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RESEARCH ARTICLE

Enhanced C-V2X Mode-4 With Virtual Cell, Resource Usage Bitmap, and Smart Roaming

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ABSTRACT Successful exchanges of cooperative awareness messages (CAMs) among neighboring vehicles are essential in the intelligent transportation system (ITS) to ensure safe autonomous driving. Especially in cellular vehicle-to-everything (C-V2X) mode-4, where the resource allocation process in the vehicles is autonomous without centralized control, efficient resource selection to minimize collisions is necessary to enhance the CAM delivery ratio (CDR). In this paper, we propose an enhanced operation of LTE C-V2X mode-4 by using virtual cells (VCs) with orthogonal resource allocation, extended master information block (EMIB) with a resource usage bitmap (RuBMP), and smart roaming in the virtual cell boundary. We propose a virtual cell manager (VCM) that monitors resource usage via CAM broadcasts from vehicles, configures the RuBMP to show the overall resource block usage, includes it in EMIB messages, and broadcasts the EMIB every 10ms. The periodic broadcast of the EMIB with the RuBMP enables vehicles to avoid selection of resources currently used by other vehicles, and minimizes collisions during CAM broadcasts. Smart roaming enables seamless, successful CAM broadcasts even at the boundary of virtual cells where resources (subchannels and subframes) must be re-selected based on the state of the next virtual cell. The analytical model of the proposed scheme (including successful CDR) is provided, and the performances are analyzed with NS-3 simulations for overlapped virtual cells in metropolitan areas with high densities of vehicles. The proposed scheme shows a 99.2% (or more) successful CAM delivery ratio for overlapped cells with up to 400 vehicles per virtual cell using four LTE sidelink subchannels.

INDEX TERMS C-V2X mode-4, virtual cell (VC), resource usage bitmap (RuBMP), extended master information block (EMIB), smart cell planning, collision resolution, sensing-based semi-persistent scheduling (SB-SPS), smart roaming.

I. INTRODUCTION

The intelligent transportation system (ITS) is expected to provide more efficient and safe driving [1] in which vehicle-to-everything (V2X) plays an important role in connected vehicle communications [2]. For vehicular communications, there are two main technologies: dedicated short-range communication (DSRC), and cellular vehicles-to-everything (C-V2X). DSRC is based on the IEEE 802.11p standard [3] while C-V2X is based on the 3rd Generation Partnership Project (3GPP) LTE and LTE Advanced (LTE-A) standards [4], which also support 5G cellular system [5]. Compared to DSRC, C-V2X supports massive coverage areas, robust scalability, low latency, higher data rates, and a QoS guarantee even in high-mobility scenarios [6].

The FCC in the U.S.A. released a report and order that prescribes C-V2X as the radio access technology of choice over DSRC [7], and the Society of Automotive Engineers (SAE) International further specified ITS stack protocols and modem configurations that must be implemented in V2X deployments in the U.S.A. [8]. 3GPP Release 14 introduced two new operational modes (mode-3 and mode-4) which are designed specifically for vehicle-to-vehicle (V2V) communications [9]. These modes accommodate low latency and high reliability by extending the functionalities of proximity services (ProSe). In mode-3, the eNodeB (eNB) base station

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performs centralized resource allocation for the vehicles within coverage range, whereas in mode-4, vehicles select radio resources autonomously without centralized resource management, as shown in Fig. 1. Both modes can be used according to the mobility scenario. A vehicle within metropolitan coverage may operate in mode-3 but shift to mode-4 in out-of-coverage highway areas for continuous transmission and desirable results [10].

For resource allocations in mode-4, vehicles use sensing-based semi-persistent scheduling (SB-SPS) where each vehicle might frequently change radio resources, which turns into the biggest problem of SB-SPS. Although the sensing components in SB-SPS significantly reduce packet collision, the unawareness of other vehicle's resource usage leads to high collision probability, which is non-negligible. Investigations have described how proper adjustments of SPS parameters on the MAC and PHY layers, such as transmission power, sensing window size, resource reservation time, and keep resource probability (Krp), can increase network performance [11], [12], [13], [14], [15]. However, such adjustments cannot fulfill the extremely stringent requirements of reliability and latency.

The primary challenging issues in C-V2X mode-4 are as follows: (i) unawareness of other vehicle's resource usage, (ii) half-duplex (HD) problems in cooperative awareness message (CAM) broadcasting, and (iii) the semi-persistent nature of SB-SPS. Although sensing components help to significantly reduce collisions in SB-SPS, autonomous resource selection without precise knowledge of other vehicle's resource usage leads to a high probability of collisions [16]. Vehicles can obtain information on resources selected by other vehicles for the next packet run only when they receive CAMs. So collisions happen if multiple vehicles select the same resources for CAM broadcasting, and the collision resolution process might take a long time (i.e., multiple CAM broadcast periods). We demonstrate avoidance of consecutive collision in our proposed scheme by using a resource usage bitmap for the awareness of resource usage to the newly joining vehicles. According to 3GPP, vehicles use half-duplex antennas for communication in C-V2X, which causes collisions. HD problems occur because vehicles using the same subchannel and the same subframe cannot listen while transmitting, which makes them unaware of resource usage by other vehicles in the same subframe. We mitigate collisions by distributing the resources in a resource map by using RuBMP. Once a vehicle selects resources and broadcasts CAM successfully it continuously uses the same resources, until it enters the virtual cell area. The semi-persistent nature of SB-SPS means vehicles use their selected resources for a series of packets; if a collision happens, it affects the entire series of packet transmissions. The lack of appropriate collision resolution mechanisms may decrease the CAM delivery performance rapidly.

In this paper, we propose an enhanced operation of the C-V2X mode-4 with configurations of virtual cells (VCs), a resource usage bitmap (RuBMP), and smart roaming.

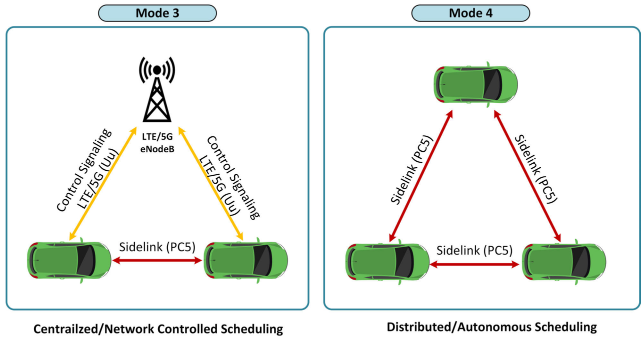


FIGURE 1. (a) Centralized vs. (b) distributed C-V2X communication scheduling.

Information on resource usages by vehicles is continuously collected by the virtual cell manager (VCM), and the RuBMP is periodically configured and broadcasted in an extended master information block (EMIB). Because the EMIB broadcast period (usually 10 ms) is much shorter than the CAM broadcast period (usually 100 ms), vehicles can select resources to avoid collisions, and collisions can be quickly resolved. Usage of the RuBMP in SB-SPS for C-V2X mode-4 leads to absolute superior performance in terms of CAM delivery ratio (CDR) and packet inter-reception ratio (PIR). NS-3 simulation results show that the bitmap-based resource management achieves the best performance in comparison to other random resource selection schemes.

The main contributions of this paper are as follows:

- Smart virtual cell planning with orthogonal subchannel allocation for virtual cells considering the topology to minimize half-duplex problems.
- Enhanced resource usage management using the EMIB with the RuBMP for precise resource allocation to avoid collisions.
- Smart roaming at the boundary of the VC where resources (subchannels and subframes) must be carefully changed to provide seamless CAM broadcasting in overlapped VC areas.

Simulation results of the proposed scheme show its efficacy in terms of CDR in various scenarios.

The rest of this paper is organized as follows. Section II presents related work on the core features of C-V2X mode-3 and mode-4, and a brief summary of the enhancements to C-V2X communication modes, which delves into the most relevant schemes for enhancement of C-V2X performance. Section III presents the proposed scheme to enhance the CAM delivery ratio by using virtual cell configurations and bitmap-based resource management. It provides detailed explanations on virtual cell planning and reallocation of resources in overlapped virtual cell areas with smart roaming. Section IV presents the analytical model of the proposed scheme. Section V provides performance analyses of the proposed scheme using the NS-3 C V2X simulator with our proposed modifications. Finally, Section V concludes this paper.

II. RELATED WORK

The 3GPP has standardized the C-V2X communication in release 14 [17]. The main focus of C-V2X is basic safety use cases. In further releases, 3GPP has been working to enable advanced use cases. The actively studied topic in C-V2X is resource management and allocations to fulfill basic reliability requirements. Approaches are classified into two categories: network-controlled approaches, and autonomous approaches. The main focus of this paper is autonomous resource allocations in C-V2X mode-4.

A. C-V2X MODE-4

To support C-V2X services, 3GPP defined some essential, cellular architectural enhancements [18]. In C-V2X mode-4, vehicles select resources autonomously, independent of other vehicles, without any centralized control. Vehicles utilize a set of pre-configured parameters in out-of-coverage areas, while vehicles within the coverage areas may be controlled by the network that configures the V2X channels and informs vehicles about configurable parameters. Mode-4 uses sensing-based semi-persistent scheduling for autonomous selection of resources [19]. The usage of resources in mode-4 depends upon the transmission's data size, and the selected resource is used for a series of contiguous transmissions that is regulated by the RC (reselection counter).

