On Enhancing Semi-Persistent Scheduling in 5G NR V2X to Support Emergency Communication Services in Highly Congested Scenarios

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ABSTRACT

3GPP Rel. 16 introduced 5G New Radio (NR) Vehicle to Everything (V2X) to support advanced use cases in Intelligent Transport Systems (ITS) with stringent Quality of Service (QoS) requirements, which include vehicular safety and traffic management applications. However, in highly congested traffic scenarios (i.e., too many vehicles in a single collision domain than the number of available channel resources), emergency vehicles performing sensing-based Semi-Persistent Scheduling (SPS) suffer from low Packet Reception Rate (PRR) and high Packet Inter-Reception time (PIR) due to scarcity of channel resources and increased collision rates. To address these issues, we propose a Priority-Based Semi-Persistent Scheduling (P-SPS) scheme which helps emergency vehicles by classifying them as high priority (HP) vehicles with higher Reselection Counter (RC) values and letting them to transmit in one of the channel resources whenever they have CAM messages ready for transmission irrespective of whether such resources are available or not. We also propose a complementary Probabilistic Collision Mitigation (PCM) scheme and an Intelligent Grant Removal (IGR) scheme to minimize the chances of collision among HP and low priority (LP) vehicles in the network. We implement the proposed enhancements to SPS in NR V2X module of the system level Network Simulator 3 (NS-3) and demonstrate how these help in improving the performance of HP and LP vehicles as compared to legacy SPS of 5G NR V2X in highly congested scenarios.

KEYWORDS

V2X, 5G NR, Vehicular Networks, ITS, NS-3 V2X Module, Semi-Persistent Scheduling (SPS)

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1 INTRODUCTION

Recurring traffic congestion is a common issue in today's transport networks even in many developed countries. The primary victims of this are emergency vehicles like ambulances carrying patients in critical condition. Practically every day, we find several emergency patient death cases making headlines whose itinerary got choked off due to traffic jams. Intelligent Transport Systems (ITS) technology helps increasing road safety and traffic efficiency by reducing road accidents and traffic congestion. ITS aims to provide the on-road users with an increased understanding of surrounding traffic conditions, thus providing seamless navigation and leveraged user travel experience, which is achieved through Vehicle-to-Everything (V2X) communications technology. V2X threads together Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), Vehicle-to-Vehicle (V2V), Vehicle-to-Network (V2N), etc. V2V applications play a crucial role in the exchange of safety messages between vehicles within a short range. 3GPP rel. 14 [1] introduced C-V2X for basic safety applications using LTE as the underlying technology. It introduced the first version of direct V2V communication using Sidelink (SL) which was further enhanced in release 15 [2]. Under release 16 [3], a new C-V2X technology was introduced on the top of 5G New Radio (NR) - a basis for future enhancements and extensions of C-V2X for ITS applications. The new flexible, scalable, and enhanced features of 5G NR in terms of reliability, latency, and data rates make it a better choice for vehicular communications. V2X needs to support two major kinds of messages for realizing various ITS use cases: (i) Cooperative Awareness Messages (CAM) – periodic messages that contain information regarding the vehicle's speed, current position, etc and (ii) Decentralized Event Notification Messages (DENM) – event-triggered notifications of road events.

This paper considers a crucial ITS use case of Emergency Vehicle Warning (EVW) in 5G NR V2X Mode 2 operation in a highly congested sub-urban region. In a situation where all vehicles are within a single collision domain, there is a severe deficiency of channel resources depriving the vehicles of effortless communication. The competition among vehicles over the limited channel resources is extremely high. Due to the channel congestion while acquiring a resource through Semi-Persistent-Scheduling (SPS) [refer Background section], EVW use case suffers from poor reliability and delay in packet reception. The availability of resources is so scarce that we even fail to create the top 20% best candidate resource list needed by SPS. Any emergency vehicle, entering such extreme congested region, must ensure that all the neighboring vehicles

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in the range of 200-300 meters receive its alert (CAM) messages. The CAM message will contain information regarding the emergency vehicle's speed, direction, and location coordinates to make delay-free navigation. The emergency vehicle is considered a high priority (HP) vehicle that broadcasts CAM messages to its neighboring vehicles which are assumed as low priority (LP) vehicles. We first propose a modified SPS – a Priority based SPS (P-SPS) for improving the performance in terms of Packet Reception Rate (PRR) and Packet Inter-Reception (PIR) of the emergency vehicles specifically while taking care that the LP vehicles are treated fairly.

Secondly, we propose collision minimization solutions to further enhance P-SPS. The first approach, Probabilistic Collision Mitigation (PCM) scheme, allows vehicles to transmit only with a certain probability to reduce collisions incurred when multiple vehicles sense the same channel resource free simultaneously and transmit in the same chosen Candidate Single-Subframe Resource (CSSR). In the second approach, Intelligent Grant Removal (IGR) scheme, we minimize collisions by intelligently estimating the CSSR after which the HP vehicle can take over once a LP vehicle finishes off its transmissions.

Thirdly, we pair P-SPS with both the collision minimization schemes – PCM and IGR – to level up the performance of P-SPS by reducing the chances of collisions in highly congested sub-urban scenarios. Finally, we present how adaptive use of P-SPS and P-SPS with PCM and IGR schemes can serve as an edge in extremely congested scenarios. Finally, these schemes are implemented and evaluated on top of NS-3 NR V2X module to assess their performance benefits and tradeoffs involved.

In summary, the key contributions are as follows:

- Demonstration of performance improvement of emergency vehicles in highly congested scenario using P-SPS against legacy SPS.
- Presenting SPS with PCM scheme for boosting performance of all the vehicles in extreme congestion scenarios.
- Enhancing performance of P-SPS by reducing collisions with PCM and IGR schemes.
- Proposing an adaptive approach of using P-SPS and the collision minimization schemes based on network congestion level for EVW use case through a comparative study.

