IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 26, 2022, accepted April 11, 2022, date of publication April 18, 2022, date of current version April 27, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3168671

Improving Performance of C-V2X Sidelink by Interference Prediction and Multi-Interval Extension

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This work was supported in part by the KDDI.

ABSTRACT Cellular Vehicle-to-Everything (C-V2X), as a next-generation V2X communication technique, has attracted much attention recently. Especially, SideLink (SL) of C-V2X in the mode 4 is a promising technique for disseminating various information in a non-line-of-sight area via direct inter-vehicle communication without requiring base stations. In order to better prevent accidents, it is important to improve the reliability and adaptability of SL. However, the Semi-Persistent Scheduling (SPS) method has a limited performance at short distances due to transmission collisions, and cannot well support applications with different transmission intervals. To solve these problems, in this paper, we propose a new packet collision avoidance method, Interference Prediction and Multi-Interval extension (IPMI), for the C-V2X SL mode 4, based on directly predicting the interference vehicles (defined as vehicles in the overlapping communication range of two vehicles using the same resource, and susceptible to packet collisions at reception), without causing extra overhead. Specifically, the proposed method selects for each vehicle a resource that has (i) a minimal number of interference vehicles and (ii) a maximal inter-vehicle distance, to reduce packet collisions. It is further extended to support applications with different transmission intervals. Simulation results confirm that compared with the conventional methods, the proposed method can achieve higher reliability and still have a promising performance even in times of partial deployment.

INDEX TERMS ITS, C-V2X, sidelink, resource allocation, semi-persistent scheduling, collision avoidance, interference prediction, multi-interval.

I. INTRODUCTION

In order to promote Intelligent Transportation Systems (ITS) and autonomous driving technology, there is an urgent need to develop new communication methods that connect Vehicles to Everything (V2X) [1]. C-V2X, as a next-generation V2X communication technique standardized in LTE and 5G, has attracted much attention recently. C-V2X supports direct communications with SideLink (SL) as well as cellular communications via Base Stations (BS) [2]. Compared with on-board sensors such as camera and LiDAR that cannot sense objects in a blind spot, SL is a promising technique for disseminating various information in a Non-Line-of-Sight (NLoS) area via direct inter-vehicle communication without requiring BSs. Because the disseminated information is of great importance for preventing accidents, it is necessary to improve the reliability of SL [3].

In the C-V2X SL, a radio resource is selected for each vehicle in the frequency (subchannel) and time (subframe) space, and used to transmit packets periodically for a short period of time, which is called Semi-Persistent Scheduling (SPS). SL supports two modes, which differ in terms of how resource is allocated. In mode 3, resource allocation is realized by a BS, but it is difficult to share information among vehicles associated with BSs of different operators [4]. In comparison, in mode 4, each vehicle selects its resource autonomously, which makes it possible to share information across different operators. But it faces the hidden terminal problem, i.e., when two vehicles hidden from each other (e.g., due to the NLoS propagation) select the same resource,

The associate editor coordinating the review of this manuscript and approving it for publication was Leandros Maglaras.

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their packets, transmitted simultaneously, collide consecutively at adjacent vehicles, which degrades system reliability.

As for this problem, a previous method suggests resource pre-reservation [13], but it does not ensure a successful reservation. Our previous work estimates the usage status of each resource by exchanging extra information between adjacent vehicles [24], so as to select a resource with the smallest number of vehicles (including hidden vehicles) sharing the resource. However, its performance is limited at short distances. In addition, most previous methods only consider the case where all vehicles transmit packets at the same interval.

In this paper, we propose a new resource allocation method, Interference Prediction and Multi-Interval extension (IPMI), for the SL mode 4, which directly predicts and minimizes the number of interference vehicles (defined as vehicles in the overlapping communication range of two vehicles using the same resource and susceptible to packet collisions at reception) without causing extra overhead, and considers the co-existence of applications with different transmission intervals. In wireless communications, even when multiple packets are transmitted simultaneously, a packet from a near vehicle may be decoded potentially because of the capture effect [5]. In order to make use of this feature and improve packet reception rate at near distances, for each candidate resource, a vehicle explicitly predicts interference vehicles with respect to each of its adjacent vehicles using this resource. And this function is extended to the case where vehicles use different transmission intervals.

The contribution of this paper is three-fold, as follows:

- The concept of interference vehicles is put forward, and packet collisions at short distances are mitigated by letting each vehicle choose a resource that minimizes the number of interference vehicles and maximizes the distance to adjacent vehicles using the same resource.
- The proposed method is enhanced to deal with the potential collisions within a period of least common multiple of transmission intervals, to consider packets collisions that may occur in the future, not in the current resource selection window.
- The above two functions are realized without causing extra overhead, which enables the incremental deployment of the proposed method (coexistence with SPS).

The effectiveness of the proposed method, under both urban and freeway scenarios (including the case of partial deployment) specified by 3GPP, is evaluated by a network simulator, with LTE-V2X release 14.

The rest of this paper is organized as follows: Section II introduces C-V2X. Section III reviews related research and points out challenges in the previous methods. Section IV presents the proposed method, and Section V illustrates the simulation results. Finally, Section VI concludes this paper and points out future work.

II. OVERVIEW OF C-V2X

Convenience and safety are two main targets of modern transportation systems. C-V2X is one of the key technologies for realizing these targets and delivering smart mobility service to users. The 3rd Generation Partnership Project (3GPP) first standardized C-V2X in Rel-14 (LTE-V2X) [6], and then fixed its latest update in Rel-16 (NR-V2X) [7], which defines advanced use cases of V2X and enhanced Ultra-Reliable and Low Latency Communication (URLLC) with 5G New Radio (5G-NR). Direct inter-vehicle communications of V2X are referred to as SideLink (SL) by 3GPP [8], [9], which use the PC5 interface [10].