1) SENSING-BASED SEMI-PERSISTENT SCHEDULING (SB-SPS)

Fig. 2 depicts the default SB-SPS mechanism. Vehicle v senses the resources used by neighboring vehicles in the previous 1000 subframes (1 second) to determine which resources are free to be used for the next packet run. Vehicles determine whether the resources are used or not based on the resource reservation interval (RRI) available in the sidelink control information (SCI) of the CAM packets received from neighboring vehicles. After sensing the resources, vehicle v at time t selects the resources for the next packet run in the 100 ms selection window ($t_1 \sim t_2$) from the list of top 20 % of the resources that are predicted as not being utilized in continued transmissions. The selection window's lower bound ($t_1 \leq 4$) relies upon the UE configuration, and the upper bound ($20 \leq t_2 \leq 100$) depends on the maximum time in the PIR. If all resources are busy, the vehicle selects an occupied resource with the lowest reference signal received power (RSRP) value [20].

Vehicles that select resources in the specified RRI transmit CAMs periodically by using the same resources until the RC (starting from 5 $\sim$ 15) reaches zero. For the next packet run, the same resources can be used with a resource reselection probability (RRP) configured within the approximate range of 0.0 $\sim$ 0.8. Otherwise, vehicles select new resources by repeating the SB-SPS process [21].

2) MASTER INFORMATION BLOCK (MIB)

The master information block (MIB) consists of basic information on the PHY system and cell-specific information that is used in cell searches by the vehicles. The MIB contains four information fields that are broadcasted through the physical broadcast channel (PBCH). The first two fields provide information regarding downlink system bandwidth and Physical HybridARQ Indicator Channel (PHICH) configuration. The downlink system bandwidth is one of six values (6, 15, 25, 50, 75, or 100) for the number of resource blocks (RBs) on downlink for communication. Notified values of RBs are mapped directly to bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz, respectively.

The PHICH configuration field indicates the amount and duration of the PHICH. In a radio frame (RF), the first four OFDM symbols in the first slot of the first subframe are used for the PBCH. The eNB base station maps the MIB to the PBCH across periods of 40 ms (four RFs) with portions transmitted in the first subframe of every frame. By using the normal cyclic prefix (CP), the PBCH occupies 72 subcarriers (6 RBs) centered on the DC subcarrier using the first four symbols of slot 1 [22].

B. PERFORMANCE ENHANCEMENT OF C-V2X MODE-4 BY SHARING RESOURCE USAGE INFORMATION

He et al. [23] proposed broadcasting control and data information by using a non-adjacent scheme (different subchannels and subframes for SCI and control information), letting them carry each other's information in a chained practice. However, the proposed scheme handles only the very next payload, just like SB-SPS. Moreover, the proposed scheme requires cross-layer processing. Bonjorn et al. [24] proposed changing the RC value forcefully in the last RRI, broadcasting the RC information through a CAM to avoid packet collisions. However, in highly congested environments, it is problematic to change RC values owing to the limited number of RC values.

Jeon et al. [25] proposed sharing information on the location of resources with other vehicles by using a CAM immediately before resource selection to avoid CAM collisions under SB-SPS. In a similar study of early reservations, Jeon and Kim [10] proposed sharing the location information with a CAM one second earlier (before the actual resource usage) to enhance SB-SPS performance. However, both of these studies cannot handle collisions by newly arriving vehicles that do not have any information about ongoing resource usage for their CAM broadcasts.

In our previous research work [16], we proposed an enhancement of the performance of C-V2X by using a cognitive collision resolution mechanism, where location information with an RC value is shared through a CAM broadcast when reaching half of the RC value of the current packet run. By using the cognitive collision resolution scheme, the wasted resource problem and the newly arriving

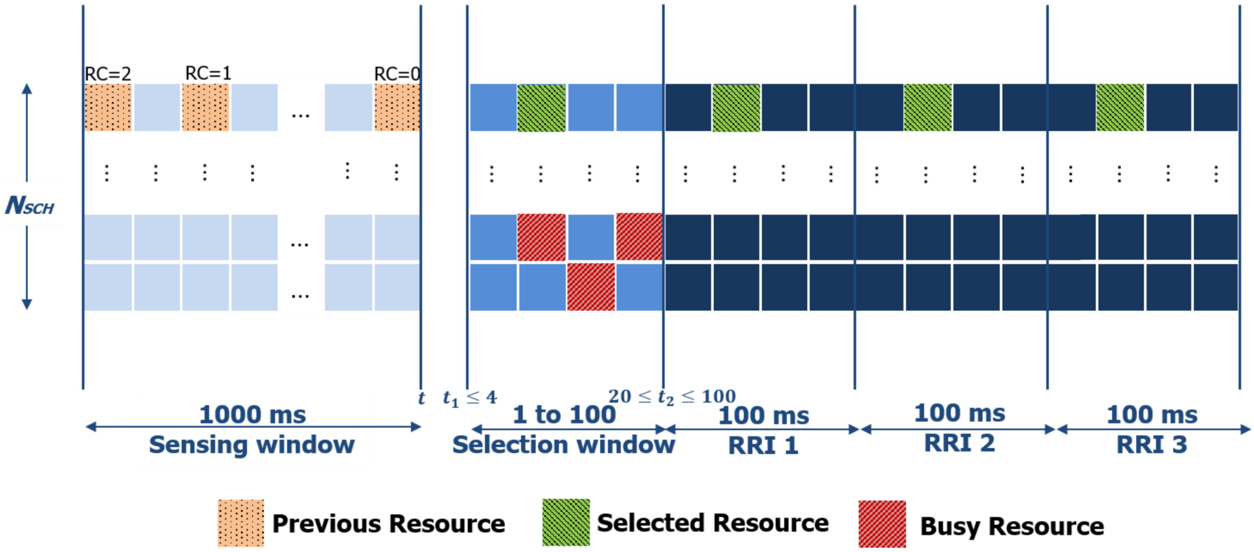


FIGURE 2. Sensing-based semi persistent scheduling (SB-SPS).

vehicle issue can be resolved, and high-reliability requirements can be achieved.

C. PERFORMANCE ENHANCEMENT OF C-V2X MODE-4 BY SOLVING HALF-DUPLEX PROBLEM

Bazzi et al. [26] proposed a full-duplex radio to increase the number of neighboring vehicles in C-V2X mode-4 for transmission. However, full-duplex radio increases the complexity of the network. Campolo et al. [27] proposed a full-duplex aided sensing and scheduling scheme for C-V2X mode-4 and achieved better performance in terms of reliability and latency. However, this work increases the system's complexity and is difficult to adopt in practical scenarios. In [28], we investigated collisions from a half-duplex problem and proposed a balanced resource allocation scheme to mitigate half-duplex collisions. For this purpose, we balanced subframe usage and candidate resources for the next streak and shared resource location and RC information with other vehicles in advance. Moreover, we introduced a collision resolution algorithm to avoid consecutive collisions in SB-SPS.

D. PERFORMANCE ENHANCEMENT OF C-V2X MODE-4 BY ADJUSTING SB-SPS PARAMETERS

Molina-Masegosa et al. [29] discussed two important investigations in SB-SPS performance. First, they discussed the advantages of SB-SPS resource allocation reduction as the distance between the receiver and transmitter increases. Second, they pointed out that collision error has the first priority among the four types of packet delivery errors. However, that study did not provide a solution to enhance SPS performance. Molina-Masegosa et al. [30] observed that SB-SPS parameters have an impact on overall performance, and Krp must specifically be regulated according to traffic load to achieve productive results.

Bazzi et al. [19] filtered out resources based on RSRP from previous resources, and investigated the importance of the resource selection method in SB-SPS. In [31] Molina-Masegosa et al. found that the size of a basic safety message (BSM) or CAM greatly affects SB-SPS performance, and they proposed new resource reselections for different sizes of messages. However, the frequent resource reselection affects performance. Molina-Masegosa et al. [32] proposed a geo-based resource scheduling scheme, where a vehicle selects resources autonomously based on location and the neighboring vehicles on the road in order to address the hidden-terminal problem. However, the scheme can cause a high collision rate when the number of available resources is less than the required number of resources for communication.

In [33] we proposed an enhancement of the performance by using virtual cells and a resource usage bitmap where the VCM continuously monitors resource usage for CAM broadcasts by vehicles, configures a RuBMP, and broadcasts information in an EMIB. By checking the RuBMP, each vehicle can easily avoid already selected and used resources. In this paper, we propose a scheme that is an extension of the work in [33]. We analyze the proposed algorithm in each scenario, and measure the CDR, especially in highly congested environments.

III. ENHANCED C-V2X MODE 4 WITH VIRTUAL CELL AND RESOURCE USAGE BITMAP

In this section, we present an enhanced C-V2X mode-4 with virtual cells, smart roaming, and bitmap-based resource management that efficiently resolves collisions in CAM broadcasts. The proposed scheme is based on the configuration of virtual cells (VCs) with orthogonal resource allocations, an extended master information block (EMIB) with a resource usage bitmap (RuBMP), and smart roaming at virtual cell boundaries. Variables related to the operation of the proposed scheme are listed in Table 1.

