Performance Enhancement of C-V2X Mode 4 with Balanced Resource Allocation

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Abstract — **Cellular vehicles-to-everything (C-V2X) is an essential technology to enhance road safety, traffic management and smart mobility. C-V2X Mode 4 uses sensing based semi-persistent scheduling (SB-SPS) to mitigate packet collisions, that consists of several mechanisms (i.e., random selection of resources, probabilistic reselection, and monitoring resource utilization pattern). The packet collision probability, however, is still non-negligible, and the CAM (cooperative awareness message) delivery ratio (CDR) is far from target requirements for high reliability and low latency applications. Especially, when the number of vehicles increases beyond 300, the packet collision probability increases in the environment of congested metropolitan area. In this paper, we analyze the performance of C-V2X Mode 4 in congested metropolitan areas, and propose a balanced resource allocation scheme that is providing a remarkable enhanced performance, considering the half-duplex communication mechanism in C-V2X Mode 4. The proposed method allocates resources in distributed manner with balanced usage of subframes, instead of random selection of resources in resource map, to mitigate CAM packet losses by half-duplex communications. From the performance analysis with simulation, we confirmed that the proposed scheme provided 97% of CDR for 500 vehicles, while the existing scheme provided only 87% for the same condition.**

Keywords—C-V2X, Mode 4, Sensing-based Semi–persistent scheduling (SB-SPS), half-duplex, resource allocation, cognitive collision resolution

I. Introduction

Since periodic high-reliable basic safety message (BSM) delivery among vehicles is essential for smart transportation and autonomous driving, international organizations have contributed to specify standards for vehicular communications, such as IEEE, ETSI, and ARIB [1] [2] [3]. The 3rd generation partnership project (3GPP) has also standardized specifications for vehicular communications, named cellular vehicles-to-everything (C-V2X) [4]. The goal of C-V2X is to prevent collisions on the road and to provide adequate traffic control, information sharing is allowed between vehicle-to-vehicle (V2V), vehicle-to-network (V2N), vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P).

The major challenges in vehicular communications for autonomous driving on smart roads are low-latency and high-reliability. For the realization of vehicular communications, 3GPP introduced two modes (Mode 3 and Mode 4) in Release 14 (Rel 14) by extending the functionalities of proximity services (ProSe). In Mode 3, the base station (eNB) performs centralized resource allocations for the vehicles in its coverage range, whereas vehicles select resources individually in distributed manner and broadcast in Mode 4 [5]. These two modes are especially designed to accommodate the requirements of high reliability and low latency, and both Mode 3 and Mode 4 can be utilized together. For more productive results, Mode 4 is used at out-of-coverage area while Mode 3 is used at in-coverage area; therefore, Mode 4 is considered as a default mode.

In C-V2X Mode 4, vehicles use sensing-based semi persistent scheduling (SB-SPS) for resource allocation [6], where every vehicles select resources autonomously in a specific interval of time (every second). The main problem is that vehicles do not have any information of the selected resource to be used by other vehicles in the next packet run. Therefore, multiple vehicles may accidently use the same resource for CAM (cooperative awareness message) broadcasting that results in collision and decreases the performance of SB-SPS. Therefore, in the selection process of resources, vehicles must estimate about the resources selected by other vehicles to avoid such collisions.

Although sensing components help to reduce collision probability in SB-SPS, the random selection of resources without shared knowledge of other vehicles leads to increased collision probability. Due to the semi-persistent nature of resource allocation in SB-SPS, collision continues for a streak of CAM broadcasting once it happens, which highly affects the CDR(CAM Delivery Ratio) performance degradation [7].

In this paper, we propose a balanced resource allocation scheme, which depends upon balanced subframe usages to mitigate the CAM loses from half-duplex communications in congested metropolitan areas. It analyzes that the resource allocation in distributed manner enhances the performance in comparision of the random selection of resources. We prove it by simultaion results that performance can be enhanced by the proposed balanced allocation of resources.