2 BACKGROUND

5G NR V2X has two modes of operation called Mode 1 and Mode 2 based on scheduling preferences. Mode 1 employs a centralized approach where the radio resources are allocated by the base station (gNodeB) to vehicles within a certain range. Mode 2 is a distributed way of operation where vehicles select radio resources independently without the participation of any gNodeBs using Semi-Persistent Scheduling (SPS) scheme.

At Physical Layer, NR V2X uses Orthogonal Frequency Division Multiplexing (OFDM) for SideLink (SL) transmissions. Support for flexible numerologies μ (subcarrier spacing : $2^{\mu} \times 15$ kHz where μ= 0,1,2,3) is useful in satisfying stringent requirements for various use cases. The time-frequency resource grid is divided into subchannels and physical resource blocks (PRBs) in the frequency domain, and into frames, subframes, and slots in the time domain. An RB consists of 12 subcarriers in the frequency domain. A 5G NR frame is of 10ms duration. It is divided into subframes of 1ms each. Each subframe is further divided into 2^{μ} slots – each consisting of 14 OFDM symbols in the time domain. The number of slots per subframe and the sub-carrier spacing (SCS) vary with the numerology. The smallest schedulable unit in the time domain for transmissions is a slot. Resources are allocated per slot. In the frequency domain, a group of adjacent PRBs in the same slot is referred to as a subchannel. The subchannel size is defined as the number of PRBs in a subchannel. A Candidate Single Subframe Resource (CSSR) is a group of one or more contiguous subchannels that are required to carry a full message. The data is organized in Transport Blocks (TBs) that are carried in Physical Sidelink Shared Channel (PSSCH). A TB contains a full packet (e.g., a CAM). A TB can occupy one or several subchannels depending on the size of the packet, the number of PRBs per the subchannel, and the Modulation and Coding Scheme (MCS) chosen for transmission based on the underlying channel state.

Not all slots can be used for SL transmissions. Slots that can be used are either pre-configured or pre-defined based on a Time Division Duplex (TDD) pattern and a bitmap. SL transmissions are only allowed in uplink slots (U) of TDD pattern. And whether an uplink slot is available for transmission or not is given by the SL bitmap. Each data packet from the higher layers is transmitted as a TB along with SideLink Control Information (SCI) which contains critical information for decoding the other vehicle's transmission.

In Mode 2 of NR V2X, the autonomous selection of channel resources (i.e., CSSRs) for V2V communications by vehicles is done by performing Sensing Based Semi-Persistent Scheduling (SPS) where vehicles sense the wireless medium and select CSSRs for transmission of their CAM/DENM packets. The working of SPS has been depicted as *colored shaded* regions in Fig. 1. The resource selection by vehicles happens in two phases in SPS:

1. *Channel Sensing:* Each vehicle continuously senses and monitors Received Signal Strength Indication (RSSI) and Reference Signal Received Power (RSRP) across all the subchannels to determine probable candidate resources based on decoding of 1st Stage SCI. It senses as long as 1000 subframes prior to the event of resource selection trigger from the higher layers. The sensing helps the vehicles to identify resources with low interference from other vehicles for their respective SL transmissions.

2. *Selection of Candidate Resources:* When resource selection is triggered at the arrival of a packet from the higher layers, each vehicle chooses its selection window which starts at [T1] as per Table 1. The upper bound of the selection window is defined by the Packet Delay Budget (PDB) [T2]. The candidate resources (CSSRs) within the selection window are identified and List-A is created based on the following two criteria: (i) if the resource is not reserved by any other vehicle in its vicinity by transmitting corresponding SCI previously and (ii) measured RSRP of the resource is less than the minimum RSRP threshold. If the size of List-A is less than 20% of the total CSSRs then repeat criteria (ii) by increasing the minimum RSRP threshold by 3dBm. List-B is then created with the best 20% of the channel resources in