A. VIRTUAL CELL AND ITS MANAGEMENT

In C-V2X mode-4, vehicles perform resource selection autonomously and are unaware of the resource selected by other vehicles. The autonomous selection of resources by vehicles without any information of resource usage by other vehicles causes high collisions, which decrease the overall performance of successful CAM delivery. For this purpose, we propose the configuration of VC in C-V2X mode 4 for highly congested metropolitan areas, to minimize collisions and half-duplex problem. VCM broadcasts EMIB with RuBMP every 10 ms same as the MIB broadcasted in LTE standards. The VCM handles the configurations of VCs and the allocation of subchannels. For each VC, a VCM continuously collects information on resource usage by vehicles from their CAM broadcasts, configures the RuBMP, and broadcasts the EMIB with the RuBMP every 10 ms, which is the MIB broadcasting interval defined in LTE. Vehicles frequently obtain the currently used resources (defined by subchannel and subframe) selected by other vehicles in the same VC and neighboring VCs, and they select resources for CAM broadcasts with a minimized collision probability.

The VCM is working on the concept of virtual eNodeB, but the VCM does not interact with each vehicle individually like C-V2X mode-3. The VCM broadcasts the EMIB with the RuBMP every 10 ms. Therefore, there are no additional resource usages to manage and interact between these entities. The VCM can be easily implemented on traffic lights, to passively collect resource usage for CAM broadcastings, and broadcast the EMIB with RuBMP to provide resource usage information in highly congested metropolitan areas. The advantage of using a virtual cell with RuBMP are: (i) cover wide area and provide seamless exchange of CAMs in the overlapped virtual cells, (ii) reduce consecutive collisions, and (iii) provide wide-area propagation of emergency warnings across multiple virtual cells by using some extra information through EMIB. The proposed method provides safer mobility on the road, reliable communication among vehicles, and reduced latency.

B. SMART VIRTUAL CELL PLANNING AND ORTHOGONAL SUBCHANNEL ALLOCATIONS

In order to maximize the CAM delivery performance under C-V2X mode-4 in highly congested metropolitan areas, we propose configurations for overlapping virtual cells with orthogonal subchannel allocations and frequency reuse. As depicted in Fig. 3, multiple overlapping VCs are configured for C-V2X service areas, and three to four subchannels are allocated for each VC, where the allocated subchannels for overlapping neighboring VCs are orthogonal avoiding frequency interference in the neighboring overlapped areas.

In the example in Fig. 3, VCs 1 and 3 are using subchannel numbers 1, 2, and 3, while VC 2 is using orthogonal subchannels 4, 5, 6, and 7, and VC 4 and 5 are using subchannels 8, 9, and 10. These orthogonal subchannel allocations and the frequency reuse with adjustable virtual cell coverage can provide highly efficient RF resource usage, especially in congested metropolitan areas where a large number of vehicles must be accommodated with limited RF resources.

For each VC, a virtual cell manager (VCM) continuously collects information on resource usage by vehicles from their CAM broadcasts, configures the RuBMP, and broadcasts the EMIB with the RuBMP every 10 ms, which is the MIB broadcasting interval defined in LTE. Vehicles frequently obtain the currently used resources (defined by subchannel and subframe) selected by other vehicles in the same VC and neighboring VCs, and they select resources for CAM broadcasts with a minimized collision probability. The area of VC coverage is adjustable based on vehicle density. Smart virtual cell planning across multiple overlapping VCs enables efficient reuse of RF resources by non-overlapping VCs, as shown in Fig. 3.

TABLE 1. Variables used in the proposed scheme.

Variable	Description
VC	Virtual cell
VCM	Virtual cell manager
L_{VC}	List of virtual cells in the vehicular network
VC_{curr}	Current virtual cell
VC_{tar}	Target virtual cell
$RSRP_{curr\_vc}$	Reference signal received power of the current virtual cell
N_{SF}	Number of sub-frames
L_{SCH}	List of subchannels in the given virtual cell
N_{SCH}	Number of subchannels in the given virtual cell
N_{res}	Number of resources in pool
N_v	Number of vehicles
$RuBMP$	Resource usage bitmap
BMP_{s_Fr}	Bitmap starting frame number
bit_{res}	Resource bits in the bitmap
SF_{alloc}	Allocated subframe
SCH_{alloc}	Allocated subchannel
SF_{res_s}	Starting subframe number of RF resource
Fr_{curr}	Current frame number
S_Fr	Starting frame number
λ	Transmission rate for packets
CAM_{tx}	CAM transmitted
CAM_{coll}	CAM that collided
CAM_{wait}	CAM that is waiting
B_{SCH}	Bytes per subchannel
S_{BMP}	Size of bitmap
Th_{rsrp}	Threshold of RSRP
$Th_{hysteresis}$	Threshold of hysteresis

The interactions between vehicles and the VCM are depicted in Fig. 4. The VCM broadcasts a primary synchronization signal (PSS) and a secondary synchronization signal (SSS) every 5 ms to vehicles for synchronization. The

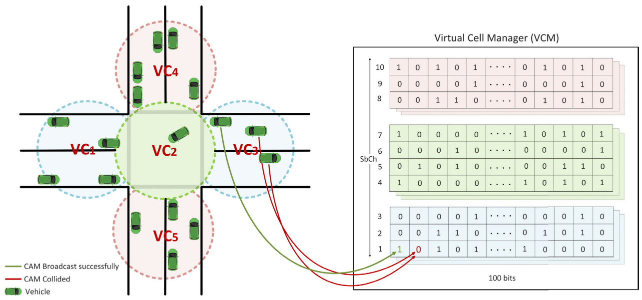


FIGURE 3. Configuration of virtual cells, resource allocations, and resource usage bitmaps.

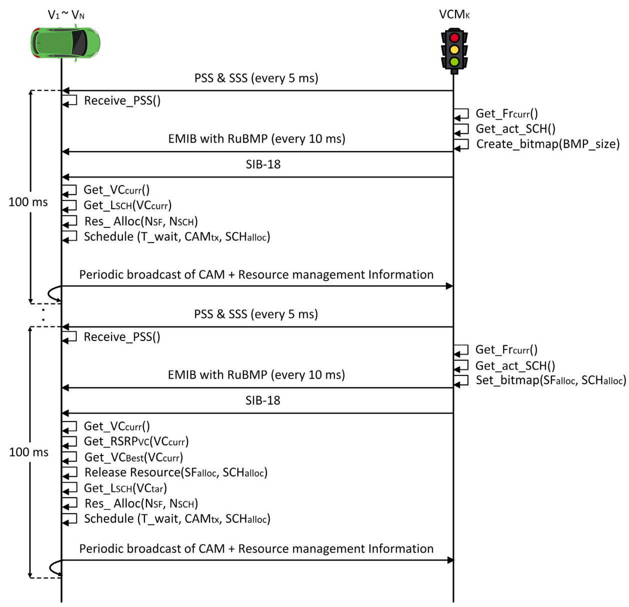


FIGURE 4. Operational sequence of bitmap-based resource management and collision resolution.

EMIB is broadcasted every 10 ms with updated content on the current frame number, the list of active subchannels, and an updated RuBMP. The VCM does not exchange signaling messages with individual vehicles, which is different from legacy mode-3. The proposed scheme's VCM just provides resource usage information by broadcasting the EMIB with the RuBMP.

Each vehicle receives the EMIB of the new VC with the RuBMP, and collects information for resource allocation by checking the resources (i.e., slots) listed in the RuBMP. The vehicle can select a currently unused resource, and broadcast a CAM by using the selected resource. The successfully selected resource is used by the vehicle until it leaves the VC. When a vehicle starts roaming at the boundary of overlapped VCs, it first selects a resource from the next VC based on the RuBMP in the EMIB, and starts a CAM broadcast using this resource. The VCM receives the CAM with the current subframe, current subchannel, and connected VC information. By using the information of current subframe and subchannel, the VCM figures out the resource usage, updates the RuBMP, and broadcasts the updated RuBMP through the EMIB. Under the 3GPP specifications, the vehicle must broadcast the CAM at 100 ms intervals.