The main contributions of this paper are (i) balanced usage of subframes to mininmize CAM delivery failure because of half-duplex, (ii) notifying candidate resource allocation information with other vehicles, which helps to avoid collision by choosing the same reosurce, and (iii) avoidance of consecutive collisions with prioritization with reselection couter (RC) value. Simulation results show the efficacy of the proposed algorithm in terms of CDR(CAM Delivery Ratio) and PRR(Packet Reception Ratio).

The rest of this paper is organised as follows. Section II briefly explains the related work including the default mechanism of SB-SPS and some approaches to enhance the performance of the SB-SPS. It also includes some schemes that are relevant to our proposal. Section III presents the distributed resource allocation with balanced usage of subframes, and collision resolution mechanism to avoid collision and enhance the CDR performance. In section IV, simulation results are presented and analyzed using the ns-3 C-V2X simulator with proposed modifications. Finally, section V concludes the paper.

II. Related Work

A. Sensing-Based Semi-Persistent Scheduling (SB-SPS)

In C-V2X Mode 4, the SB-SPS is used in resource scheduling for the autonomous selection of resources [8]. The selected subchannel in frequency domain may be reused for a series of consecutive transmissions in SB-SPS. The reservation of subchannels per subframe is fully dependent upon the transmission data size.

Figure 1 indicates the default mechanism of SB-SPS. After sensing the resources (yellow) in previous 1000 ms sensing window, vehicles select the resources at time T, for their next packet transmissions. From the list of resources that are free to use or predicted to be not used in future, the resources are selected (green), in the selection window $(T_1 \sim T_2)$. The lower bound $(T_1 \leq 4)$ depends upon vehicular user equipment (V-UE) configuration, and the upper bound of the selection window $(20 \leq T_2 \leq 100)$ defines the packet inter-reception (PIR)'s maximum time. If all resources are busy (red) then vehicle selects the resource of less RSRP (reference signal received power).

After the resource selection in specific time interval of resource reservation interval (RRI), vehicle periodically transmits CAM, and uses the same resource until reselection counter (RC)$(5\ to\ 15)$ reaches to 0. The same resource may be used with the resource reselection probability (RRP)$(0.0\ to\ 0.8)$. Otherwise, vehicle selects new resource again based on the information of selection window.

B. Enhancements of SB-SPS

Safety related applications mainly focused in 3GPP Release 14, while 5G New Radio (NR)-based V2X advances the feature of LTE-V2X in Release 15 and 16 [7]. Resource allocation and management is an active research topic. The performance of SB-SPS has been extensively studied in the literature. Two important observations made by Molina-Masegosa et al. in [9] are following: i) collision dominates errors in safety-critical range, and ii) transmitter and receiver distance is inversely proportional to the merit of SB-SPS resource selection. However, they did not provide good solution to solve the problem. Molina-Masegosa et al. [10] discuss the SB-SPS parameters impact on performance, and it shows that for best PDR (packet delivery ratio), the RRP can be adjusted according to the traffic load. Bazzi et al. [8] also discuss the impact of RRP on performance in a related study where the resources are filtered out based on RSRP.

He at al. [11] showed that the packet collision is controlled by separating the control and corresponding data payload by letting them carry the information about reservation in chained manner. However, the proposed scheme reserve resources only for subsequent control and data payload like SB-SPS. It requires data channel to carry information, which leads cross layer processing. Bonjorn et al. [12] proposed to resolve the packet collision by forcefully changing the RC value in the last RRI to avoid resource overlapping, and broadcasting the RC information to other vehicles. However, it is difficult to change the RC value in congested scenarios because of the limited RC values.

Jeon et al. [13] proposed to immediately broadcast the resource location information before reselection of resources, while Jeon et al. [7] proposed to broadcast the location information of reserved resource one second before of the actual usage of the resources. However, the schemes in [7] and [13] do not resolve the collisions by newly joining vehicles which are not aware of the reservation of ongoing vehicles, moreover their schemes waste the resources due to the passing vehicles in opposite lane.