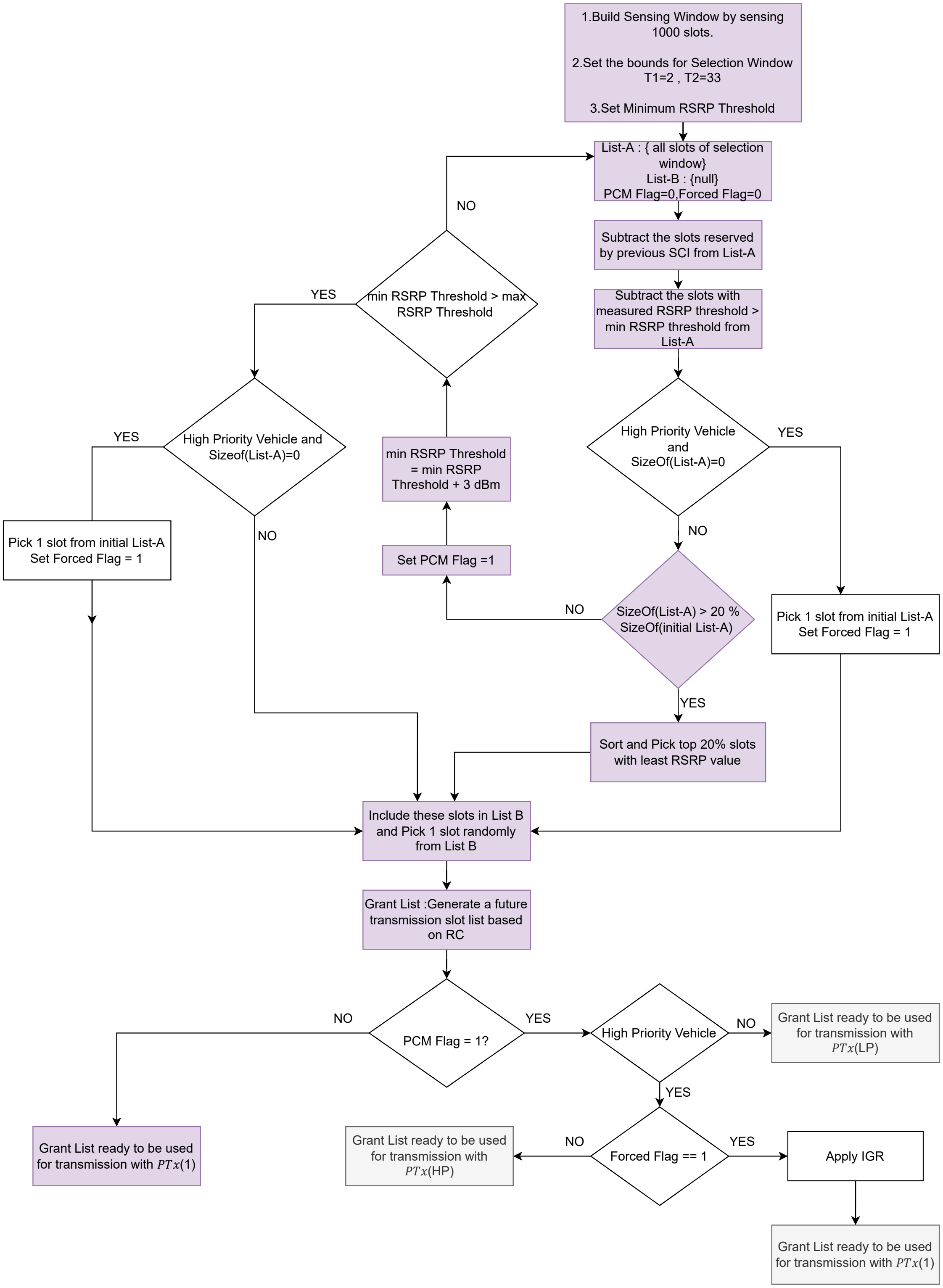

Figure 1: Working of proposed P-SPS with PCM and IGR schemes. The *colored shaded* regions depict the working of legacy SPS of NR V2X in Mode 2.

List-A. Out of this list of CSSRs, a vehicle randomly selects a channel resource to broadcast its CAM or DENM packets over sidelink channel to its neighboring vehicles.

The same channel resource is utilized for transmitting its packets periodically which is given by Resource Reservation Interval (RRI) till the Re-selection Counter (RC) becomes zero. In legacy SPS, RC is randomly chosen from the range [5,15]. Once RC becomes zero, a vehicle has to decide whether it should continue using the same reserved resource or select a new channel resource based on the Probability of Resource Keep (pKeep) value.

3 RELATED WORK

Based on the recent developments in V2X communication and 3GPP Rel 16 [3], researchers from Centre Tecnològic de Telecomunicaciones de Catalunya (CTTC) and the National Institute of Standards and Technology (NIST) have built NR V2X module on top of NS-3 [?]. Using this module, they studied the impact of numerology, MCS, pKeep, and the number of retransmissions on the performance of SPS algorithm in terms of throughput, PRR, and PIR in [4]. In [5], they also have studied the impact of PIR on numerologies and the size of the resource selection window, employing both sensing-based and random resource selection schemes. A comprehensive tutorial on 5G NR V2X communications is given in [9]. Earlier works on C-V2X (refer [8, 14, 15]) involved studying the effect of parameters like RRI and pKeep in high-density vehicular networks and improving the performance of legacy SPS. In [10], Haider et al. studied the effect of varying transmit power in different vehicular scenarios. They showed that the power control mechanism for CAM transmissions in the proposed algorithm achieved significant performance enhancement in terms of PRR in high-density traffic scenarios. [12] brings short duration of sensing period before resource selection happens in order to reduce packet collisions as compared to the legacy SPS. Anshika et al. [6] studied the effect of variation in both pKeep and RC in legacy SPS in low, medium, and high-density scenarios and proposed a traffic-aware SPS scheme (TA-SPS) that tunes the values of pKeep and RC adaptively as per current traffic conditions.

The past works on C-V2X that focused on reducing collision of CAM messages used the concept of reselection lookahead counters [13]. Additional RC information has been added in SCI, thus letting other vehicles know till what time it would be using that resource. In [11], Jianhua et al. segregated subchannels into control channels and data channels for transmission of control packets and data packets, respectively. A vehicle informs other vehicles of its packet transmission intervals in advance by sending Scheduling Assignment (SA) packets in the control subchannel prior to sending data packets in the data subchannel. Also, the SA packets, which carry scheduling information, are piggybacked with the last data packet sent so that the other vehicles can schedule their packets without collision.

Compared to these prior works, in this work, we propose a performance enhancement of SPS for EVW use case in highly congested scenarios. To the best of our knowledge, this is the first work which brings in the concept of improving the performance of emergency vehicles by causing minimal effect on other vehicles in the network. Most of the works defined vehicle congestion to have a density of nearly 80 vehicles/km [10] to 200 vehicles/km [11] emulating a typical traffic congestion in physical world. However, we consider a network congestion scenario in the time-frequency resource grid in semi-urban scenario. Such a situation can arise not only due to road traffic congestion but also in the limited availability of channel resources under policy constraints where the use of bandwidth is restricted. Our simulations have been carried out on a network scenario where one channel resource is available for every three vehicles with a vehicle density of 500 vehicles/km per lane.

4 PROPOSED WORK

This section presents our proposed enhancements to SPS scheme in order to support EVW use case in highly congested scenarios. We first present P-SPS and then introduce novel schemes (PCM and IGR) on top of P-SPS for further reducing collisions and thereby boosting up the performance of HP vehicles while giving LP vehicles fair chance.

