This article has been accepted for publication in IEEE Transactions on Wireless Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TWC.2023.3326852

Resource Reservation Coordination for Vehicle Platooning in C-V2X Networks

Xin Gu, Jun Peng, *Senior Member, IEEE,* Lin Cai, *Fellow, IEEE,* Weirong Liu, Xiaoyong Zhang, and Zhiwu Huang

***Abstract*—High-reliability and low-latency communication is essential for timely information exchange in vehicle platooning. As a key enabler of this, the cellular vehicular-to-everything (C-V2X) network uses a sensing-based semi-persistent scheduling (SPS) protocol, where radio resources are reserved for a number of transmissions with reduced resource re-allocation and control overhead. However, consecutive access collisions may be caused by reservation conflict, which leads to long delay and threatens platoon's stability and safety. In this paper, a coordinating resource reservation (CRR) protocol is proposed for vehicle platooning. By implementing error detection with coordination among platoon vehicles, the resource reservation is improved for reduced collisions and delay. Specifically, packet reception/loss information is sent out by platoon vehicles through their own packets. Such information is shared with transmitters and guides them to reserve new resources when access collision occurs. As a result, long delay is avoided while no extra feedback packet is introduced. Furthermore, Markov analysis is presented to evaluate the performance of SPS and the proposed CRR for vehicle platooning, providing the quantified performance gains. Finally, simulation results demonstrate the superiority of the proposed CRR in reducing packet loss and latency, compared with the legacy SPS and other state-of-the-art solutions.**

***Index Terms*—Vehicle platooning, medium access control, resource reservation, cellular vehicle-to-everything.**

I. Introduction

Vehicle platooning utilizes automated driving and communication to let a group of vehicles travel closely in a train-like manner. The advantages include increasing road capacity, saving fuel, and reducing gas emissions [1]. The platoon's safety and stability rely on reliable and timely exchange of status information among vehicles [2]. The status information is contained in small packets called beacon messages, which are transmitted periodically among vehicles. The Third Generation Partnership Project (3GPP) has introduced the cellular vehicle-to-everything (C-V2X) network to support advanced applications such as vehicle platooning [3]. However, how to share radio resource by platoon vehicles is challenging, given the limited wireless resource, dynamic channel condition, high vehicular mobility, and interference coming from non-platoon vehicles.

Another challenge of communication design for vehicle platooning arises from the platoon's characteristics. Compared with beacon broadcasting of non-platoon vehicles, communications for platooning has more stringent reliability requirements. The reason is that platoon vehicles usually travel closely in close coordination, which requires high-rate and high-reliability communications [4]. Specifically, platoon vehicles may need to use information from multiple neighbors, including predecessors and followers. This is determined by the information flow topology (IFT), a key component of the platoon system [5]. Considering a scenario where platoon and non-platoon vehicles coexist and compete for spectrum resource, how to enable the reliability of platoon communication has not been sufficiently addressed, which motivated our work.

Resource reservation is desirable for periodical beacon broadcast of vehicles with reduced resource re-allocation and control overhead [6]. The cellular vehicle-to-everything (C-V2X) has adopted a distributed resource reservation medium access control (MAC) protocol, which is the sensing-based semi-persistent scheduling (SPS) [7]. However, SPS encounters successive packet losses and unbounded delay caused by conflicting reservations.

Recently, many researches have been conducted by modifying the current protocol SPS to achieve improved reliability and control long delay. Simultaneous resource selection and hidden terminals are two main causes of access collision in SPS [8]. To handle the simultaneous resource selection conflict, recent literature proposed to detect the conflict beforehand, but the hidden terminal problem remains unsolved [9]. Furthermore, some researches were conducted to limit the duration of using the same resources [10], so that the delay caused by consecutive collisions is limited within several seconds for enhanced road safety. Nevertheless, a few seconds of delay can lead to crash for a platoon with the inter-vehicle distance less than 15 m during the braking process, and the delay beyond 100 ms can cause large disturbances in a platoon, according to [5]. From the above analysis, more efficient resource reservation is needed for supporting the stringent communication requirements of platooning.

Feedback from the receivers can guide the transmitter to reserve new resources when collision occurs, so that long delay caused by consecutive collisions is avoided. Considering the relatively stable car-following mode of platooning, it is potential to exploit inter-vehicle coordination for collision feedback in medium access. In this paper, a coordinating

This work was supported in part by the National Natural Science Foundation of China under Grants 61873353 and 62172448. *(Corresponding author: Zhiwu Huang.)*

X. Gu and Z. Huang are with the School of Automation, Central South University, Changsha 410075, China (e-mail: guxin15@csu.edu.cn; hzw@csu.edu.cn).