In our previous research [14], we proposed cognitive collision resolution mechanism to resolve the performance issue in SB-SPS and consider half-duplex problem as the future work. The proposed scheme provides sharing of location information of candidate resource by broadcasting in

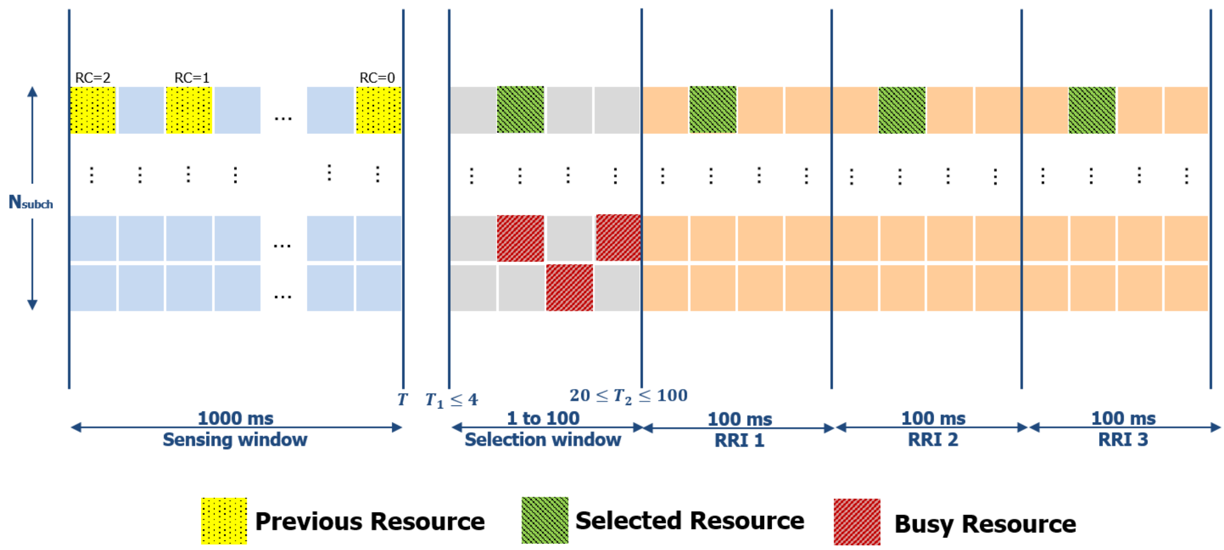


Figure 1: Sensing-Based Semi Persistent Scheduling (SB-SPS)

Figure 2: Half-Duplex Problem

half of the current packet run and the RC value of current packet run to mitigate collisions. Moreover, to avoid half-duplex problem, the usage of sub-frames are balanced according to their current usages. In such manner, the problem of resource wastage and collisions by newly joining vehicle can be avoided, and high reliability requirements can be fulfilled.

III. Balanced Resource Allocation Scheme in Semi-Persistent Scheduling

In this section, we explain the details of balanced resource allocation scheme. The main goal is to mitigate the collisions by half-duplex with following steps:

- Balance the usage of the subframes and candidate resources for the next packet run.
- Share the information of candidate resource in advance with other vehicles and RC value of current packet run.
- Avoid consecutive collisions with adjusted RRP.

A. Mitigation of collsions by half-duplex communications in C-V2X

In the default mechanism of SB-SPS, in the first 1000 ms of sensing window vehicles sense resources, and then each vehicle individually selects resources randomly, which causes decreased performance especially in congested scenarios due to autonomous resource selection without having the information of the selected resources by other vehicles. Although, the sensing helps to avoid collision, the collision level is still not negligible compared to the desired performance. Due to the half-duplex communication in C-V2X, vehicles that transmit CAM in the a subframe cannot receive CAM from other vehicles in the same subframe, and this half-duplex communication causes high collision in C-

Algorithm 1: Candidate Resource Selection

Procedure Select Candidate Resource (RRI, N_{SCh})
  While True **do**
    Update_Sensing_Window ($txSCh$, $txSFr$, $txFr$)
    $Cand\_r \leftarrow$ list of top 20% free candidate resources after balancing the subframes
    $Cand\_rtxSCh \leftarrow random(1, N_{subCh})$
    $Cand\_rtxSFr \leftarrow random(1, RRI)$
  End while
End procedure