4.1 System Model

Here we consider a sub-urban scenario where the vehicles are in close proximity to each other (i.e., a single collision domain in the context of V2X communications) and running from East to West on multiple lanes. The vehicles have variable speed within a lower range for LP vehicles and a higher range for HP vehicles. All of HP and LP vehicles transmit CAM messages at certain intervals given by RRI, to exchange location information using 5G NR V2V technology. All the vehicles are within the awareness range of each other, thus enabling single-hop communication for all vehicles. Since the vehicles are in a single collision domain, the scenario gets more congested and one time-frequency resource – CSSR – can be used by only one vehicle at any instant of time. Emergency vehicles like ambulance, fire brigade, and other HP vehicles find it difficult to transmit data with high reliability in such a congested scenario, making the realization of EVW use case very challenging. EVW use case allows an active emergency (HP) vehicle to indicate its presence through CAM packets with a periodicity of 100ms to its nearby vehicles. This is also an active safety use case as it helps in reducing the risk of collision between the emergency vehicle and nearby vehicles sharing the same road segment. Our work assists the emergency (HP) vehicles in transmitting their CAMs with higher PRR so that most of the other (LP) vehicles receive these packets and make an informed decision to give way to the HP vehicles.

4.2 P-SPS

The objective of P-SPS is to guarantee that packets transmitted by emergency vehicles (HP) are received by all of its neighboring vehicles. During the resource selection phase, when there is a shortage of resources (CSSRs) to such an extent that the vehicles cannot even obtain the top 20% of single-subframe resources in List-A, P-SPS ensures that the HP vehicle has at least one slot in its List-B. Thus even in severe traffic congestion scenarios, the emergency vehicle can manage to transmit CAM packets. In the worst case, the emergency vehicle would transmit choosing a channel resource which is already in use by some neighboring vehicle(s). To reduce the time streak of collided packet transmissions and to increase the probability of getting a free resource by the HP vehicle, we segregate RC ranges of HP and LP vehicles in the network. The LP vehicles get a smaller value of RC from the range [5-10] and the HP vehicles get higher RC value from the range [10-15]. This ensures even though a HP vehicle forcefully acquires an already occupied resource of some LP vehicle(s), initially there would be collisions, but the LP vehicle finishes its RC soon and has to perform SPS again by sensing the channel. Meanwhile the HP vehicle can now continue transmitting in the same resource until the RC expires. Fig. 2 shows that $vehicle_A$ (LP vehicle) is transmitting and a HP vehicle enters the road segment with no free resources left for transmitting its CAMs. The HP vehicle starts transmitting its CAMs in the same slot at a RRI of 100ms and faces collisions indicated through solid hashes. The LP vehicle ($vehicle_A$) finishes off soon due to lower value of RC and then the HP vehicle takes over the resource and transmits without any collision as indicated by lighter hashes. In this way, the proposed P-SPS scheme ensures that CAMs of the emergency vehicle are treated with immediate resource allocation.

4.3 SPS with PCM Scheme

The uncertainty of which channel resource the vehicle would select/re-select after the expiry of RC causes the legacy SPS to lose its effectiveness due to too many collisions in highly congested scenarios. When two or more vehicles sense the wireless medium simultaneously, they find the same chosen resource as free and end up transmitting their packets using the same resource. The condition worsens in congestion scenarios like intersections, which are high collision-prone locations due to presence of many vehicles in the same collision domain. There are a lesser number of free single-subframe resources and more vehicles competing to acquire channel resources for their transmissions. Reducing collisions can help us achieve better improvement in Key Performance Indicators (KPIs) like PRR and PIR irrespective of the nature of the vehicle i.e., whether it is a HP or a LP vehicle. To minimize the potential risk of collisions, we propose PCM scheme where a vehicle, after randomly selecting a CSSR from List-B for its packet transmissions, first transmits a single packet after which it can only transmit its packets with a probability P_{Tx}. Fig. 3 shows an example where three vehicles are simultaneously sensing the wireless medium and find it empty. Using the PCM scheme, after sending the first packet, these three vehicles have to decide whether to transmit or not, defined by P_{Tx}. This reduces the chances of colliding despite choosing the same resource. The vehicles which refrained from sending their subsequent CAM packets go back to performing SPS again and therefore improve the sensing knowledge of all the vehicles in the network.

4.4 P-SPS with PCM and IGR Schemes

Intelligent Grant Removal in P-SPS: A drawback of P-SPS is letting a HP vehicle forcefully acquire the CSSR that is already being used by a LP vehicle, letting their packets collide over air and then patiently waiting for the LP vehicle to finish off on account of usage of lower RC range. IGR scheme intelligently creates the grant list containing future transmissible slots by skipping some probable collision prone slots. Considering the worst-case common collision region of 9 slots, as shown in Fig. 4, we can make the HP vehicle skip nine single-subframe resources and then transmit its CAM packets from the tenth slot on wards till its RC expires. This would avoid unnecessary initial collisions between the HP and LP vehicles.

To this, we add the PCM scheme to minimize collision risk when two vehicles sense the channel simultaneously and find it as empty. We have assigned a lower probability of transmission (P_{Tx}) for HP vehicle than LP vehicle(s) in the network. Lower P_{Tx} causes the HP vehicle to perform sensing more frequently and thus have more improved knowledge about channel usage by other vehicles. When it finds a free channel resource, it occupies it and transmits for a longer duration as it has a higher range of RC than that of LP vehicles. Though the LP vehicles have higher P_{Tx}, the lower value of RC causes it to finish off their transmissions quickly. The whole process is presented through a flowchart in Fig. 1.

5 SIMULATION SETUP

The proposed enhancements to the legacy SPS scheme are implemented on the NR V2X Mode 2 module of NS-3 [**?**]. The emergency vehicle use case in the suburban region is a single-hop scenario where all the vehicles are within an awareness range of 200m as shown in Fig. 5. We have taken 15 vehicles in 3 lanes, with 5 vehicles per lane. Vehicles are placed with 2m of inter-vehicular distance. We have considered only one HP vehicle and rest of them are LP vehicles. The speed of HP (emergency) vehicle is in the range of 23-27m/s, and the speeds of LP vehicles are set in the range of 20-25m/s. The emergency vehicle enters the already congested scenario by joining as the last vehicle in the middle lane. All the vehicles are broadcasting CAM messages of 300 bytes with a periodicity of 100ms. Table 1 shows various simulation parameters. The condition of extreme vehicular congestion has been emulated by varying the number of channel resources (CSSRs) available as compared to the number of vehicles present in the single collision domain. Resource Availability Ratio (RAR) is given by:

$$RAR = \frac{Number\ of Resources\ Available}{Total\ Number\ of\ Vehicles} \tag{1}$$

The number of available channel resources (CSSRs) is varied incrementally from 5 till 15 by changing bitmap pattern of SL as given in Table 1.