Algorithm 1 Periodic Broadcasts of CAMs by Vehicles

/*Scheduled at Vehicle initialization (Period: 100ms) */

1: **procedure** Broadcasts_CAMs(Th_{rsrp}, $imsi$, $Th_{hysteresis}$)
2: $VC_{curr} \leftarrow Get\_VC_{curr}()$
3: $Fr_{curr} \leftarrow Get\_Fr_{curr}(VC_{curr})$
4: $L_{SCH} \leftarrow Get\_L_{SCH}(VC_{curr})$
5: $RuBMP \leftarrow Get\_BitMap(VC_{curr})$ ▷ Retrieve every 10 ms
6: $SF_{Prev\_alloc}, SCH_{Prev\_alloc} \leftarrow Get\_Prev\_Res(imsi)$
7: $SF_{alloc}, SCH_{alloc} \leftarrow Select\_Res(Fr_{curr}, L_{SCH}, RuBMP, SF_{Prev\_alloc}, SCH_{Prev\_alloc})$
8: **if** $VC_{curr} \neq NULL$ **then** ▷ Not first resource allocation
9: $RSRP_{curr\_vc} \leftarrow Get\_RSRP_{VC}(VC_{curr})$
10: **if** $RSRP_{curr\_vc} < Th_{rsrp}$ **then**
11: $VC_{tar} \leftarrow Select\_Best\_VC(Th_{hysteresis}, VC_{curr})$
12: **if** $VC_{tar} \equiv NULL$ **then**
13: *break* ▷ Re-try in next CAM cycle
14: **end if**
15: $L_{SCH} \leftarrow Get\_L_{SCH}(VC_{tar})$
16: $SF_{alloc}, SCH_{alloc} \leftarrow Select\_Res(Fr_{curr}, L_{SCH}, RuBMP, SF_{Prev\_alloc}, SCH_{Prev\_alloc})$
17: **end if**
18: **end if**
19: $CAM \leftarrow Create\_CAM()$
20: $T_{sbfr} \leftarrow Get\_T_{tx}(SF_{alloc})$ ▷ Period of 100 ms
21: $T_{wait} \leftarrow T_{sbfr} - Get\_T_{curr}()$
22: $Schedule(T_{wait}, CAM_{tx}, SCH_{alloc}, SF_{alloc})$
23: $Store\_Prev\_Res(imsi, SCH_{alloc}, SF_{alloc})$
24: **end procedure**

C. RESOURCE SELECTION AND PERIODIC CAM BROADCAST BY VEHICLES

Algorithm 1 shows the detailed procedure of periodic CAM broadcasts by vehicles (UEs) from receiving the PSS for CAM broadcasts. Lines 2-7 show that when a vehicle joins the first VC, it collects information on the current VC (VC_{curr}), including the list of active subchannels (L_{SCH}), and performs resource selection using Algorithm 2. When the vehicle enters the VC, it checks the RSRP of the current VC as defined in line 9. If the RSRP of the current VC is less than the threshold value (Th_{rsrp}, set to -120 dBm), the vehicle scans the available neighboring VCs and chooses the best VC by executing Algorithm 3. After joining the target VC, the previously connected VC's VCM continuously monitors the usage of that specific resource. If the resource is no longer used by the vehicle, the VCM updates the status of the resource in the RuBMP by setting it to 0, which indicates the resource is free that can be used by other vehicles. When a vehicle successfully selects a resource for CAM broadcast, it gets the time of the selected resource, defined by the subchannel and subframe (T_{sbfr}), calculates the wait time (T_{wait}), and then schedules CAM transmission by using the wait time and the selected subchannel number (SCH_{alloc}).

The bitmap-based resource selection algorithm is described in Algorithm 2. In line 5, the vehicle checks the resource bits in the updated RuBMP received from the VC. If the resource bit is 0, it means a collision occurred, and the vehicle must reselect resources. Lines 6-27 show random resource allocation using the bitmap. The vehicle selects a subchannel randomly from the list of active subchannels

Algorithm 2 Resource Selection for CAM Broadcasts

```
/* Invoked by Algorithm 1*/
1: procedure Select_Res(Fr_curr, L_SCH, BMP, SF_Prev_alloc, SCH_Prev_alloc)
2:   N_SCH, S_SCH ← Get_SCH_info(L_SCH)
3:   N_ava_res ← Get_available_resource(BMP, L_SCH)
4:   bit_res ← Get_bit_res(BMP, SF_Prev_alloc, SCH_Prev_alloc)
5:   if bit_res ≡ 0 then
6:     SCH_alloc ← S_SCH + rand(0, N_SCH)
7:     while True do
8:       if N_ava_res ≡ N_SF − 1andrand(0, 1) ≡ 0 then
9:         SCH_alloc ← (SCH_alloc + 1)%N_SCH
10:        S_Fr ← Get_S_Fr(Fr_curr)
11:        SF_res_s ← Get_Fr_res(Fr_curr, L_SCH, SCH_alloc, S_Fr, BMP, bit_res)
12:      end if
13:      i ← 0
14:      j ← rand(0, N_SF − 1)
15:      while i < N_SF do
16:        if GetBit(bit_res, j) ≡ 0 then
17:          SF_alloc ← j + SF_res_s
18:          break
19:        end if
20:        i + +
21:        j ← (j + 1)%N_SF
22:      end while
23:      if SF_alloc ≠ −1‖SCH_alloc ≠ 0 then
24:        break
25:      end if
26:      SCH_alloc ← (SCH_alloc + 1)%N_SCH
27:    end while
28:  end ifreturn SF_alloc, SCH_alloc
29: end procedure
```

Algorithm 3 Select Best Virtual Cell

```
/*Invoked for the 100ms UE Process*/
procedure Select_Best_VC(Th_hysteresis, VC_curr)
  L_VC ← Get_VC_list()
  RSRP_curr_vc ← Get_RSRP_vc(VC_curr)
  VC_tar ← NULL
  for VC ∈ L_VC do
    RSRP_VC ← Get_RSRP_vc(VC)
    if RSRP_curr_vc + Th_hysteresis < RSRP_VC then
      RSRP_curr_vc ← RSRP_VC
      VC_tar ← VC
    end if
  end for
  if VC_tar ≠ VC_curr then return VC_tar
  elsereturn NULL
  end if
end procedure
```

in the specific VC (line 6). If only the last bit (subframe) is available from a bit set of 10 bits (a frame), and its random choice is 0, then it tries to select the next subchannel by incrementing the subchannel number to get the start subframe number for a free resource using *Get_Fr_res*() as shown in line 11. After randomly selecting a subframe from a specific frame, it checks all the subframes sequentially, finds a resource that is not occupied, and selects the first unoccupied resource from the frame. In the end, the resource allocation algorithm returns the subframe number (SF_{alloc}) and subchannel number (SCH_{alloc}) of a resource that is free to use.

D. VCM'S BROADCASTS OF THE RESOURCE BITMAP THROUGH EMIB

After joining a VC in the vehicular network, a vehicle receives the EMIB that contains the necessary VC-specific information and PHY system information. The content of the EMIB is carried through the physical broadcast channel (PBCH). For the sake of performance enhancement and to meet the stringent 3GPP reliability and latency requirements, we propose extending the MIB to include the current frame number (Fr_{curr}), the list of active subchannels (L_{SCH}), and the RuBMP. This bitmap information is provided to each vehicle through EMIB broadcasts for its virtual cell. The current frame number is used for synchronization between the vehicle and its VC. Each VC uses specific subchannels in its communication range for precise frequency reuse and to avoid half-duplex problems. The list of active subchannels (L_{SCH}) is provided through the EMIB, and the vehicle chooses resources from the specific subchannels of the connected VC. By receiving the EMIB with the RuBMP, each vehicle can confirm successful CAM transmission by checking whether its resource bit is 0 or 1 in the RuBMP. If the bitmap shows the resource bit is 1, it confirms that the CAM broadcast was successful; otherwise, there was a collision, and the vehicle must try to select another resource. In the starting period, the bitmap shows all resource bits are 0 (resources are not allocated yet), so vehicles can randomly select resources from the first 10 resource bits of the bitmap. EMIB includes some additional bytes for the current frame number (Fr_{curr}), the list of active subchannels (L_{SCH}), and the RuBMP. However, these extra bytes produce a very low communication overhead because the number of CAM messages and EMIB messages remains the same in communication.

Feilds	Priority	Frequency Resource location	Time gap	MCS	ReTx index	Reserved
Bits	4 bits	X bits	4 bits	5 bits	1 bit	15-X bits

FIGURE 5. SCI format 1 [19].

E. SHARING RESOURCE SELECTION INFORMATION (CURRENT SUBFRAME NUMBER, SUBCHANNEL NUMBER, AND CONNECTED VIRTUAL CELL) THROUGH THE CAM

Each vehicle broadcasts a CAM every 100 ms by using control and data channels. The physical sidelink control channel (PSCCH) is used to broadcast the sidelink control information, which contains the information for the receiver about receiving and demodulating the PSSCH used in broadcasting data packets. The SCI and the data packets are sent during the same transmission time interval (TTI). The SCI includes priority, RRI, frequency resource location, time gap, the modulation and coding scheme (MCS), and

Algorithm 4 Configuration_Update_RuBMP_by _VCM

/* VCM Process is Scheduled to be Invoked at Every 10ms */

procedure Configuration_Update_RuBMP_by_VCM()

$SF_{alloc}, SCH_{alloc} \leftarrow Receive\_CAM()$

$byte\_addr \leftarrow SCH_{alloc} \times 13$

$byte\_offset \leftarrow SF_{alloc}/8$

$bit\_offset \leftarrow SF_{alloc}\%8$

$res\_byte \leftarrow RuBMP[byte\_addr + byte\_offset]$

$res\_byte \leftarrow res\_byte| \sim (0 \times 1 \ll bit\_offset)$

$RuBMP[byte\_addr + byte\_offset] \leftarrow res\_byte$

end procedure

retransmission (ReTx) index, as shown in Fig. 5 [19]. In the current C-V2X mode-4, vehicles do not share their resource selection information with other vehicles, which creates a high probability of collisions because of the random selection of resources. Therefore, to avoid collisions, it is essential to provide resource usage information to vehicles. For this purpose, we propose to extend the SCI content in the CAM to include the current subframe number and subchannel number to enable the VCM to easily confirm and update the bitmap from the currently allocated subframe number (SF_{alloc}) and subchannel number (SCH_{alloc}) of each CAM, as shown in Algorithm 4. However, upon usage of the same subframe and subchannel by two or more vehicles, collisions may occur and the extended CAM is not received by the VCM, so the resource bit is reset to 0.