In order to transmit a packet by SL, a Candidate single Subframe Resource (CSR) needs to be selected, which is a rectangle area in the frequency (subchannel) and time (subframe) space, as shown in Figure 1. It consists of two parts, one is a Physical Sidelink Shared CHannel (PSSCH) part for delivering data information and the other is an adjacent Physical Sidelink Control CHannel (PSCCH) part. Both parts are further composed of Resource Blocks (RB), the minimal resource unit. The amount of RBs per CSR is allocated based on the packet size and the Modulation and Coding Scheme (MCS). In the transmission, vehicle information (position and speed) as data and the resource scheduling information for the next transmission are included in PSSCH and PSCCH, respectively, and the latter enables periodical transmissions.

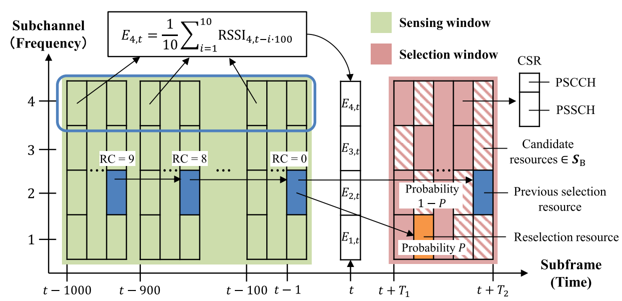


FIGURE 1. Resource reselection with the SPS algorithm (RRI = 100ms).

LTE-V2X SL supports two modes, mode 3 in which a BS manages resource allocation for all its associated vehicles and mode 4 in which a CSR is selected by each vehicle in a distributed way. Mode 1 and mode 2 in the NR-V2X are equivalent to mode 3 and mode 4 in LTE-V2X, respectively. C-V2X is a general term including both LTE-V2X and NR-V2X. In this paper, we focus on LTE-V2X but the proposed method can be applied to NR-V2X as well. When there is no ambiguity, the terms "resource" and "CSR" are used interchangeably.

A. MODE 3

In mode 3, each BS, with relatively large computing capacity, manages resource allocation for all vehicles in its coverage in a centralized way, which makes it possible to meet the application requirements such as reliability and latency. However, mode 3 is limited to the coverage of BSs [11], and it works only for vehicles associated with the same operator [4]. When vehicles associated with different operators run in the same area, the communication reliability will be degraded.

B. MODE 4

Mode 4 is designed to work in a distributed way, without requiring BSs, which enables it to work in mountainous or disaster areas outside the coverage of BSs. Besides, all vehicles communicate with the same frequency band, and exchange information regardless of operators. But it is necessary to configure initial parameters to meet the requirement of a local region [12]. By using channel sensing and the SPS scheme, each vehicle can select a resource with a low collision probability, and use it for periodical transmission in a short interval. In the following, we review the SPS algorithm.

1) CHANNEL SENSING

Denote resource reservation interval as RRI. In order to monitor the usage status of each CSR, each vehicle calculates $E_{f,t}$, average RSSI corresponding to a CSR in the sensing window, defined between $t-1000$ and $t-1$ [ms] (f is subchannel and t is subframe time).

$$E_{f,t} = \frac{\mathrm{RRI}}{1000}\sum\nolimits_{i=1}^{1000/\mathrm{RRI}} \mathrm{RSSI}_{f,t-i\cdot\mathrm{RRI}}. \tag{1}$$

For example, when RRI is configured to 100ms in (1), a vehicle always collects ten RSSI for a CSR in the past 1 second (sensing window) and computes the average.

2) RESELECTION CANDIDATES

Each vehicle uses a Reselection Counter (RC) to manage how many times its periodical transmission will continue, and decreases its RC per transmission. When its RC reaches 0, with a reselection probability (P), a vehicle will try to select a new CSR, in order to avoid potential consecutive transmission collisions.

First, a set of candidate resources will be selected from a selection window based on the average RSSI per CSR. The selection window, as shown in Figure 1, is defined as $[t+T_1, t+T_2]$ $(T_1 \leq 4, 20 \leq T_2 \leq 100\,[\mathrm{ms}])$. Denote the set of all CSRs in the selection window as $\boldsymbol{S}_\mathrm{A}$. Next, 1) the CSRs with an average RSSI above the Reference Signal Received Power (RSRP) threshold, and 2) the CSRs reserved by other vehicles, are excluded from $\boldsymbol{S}_\mathrm{A}$ and the remaining CSRs form $\boldsymbol{S}'_\mathrm{A}$. The above procedures are repeated by increasing the RSRP threshold at a step of 3dB until $|\boldsymbol{S}'_\mathrm{A}|$ is greater than or equal to 20% of $|\boldsymbol{S}_\mathrm{A}|$ ($|\boldsymbol{S}|$ is the cardinality of $\boldsymbol{S}$).

3) RESOURCE RESELECTION

$\boldsymbol{S}'_\mathrm{A}$ is sorted in the increasing order of $E_{f,t}$, and the top 20% CSRs form a set $\boldsymbol{S}_\mathrm{B}$. Then, a CSR is randomly selected from $\boldsymbol{S}_\mathrm{B}$. Meanwhile, the RC is initialized by a value randomly selected from a window $[\mathrm{RC}_{\min}, \mathrm{RC}_{\max}]$, where $\mathrm{RC}_{\min} = 5\cdot \mathrm{RRI}_{\max}/\mathrm{RRI}$ and $\mathrm{RC}_{\max} = 15\cdot \mathrm{RRI}_{\max}/\mathrm{RRI}$ are defined by RRI. Here, $\mathrm{RRI}_{\max}$ is the maximal value of RRI.

III. RELATED RESEARCH AND ITS PROBLEMS

A. RELATED RESEARCH

In order to prevent packet collisions in the selected resource, a pre-reservation method was suggested in [13]. Usually when RC is decreased to 0, a vehicle will try to select a new CSR and does not include the reservation information for current CSR in PSCCH. In the pre-reservation method, the new CSR to be used for the next transmission is included instead, as a temporary reservation [13]. If other vehicles do not pre-reserve the same new CSR, this pre-reservation is successful, and the new CSR will be treated as a formal reservation, and used for the next transmission without collisions. However, the pre-reservation is also susceptible to failure when multiple vehicles pre-reserve the same CSR. Besides, it is necessary to modify the default format of PSCCH and this procedure is not compatible with the SPS method.