5.1 Key Performance Indicators

To study the performance of the proposed schemes, we have used the following performance metrics.

(1) Packet Reception Rate (PRR): It is defined as the ratio of number of vehicles which successfully received the CAM packets of a target vehicle to the total number of neighbouring vehicles in its vicinity of 200m. PRR of a $vehicle_i$ is calculated by averaging the individual ratios for its transmitted CAM packets during the simulation time.

$$PRR_i = \frac{\sum_{j=1}^{M} \frac{No.\ of\ Vehicles\ Successfully\ Received\ CAMs}{Total\ Number\ of\ Neighbors\ of\ Vehicle_i}}{M} \tag{2}$$

where M is the total number of CAM messages transmitted by $vehicle_i$, $1 \leq j \leq M$.

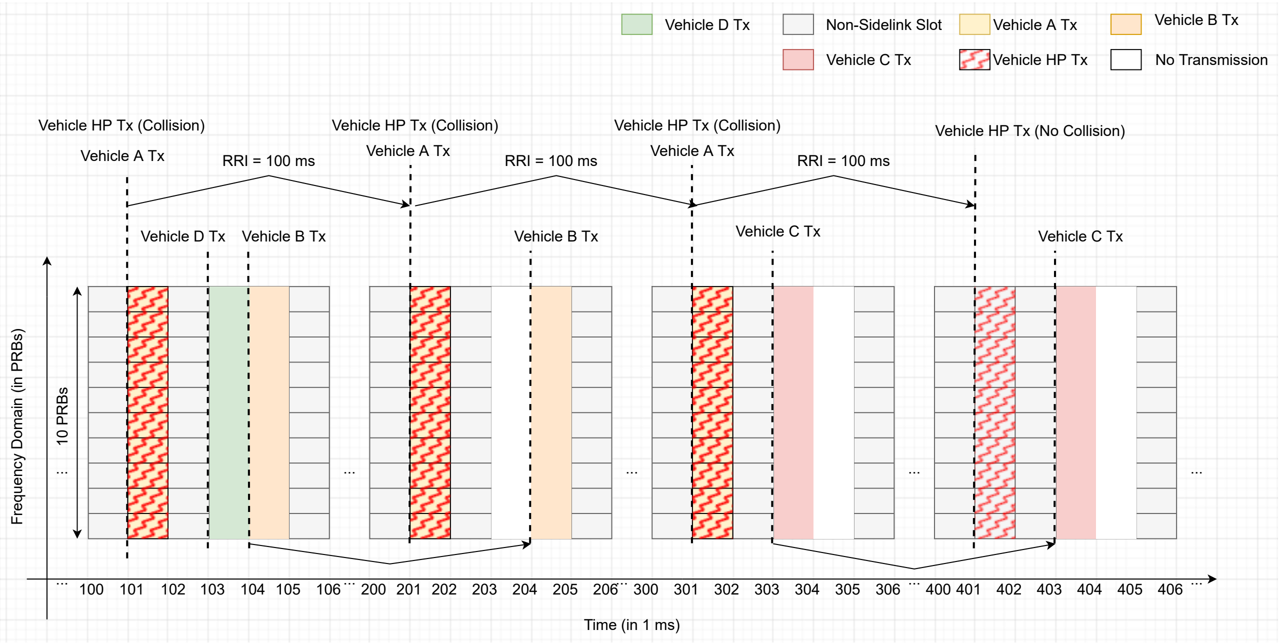

Figure 2: An example illustrating Priority based Semi-Persistent Scheduling (P-SPS) Scheme.

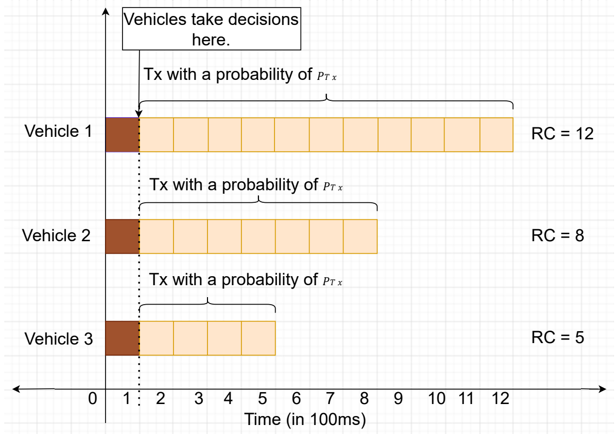

Figure 3: An example illustrating the collision minimization process of PCM.

(2) Packet Inter-Reception (PIR): It is the time gap between two consecutive successful CAM packet receptions at the neighboring vehicle from a given target vehicle.

6 PERFORMANCE RESULTS

In this section, we present the performance results of P-SPS, the collision mitigation schemes (PCM and IGR) and a comparative study among them. Experiments are performed by varying RAR to emulate different traffic congestion levels in a single-hop 5G NR V2V network.

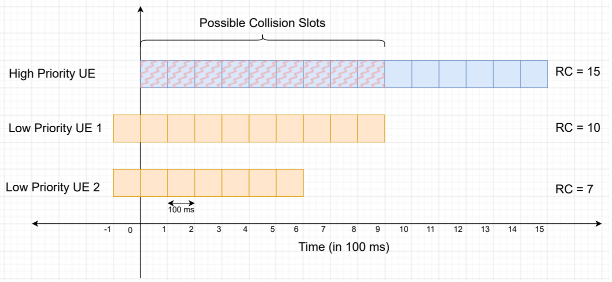

Figure 4: An example illustrating Intelligent Grant Removal (IGR) in P-SPS.