F. SMART ROAMING WITH RE-ALLOCATION OF RESOURCES IN OVERLAPPED VIRTUAL CELLS

Vehicles receive the PSS every 5 ms from the VCM and check the RSRP value. When a vehicle approaches the boundary of overlapped VCs, it senses several weakened RSRP value of the current VC. If the RSRP value of the current VC is less than the threshold value (Th_{rsrp}, -120 dBm), the vehicle prepares to roam and chooses the best neighbor VC by checking the RSRP values of the current VC and the target VC. Algorithm 3 describes the procedure for determining the best VC when vehicles initially join a network or join a VC based on their position on the road. The algorithm shows that the vehicle first collects the list of VCs (L_{VC}) and the current VC's RSRP ($RSRP_{curr\_vc}$). The vehicle then compares the RSRP of each VC in the list against $RSRP_{curr\_vc}$. We introduce a threshold ($Th_{hyteresis}$), that is set to 1 dBm to avoid hysteresis (bounce back) issues in roaming between overlapped VCs. If the current VC's RSRP ($RSRP_{curr\_vc}$) + $Th_{hysteresis}$ is less than the RSRP of other VCs from the list, the vehicle prepares to roam to a new VC. Vehicles do not perform any specific operation to release resources from the previous VC. When the old resource is no longer used, the VCM does not receive a CAM using this resource, and the VCM simply sets that resource bit to 0 in the RuBMP. By using this simple reallocation of resources in overlapping VCs, the probability of collision is mitigated, and performance is enhanced.

G. IMPLEMENTATION AND COMPLEXITY

The proposed scheme consumes very limited additional resources for the management and interaction between virtual cell (VC), extended master information block (EMIB), resource bitmap (RuBMP), and virtual cell manager (VCM). The VCM can be easily implemented on traffic lights/roadside unit. The VCM broadcasts the EMIB with RuBMP in the range of its virtual cell. Each vehicle receives EMIB with RuBMP and selects resources that are free to use from RuBMP. By adding some extra bytes in the EMIB and CAM to provide some useful information to the vehicle and VC, the proposed scheme has multiple advantages: (i) consecutive collision avoidance, (ii) minimize half-duplex problems, (iii) cover wide-area for seamless exchange of CAM, and (iv) reduce collision resolving time if happens. By using the proposed scheme, the road safety can be more reliable by adding some extra bytes in EMIB for prompt safety warnings (e.g., wide-area propagation of emergency warnings across multiple virtual cells). The proposed scheme has limited communication overhead because it is working under the LTE standards.

IV. ANALYTICAL MODEL

This section presents an analytical model for the bitmap-based resource management scheme, and quantifies the CAM delivery ratio (CDR) as a function of the distance between the receiver and the transmitter. For this purpose, multiple-lane linear and crossway topologies are considered with random positions of vehicles using SUMO [34]. All vehicles transmit λ packets per second using the 20 MHz bandwidth with transmission power (P_{tx}) of 23 dBm. The parameters used in the analytical modeling of the proposed scheme are shown in Table 2. For CDR modeling, four mutually exclusive errors presented in [35] are evaluated.

- Errors from half-duplex transmissions (HD errors). Since C-V2X mode-4 uses half-duplex radio, a vehicle cannot listen to other vehicles while broadcasting its own CAM in the same subframe. HD errors do not depend on the scheduling scheme and transmitter-receiver distance but on the probability of at least two transmitting vehicles using the same subframe.
- Errors from a weak received signal power P_{rx} below the sensing power threshold (SEN error). A CAM received with a weak P_{rx} lower than P_{SEN} cannot be decoded and produces a SEN error. SEN errors are strongly related to transmitter-receiver distance and transmission power P_{tx}. SEN errors do not include HD errors.
- Errors from propagation effects (PRO error). A PRO error occurs when a CAM is received with a high received signal power but the received signal-to-noise ratio (SNR) is not acceptable to correctly decode the CAM. PRO errors also depend on transmitter-receiver

TABLE 2. Variables used in the proposed analytical model.

Variable	Description
v_{tx}	Transmitting vehicle
v_{rx}	Receiving vehicle
v_i	Interfering vehicle
$d_{t,r}$	Distance between transmitting and receiving vehicles
$d_{t,i}$	Distance between transmitting and interfering vehicles
$d_{i,r}$	Distance between interfering and receiving vehicles
P_{tx}	Transmission power
P_{rx}	Received signal power
P_i	Signal power of interfering vehicle v_i
$PL(d_{t,r})$	Pathloss at $d_{t,r}$
P_{SEN}	Sensing power threshold
$BL(s)$	Block error rate (BLER) for an SNR equal to s
RRI	Resource reservation interval (100ms)
N_0	Noise power
SNR	Signal-to-noise ratio
$SINR$	Signal-to-interference and noise ratio
CDR	CAM delivery ratio
$P_{SIM}(d_{t,i})$	Probability that vehicles v_t and v_i use same resource at the same time
$P_{INT}(d_{t,r}, d_{t,i})$	Probability that the interference of interfering vehicle v_i is greater than the threshold value that determines the correct CAM reception when two or more vehicles transmit using the same resources
ε_{HD}	Probability of CAM failure due to half-duplex (HD error)
$\varepsilon_{SEN}(d_{t,r})$	Probability of CAM failure due to weak P_{rx} (SEN error)
$\varepsilon_{PRO}(d_{t,r})$	Probability of CAM failure due to propagation effects (PRO error)
$\varepsilon_{COL}(d_{t,r})$	Probability of CAM failure due to CAM collision (COL error)
σ	Variance in shadowing (SH)
C_{res}	Candidate resources
Fr_{res}	Resource frame
O_{res}	Occupied resources

distance, transmission power, and the MCS. PRO errors exclude HD and SEN errors.

- Errors from a CAM collision (COL error). A COL error occurs when two vehicles use the same resource (the same subframe and subchannel) for CAM broadcasting, and the associated signal-to-interference plus noise ratio (SINR) is not sufficient to correctly decode the CAM. COL errors depend on transmitter-receiver distance, transmission parameters, traffic density, propagation, and the scheduling scheme. COL errors exclude all other errors.

In the following analysis, the transmitting vehicle is denoted v_{tx}, and the receiving vehicle is v_{rx}. The distance between both vehicles is denoted $d_{t,r}$. The model assumes that the packet is received successfully when none of these four possible errors occur. Note that all these errors are mutually exclusive. The CDR can be obtained as:

$$CDR(d_{t,r}) = (1 - \varepsilon_{HD}) \cdot (1 - \varepsilon_{SEN}(d_{t,r}))\cdot (1 - \varepsilon_{PRO}(d_{t,r})) \cdot (1 - \varepsilon_{COL}(d_{t,r})), \quad (1)$$

where, ε_{HD}, ε_{SEN}, ε_{PRO}, and ε_{COL} are the probability that CAM failure is due to HD, SEN, PRO, and COL errors, respectively.

The proposed analytical model is based on the proposed model in [35], which was designed for performance evaluation of C-V2X mode-4. In this paper, we introduce new expressions to evaluate HD and COL errors considering the updated C-V2X mode-4 operations. Since SEN and PRO errors are independent of scheduling schemes, we utilized them as they are presented in [35].

A. HALF-DUPLEX ERRORS (ε_{HD})

ε_{HD} is the probability of CAM transmitted by vehicle v_{tx} cannot be received by vehicle v_{rx} due to the HD effect when the resources of v_{tx} and v_{rx} use the same subframe. In our proposed scheme, this probability depends upon orthogonal subchannel allocation in virtual cells. According to the proposed scheme, one virtual cell can have a maximum of N_{SCH} subchannels, and all vehicles select resources randomly from L_{SCH} using subframes in one resource reservation interval (N_{SF_RRI}) (100 subframes). If the total number of vehicles (N_v) is less than or equal to N_{SF_RRI} (100 subframes) then ε_{HD} will be 0 because of the balanced distribution of resources. If the total number of vehicles (N_v) is greater than N_{SF_RRI} then ε_{HD} can be measured by using Eq. (1). The proposed enhanced C-V2X mode-4 tries to minimize the HD effect by using orthogonal subchannel allocation. To this aim, the probability that v_{rx} cannot receive a CAM transmitted by v_{tx} due to the HD effect is expressed as:

$$\varepsilon_{HD} = \begin{cases} \dfrac{N_{SCH} - 1}{(N_{SCH} \cdot N_{SF\_RRI}) - 1}, & \text{if} N_v > (N_{SF\_RRI}) \\ 0, & \text{if} N_v \leq (N_{SF\_RRI}). \end{cases} \quad (2)$$

B. SENSING POWER THRESHOLD ERRORS (ε_{SEN})

ε_{SEN} is the probability of CAM delivery failure due to a weak P_{rx} that is less than P_{SEN}. The ε_{SEN} does not depend upon the scheduling scheme, so, the derived probability ε_{SEN} from [35] can also be utilized in the proposed scheme. To calculate the SEN error probability, path loss (PL) and shadowing (SH) are considered. The PL is modeled with a log distance function and SH is modeled with a log-normal random distribution with the zero mean and variance σ. The SEN error probability can be expressed as:

$$\varepsilon_{SEN}(d_{t,r}) = \frac{1}{2}\left(1 - erf\left(\frac{P_{tx} - PL(d_{t,r}) - P_{SEN}}{\sigma\sqrt{2}}\right)\right), \quad (3)$$

where erf is the well-known error function, P_{tx} is transmission power, $PL(d_{t,r})$ is the pathloss at distance $d_{t,r}$, and σ is the variance in shadowing. The detailed calculations of SEN probability can be found in [35].