J. Peng, W. Liu and X. Zhang are with the School of Computer Science, Central South University, Changsha 410075, China (e-mail: pengj@csu.edu.cn; frat@csu.edu.cn; zhangxy@csu.edu.cn).

L. Cai is with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC V8W 3P6, Canada (e-mail: cai@ece.uvic.ca).

resource reservation (CRR) MAC protocol is proposed for vehicle platooning. With CRR, consecutive collisions are reduced by coordination among platoon vehicles. The error detection procedure is integrated into SPS, so that platoon vehicles in the neighborhood can remind each other of transmission errors using the sidelink control information (SCI) reserved fields [11]. Different from other collision reduction methods which introduce extra feedback messaging or complicate the protocol, CRR can resolve reservation conflicts without extra feedback payload and is easy to implement. The reliability of platoon communication is improved especially at high network load. Moreover, CRR extends SPS and is backward compatible with the C-V2X standard.

To evaluate the performance of the proposed solution, analytical models are presented based on the Markov chain for the sensing-based SPS with and without coordination. The models incorporate all the important parameters concerning resource reservation, IFT, road traffic, and channel condition. In our preliminary work presented in [12], the SPS protocol was analyzed. We derived the probability that a platoon vehicle successfully delivers periodic beacons to all designated receivers, which indicates communication reliability. In this paper, we further analyze the reliability improvement with coordination. Moreover, the delay distribution is derived for comparison, which proves and quantifies the performance gains in terms of delay thanks to our proposed CRR protocol. The contributions of this paper are summarized as follows.

- A coordinating resource reservation MAC protocol, CRR, is proposed for vehicle platooning. Through coordinating medium access, consecutive collisions and long delay caused by conflicting reservation are reduced. CRR is backward compatible with the C-V2X standard and enables high-reliability and low-latency communication for close coordination among platoon vehicles.
- An analytical framework is developed for both the existing SPS and the proposed protocol. With the framework, provable performance gains are achieved and quantified. The analysis can also be used for guiding the system configuration and parameter control.
- Extensive experiments via simulations are conducted to verify the analysis. Meanwhile, the simulation results demonstrate the performance superiority of the proposed CRR over the existing SPS and other state-of-the-art solutions, in terms of reliability and delay performances.

The remainder of this paper is organized as follows. The following section summarizes the related work. Section III describes the system model and discusses the resource allocation problem in platoon communication. Section IV presents the proposed resource reservation solution. Section V provides the performance analysis of both the 3GPP SPS and the proposed solution based on Markov models. Section VI presents the simulations to verify the performance of the proposed CRR when compared with the 3GPP SPS and other state-of-the-art solutions. Finally, the conclusion is given in Section VII.

II. Related Work

During the past two decades, vehicle platooning has attracted much attention for improving traffic efficiency and safety. The safety and stability of platoons rely on reliable inter-vehicle communications, where developing efficient medium access is significant.

Generally, the medium access approaches for vehicle platooning can be categorized into the centralized and distributed ones, according to the existence of a centralized entity for resource allocation [13]. The entity can be base stations, access points, etc. Authors in [14] assumed that eNodeBs control the allocation of vehicle-to-vehicle transmission resources in platoon. To include more vehicles in a platoon and consume less power, a two-step sub-channel allocation strategy was proposed in [15]. In the strategy, the base station allocates the sub-channel resources to each platoon head, which then performs the intra-platoon allocation. Although centralized MAC can achieve fair resource allocation based on the perfect global channel state information (CSI) collected from vehicles, the channel usage efficiency is hindered by the large CSI overhead in dense scenarios [16]. Moreover, centralized resource allocation faces the single point-of-failure problem.

Compared with the centralized MAC, the distributed medium access does not rely on centralized entities [17]. Platoon vehicles can select resources individually based on their sensing results. C-V2X and IEEE 802.11p are two standards both supporting distributed resource allocation for direct vehicle-to-vehicle (V2V) communications. Authors in [18] compared these two technologies for highway platooning. The results showed that C-V2X achieves more reliable communication performance in high-density scenarios and allows for shorter inter-vehicle distances than IEEE 802.11p. The sensing-based SPS adopted in C-V2X networks empowers distributed resource reservation and has been adopted in industry recently [19].