Algorithm 2: Resource Allocation algorithm

Procedure R.A (RRI, C_1, C_2, N_{SCh}, PRR)
// Initialize SPS parameters
  $txSCh \leftarrow random(1, N_{subCh})$
  $txSFr \leftarrow random(1, RRI)$
  $RC \leftarrow random(C_1, C_2)$
  $RCthreshold \leftarrow RC/2$
  $T \leftarrow 0$ // Current time
  while True **do**
    if $T \equiv txSFr$ **then**
      $txPkt(txSCh)$ // Transmit a packet
      if $RC > 0$ **then**
        $txSFr \leftarrow txSFr + RRI$
        $RC \leftarrow RC - 1$
        if $RC \equiv RCthreshold$ **then**
          Update_Candidate_Sensing_Window ($Cand\_rtxSCh, Cand\_rtxSFr$, $Cand\_rtxFr$)
          Collision_Resolution(RC, N_{SCh}, $txSFr, RRI, C_1$, C_2, N_V, V)
          if $RC \equiv 0$
            $RC_{V_{ID}} \leftarrow Cand\_rRC$
            $txSCh_{V_{ID}} \leftarrow CrtxSCh$
            $txSFr_{V_{ID}} \leftarrow CrtxSFr$
            if $random(0, 1) < PRR$ **then**
              $Cand\_rtxSFr \leftarrow txSFr + RRI \times (RC + 1)$
              $Cand\_rtxSCh \leftarrow txSCh$
            else
              Candidate_Resource_Selection(RRI, N_{SCh})
      else
        Update_Sensing_Window($txsbCh$, $txSFr$, $txFr$)
    $T \leftarrow T + 1$ // Push time
  End while
End Procedure