C. PROPOGATION EFFECT ERRORS (ε_{PRO})

The scheduling scheme in C-V2X mode-4 does affect the probability of CAM loss due to the propagation effects.

Thus, the expression for the probability of ε_{PRO} from [35] is applicable to this study. ε_{PRO} depends upon the receiver's PHY layer performance. The performance of the PHY layer is modeled with the link-level look-up tables (LUTs) included in [36]. Block error rate (BLER) is presented in the LUTs as a function of SNR. LUTs are provided according to different parameters (packet size, MCS, scenario, and relative speed). The SNR at the receiver can be computed as a random variable in decibels:

$$SNR(d_{t,r}) = P_{rx}(d_{t,r}) - N_0 = P_{tx} - PL(d_{t,r}) - SH - N_0, \quad (4)$$

where N_0 denotes noise power, and it is worth noting that for a given distance the path loss is constant. SNR follows the same distribution as shadowing but with a different mean $P_{tx} - PL(d_{t,r}) - N_0$. PRO error probability can be expressed as:

$$\varepsilon_{PRO}(d_{t,r}) = \sum_{s=-\infty}^{+\infty} BL(s) \cdot f_{SNR|P_{rx}>P_{SEN},d_{t,r}}(s), \quad (5)$$

where

$$f_{SNR|P_{rx}>P_{SEN},d_{t,r}}(s) = \begin{cases} \dfrac{f_{SNR}, d_{t,r}(s)}{1-\varepsilon_{SEN}}, & \text{if } P_{rx} > P_{SEN} \\ 0, & \text{if } P_{rx} \leq P_{SEN}. \end{cases} \quad (6)$$

$BL(s)$ is the BLER obtained from the LUTs in [35] for an SNR that is equal to s. The PDF of the SNR at distance $d_{t,r}$ for SNR values, lies in $P_{rx} > P_{SEN}$, as taken from Eq. (6). In Eq. (6) $P_{rx} > P_{SEN}$ is normalized by $1 - \varepsilon_{SEN}$ to ensure that the integration between $-\infty$ and $+\infty$ of the PDF of the SNR is equal to 1.

D. CAM COLLISION ERRORS (ε_{COL})

COL errors occur when v_{tx} and an interfering vehicle v_i are transmitting using the same resources (subframe and subchannel), and the interference generated by v_i causes CAM delivery failure at v_{rx} due to an insufficient SINR. Hence, the COL error probability depends upon the probability that two or more vehicles are using the same resource. The COL errors are related to the scheduling scheme. We propose a COL error model based on our proposal in this paper. Probability $\varepsilon_{COL}(d_{t,r})$ can be expressed as:

$$\varepsilon_{COL}(d_{t,r}) = 1 - \prod_i \left(1 - \varepsilon^i_{COL}(d_{t,r}, d_{t,i}, d_{i,r})\right). \quad (7)$$

Interfering vehicle v_i causes COL errors, if v_i and v_{tx} simultaneously transmit using the same resource. Thus, the probability of COL error due to v_i can be expressed as:

$$\varepsilon^i_{COL}(d_{t,r}, d_{t,i}, d_{i,r}) = P_{SIM}(d_{t,i}) \cdot P_{INT}(d_{t,r}, d_{i,r}). \quad (8)$$

In Eq. (8), $P_{SIM}(d_{t,i})$ is the probability that two or more vehicles are using the same resource simultaneously, whereas $P_{INT}(d_{t,r}, d_{i,r})$ is the probability that the interference by v_i is greater than the threshold value that determines correct CAM reception when two or more vehicles transmit using the same resource.

1) THE PROBABILITY THAT $P_{INT}(D_{T,R}, D_{I,R})$ IS HIGHER THAN THE THRESHOLD VALUE

For the $P_{INT}(d_{t,r}, d_{i,r})$ expression, the negative effect of interference by v_i on the v_r is considered as additional noise [35]. The receiver side SINR can be computed with the following expression:

$$SINR(d_{t,r}, d_{i,r}) = P_{rx}(d_{t,r}) - P_i(d_{i,r}) - N_0, \quad (9)$$

where P_i is the signal power of v_i received at v_{rx}. Thus, SINR is the summation of two random variables P_{rx} and P_i. By using the mean of the cross-correlation of the PDF of P_{rx} and P_i, the PDF of the SINR can be calculated. Then, the probability of packet loss due to a low SINR can be calculated as:

$$P_{SINR}(d_{t,r}, d_{i,r}) = \sum_{s=-\infty}^{+\infty} 0BL(s) \cdot f_{SNR|P_{rx}>P_{SEN},d_{t,r},d_{i,r}}(s). \quad (10)$$

Eq. (10) includes CAM failure due to propagation effects. Since the probability of CAM failure due to propagation effects is already included in PRO errors (ε_{PRO}) only collision errors are considered in this normalization:

$$P_{INT}(d_{t,r}, d_{i,r}) = \frac{P_{SINR}(d_{t,r}, d_{i,r}) - \varepsilon_{PRO}(d_{t,r})}{1 - \varepsilon_{PRO}(d_{t,r})}. \quad (11)$$

2) THE PROBABILITY THAT VEHICLE V_{TX} AND VEHICLE V_I TRANSMIT USING THE SAME RESOURCES(SUBCHANNEL AND SUBFRAME) AT THE SAME TIME

The probability $P_{SIM}(d_{t,i})$ depends upon the scheduling scheme used. In the proposed scheme, vehicles choose resources randomly from orthogonally allocated subchannels. The probability of v_t and v_i using the same resource can be calculated with this expression:

$$P_{SIM}(d_{t,i}) = \frac{C_{res}(d_{t,i})}{N_{SF\_RRI} \cdot N_{SCH}}, \quad (12)$$

where $C_{res}(d_{t,i})$ denotes the candidate resources, which are common between v_t and v_i for CAM broadcasts. In the proposed scheme, the vehicle randomly chooses resources (i.e., subframe and subchannel). Then, for the availability of resources, the vehicle checks the whole resource frame (Fr_{res}) for all allocated subchannels in the VC and identifies occupied resources (O_{res}) on these allocated subchannels. Therefore, the candidate resources can be calculated as:

$$C_{res}(d_{t,i}) = (Fr_{res} \cdot N_{SCH}) - O_{res}. \quad (13)$$

By using $P_{SIM}(d_{t,i})$ and $P_{INT}(d_{t,r}, d_{i,r})$, the probability of experiencing a COL error is calculated for each potential v_i using Eq. (8) and ε_{COL} is calculated with Eq. (7). The CDR is obtained by utilizing Eq. (1), with ε_{HD}, ε_{SEN}, ε_{PRO}, and ε_{COL} errors computed using Eqs. (2), (3), (5), and (7), respectively.

TABLE 3. Simulation parameters.

General Parameters	Description
Road layout	Linear, crossway (5+5 lanes)
Maximum number of vehicles in one virtual cell	300 (using 3 subchannels) 400 (using 3 subchannels)
Vehicle speed	60km/h
Pathloss model	WINNER +B1
CAM awareness range	100 - 500m
NS-3 version	3.27
V-UE Parameters	
Message size	190 bytes
Transmission power	23dBm
Resource reservation interval	100ms
Modulation and coding scheme	13
Resource pool parameters	
Channel bandwidth	20 MHz
Number of subchannels	10
Subchannel scheme	Adjacent
Subchannel size	10 RBs
Lowest RB subchannel index	0
Subframes per frame	10
Frames per RRI	10

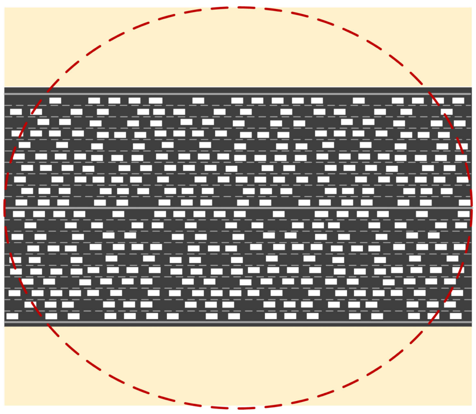


FIGURE 6. Three hundred stationary vehicles in one virtual cell with 300 m radius.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

A. PERFORMANCE ANALYSIS METHODOLOGY AND DATA COLLECTION

For the performance analysis, we implemented the proposed scheme on the network simulator 3 (NS-3) C-V2X mode-4 module introduced by F. Eckermann et al. [37]. The default C-V2X Sim [37] performs V2V communication as defined in 3GPP standards and validates results by two parameters: (i) packet reception ratio (PRR) which is calculated by X/Y, where Y is the number of vehicles that are located in the baseline distance (a, b) from the transmitter, and X is the number of vehicles with successful packet reception among Y, and (ii) packet inter-reception ratio (PIR) that describes the time between two successful receptions of two different successive packets transmitted from vehicle A to vehicle B.