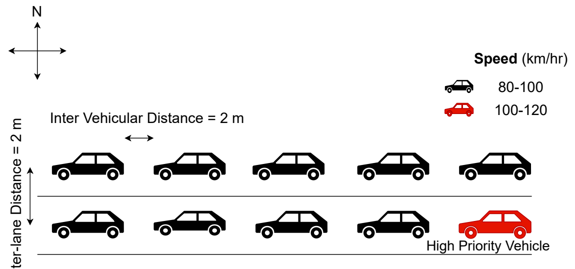

Figure 5: Vehicular scenario: Sub-urban Highway.

6.1 Evaluation of P-SPS Scheme

In the first set of experiments, we compare the performance of the HP (emergency) vehicle in terms of PRR in P-SPS against legacy

Table 1: Simulation Parameters

<table>
<tr><th>Parameter</th><th colspan="2">Value</th></tr>
<tr><td>Deployment</td><td colspan="2">3 Lanes and 5 Vehicles Per Lane</td></tr>
<tr><td>Vehicle Speed</td><td colspan="2">HP = [80 - 120] km/hr
LP = [100 - 120] km/hr</td></tr>
<tr><td>Simulation Time</td><td colspan="2">20 seconds</td></tr>
<tr><td>No. of Simulation Runs</td><td colspan="2">100</td></tr>
<tr><td>Packet Size</td><td colspan="2">300 Bytes</td></tr>
<tr><td>Data Rate</td><td colspan="2">24 Kbps</td></tr>
<tr><td>Packet Generation Frequency</td><td colspan="2">10 Hz</td></tr>
<tr><td>Resource Counter</td><td colspan="2">HP = [10,15]
LP = [5,10]</td></tr>
<tr><td>Probability of Transmission</td><td colspan="2">For P-SPS+PCM+IGR:
HP = 0.3
LP = 0.6</td></tr>
<tr><td>Selection Window Size</td><td colspan="2">32 slots
T1 = 2 seconds
T2 = 33 seconds</td></tr>
<tr><td>TDD Pattern</td><td colspan="2">DL|DL|DL|DL|F|UL|UL|UL|UL|UL</td></tr>
<tr><td rowspan="12">SL Bitmap</td><td>Number of Time Slots for Sidelink</td><td>BitMap</td></tr>
<tr><td>5</td><td>1|1|0|0|0|0|0|0|0|1</td></tr>
<tr><td>6</td><td>1|1|0|0|0|0|0|0|1|1</td></tr>
<tr><td>7</td><td>1|1|0|0|0|0|0|1|1|1</td></tr>
<tr><td>8</td><td>1|1|1|0|0|0|0|0|1|1</td></tr>
<tr><td>9</td><td>1|1|1|0|0|0|0|1|1|1</td></tr>
<tr><td>10</td><td>1|1|1|1|0|0|0|0|1|1</td></tr>
<tr><td>11</td><td>1|1|1|1|0|0|0|1|1|1</td></tr>
<tr><td>12</td><td>1|1|1|1|1|0|0|0|1|1</td></tr>
<tr><td>13</td><td>1|1|1|1|1|0|0|1|1|1</td></tr>
<tr><td>14</td><td>1|1|1|1|1|1|0|1|1|1</td></tr>
<tr><td>15</td><td>1|1|1|1|1|1|1|1|1|1</td></tr>
<tr><td>Frame Structure</td><td colspan="2">μ = 0 (SCS = 15 kHz)</td></tr>
<tr><td>MCS</td><td colspan="2">14</td></tr>
<tr><td>RSRP Threshold</td><td colspan="2">Min= -128 dBm
Max = -80 dBm</td></tr>
<tr><td>Radio Reservation Interval</td><td colspan="2">100 ms</td></tr>
<tr><td>Carrier Frequency</td><td colspan="2">5.89 GHz</td></tr>
<tr><td>Channel bandwidth</td><td colspan="2">2 MHz</td></tr>
<tr><td>Number of subchannels</td><td colspan="2">1</td></tr>
<tr><td>Subchannel Size</td><td colspan="2">10 RBs</td></tr>
</table>

SPS at different congestion levels by varying RAR. It is to be noted that number of vehicles is fixed at 15 (one HP vehicle and 14 LP vehicles) but the number of available CSSRs is varied from 5 to 15 to emulate different congestion levels for channel resources in the network. As shown in Fig. 6 when RAR is 5/15 (= 1/3) i.e., all the 15 vehicles are competing for merely five resources - a case of acute traffic congestion, the HP vehicle in P-SPS manages to get a PRR of 65.7%. This is about 6% rise in PRR than that of legacy SPS. P-SPS ensures the HP vehicle is always able to transmit its CAM packets by forcefully acquiring a CSSR that is currently being utilized by one of the LP vehicles present in the single collision domain. We achieve this increase in PRR at the expense of LP vehicles whose PRR is affected as shown in Fig. 6. The decrease in PRR of LP vehicles by 5.4% is still justifiable over the fact that CAM messages broadcasted by the emergency vehicle are of great importance. When RAR is 6/15 (= 2/5), there is 2.4% improvement in PRR of the HP vehicle. The difference in PRR gradually decreases and becomes almost same of LP vehicles as contentions for channel resources decrease.

The same experiment has been repeated by keeping 30 vehicles in a single collision domain. We have got a similar trend as shown in Fig. 7. As long as the RAR is maintained, indicating the level of congestion, with respect to the number of resources available and number of vehicles, we obtain similar PRR trend for the HP and LP vehicles. Fig. 8 shows the variation of PRR w.r.t. RAR where there are 2 HP vehicles and 28 LP vehicles. Here also we see that the HP vehicles have attained higher PRR when compared to PRR of vehicles using the legacy SPS.

