRR as functions of CBR at $v = 15$ km/h.

This is expected, because there is higher predictability with a larger P_k, which SPS can exploit to avoid conflicts in resource allocations. In Fig. 14(a), there is up to 4% growth of PRR in SPS by increasing P_k from 0 to 0.8. As for GRaSPS, the increase is smaller, but it still outperforms SPS by a few percent. As the congestion level rises, there is still the impact of the increased predictability, but it is overshadowed by the difference that the two compared schemes produce by implicit and explicit reservations. Fig. 14(b) shows that the performance gap between the two schemes can even exceed 10%. It is noteworthy that the best PRR result with $P_k = 0.8$ (the maximum allowed by the standard) in SPS is lower than the PRR with the lowest P_k with GRaSPS in both



(a) v = 60 km/h, ρ = 120 vehicles



(b) v = 15 km/h, ρ = 270 vehicles

FIGURE 14. Impacts of higher resource keeping probabilities on SPS and GRaSPS, under two different traffic densities.

experimented traffic densities. In summary, both schemes benefit from the reduced uncertainty in the resource use under larger P_k, but the explicit reservation in GRaSPS has an even larger impact in the PRR performance as the collision-free resource allocation becomes increasingly difficult due to higher traffic loads.

In summary, the proposed GRaSPS enhancement significantly outperforms SPS. It is more robust under congestion hence degrade more gracefully than SPS, and more reliably convey the resource use information to the farther edge of the C-V2X communication range. We also observe that resolving the half-duplex packet collisions is crucial to achieve high performance under congestion. We believe that the explicit reservation is a powerful performance booster for which we do not need to add other wireless resources than a piggy-backed signaling mechanism.

V. CONCLUSION

The possibility of failed coordination in distributed resource selection stemming from various reasons such as vehicle topology change makes the resource reselection feature in SPS indispensable to reduce packet collisions in C-V2X Sidelink Mode 4. However, it also adds to the uncertainty of the resource usage whose pattern is exploited to select the least likely resource to be used by other vehicles. In this article, we proposed a solution to reduce the uncertainty of the resource selection, in which each vehicle explicitly announces the reservation information for the second next reselection in the SPS algorithm. This enhancement to the SPS algorithm that makes the reservation available one second ahead on average brings unconditional performance improvement over SPS in both latency and reliability. The fraction of vehicles with the minimum packet inter-reception time (PIR) value increases by a few percent in the high 90% range over SPS, where the proposed scheme keeps it above 95%. The packet reception ratio (PRR) improvement at the fringe of the communication range is 15-25% depending on the congestion level. The performance gap between the proposed method and SPS widens under heavier congestion and at farther communication ranges. On the cost side, the proposed mechanism can be implemented within the C-V2X framework up to two subchannels, but the additional signaling bits could be more readily afforded in the NR V2X standards where more subchannels can be utilized for V2X communication. We further showed that the proposed scheme handles half-duplex collisions well. Compared with SPS and a hypothetical scheme that reserves for the immediately next packet run, the proposed scheme can significantly reduce the probability of the half-duplex collisions. In fact, we observed that as congestion increases, the hypothetical scheme converges to SPS in performance whereas the proposed scheme distinguishes itself from them. It implies that the half-duplex collisions become more frequent under congestion, and it becomes crucial to control it, which the proposed scheme has a clear advantage. A future extension of this work could be in the area of fairness, specifically the conditions under which the explicit reservation can be overridden or compromised, to prevent possible preemptive resource occupations. We hope that the findings in this article are reflected in the future standardization process in the ongoing C-V2X evolution.

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