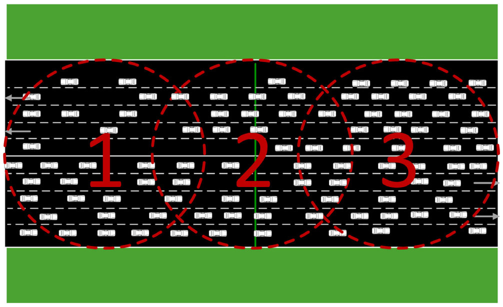


FIGURE 7. Linear topology of three virtual cells each with a 300 m radius.

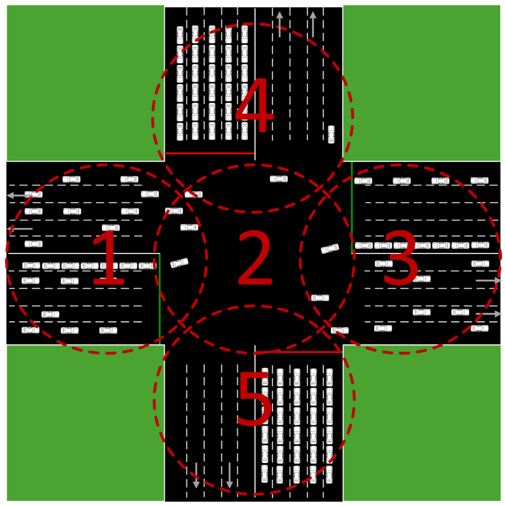


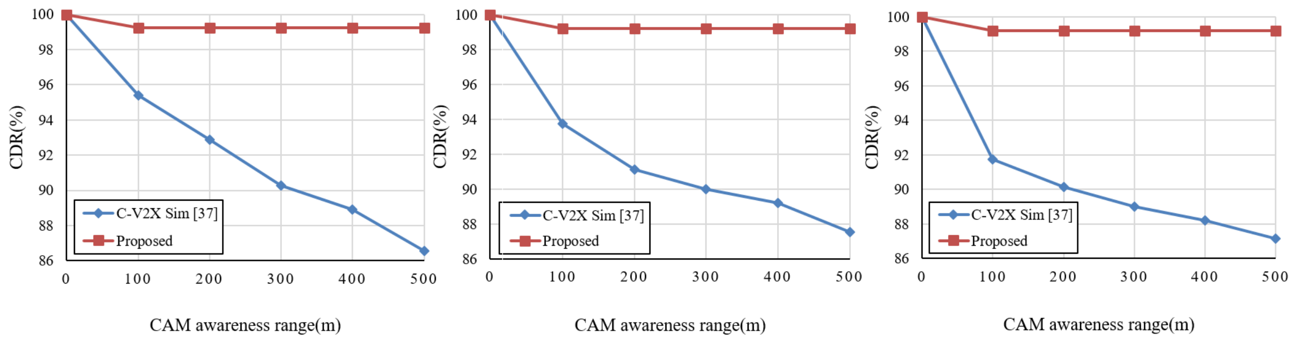
FIGURE 8. Crossway topology of five virtual cells with a 300 m radius.

This paper presents the concept of virtual cell, resource usage bitmap (RuBMP), and smart roaming and implemented in the default C-V2X Sim [37]. For the real-time assessment, we use the SUMO simulator with NS-3 C-V2X mode-4 module. SUMO provides the traces of random positions of vehicles on the road to NS-3, and NS-3 uses these traces to run simulations. We evaluate our proposed scheme in different scenarios: stationary and mobile (linear and crossway topology). We validate our results with different parameters: (i) CAM delivery ratio (CDR), (ii) packet inter-reception ratio (PIR), and (iii) collision resolving time (CRT).

B. SYSTEM ENVIRONMENT AND SCENARIO

1) SYSTEM PARAMETERS

In this section, the performance of the proposed scheme is analyzed based on the measurements of simulation experiments in comparison with the basic C-V2X module in the NS-3 network simulator [37]. Up to 400 vehicles were placed in a fully congested crossway scenario as shown in Fig. 3. All vehicles moved from one location to another. Simulations were conducted by using MCS 13; the CAM length was set to 190 bytes with transmission power at 23 dBm. The WINNER+B1 model was used to coordinate



(a) Stationary Scenario (b) Linear Scenario (c) Crossway Scenario

FIGURE 9. CAM delivery ratio from increasing ranges of CAM awareness for 400 vehicles with cellular bandwidth of 20 MHz in (a) a stationary scenario, (b) a linear scenario, and (c) a crossway scenario in a virtual cell with a 300 m radius.

with 3GPP in NS-3. The CAM awareness range was set between 100 ∼ 500 m at a channel bandwidth of 20 MHz, and the CDR was used as the performance metric. The simulation parameters are shown in Table 3.

2) STATIONARY SCENARIO

In the stationary scenario, up to 300 vehicles were stationary in one virtual cell with a radius of 300 m, as shown in Fig. 6. For a more realistic assessment, we used a setting similar to the urban scenario. The positions of the vehicles were random, and the number of lanes on the bidirectional road was set to 10 + 10, which makes the road wider to include all 300 vehicles in one virtual cell.

3) MOBILE SCENARIOS

For simulation of vehicular traffic in mobile scenarios, two topologies were used: linear and crossway.

- Linear topology
  In the linear topology, a two-way road with a length of 1.7 km was considered with three virtual cells, each configured with a 300 m radius and 50 m overlapping areas. For a more realistic assessment, vehicular traffic was simulated in SUMO with 5 + 5 lanes. All vehicle speeds were random based on the position of the vehicle, as shown in Fig. 7. Red dotted lines show the virtual cells; all vehicles were located within range of a virtual cell, and they randomly changed position from one lane to another based on their speed.
- Crossway topology
  In the crossway topology, an intersection with a length of 1.7 km was considered with five virtual cells. Each VC had a 300 m radius and 50 m overlapping areas. For more realistic assessments, vehicular traffic was simulated in SUMO with 5 + 5 lanes. All vehicle speeds were random based on the position of the vehicle, as shown in Fig. 8. Red dotted lines show the virtual cells; all vehicles were located within the range of a virtual cell and randomly changed position from one lane to another based on their speed.

C. PERFORMANCE ANALYSIS

1) PERFORMANCE ANALYSIS WITH DIFFERENT RATES OF CAM AWARENESS RANGE

Fig. 9 depicts the CAM delivery ratios when increasing the range of CAM awareness on a cellular bandwidth of 20 MHz using the stationary, linear, and crossway scenarios in a virtual cell with a 300 m radius. Fig. 9(a) compares the CDR curves obtained with the proposed enhanced C-V2X mode-4 scheme versus the default C-V2X Sim [37] for 300 stationary vehicles in a VC (a fully congested scenario). Fig. 9(a) clearly shows that the proposed scheme provided consistently higher CDR values of up to 99.25% with increasing ranges for CAM awareness. The CDR of C-V2X Sim decreased as the CAM awareness range increased. The proposed scheme was capable of providing high CDR values in high-density traffic by avoiding RF interferences and CAM collisions for increased ranges of CAM awareness.

Fig. 9(b) compares the CDR of the proposed scheme and the default C-V2X Sim [37] in a linear topology of 300 vehicles per VC. Fig. 9(b) clearly shows that the proposed scheme had consistently high CDR values of up to 99.20% with increasing ranges of CAM awareness, whereas the CDR of C-V2X Sim decreased as the CAM awareness range increased. The proposed scheme was able to provide high CDR values in high-density traffic by avoiding system interference and CAM collisions with increased ranges of CAM awareness.

Fig. 9(c) compares the proposed scheme's CDR curves with the default C-V2X Sim [37] for the crossway topology where 400 vehicles are in the central VC (VC 2). Fig. 9(c) clearly shows that the proposed scheme provided consistently high CDR values of up to 99.20% with the increased ranges of CAM awareness, whereas the CDR for C-V2X Sim decreased as the CAM awareness range increased. The proposed scheme was able to provide high CDR values in high-density traffic by avoiding system interference and CAM collisions with increasing ranges of CAM awareness in the crossway topology.

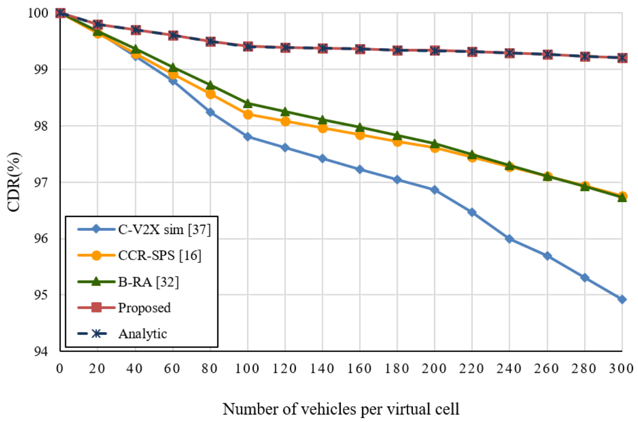


FIGURE 10. CAM delivery ratio for an increasing number of vehicles at the 20 MHz bandwidth for a stationary scenario in a virtual cell with a 300 m radius.