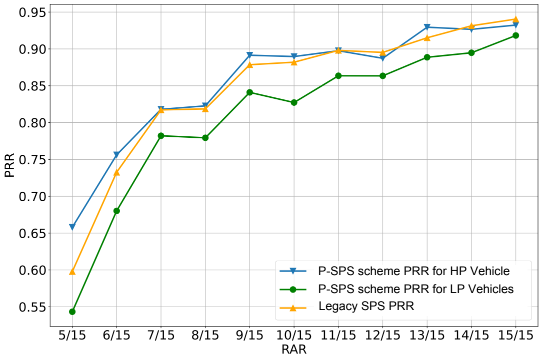

Figure 6: Variation in PRR vs RAR for P-SPS and Legacy SPS schemes in sub-urban scenario.

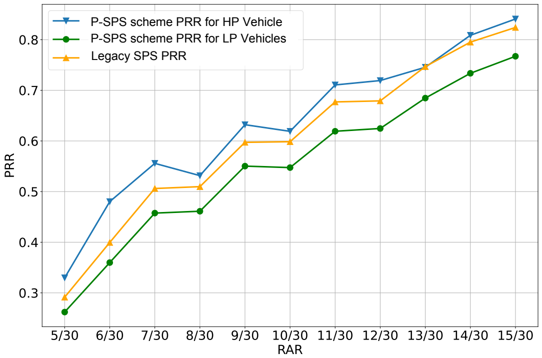

Figure 7: Variation in PRR vs RAR for P-SPS and Legacy SPS schemes in sub-urban scenario for 30 Vehicles.

6.2 Evaluation of legacy SPS with PCM scheme

Our second set of experiments involves applying PCM scheme to improve the performance of legacy SPS by reducing number of collisions in highly congested scenarios. Here we report PRR and PIR

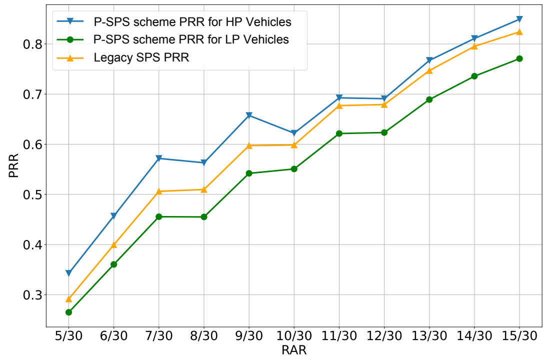

Figure 8: Variation in PRR vs RAR for P-SPS and Legacy SPS schemes in sub-urban scenario for 2 HP vehicles.

metrics as we vary the probability of transmission from $P_{Tx}(0.01)$ to $P_{Tx}(1)$ by keeping RAR fixed at 5/15. The case of $P_{Tx}(1)$ depicts the legacy SPS. Even when multiple vehicles select the same channel resource, by varying P_{Tx}, the proposed PCM scheme controls the chances of a vehicle transmitting in the chosen channel resource. The lesser the value of P_{Tx}, the chances of collision are highly reduced. As shown in Fig. 9, $P_{Tx}(0.01)$ gives the highest PRR of 77% - an increase of 22.7% against the legacy SPS. As expected, this gain comes at the cost of PIR, which is increased by 25ms due to increased delays in packet reception. Hence, there is a tradeoff between these performance measures. To balance these two metrics, $P_{Tx}(0.1)$ is observed to be the sweet spot for transmissions, where we have a significant gain of 23.7% increase in PRR and 64ms decrease in PIR as compared to the legacy SPS in Fig. 9.

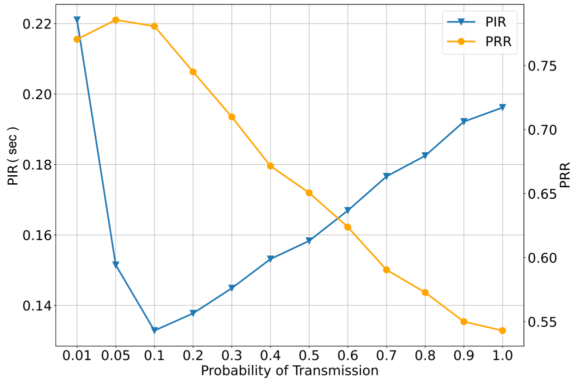

Figure 9: Variation in PRR and PIR vs P_{Tx} for legacy SPS with PCM scheme when RAR is $1/3$.

6.3 Evaluation of P-SPS with PCM and IGR schemes

Having observed appreciable performance improvement in pairing the proposed PCM scheme with the legacy SPS, we apply it to P-SPS along with IGR for further shortening the duration of collision streak between HP and LP vehicles present in the single collision domain. When the HP vehicle having no channel resources transmits in one of the channel resources that is being utilized by a LP vehicle, the proposed IGR scheme predictively skips probable transmission slots to be used by the LP vehicle since it chooses its RC value from a relatively higher range of RC values. This enhances performance further by reducing collisions. The value of P_{Tx} controls how often a vehicle will relinquish its chosen channel resource. As soon as a vehicle relinquishes its resources, P-SPS is performed to sense the packets which are being transmitted by its neighbouring vehicles. The more a vehicle senses the channel the more it gets knowledge of its occupancy level. Thus we take $P_{Tx}(0.3)$ for the HP vehicle and $P_{Tx}(0.6)$ for the LP vehicles, so that the HP vehicle gets better knowledge of the channel compared to the LP vehicles. The results are best at these values of P_{Tx}. Choosing lesser P_{Tx} for the HP vehicle ensures higher PRR with minimal compromise to PIR as in the case of $P_{Tx}(0.01)$. The chosen P_{Tx} for the LP vehicles takes care of the performance of the LP vehicles such that their performance is nearly unaffected as compared to the legacy SPS.