Previous analytical works showed that consecutive collisions may be caused by conflicting reservation in SPS [20]. Consecutive collisions lead to long delay, which impairs the platoon's safety. To address this issue, increasing research efforts were devoted to enhancing SPS for improved reliability and reduced delay. Authors in [21] proposed a hybrid communication scheme to enhance the network reliability. The C-V2X users were assumed to maintain reliable communication and also effectively use the dedicated short-range communications (DSRC) network.

For the delay reduction, an extension to the legacy SPS algorithm was proposed and evaluated in [10]. The risks of consecutive packet losses are reduced by limiting the time of using the same resources, but the achieved delay is still too long for platoon communication. Similarly, a resource alternative selection (RAS) algorithm was designed in [22], where multi-resources are reserved and allocated alternatively during one reservation period. This approach can be effective in reducing communication delay. However, the potential impact of RAS on other network performances such as reliability and throughput should be carefully evaluated. Despite these efforts, the achieved performance gain from these solutions is not enough to meet the stringent requirements of platoon communication.

More recently, how to enhance SPS for vehicle platooning has attracted increasing attention. [23] investigated the

This article has been accepted for publication in IEEE Transactions on Wireless Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TWC.2023.3326852

effect of communication delay on the platoon stability. By implementing multiple SPS parallel sessions, redundant transmissions were reduced and resource usage efficiency was improved. In [24], a spectrum sensing scheduling scheme was proposed to reduce the platoon safety risk caused by the increased communication delay when vehicles newly join the platoon. However, both studies focused on a specific information flow topology, leaving the evaluation and improvement of SPS for platooning with various information flow topologies as an open issue.

The feedback scheme is an effective way for reducing packet losses caused by simultaneous resource selection or hidden terminals. With feedback from neighboring vehicles, the vehicles suffering from persistent packet collisions can quickly react and change resources. However, additional overhead may be caused, which limits the channel usage efficiency [6]. One way to reduce overhead is to use padding/reserved bits to facilitate feedback, as demonstrated in [25], where padding bits in the transport block of periodic messages were used for broadcast feedback. As a result, the hidden terminal problems are relieved. However, the limited and changeable padding space size may lead to inadequate channel monitoring and unstable performance. In [9], the piggybacking of lookahead information on periodic safety messages was proposed, reducing message collisions caused by ignorance of other vehicles' internal decisions. Nevertheless, the hidden terminal problem remains unsolved.

From the above analysis, existing works have not adequately addressed the issue of reducing packet losses caused by resource reservation conflicts in SPS, while minimizing additional overhead for high-density platoon vehicles. Motivated by this, we propose a solution that utilizes the SCI reserved fields to facilitate efficient feedback exchange among platoon vehicles, thereby enabling effective coordination of resource reservation without incurring extra feedback packets. Different from the state-of-the-art methods, the proposed solution can efficiently reduce collisions and delay arising from both simultaneous resource selection and hidden terminals, considering the topology characteristics of platooning vehicles.

III. System Model and Problem Analysis

A. Network Model

In this paper, we consider the scenario where a platoon and several non-platoon vehicles coexist on a two-way road. The platoon vehicles are denoted by $\mathcal{V}^{\mathrm{p}} = \{v_0, v_1, v_2, \ldots, v_m\}$, where v_0 represents the platoon leader (PL) and the rest represent the platoon members (PMs) along the reverse direction of movement. A vehicle platoon P consists of one PL and m PMs. v_1 is the PM right after the PL and v_m is the PM at the platoon tail. The subscripts are their identities (IDs) in the platoon.

The PL is responsible for the steering control and platoon formation. Each PM needs to keep a desired short distance with the predecessor through precise control of the throttle and brake. The set of all vehicles on road, no matter whether they belong to a platoon or not, is denoted by $\mathcal{V}^{\mathrm{a}} = \mathcal{V}^{\mathrm{p}} \cup \mathcal{V}^{\mathrm{n}}$, where $\mathcal{V}^{\mathrm{n}} = \{v_{m+1}, v_{m+2}, \ldots, v_n\}$ is the set of non-platoon vehicles. Thus, $\mathcal{V}^{\mathrm{a}} = \{v_0, v_1, \ldots, v_n\}$.