2) CDR PERFORMANCE ANALYSIS FOR STATIONARY SCENARIO

Fig. 10 depicts the CDR when the number of vehicles in one cell is increased to 300 (a congested scenario) when using three subchannels with 20 MHz channel bandwidth. The results show that the proposed scheme enhanced performance remarkably, even in a congested scenario of 300 vehicles. CDR was up to 99.20% at 20 MHz, as shown by the red line. The navy blue line shows the analytical model, which is very close to the simulation results (red line). Yellow and green lines show previous researches in mode-4 (CCR-SPS and B-RA) with CDR at almost 97% (or more). On the other hand, the CDR of the C-V2X Sim decreased to 95% at 20 MHz (the blue line) proving that, in comparison with C-V2X Sim, the proposed scheme enhances performance by almost 5% from using the RuBMP. The proposed scheme mitigates half-duplex collisions, especially in the congested scenario when the number of vehicles increased to 300 in one virtual cell.

3) CDR PERFORMANCE ANALYSIS FOR LINEAR TOPOLOGY

To guarantee safety, vehicular communication must be scalable. Fig. 11 depicts the CAM delivery ratio when the number of vehicles increases to 300 in the central cell (VC 2) in the linear topology using three subchannels with 20 MHz bandwidth. The vehicle density is the maximum for one VC with three subchannels. The vehicles were randomly located on 5 + 5 lanes and communicated while passing each other in opposite lanes. The results indicate that the proposed scheme (red line) provided a higher CDR of up to 99% for similar congestion scenarios, compared to the C-V2X simulator algorithm in which CDR decreased to 93%. The navy blue line shows the analytical model, which is very close to the simulation. However, higher congestion level decreased the CDR. The improvement in CDR is due

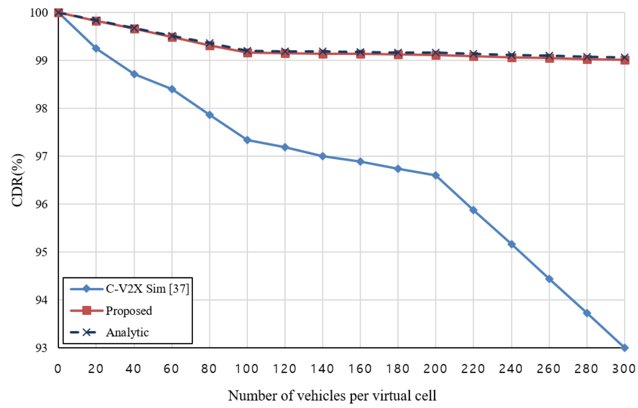


FIGURE 11. CDR for increasing numbers of vehicles in a VC with a 300 m radius in a linear topology at the 20MHz bandwidth.

to collision avoidance in the proposed scheme by using the RuBMP in the EMIB.

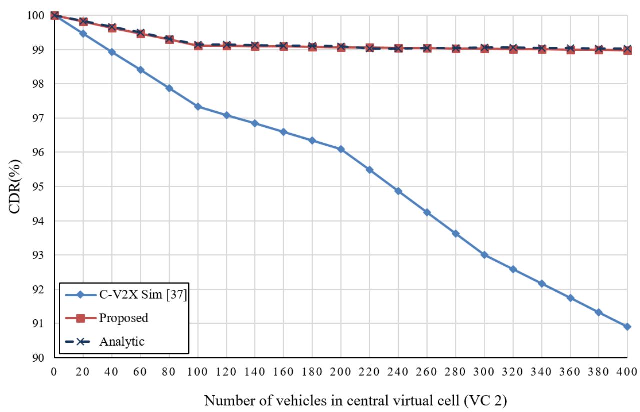


FIGURE 12. CDR for increasing numbers of vehicles in a VC with a 300 m radius in a crossway topology at the 20 MHz bandwidth.

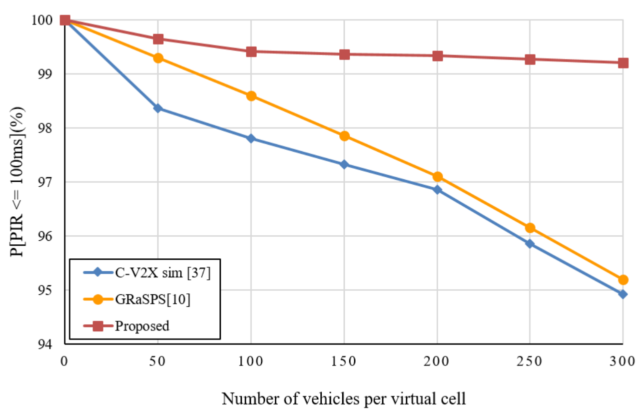


FIGURE 13. Fraction of the PIR <= 100 ms for an increasing number of vehicles at 20 MHz bandwidth.

4) CDR PERFORMANCE ANALYSIS FOR CROSSWAY TOPOLOGY

Fig. 12 depicts the CDR when the number of vehicles is increased to 400 (highly congested) in one central cell in the crossway topology using four subchannels with 20 MHz channel bandwidth. That vehicle density is the maximum for one VC with four subchannels. The vehicles were randomly located on 5 + 5 lanes and communicated while passing each other in opposite lanes. The results indicate that using the same crossway topology, the CDR of the proposed scheme (red line) stayed at 99% (or more) in comparison to the CDR of the C-V2X Sim, which fell to around 91% (blue line). The navy blue line shows the analytical model, which is very close to the simulation results. In the default SB-SPS mechanism, collisions increased with the higher number of vehicles due to the usage of the same resources, which caused collisions for a number of packet runs, as shown in the results.

5) PACKET INTER-RECEPTION RATIO (PIR) PERFORMANCE ANALYSIS

Fig. 13 compares the performance of the fraction of PIR values no larger than a 100 ms RRI keeping the CAM update rate. We can see that as the number of vehicles increased, the PIR value decreased for all schemes due to increased congestion in all cases. However, the proposed scheme successfully kept the PIR above 99% (red line), specifically in highly congested metropolitan areas. The orange line shows the GRaSPS scheme [10], which provided slightly higher PIR than the C-V2X Sim (blue line). We can conclude that the proposed scheme clearly outperformed the C-V2X simulator and the GRaSPS scheme, even in severe congestion.

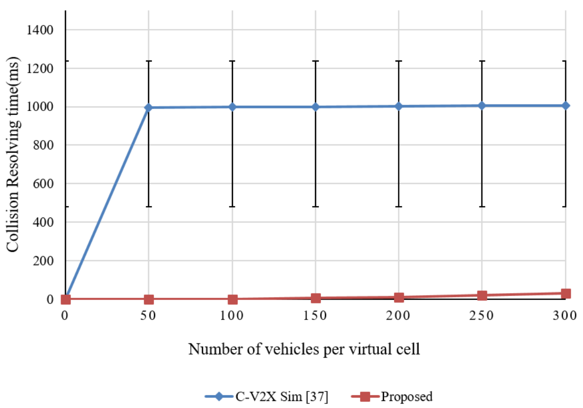


FIGURE 14. Collision resolving time for increasing numbers of vehicles at the 20 MHz bandwidth in a VC with a 300 m radius.

6) PERFORMANCE ANALYSIS WITH COLLISION RESOLVING TIME

Fig. 14 depicts the collision resolving time (CRT) when the number of vehicles in one VC increases to 300 (a congested scenario) using three subchannels with 20 MHz channel bandwidth. The results show that the proposed scheme decreases the CRT remarkably, even in a congested scenario of 300 vehicles in which the proposed scheme's CRT was less than 30 ms (red line). On the other hand, the C-V2X simulator (blue line) had longer collision resolving time even in lower congestion levels. The default SB-SPS has no collision resolution mechanism, and therefore, if a collision occurs, it continues for almost one second, as shown in Fig. 14. Hence, the proposed scheme enhanced the performance of collision resolving remarkably by using the RuBMP, in comparison with the C-V2X Sim, and resolves the half-duplex collision issue, especially in congested scenarios when the number of vehicles is up to 300 in one virtual cell using three subchannels with 20 MHz channel bandwidth.

VI. CONCLUSION

C-V2X mode-4 has severe challenging problems in CAM delivery performance, including (i) unawareness of other vehicle's resource usage, (ii) half-duplex problems in CAM broadcasts, and (iii) the semi-persistent nature of SB-SPS. To resolve these major challenges in C-V2X mode-4, we proposed an enhanced C-C2X mode-4 with virtual cells, providing orthogonal subchannel allocation, periodic broadcasts of a resource usage bitmap using an extended master information block, and smart roaming. For efficient cellular network management, we defined a virtual cell manager that monitors CAM broadcasts by each vehicle, configures the RuBMP that shows the usage of each resource block, prepares EMIB messages with the RuBMP, and broadcasts the EMIB every 10 ms. The performance of the CAM delivery ratio was analyzed with NS-3 simulations. For 300 vehicles in one virtual cell with three subchannels, the CDR from the proposed scheme was more than 99.2% at the 20MHz bandwidth. We showed that the proposed scheme outperformed the basic random resource allocation scheme (C-V2X Sim) by up to 5%. For future work, we will extend this work to enhance the performance of C-V2X mode-3.

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