Furthermore, [14] investigated how to reduce packet collision probability in the coexistence of different transmission intervals. In such cases, it is necessary to consider not only resources in the current selection window but also their periodical use in the future. To this end, resource usage in a period of least common multiple of transmission intervals is checked, and a resource will be precluded if it will lead to a future collision. However, simply precluding reserved resources will reduce the number of available resources for selection, and potentially increase interferences on non-reserved resources.

Pre-configured parameters are important in mode 4, because all vehicles select their CSRs in a distributed way without BS supports. Appropriate configurations, considering a variety of V2X use cases, were studied in [15] and [16]. In particular, the relationship between reselection probability and congestion degree was studied in [15], which shows that a decrease of reselection probability does not always lead to the improved reliability in a highly congested environment. Furthermore, a method that controls the duration of consecutively using a resource is studied in [17]. By defining the maximum number that a vehicle can reselect the same resource, this method helps to reduce the probability of successive collisions. An optimal allocation method, which considers the difference in packets sizes, is studied in [18]. By avoiding both resource holes and overlapping, this method helps to maximize the number of vehicles that can be supported in the network. It is known that packet loss increases due to transmission collision in a congestion environment [19]. To solve this problem, a distributed congestion control (DCC) was studied in [20], which suggests dropping packets (enlarging RRI) in order to reduce the Channel occupation Ratio (CR) of each vehicle if the Channel Busy Ratio (CBR) caused by all vehicles exceeds a threshold value. Moreover, there is a congestion control based on coordinately changing transmission power, which helps to improve Packet Reception Ratio (PRR) at nearby vehicles [21]. However, the controls of packet drop and transmission power may degrade Age of Information (AoI) [22]. Therefore, it is necessary to investigate other methods.

In addition to C-V2X SL, the Dedicated Short-Range Communication (DSRC) method has been studied before as a means of inter-vehicle communications, outside the framework of cellular communication. A comparison between

DSRC and C-V2X is reported in [23], which shows that DSRC is better in terms of latency in some scenarios while SL achieves higher reliability by resource reservation.

B. CONSIDERING THE HIDDEN TERMINAL PROBLEM

In order to avoid packet collisions caused by adjacent vehicles (including hidden vehicles from which packets cannot be directly received), we studied how to exchange resource usage information via PSSCH among vehicles, and on this basis select a CSR, which is called SPS with Collision Avoidance (SPS-CA) hereafter [24].

First, Resource Busy Information (RBI) is computed at each vehicle by monitoring CSRs in the last RRI (between previous transmission time to the next transmission). RBI is a flag vector, where each bit corresponds to a CSR, set to 1 when a packet in the corresponding CSR is decoded correctly, and 0 otherwise. The bit corresponding to the CSR that a vehicle currently uses is cleared to 0 because it cannot detect this using a half-duplex transceiver.

Each vehicle adds RBI to the PSSCH of its transmission as addition information. When a vehicle A received a packet from another vehicle B, and selects a CSR whose associated flag bit is set in the RBI received from B, a packet collision will occur at B in the selected CSR. In this way, A could predict a potential packet collision for each CSR whose flag bit is set to 1 by adjacent vehicles. Furthermore, the sum of flag bit corresponding to each CSR received from all adjacent vehicles in the last RRI is used to represent the resource usage of each CSR.

Then, resource candidates are generated as $\boldsymbol{S}'_{\mathrm{A}}$, in the same way as in Sec.II.A2. But different from Sec.II.A3, all resources in $\boldsymbol{S}'_{\mathrm{A}}$ are sorted in the increasing order of the resource usage (as a primal key) and in the increasing order of RSSI (as a secondary key), and a CSR is randomly selected from the top 20% of $\boldsymbol{S}'_{\mathrm{A}}$.

Disseminating additional information about resource usage in SPS-CA does help to estimate resource usage and mitigate packet collisions, but at the cost of extra overhead. Because SPS-CA also considers resource usage caused by hidden terminals, its PRR is improved in the long-distance range, but its effectiveness in the short-distance range is small. In vehicular networks, especially safety related applications, it is expected to disseminate packets preferentially to neighbor vehicles than those far away. Furthermore, in the real environment, applications with different requirements will transmit packets at different intervals, which is not well investigated yet. Therefore, it is necessary to solve all these problems simultaneously.

IV. PROPOSED METHOD

To solve the aforementioned problems in one framework, we propose the Interference Prediction and Multi-Interval extension (IPMI) method, to further improve the reliability of SL mode 4 in the short-distance range without causing extra overhead, and support different transmission intervals.

Vehicles from which a packet is received recently (e.g., within 1.5 seconds) are called adjacent vehicles. Vehicles, in the overlapping communication range (interference area) of two adjacent vehicles using the same resource and susceptible to packet collisions at reception, are called interference vehicles. In this way, for a vehicle selecting resources, its interference vehicles are associated with each adjacent vehicle, and change per resource.

In the resource selection process, first, a vehicle predicts interference vehicles associated with each adjacent vehicle, based on vehicle location information. Among adjacent vehicles using the same resource, the vehicle with the largest number of interference vehicles and the shortest inter-vehicle distance is selected to represent the resource, i.e., the resource has the same number of interference vehicles and inter-vehicle distance as the selected vehicle. When vehicles use different transmission intervals, to consider the potential collisions due to periodical transmissions in the future, resources in a period of least common multiple of transmission intervals, longer than the current selection window, are checked, and their impacts are reflected in the current selection window. Finally, in the selection window, a set of resources with a minimal number of interference vehicles and a maximal inter-vehicle distance, are found, from which one is randomly selected for the transmission. In the following, we will describe the IPMI algorithm in detail.

A. PREDICTION OF INTERFERENCE VEHICLES

Different from the previous method [24] where each vehicle predicts the usage status of each resource and selects the least used one, in the proposed method, each vehicle predicts interference vehicles of each adjacent vehicle, aiming to minimize the number of interference vehicles susceptible to packet collisions due to simultaneous transmissions from the vehicle and its adjacent vehicle.

When transmission collisions occur at a vehicle, several packets are simultaneously received from multiple vehicles. A packet from a near vehicle may be decoded potentially because of the capture effect. The proposed method will use this feature.