The information flow topology (IFT) is a key component of a platoon system, and it describes the way a vehicle obtains information from others. Commonly used IFTs include predecessor following, predecessor-leader following, bidirectional, bidirectional leader, two-predecessor following, and so on. Thanks to the advance in vehicle-to-vehicle communication, more general IFTs can be applied, e.g., r-predecessor following, which adds to the flexibility and effectiveness of platoon control.

To study the general case of IFT, we assume that the platoon vehicle v_i uses the information from r predecessors and l followers when $i \in [r, m-l], r+l < m$, as in [5]. Here r and l are constants set by the control strategy of the platoon. When $i \in [0, r-1]$, v_i uses the information from i predecessors and l followers. When $i \in [m-l+1, m]$, v_i uses the information from r predecessors and $(m-i)$ followers. For any receiver v_i, the set of transmitters is denoted by $\mathcal{V}_i^{\mathrm{T}}$. For any transmitter v_i, the set of receivers is denoted by $\mathcal{V}_i^{\mathrm{R}}$. Both sets can be derived based on the above IFT. Let a_i denote the lowest index and b_i denote the highest index of vehicles in $\mathcal{V}_i^{\mathrm{R}}$.

The following assumptions are given. All platoon vehicles are homogeneous and have the same transmit power P^{t}. The inter-vehicle gap between any two consecutive platoon vehicles is assumed as d_{g}, and all vehicles are assumed to have the same length d_{v}. Platoon vehicles can recognize each other through the ID field included in the beacon message, which also contains the platoon vehicle number. All platoon vehicles exchange beacon messages at the same rate.

B. Channel Model

The physical and MAC layers are considered as follows. In C-V2X, the Single Carrier-Frequency Division Multiple Access (SC-FDMA) is adopted, with 10 MHz or 20 MHz channels supported on the 5.9 GHz ITS band [27]. The time-frequency domains are organized into orthogonal wireless resources, i.e., resource blocks (RBs), each of which spans 12 consecutive sub-carriers at a sub-carrier spacing of 15 kHz during one subframe (1 ms). One RB is the smallest resource unit, which is 180 kHz wide in frequency and occupies 1 ms of time duration [27]. The entire channel is divided into multiple sub-channels, each of which consists of a group of RBs in the same sub-frame which is 1 ms. The sub-channels are used to transmit both control and data information. The control information is also referred to as the sidelink control information (SCI), which contains the module and coding scheme (MCS), the used RBs, and the reserved sub-channels for the following transmission.

In the MAC layer, we assume that the sensing-based SPS is used by both platoon and non-platoon vehicles for periodic beacon broadcasting. Following the 3GPP standard [27], no estimation of channel state information (CSI) is adopted considering the difficulty of collecting the CSI information from the receivers. For small packets transmitted in a periodical way, the SPS protocol can achieve high reliability with reduced resource re-allocation and control overhead.

The channel model is given in the following. Let $\mathcal{R}^{\mathrm{a}} = \{r_0^{\mathrm{u}}, r_1^{\mathrm{u}}, r_2^{\mathrm{u}}, \ldots, r_n^{\mathrm{u}}\}$ denote the set of resources reserved by