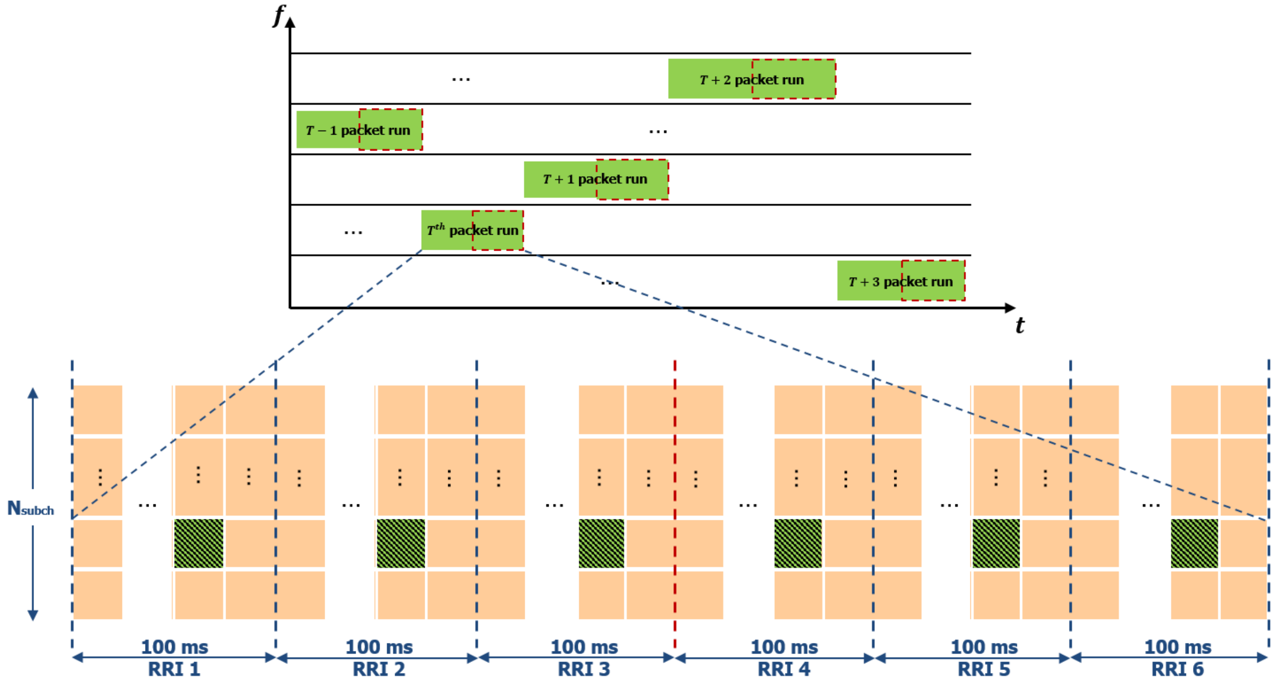


Figure 3: Broadcasting Candidate Resource Information

Algorithm 3: Collision Resolving algorithm

Procedure Collision Resolving ($RC, N_{SCh}, txSFr, RRI, C_1, C_2, N_V, V$)
  $Cand\_rtxSCh \leftarrow random(1, N_{SCh})$
  $Cand_{rtxSFr} \leftarrow txSFr + RRI + RC + random(1, RRI)$
  $Cand\_rRC \leftarrow random(C_1, C_2)$
  while True **do**
    for $(V_{ID1} \leftarrow 0; V_{ID1} < N_V; V_{ID1}++)$ **do**
      $txSCh_1 \leftarrow V[V_{ID1}].txSCh$
      $txSFr_1 \leftarrow V[V_{ID1}].txSFr$
      $Cand\_rtxSCh_1 \leftarrow V[V_{ID1}].Cand\_rtxSCh$
      $Cand\_rtxSFr_1 \leftarrow Veh[V_{ID1}].Cand\_rtxSFr$
      $RC_1 \leftarrow V[V_{ID1}].RC$
      for $(V_{ID2} \leftarrow 0; V_{ID2} < N_V; V_{ID2}++)$ **do**
        if $(V_{ID1} \equiv V_{ID2})$ **then**
          Continue
        $txSCh_2 \leftarrow V[V_{ID2}].txSCh$
        $txSFr_2 \leftarrow V[V_{ID2}].txSFr$
        $Cand\_rtxSCh_2 \leftarrow V[V_{ID2}].Cand\_rtxSCh$
        $Cand\_rtxSFr_1 \leftarrow V[V_{ID1}].Cand\_rtxSFr$
        $RC_2 \leftarrow V[V_{ID2}].RC$
        if $Cand\_rtxSCh_1 \equiv Cand\_rtxSCh_2$ **and** $Cand\_rtxSFr_1 \equiv Cand\_rtxSFr_2$ **then**
          if $RC_1 < RC_2$ **then**
            $RC_1 \leftarrow CrRC$
            $txSCh_1 \leftarrow Cand\_rtxSCh$
            $txSubFr_1 \leftarrow Cand\_rtxSFr$
          else
            $RC_2 \leftarrow Cand\_rRC$
            $txSubCh_2 \leftarrow Cand\_rtxSCh$
            $txSubFr_2 \leftarrow Cand\_rtxSFr$
      End for
    End for
  End while
End procedure

V2X as shown in Figure 2. The proposed scheme mitigates the collisions caused by half-duplex communications by balancing the subframes resource usage and avoid wastes of candidate resources in the same subframe. By using the balanced resource allocation scheme, half-duplex collisions were mitigated up to 500 vehicles and the performance was enhanced up to 97% by using the performance criteria of CDR.

B. Sharing candidate resource information

The proposed scheme broadcasts the information of candidate resource and RC value of current packet run to inform other vehicles about future expected usage of candidate resource as shown in Figure 3. In current packet run, when RC reaches to the threshold value (shown by red dotted box) it starts to share candidate resource information in next RRI's to inform other vehicles about candidate resource. When the RC value reaches to 0, it may use the same resources by using RRP or selects new resource as a candidate resource through subframe balancing scheme by sorting the subframe according to their usage as described in Algorithm 1. The information of candidate resources are periodically informed to other vehicles to mitigate collisions. The RC value of each vehicle is also broadcasted to other vehicles, and the vehicle with lesser RC value obtains higher priority to select the same candidate resource for its future transmissions. This distributed resolution with RC values mitigates the collision probability. The overall process of resource allocation is describe in Algorithm 2.