Assume vehicle i needs to select a resource and is checking a candidate resource r. For each of its adjacent vehicle j that currently uses r, vehicles, in the overlapping area of communication ranges of i and j, form a set of interference vehicles $\boldsymbol{I}_{i,j}$. E.g., in Figure 2, the set of interference vehicles between i and $j = 1$ is $\boldsymbol{I}_{i,1} = \{4, 5, 7\}$. The required communication range of a vehicle is defined by using the vehicle's position as a center and a distance D as a radius. Although i does not know the instantaneous position of j, it can predict this based on position and speed information received from j in the past, e.g., within 10 seconds.

Algorithm 1 shows the pseudo-code for predicting interference vehicles. The input is the ID of vehicle i, and the output is $\boldsymbol{I}$, a set of interference vehicles between i and its adjacent vehicles. j denotes an adjacent vehicle of i (line 4). From

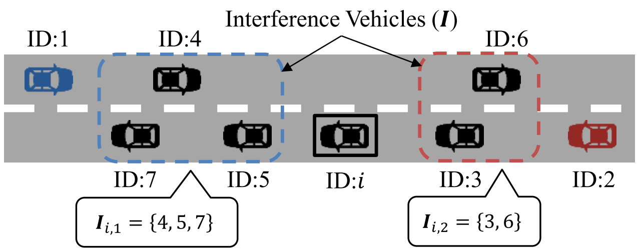


FIGURE 2. Set of interference vehicles.

Algorithm 1: Prediction of Interference Vehicles

1: **Procedure: PredictInterferenceVehicles**
2: **Input:** i
3: **Output:** $\boldsymbol{I}$ *# Set of the interference vehicles*
4: **for** each vehicle j whose signal is received by i within 1.5s **do**
5: $\quad \boldsymbol{I}_{i,j} \leftarrow \emptyset$ *# Initialization of* $\boldsymbol{I}_{i,j}$
6: $\quad$ **for** each vehicle k whose signal is received by i within 10s **do**
7: $\quad\quad$ **if** $\|P_i - P_k\| < D$ and $\|P_j - P_k\| < D$ **then**
8: $\quad\quad\quad$ *# Vehicle k is a potential interference vehicle of i and j*
9: $\quad\quad\quad \boldsymbol{I}_{i,j} \leftarrow \{k\} \cup \boldsymbol{I}_{i,j}$
10: $\quad\quad$ **end if**
11: $\quad$ **end for**
12: **end for**
13: **return**

line 6 to 11, for each adjacent vehicle k of i, its Euclidean distance to i, $\|P_i - P_k\|$, and that to j, $\|P_j - P_k\|$ are computed separately. If both distances are less than the required communication range D, which means k lies in the overlap range of i and j, k is added to $\boldsymbol{I}_{i,j}$.

B. EXTENSION OF MULTI-INTERVAL

Each vehicle uses a different transmission interval depending on application requirement. When a small transmission interval is used, the number of resource candidates in the selection window decreases, and it means more transmissions in the future under the periodical transmission policy. Therefore, it is necessary to estimate the status of a resource not only at the selection time (in the selection window) but also consider potential interference due to future transmissions. However, SPS cannot achieve this because SPS only considers a selection window equaling to the transmission interval.

Here, we take for example the coexistence of transmission intervals (RRI) of 20, 50 and 100ms, and it is easy to extend to other RRI values. Figure 3 shows an example, where the RRIs of i and j equal to 20ms and 50ms, respectively, and their least common multiple is 100ms. If i selects No. 5 resource and j selects No. 45 resource, no collision occurs in the selection windows (0-19) of i. But within a window of 100 ms, i will also use resources with No. 25, 45, 65 and 85, separated by its RRI $= 20$, and j will also use No.95 resource. Here, at No. 45 resource, the first transmission of j collides with the 3rd transmission of i. However, No. 45 resource is not included in the selection window of i ($\boldsymbol{S}_{\mathrm{A}}$), so its collision cannot be avoided. In the proposed method, based on interference status of resource candidates ($\boldsymbol{S}_i$) in a large window ($\boldsymbol{S}_{\mathrm{lcm}}$) whose length is least common multiple of different RRIs, i can take this collision into account.

When the number of vehicles is large, it is not possible to completely avoid potential collisions in the future. Therefore, simply precluding resources that could cause future interferences may even fail [14]. Instead, our policy is to project the potential collisions in the future to the current selection window, and select the resource with a new metric, the number of interference vehicles.

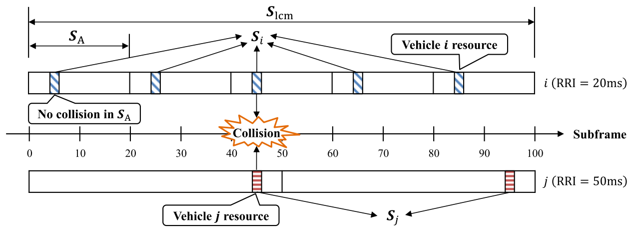


FIGURE 3. Consideration of multiple transmission intervals.

The scheme that supports different RRIs is shown in Algorithm 2. The input is the ID of vehicle i, and the output is table T that considers future resource usage in the current selection window of i. T has two columns, one is T_r^I reflecting the number of interference vehicles between vehicle i and its adjacent vehicle considering $r \in \boldsymbol{S}_{\mathrm{lcm}}$ as a candidate resource, and the other is T_r^D, the corresponding inter-vehicle distance. In line 5 to 7, T_r^I and T_r^D are initialized properly. Then, T is computed by two steps.

In the 1st step (line 10), $\boldsymbol{S}_j$ is a set denoting future resources up to $\mathrm{RRI}_{\mathrm{lcm}}$ ahead that will be used by vehicle j. It should be noted that vehicle j may change its resource in this period, but such information is not known in advance because only the resource for the next transmission is reserved. For simplicity, it is assumed that vehicle j will use the same resource in this period. Next, in line 11 to 15, T_r^D and T_r^I are updated to record the distance $\|P_i - P_j\|$ and the number of interference vehicles.