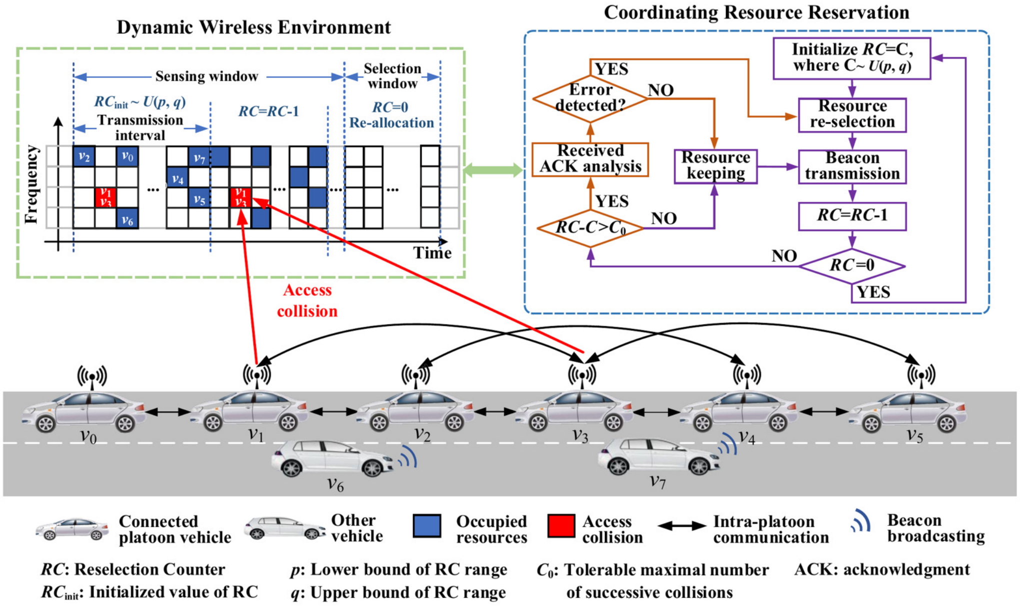


Fig. 1. System model of the proposed coordinating resource reservation MAC protocol for vehicle platooning, where RC_{init} is the initialized value of RC, which follows the uniform distribution between p and q, i.e., $RC_{\text{init}} \sim U(p,q)$.

all vehicles, where r_i^{u} is the resource reserved by v_i. Let $d_{i,j}$ denote the distance between v_i and v_j. Consider a transmitter-receiver pair (v_i, v_j) in the platoon, $d_{i,j} = |i-j|\,(d_{\text{g}} + d_{\text{v}})$ if $i,j \leq m$. Here d_{g} denotes the inter-vehicle gap between two consecutive platoon vehicles, and d_{v} denotes the vehicle length. The power received by v_j, denoted by $P_{i,j}^{\text{r}}$, is a function of $d_{i,j}$, i.e.,

$$P_{i,j}^{\text{r}} = P^{\text{t}} K_0 d_{i,j}^{-\gamma}, \tag{1}$$

where K_0 is a constant determined by the antenna characteristics and the average channel attenuation. γ is the path-loss exponent. Then the signal to interference plus noise ratio is

$$SINR_{i,j} = \frac{P_{i,j}^{\text{r}}}{\sum_{k \neq i, r_k^{\text{u}} = r_i^{\text{u}}} P_{k,j}^{\text{r}} + N}, \tag{2}$$

where $\sum_{k \neq i, r_k^{\text{u}} = r_i^{\text{u}}} P_{k,j}^{\text{r}}$ is the sum of interference power received by v_j, and N is the noise power. The interference is caused when other vehicles near the receiver v_j select the same resource as the transmitter v_i does. Let $SINR_{\text{T}}$ denote the lower bound of SINR, above which the packet can be successfully delivered, i.e., $SINR_{i,j} \geq SINR_{\text{T}}$. According to (2), the SINR can be lower than the threshold if too much interference is caused by resource allocation conflict.

IV. Coordinating Resource Reservation for Vehicle Platooning in C-V2X

The procedure of the sensing-based SPS is described as follows. Each transmitting vehicle selects and reserves one sub-channel (also called one resource) for periodical beacon transmissions. The period that a resource is reserved for a number of transmissions is called a semi-persistent period. A reselection counter (RC), randomly initialized between p and q, is used to determine the duration of a semi-persistent period. p and q are both integers configured by the system.

To select a resource with low interference, the transmitting vehicle measures the reference signals received power of all the sub-channels, during the past 1000 ms, which is called the sensing window. Given a pre-configured threshold, the resources with reference signals received power values below the threshold are the candidate resources. If the proportion of candidate resources among all the selection window resources is less than 20%, the threshold is incremented by 3 dB repeated until the condition of 20% is met. Then, the transmitting vehicle randomly selects one resource from the candidate ones. This resource is reserved for a number of transmissions, defined by RC. After each transmission, the value of RC is decremented by 1. When the value of RC equals zero, the vehicle will reselect and reserve a new resource with the probability $(1-p_0)$, where p_0 is the probability of resource keeping.

In SPS, conflicted reservations may cause successive packet losses and unbounded delay, which threatens platoon's stability and safety. In the scenario where platoon and non-platoon vehicles coexist, how to provide reliable communication has not been fully addressed. Motivated by this, a reliable MAC protocol is designed for platoon communication and it is backward compatible with the C-V2X standard. Specifically, we propose a coordinating resource reservation protocol, where an error detection scheme is integrated into SPS. Fig. 1 shows the procedure of the proposed coordinating resource reservation MAC protocol. The protocol extends the 3GPP SPS to provide high-reliability and low-latency communication for vehicle platooning.