C. Collision resolution with RC value

In standard SB-SPS, each vehicle selects resources randomly for a specific interval (approximately 1 sec) without informing other vehicles, which results in collision, and decreases the performance. In this paper, we introduce a collision-resolving algorithm to avoid collision by comparing

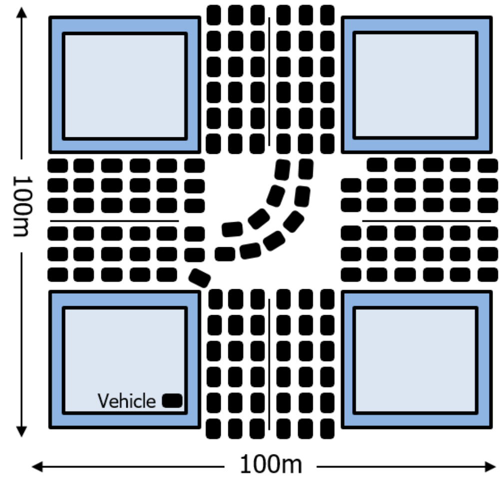


Figure 4: 500 vehicles with static intersection scenario

the RC values of vehicles that is described in Algorithm 3. Two or more vehicles, after reaching their threshold value in current packet run, may select the same resources as their candidate resources for their next packet run. Vehicles compare their RC values of current packet run, the vehicle with lesser RC value selects the candidate resource for the next packet run, and other vehicles reselect other candidate resources for the next packet run. The major reason of providing higher priority to the lesser RC value vehicle is because it has less time to select candidate resource compared with other vehicles. In such manner, the proposed collision-resolving mechanism mitigates collision and resource wastage, and provides continuity of transmission and enhances the performance.

IV. Simulation Results and Performance Analysis

A. *System environment and scenario*

Simulations are conducted using C-V2X Mode 4 [15] on ns-3 simulator. Up to 500 vehicles are included in a fully congested static intersection scenario of 100m × 100m, which is shown in Figure 4. All vehicles are in the communication range of other vehicles and receiving packet from others, which considered as a high density traffic scenario. LTE uses WINNER+B1 model for V2X services.

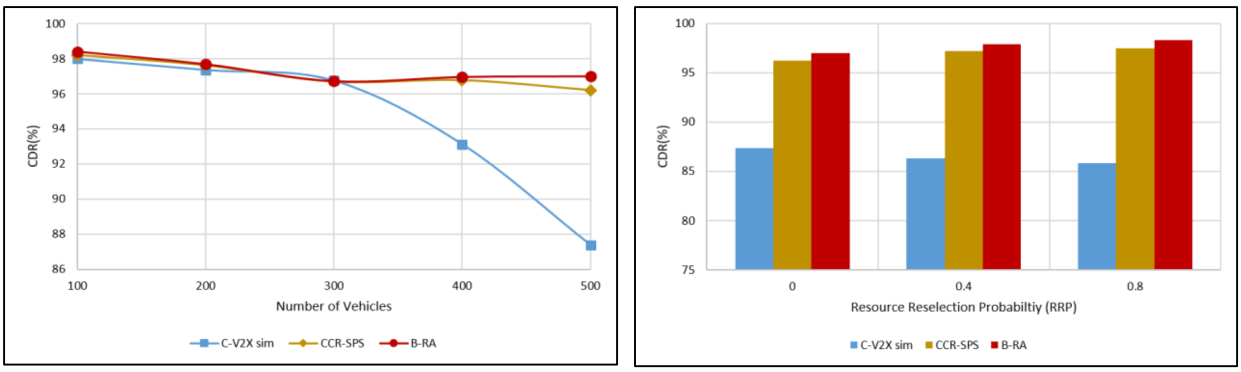
Table 1: Simulation Parameters

General Parameters	
Number of V-UEs	0...500
Channel model	WINNER+ B1
Base distance	150m
Ns-3 version	3.27
Vehicular-UE Parameters	
Message Size	190 bytes
Transmission power	23 dBm
Resource reservation period	100ms
Modulation and Coding Scheme	20
Resource reselection probability	0.0,0.4 & 0.8
T_1, T_2	4ms, 100 ms
Resource Pool Parameters	
Channel bandwidth	20 MHz
Number of subchannels	10
Subchannel Scheme	Adjacent
RBs per subchannel	10