In the 2nd step (line 18), for each of the candidate resource r in the selection window $\boldsymbol{S}_{\mathrm{A}}$ used by i, its number of interference vehicles and inter-vehicle distance, corresponding to its future use due to periodical transmissions, are updated by the values of the specific resource with the minimal inter-vehicle distance. This is because the nearest neighbor causes the largest interference when using the same resource. In this way, the future status of a resource is projected to the selection window, and taken into account in the resource selection.

C. IPMI ALGORITHM

The whole IPMI algorithm is shown in Algorithm 3. First, for vehicle i, its set of interference vehicles, $\boldsymbol{I}$, is computed (line 2), based on Algorithm 1 in Sec. IV. A. Next, for each resource in the selection window of i, table T containing the number of interference vehicles and inter-vehicle distance, considering packet collisions in the future, is computed (line 3), based on Algorithm 2 in Sec. IV. B. Then, resources

Algorithm 2: Extension of Multi-Interval

Procedure: ExtendMultiInterval
Input: $i, \boldsymbol{I}$
Output: T
 # Initialization of table T
for each resource r of $\boldsymbol{S}_{\mathrm{lcm}}$ **do**
  $T_r^I \leftarrow 0$ and $T_r^D \leftarrow \infty$
end for
 # 1st step
for each vehicle j whose signal is received by i within 1.5s **do**
  Set future resources of j to $\boldsymbol{S}_j$
  for each resource r of $\boldsymbol{S}_j$ **do**
    if $\|P_i - P_j\| < T_r^D$ **then**
      $T_r^D \leftarrow \|P_i - P_j\|$ and $T_r^I \leftarrow |\boldsymbol{I}_{i,j}|$
    end if
  end for
end for
 # 2nd step
for each resource r of $\boldsymbol{S}_{\mathrm{A}}$ **do**
  Set future resources of r used by i to $\boldsymbol{S}_i$
  for each resource m of $\boldsymbol{S}_i$ **do**
    if $T_m^D < T_r^D$ **then**
      $T_r^D \leftarrow T_m^D$ and $T_r^I \leftarrow T_m^I$
    end if
  end for
end for
return

in set $\boldsymbol{S}_{\mathrm{A}}$ are sorted (line 4) in the increasing order of the number of interference vehicles (as a primal key), and in the decreasing order of inter-vehicle distance (as a secondary key). Finally, the resources with the same optimal parameters (the number of interference vehicles and inter-vehicle distance) form a new set $\boldsymbol{S}_{\mathrm{B}}$ (line 5-13), from which a resource is randomly selected for vehicle i (line 14).

Algorithm 3: IPMI Algorithm

1: Set resource-allocation vehicle to i
2: $\boldsymbol{I} \leftarrow$ PredictInterferenceVehicles (i)
3: $T \leftarrow$ ExtendMultiInterval $(i, \boldsymbol{I})$
4: Sort $\boldsymbol{S}_{\mathrm{A}}$ in the increasing order of $T^I_{r\in\boldsymbol{S}_{\mathrm{A}}}$ and in the decreasing order of $T^D_{r\in\boldsymbol{S}_{\mathrm{A}}}$
5: Set the first resource of $\boldsymbol{S}_{\mathrm{A}}$ to r_f
6: Move the first resource from $\boldsymbol{S}_{\mathrm{A}}$ to $\boldsymbol{S}_{\mathrm{B}}$ *# Initial $\boldsymbol{S}_{\mathrm{B}}$ is $\emptyset$*
7: **for** each resource r of $\boldsymbol{S}_{\mathrm{A}}$ **do**
8:   **if** $T_r^I = T_{r_f}^I$ and $T_r^D = T_{r_f}^D$ **then**
9:     Move the resource r from $\boldsymbol{S}_{\mathrm{A}}$ to $\boldsymbol{S}_{\mathrm{B}}$
10:   **else**
11:     **break**
12:   **end if**
13: **end for**
14: Select a resource randomly from $\boldsymbol{S}_{\mathrm{B}}$ for vehicle i

D. COMPARISON OF KEY FUNCTIONS

The comparison of key functions among SPS, SPS-CA [24], IPMI and IPMI+ (IPMI run at base stations) is summarized in Table 1 O means yes and X means no. In order to confirm the upper bound of IPMI, IPMI+, in which BSs learn the instantaneous positions of all vehicles and allocate resources in a centralized way, is also included. The key functions in the comparison are 1) prediction of interference vehicles, 2) multi-interval extension and 3) without extra overhead. IPMI outperforms SPS and SPS-CA which implement only one feature. The resource usage in SPS-CA is a little similar to the number of interference vehicles in IPMI, but it focuses more on the interference at the transmitting vehicle. By collecting resource usage information from adjacent vehicles, it helps to mitigate the hidden terminal problem. In comparison, IPMI focuses more on the interference at receiving vehicles, and considers the nearest vehicle (using the same resource) that has the largest interference, which helps to control interference at the short-distance range. Compared with IPMI+, IPMI has another feature, not requiring BSs.

TABLE 1. Comparison of key functions among different methods.

Function	SPS	SPS-CA	IPMI	IPMI+
Prediction of interference vehicles	×	○	○	○
Multi-interval extension	×	×	○	○
Communication without overhead	○	×	○	×

SPS: Semi-Persistent Scheduling
SPS-CA: SPS with Collision Avoidance
IPMI: Interference Prediction and Multi-Interval extension
IPMI+: IPMI run at base stations

V. SIMULATION EVALUATION

Simulation evaluation is performed on the network simulator Scenargie [26] enhanced with the C-V2X function (3GPP Rel-14 compliant), using the urban and freeway scenarios specified by 3GPP. Four methods summarized in Table 1 will be evaluated and compared.

A. EVALUATION METRICS

Packet Reception Ratio (PRR) and Packet Collision Ratio (PCR) are used as the main metrics in the evaluation.

- PRR indicates how reliably packets sent by broadcast arrive at vehicles within the required communication range (D), and is calculated as the percentage of packets correctly decoded at target vehicles. Besides, its results are computed per distance between transmitting vehicles and receiving ones, to show how PRR changes with distances.
- PCR reflects how often packet failure occurs due to simultaneous transmissions from multiple vehicles (packet collisions), and is computed as the percentage of failed packets due to packet collision. Its results are also computed per distance, in a same way as PRR.