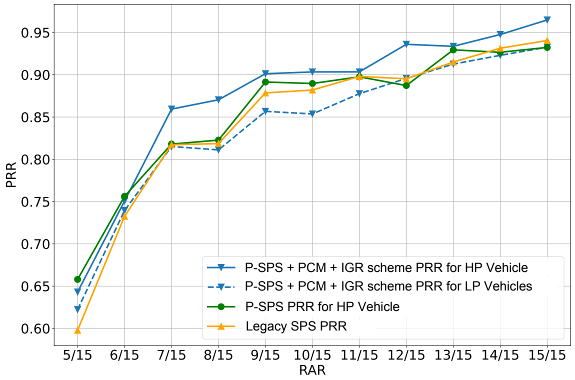

Figure 10: Variation in PRR vs RAR for P-SPS+PCM+IGR, P-SPS for HP vehicle as to Legacy SPS.

Fig. 10 shows the variation in PRR for different RAR values for P-SPS+PCM+IGR schemes and the legacy SPS. As shown in the figure, in extreme resource scarcity case of RAR being 5/15, the HP vehicle has an increase in PRR by 4.6% compared to the legacy SPS i.e., lesser improvement than that in P-SPS. However, the LP vehicles get a boost in PRR by 2.5%. So, the performance of both HP and LP vehicles has improved against the legacy SPS. When RAR is set to more than half, an improvement of 2% in PRR is maintained by the HP vehicles whereas the LP vehicles perform almost same as the vehicles in the legacy SPS. However, when there are ample resources available for all the vehicles (i.e., RAR > 1), we can switch over to the legacy SPS. A significant improvement is observed in PIR metric, which has been reduced for the HP vehicle while it is comparable for the LP vehicles as shown in Fig. 11 as compared to PIR of Legacy SPS. Thus the LP vehicles in P-SPS with PCM and IGR schemes do not suffer from any performance degradation.

6.4 Comparative study between legacy SPS and proposed SPS enhancements

We categorize the results shown in Fig. 10 based on similar behavior into two categories: when RAR(%) is less than 40% and when it is greater than 40%. When it is less than 40%, the differences in the PRR

Table 2: Performance of P-SPS and P-SPS+PCM+IGR schemes w.r.t. Legacy SPS

RAR %	SPS scheme	HP Vehicle		LP Vehicle	
		Avg. PRR	Avg. PIR	Avg. PRR	Avg. PIR
≤ 40%	P-SPS	70.7% (+4.2%)	143 ms (-14 ms)	61.17% (-5.33%)	173ms (+16 ms)
	P-SPS + PCM + IGR	69.68% (+3.2%)	156 (-1 ms)	68.09% (+1.5%)	152 ms (-4 ms)
>40%	P-SPS	88.83% (+0.22%)	113 (-0.5 ms)	85.09% (-3.5%)	118 ms (+5 ms)
	P-SPS + PCM + IGR	91.33 % (+2.7%)	109 ms (-4 ms)	87.53 % (-1%)	115 ms (+1 ms)

are significant between the proposed schemes and the legacy SPS. As RAR increases, the differences almost vanish. Table 2 summarizes the performance results of P-SPS and P-SPS paired with PCM and IGR schemes. Further, it also shows how these results are better (green for improvement in PRR/PIR) or worse (red for deterioration) w.r.t. to the legacy SPS scheme. The HP vehicle in P-SPS performs best when RAR<=40% with an increase of about 4.2% in PRR and a decrease of about 14ms in PIR. However, at the same time, the performance of LP vehicles is negatively affected. P-SPS with PCM and IGR schemes achieves an overall improvement over the legacy SPS by treating all the vehicles fairly. When the congestion level (RAR) goes beyond 40%, P-SPS with PCM and IGR schemes has a clear-cut edge over other schemes.

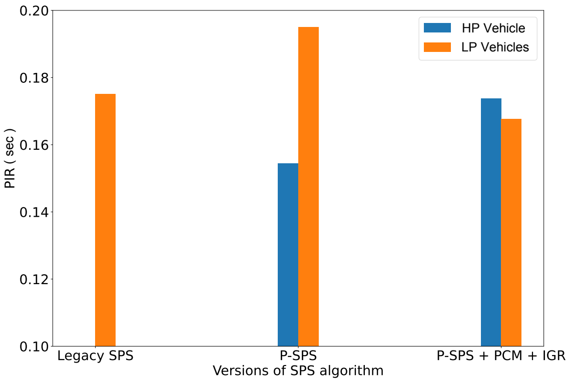

Figure 11: Comparison of P-SPS+PCM+IGR, P-SPS, and legacy SPS schemes in terms of PIR where RAR is kept as 5/15.

Fig. 11 shows PIR of HP and LP vehicles for different schemes when RAR is 5/15. The HP vehicle has the least PIR in P-SPS. The LP vehicles are deprived of free channel resources in highly congested scenarios and therefore suffer from higher PIR than the legacy SPS. This issue is mitigated by employing P-SPS in conjunction with PCM and IGR schemes. Here PIR of LP and HP vehicles is reduced compared to the legacy SPS and they are treated fairly. Thus P-SPS+PCM+IGR performs the best of both schemes.

7 CONCLUSIONS AND FUTURE DIRECTIONS

This paper studied the problem of offering improved 5G NR V2X communication services for emergency vehicles in highly congested scenarios. Through consecutive enhancements over the legacy SPS, we reported PRR rise of 3.2% for the HP vehicle and rise of 1.5% for the LP vehicles in extreme congestion scenario and of 2.7% rise in PRR for the HP vehicles as the congestion wanes out. The LP vehicles are treated fairly and are negligibly affected when the proposed enhancements to SPS are employed to improve the performance of emergency vehicles.

Future extensions to this work could include developing an analytical model for the proposed collision reduction schemes – PCM and IGR – to accurately incorporate the optimal probability of transmission (P_{Tx}) value as a function of RAR. Also, disseminating the RC information of LP vehicles in IGR scheme can help the HP vehicle know the exact number of channel resources to skip in the grant list.

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