The CAM message size is set to 190 bytes. Channel bandwidth is 20 MHz and the number of sub-channels is 10, where each subchannel have 10 resource blocks. Control and data payload are transmitted in the same transport block (TB) of sub-channels as adjacent scheme with the transmission power of 23 dBm. The parameters of the simulation are shown in Table 1.

B. *Performance analysis with CAM Delivery Ratio (CDR)*

Figure 5(a) depicts the CAM delivery ratio (CDR) when the number of vehicles increases up to 500, with the cellular bandwidth of 20 MHz. Results indicate that the balanced resource allocation (B-RA) scheme shown by red line has higher value of CDR around 97% at high-density traffic condition with 500 vehicles. Yellow line shows CCR-SPS, which shows CDR around 96% without the mitigation of half-duplex collisions and blue line shows existing C-V2X sim, which shows PDR around 87%. It is proven that the proposed scheme with balanced resource allocation (B-RA) enhances the performance by balancing the subframes in comparison of existing scheme (C-V2X sim in Figure 5)



(a) (b)

Figure 5: (a) CAM Delivery Ratio for an increasing number of vehicles and cellular bandwidth of 20 MHz on the static intersection scenario of (100 × 100 m). (b) CAM Delivery Ratio for an increasing number of RRP values with 500 vehicles and cellular bandwidth of 20 MHz on the static intersection scenario of (100 × 100 m)

around 10% and resolves the collision issue in half-duplex, especially in congested scenarios, when the number of vehicles increased up to 500.

C. Performance analysis with different Resource Reselection Probability (RRP) rates

Figure 5(b) depicts CDR when the number of vehicle is 500 (highly congested) and the channel bandwidth is 20 MHz with different values of RRP (0.0, 0.4, and 0.8). The results indicate that the performance is increased with higher values of RRP, the higher value of RRP shows around 98% of CDR. In default mechanism due to the semi-persistent nature of SB-SPS, vehicle selects resource for specific time interval, and at the end of the current packet run, vehicle uses RRP to either change the resource or use same resource for the next packet run. Collision increases at the higher values of RRP due to usage of the same colliding resource without the information of its collision, it continued for the several next packet runs, which continue collisions for a number of packet runs. It is indicated by C-V2X sim, which decreases the performance to 85% at higher value of RRP.

V. Conclusion

In this paper, we analyzed the impact of random selection of resources in C-V2X Mode 4 with half-duplex communications, and proposed a balanced resource allocation (B-RA) scheme minimizing the collisions caused by half-duplex communication. For this purpose, we balance the usage of subframes and candidate resources for the next packet run, share information of candidate resource in advance with other vehicles, and enhance the performance with proper configuration of resource reselection probability. We showed simulation results for various traffic congestion levels in metropolitan areas. The CAM delivery ratio performance of the proposed balanced resource allocation scheme is around 97% for 500 vehicles in 100m x 100m area. It shows that the balanced resource allocation scheme outperforms the basic SB-SPS random allocation of resources mechanism The main contributions of this paper are (i) enhanced algorithm with balanced usage of subframes to mininmize CAM delivery failure because of half-duplex, (ii) enhanced performance with sharings of candidate resource allocation information with other vehicles, which helps to avoid collision by choosing the same reosurce, and (iii) enhanced scheme to avoide consecutive collisions with prioritization with reselection counter (RC) value. For the future work, we will extend this work with mobility and different scenarios, evaluate the performance with C-V2X Mode 3, and make comparison of Mode 3 & 4.

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