B. SIMULATION ENVIRONMENT AND CONDITIONS

In the evaluation, we use the scenarios [27] defined by 3GPP, including both an urban model for cities and a freeway model for highway. The number of vehicles is different in each scenario, and changes with the speed, e.g., the inter-vehicle distance between adjacent vehicles on the same lane is set to be greater than or equal to the distance that vehicles move in

TABLE 2. Common simulation parameters.

Item	Value
Simulator	Scenargie with C-V2X extension
Communication method	LTE-V2X sidelink mode 4
Frequency	5.9GHz
Bandwidth	10MHz
Subchannel	1
Packet size	128 bytes (without header)
RRI	20, 50, 100ms
Propagation model	ITU-RP.1411
Reselection counter	Random in [RC_{min}, RC_{max}]
Reselection probability	1.0
Selection window	[0, each RRI]
Number of executions	20 times
Simulation time	50s

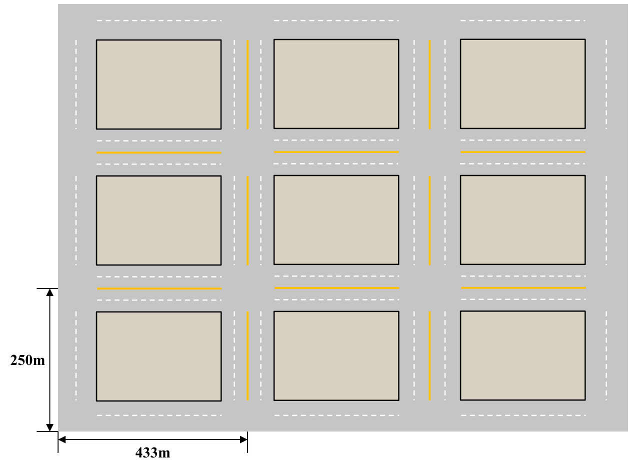


FIGURE 4. Simulation area (urban model).

2.5 seconds. Each vehicle has a random initial position, and moves at a fixed speed. In the urban model, each vehicle also randomly changes its moving direction at intersections. The number of subchannels is set to 1 in all scenarios in order to emulate a highly congested environment. The packet size (except for PSCCH and header) is set to 128 bytes including vehicle location, according to [28]. There are three types of RRIs (20, 50, 100 ms) in the simulation, which are allocated equally, i.e., the number of vehicles for each RRI is the same, and for each vehicle one RRI is used throughout the simulation. RC is selected randomly within [RC_{min}, RC_{max}] based on RRI. The reselection probability (P) is set to 1.0, i.e., resource reselection always will be performed when RC reaches 0. The selection window size [T_1, T_2] is [0, RRI] and changes with RRI. Initial packet in each vehicle is generated at a random time and subsequent packets are generated at a fixed interval specified by RRI. Simulation results are averaged over 20 runs with different network topologies. All simulations run for 50 seconds, during which communications are performed from 10 to 40 seconds. Main simulation parameters are shown in Table 2.

1) URBAN MODEL

In the urban model, a scenario with 1299 × 750 meter (9 grids each with 433 × 250 meter) is used, which is defined by 3GPP for V2X simulation in the city environment. All vehicles move on the road at the same, fixed speed, 15 or 60 km/h. The number of vehicles depends on the speed, 591 vehicles (96.1 vehicles per 1 km) at the speed 15 km/h and 147 vehicles (23.9 vehicles per 1 km) at the speed 60 km/h. The road has two lanes on each side (four lanes in total), and there are buildings on the roadsides that obstruct wireless propagation. The required communication range (D) is approximately a distance that vehicles move in 4 seconds, being 133.3 m when vehicles move at the speed 60 km/h in the opposite direction and is set to 150 m. The simulation environment of the urban model is shown in Figure 4.

2) FREEWAY MODEL

In the freeway model, a scenario with a straight road of 3 km is used. All vehicles move on the road at the same, fixed speed, 70 or 140 km/h. The number of vehicles is sets to 369 (20.5 vehicles per 1 km) at the speed 70 km/h and 126 (7 vehicles per 1 km) at the speed 140 km/h. The road has three lanes on each side (six lanes in total), and there are no buildings on the roadsides. Each vehicle, when reaching either end of the road, starts to move in the opposite direction. To get a stable result, only vehicles within 1 km from the road center are evaluated. Furthermore, the required communication range (D) is approximately set to a distance that vehicles move in 4 seconds, being 311.1 m when vehicles move at the speed 140 km/h in the opposite direction and set to 320 m. The simulation environment of the freeway model is shown in Figure 5.

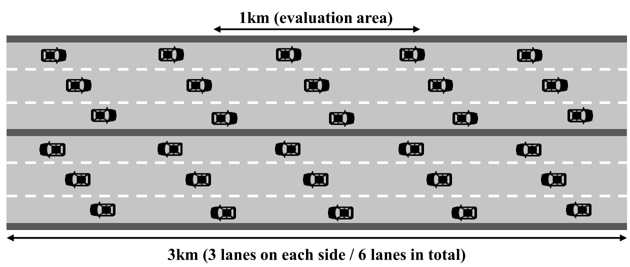


FIGURE 5. Simulation area (freeway model).

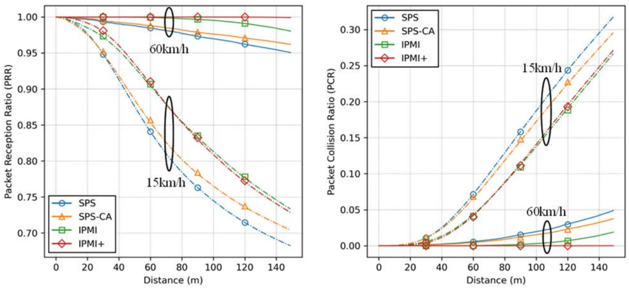
C. SIMULATION RESULTS AND DISCUSSIONS

1) RELIABILITY

a: URBAN MODEL

The results of PRR and PCR, with respect to communication distance in the urban model, are shown in Figure 6. In Figure 6 (a), IPMI achieves higher PRR than SPS and SPS-CA, regardless of the communication distance.

In Figure 6 (b), PCR of IPMI is much reduced in the range where PRR has a large improvement, which infers that the main reason of PRR improvement lies in the PCR reduction. Furthermore, in the 60km/h scenario, IPMI has a similar performance as PIMR+ when the distance is no more than 100m. In the 15 km/h scenario, IPMI has a similar performance as IPMI+ in the whole range. IPMI+ is even slightly inferior to IPMI after 70 m, probably because D is at most 33.3 m and the optimization of PRR is mainly for vehicles in this range.



(a) Packet Reception Ratio (PRR) (b) Packet Collision Ratio (PCR)

FIGURE 6. **Reliability in the 15 or 60 km/h scenarios (urban model): (a) Packet reception ratio (PRR), (b) Packet collision ratio (PCR).**

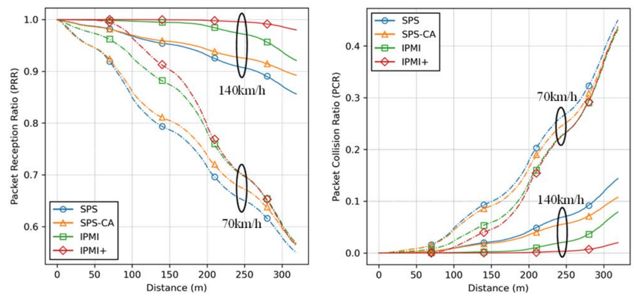
Furthermore, Table 3 shows PRR and PCR values for the 4 seconds distance between vehicles in the same or opposite direction in the urban model. At the speed 60km/h, PRR in all methods is greater than 95%, even at a distance of 133.3 (in the opposite direction). However, when the speed is 15km/h, PRR of SPS and SPS-CA is degraded to below 95% in the opposite direction, and only IPMI and IPMI+ can achieve a PRR above 95%. Compared with SPS, IPMI improves PRR by about 3.1% at the distance 33.3m (at the speed 15km/h). In the short distance range, SPS-CA can hardly improve PRR compared with SPS, but IPMI can, which is a promising property for applications requiring ultra-reliability.

b: FREEWAY MODEL

The results of PRR and PCR, with respect to communication distance in the freeway model, are shown in Figure 7. In Figure 7 (a), IPMI achieves higher PRR than SPS and SPS-CA at both speeds (140 km/h and 70 km/h), regardless of communication distance. Its improvement is large in the short distance range but decreases as the distance increases, almost no effect when the vehicle density is relatively high at the speed 70 km/h. This is because with LOS paths between vehicles in the freeway model, the capture effect is obvious at a short distance, while the impact of interferences becomes dominant at a long distance. Actually, in the long-distance range (at 70km/h), all methods, including IPMI+, have a similar poor performance because wireless signals propagate more than necessary, which leads to many interferences. To solve this problem, other methods such as transmission power control need to be considered, which is left as future work.

TABLE 3. **PRR and PCR at 4 seconds distance (same or opposite direction) in the urban model.**

Scenario	Distance	Method	PRR (%)	PCR (%)
60km/h (147 vehicles)	66.7m (same direction)	SPS	98.24	0.717
		SPS-CA	98.62	0.560
		IPMI	99.89	0.043
		IPMI+	100.00	0.000
	133.3m (opposite direction)	SPS	**95.72**	3.768
		SPS-CA	96.72	2.883
		IPMI	**98.69**	1.143
		IPMI+	99.97	0.003
15km/h (591 vehicles)	16.7m (same direction)	SPS	98.51	0.161
		SPS-CA	98.25	0.187
		IPMI	98.93	0.115
		IPMI+	99.48	0.056
	33.3m (opposite direction)	SPS	**93.81**	1.456
		SPS-CA	94.03	1.403
		IPMI	**96.70**	0.777
		IPMI+	97.45	0.602



(a) Packet Reception Ratio (PRR) (b) Packet Collision Ratio (PCR)

FIGURE 7. **Reliability in the 70 or 140 km/h scenarios (freeway model): (a) Packet reception ratio (PRR), (b) Packet collision ratio (PCR).**

The PRR and PCR values for 4 seconds distance between vehicles in the same or opposite direction in the freeway model are shown in Table 4.

At the speed 140 km/h, PRR in all methods is over 95% in the same direction, but in the opposite direction, only IPMI+ can achieved a PRR above 95%. At the speed 70 km/h (with a high congestion degree), SPS and SPS-CA do not achieve a PRR above 95% in the same direction. And in the opposite direction all methods fail to achieve a PRR 90%. In this extreme case, IPMI improves PRR by about 11% compared with SPS, and its effect is the largest in all scenarios and distances, which confirms that the proposed IPMI method is effective in improving the performance in the congested environment.

2) EVALUATION OF PARTIAL DEPLOYMENT

In the previous evaluations, it is assumed that all vehicles use the same method, e.g., IPMI. But it usually takes time for a new technology to spread in the world. Therefore, here, we evaluate the performance of IPMI in the partial deployment (i.e., some vehicles use IPMI while other vehicles use

TABLE 4. PRR and PCR at 4 seconds distance (same or opposite direction) in the freeway model.

Scenario	Distance	Method	PRR (%)	PCR (%)
140km/h (126 vehicles)	155.6m (same direction)	SPS	95.122	2.238
		SPS-CA	95.701	1.968
		IPMI	99.440	0.258
		IPMI+	99.958	0.019
	311.1m (opposite direction)	SPS	**86.201**	13.399
		SPS-CA	89.633	10.064
		IPMI	**92.716**	7.072
		IPMI+	98.248	1.700
70km/h (369 vehicles)	77.8m (same direction)	SPS	90.449	2.095
		SPS-CA	90.951	1.981
		IPMI	95.550	0.981
		IPMI+	99.068	0.207
	155.6m (opposite direction)	SPS	**78.352**	10.265
		SPS-CA	80.163	9.398
		IPMI	**87.022**	6.199
		IPMI+	89.831	4.873

SPS), by changing the deploy rate of vehicles that use IPMI. We will investigate at which deploy rate there is a merit for vehicles using IPMI and whether there is a harm on vehicles still using SPS. To this end, two PRRs are calculated. One measures the percentage of packets, transmitted by a vehicle using IPMI and correctly received by other vehicles (using either IPMI or SPS), and the other is for packets from vehicles using SPS.

a: URBAN MODEL

Figure 8 shows the PRR with respect to communication distance in the urban model. Here, the rate in a legend is the percentage of vehicles using the method. In Figure 8 (a), IPMI achieves higher PRR than SPS in any deploy rate, regardless of distance. In addition, its improvement increases with the deploy rate, i.e., the more vehicles use IPMI, the higher improvement in PRR. Furthermore, PRR of the rest vehicles using SPS also is higher than that of SPS (100%) where only SPS is used, regardless of distance. This is because in IPMI, a vehicle tries to select a resource that has the least impact on adjacent vehicles, regardless of whether an adjacent vehicle uses SPS or IPMI, which helps to reduce interference on vehicles using SPS. Next, in Figure 8 (b), IPMI is still superior to SPS at the speed 15 km/h, where the channel is much congested. The increase in the deploy rate of IPMI does not lead to obvious differences in PRR of vehicles using IPMI, and in all cases, PRR of vehicles using SPS is not degraded compared with the case where all vehicles use SPS.

b: FREEWAY MODEL

Figure 9 shows the PRR with respect to communication distance in the freeway model, where the deploy rate of IPMI is used as a parameter. In Figure 9 (a), at the speed 140 km/h, IPMI achieves higher PRR than SPS in any deploy rate, and

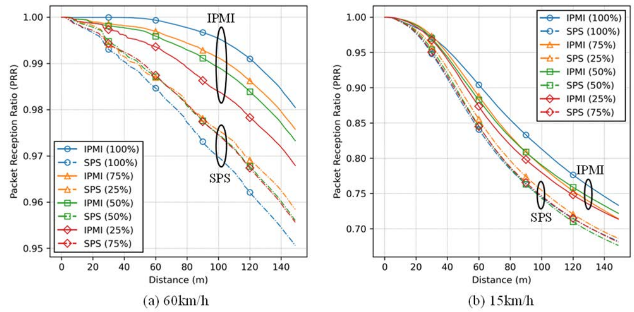


FIGURE 8. Reliability of SPS and IPMI in the urban model: (a) PRR at 60km/h, (b) PRR at 15km/h. IPMI (100%) and SPS (100%) are PRRs where all vehicles use IPMI or SPS. IPMI (75%) and SPS (25%) correspond to a PRR of 75% vehicles applying IPMI and a PRR of the rest 25% vehicles still using SPS, respectively. Similarly, IPMI (50%) and SPS (50%) correspond to PRRs where 50% vehicles apply IPMI while the rest 50% vehicles still use SPS, and IPMI (25%) and SPS (75%) correspond to PRRs where 25% vehicles apply IPMI while the rest 75% vehicles still use SPS.

PRR of the rest vehicles using SPS is not degraded. In general, PRR of vehicles using IPMI can reach 95% at a distance up to 200m. Next, in Figure 9 (b), at the speed 70 km/h, the superiority of IPMI over SPS gets smaller, especially in the long-distance range, because of severe interferences caused in the congested environment.

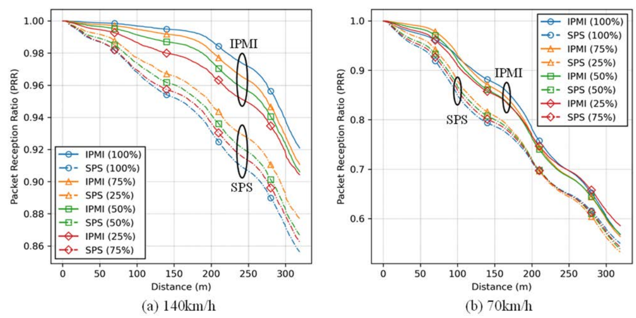


FIGURE 9. Reliability of SPS and IPMI in the freeway model: (a) PRR at 140km/h, (b) PRR at 70km/h. IPMI (100%) and SPS (100%) are PRRs where all vehicles use IPMI or SPS. IPMI (75%) and SPS (25%) correspond to a PRR of 75% vehicles applying IPMI and a PRR of the rest 25% vehicles still using SPS, respectively. Similarly, IPMI (50%) and SPS (50%) correspond to PRRs where 50% vehicles apply IPMI while the rest 50% vehicles still use SPS, and IPMI (25%) and SPS (75%) correspond to PRRs where 25% vehicles apply IPMI while the rest 75% vehicles still use SPS.

Based on all the above results, we can see that IPMI can improve PRR, especially in the short distance range, although actual improvement depends on the environment (urban or freeway), vehicle speed, and deploy rate. It is confirmed that partial deployment is also beneficial, and does not cause harm to vehicles not using this technique. There is still room for improvement, especially in the congested freeway environment, where the performance is interference limited, and a further investigation is necessary.

VI. CONCLUSION

In this paper, we have proposed a new resource scheduling method (IPMI) for C-V2X sidelink (mode 4). The proposed method predicts interference vehicles for each candidate resource (using position information received from adjacent vehicles), and reduces packet collisions by minimizing the number of interference vehicles at the selected resource, which neither modifies the format of PSCCH nor causes extra overhead. It is further enhanced to support applications with different transmission intervals, by considering potential packet collisions in the future. Compared with SPS, the proposed IPMI method improves PRR by 3.1% at 33.3 m in the urban model (15km/h) and by 11% at 155.6 m in the freeway model (70km/h). In addition, we confirmed that IPMI still achieves good performance in times of partial deployment, which is a promising feature to enable its incremental deployment.

In the future, we will try to enhance the proposed method to deal with channel congestion, evaluate its performance in more realistic environments where vehicles move at different, time-varying speeds and transmit packets with different sizes, and extend it to the NR-V2X (Rel-16) system.

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