As shown in Fig. 1, the coordinating resource reservation is operated among platoon vehicles. An error detection procedure is performed before the value of RC is decremented to $(C - C_0)$, where C is the initialized value of RC and C_0 is the tolerable maximal time of successive collisions. Here C_0 is determined by

$$C_0 = \lfloor \frac{D_{\text{th}}}{t_0} \rfloor, \tag{3}$$

where D_{th} is the delay threshold given by the platoon application, and t_0 is the time duration for each transmission interval. Therefore, the error detection procedure is executed during the front C_0 transmission intervals after a new resource is reserved.

The above error detection relies on the packet acknowledgment information piggybacked in the neighbor vehicles' packets. With the relatively stable car-following construct in platooning, each platoon vehicle is aware of whose beacon messages should be received and utilized based on the information flow topology. Moreover, all the platoon vehicles periodically broadcast their beacon messages. Such construct stability and transmission periodicity enable the possibility for packet acknowledgment through piggybacking and error detection.

For any vehicle v_i, once it fails to transmit beacon messages to any vehicle in $\mathcal{V}_i^{\text{R}}$, the packet loss information will be piggybacked in the SCI reserved fields of the receiver's beacon message in the next transmission interval. If the packet loss results from the resource selection conflict, upon receiving the piggybacked packet loss information, the transmitter v_i will reselect new a resource so as to avoid consecutive collisions in the future. The proposed MAC protocol can also mitigate the impact of the fading effect on the performance. Given the channel coherence time, if the reserved sub-channel is deep fading, it is desirable that the transmitter switches to a new one by resource reselection. Meanwhile, such reselection does not cause any additional bandwidth usage.

Instead of implementing the negative acknowledgment (NACK) mechanism which requires additionally allocated resources [26], the packet reception/loss information is contained in the existing reserved fields of SCI. As a result, the reliability of platoon communication is improved while no extra feedback messaging is introduced.

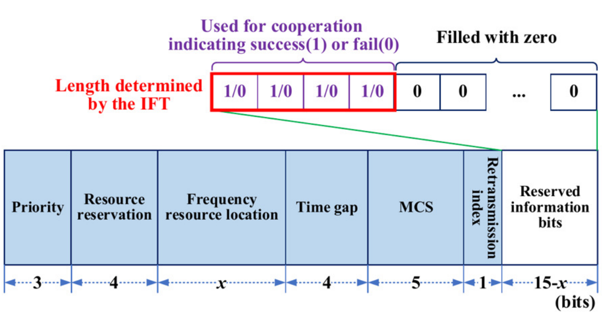


Fig. 2. SCI format 1 fields in C-V2X and the utilized of reserved bits for packet acknowledgment indicators among platoon vehicles.

According to [27], the SCI format 1 contains the message priority, the resource reservation interval, frequency resource location of initial transmission and retransmission, the time gap between the initial transmission and the optional second transmission, the MCS, the retransmission index and some reserved bits, as shown in Fig. 2. The reserved information field occupies $(15 - x)$ bits, where x equals the number of bits utilized for frequency resource location. x is calculated based on the number of subchannels as follow,

$$x = \lceil \log_2 \left(N_{\text{subCH}}(N_{\text{subCH}} + 1)/2 \right) \rceil, \tag{4}$$

where N_{subCH} is the number of subchannels used for transmission. Assuming N_{subCH} as 2, we have $x = 2$, then 13 bits are left for the reserved field. The field size is adequate for the implementation of our designed coordination when assuming $r + l < 10$ in a platoon. The details are as follows.

Let n_{fb} denote the larger number between r and l. In our design, each platoon vehicle v_i detects whether it successfully receives the messages from $\min\{i, n_{\text{fb}}\}$ processors and $\min\{m-i, n_{\text{fb}}\}$ followers. The set of platoon vehicles involved in the error detection and coordination is denoted by $\mathcal{V}_i^{\text{c}}$, which can be represented by $\mathcal{V}_i^{\text{c}} = \{v_j | i - \min\{i, n_{\text{fb}}\} \leq j \leq i + \min\{m - i, n_{\text{fb}}\}, j \neq i\}$.

Since the number of receivers is assumed no more than 10 in IFT, at most 10 bits in the SCI reserved fields are needed for the designed coordinating resource reservation. For any platoon vehicle v_j, it uses each bit to indicate whether it has successfully received messages from every vehicle in $\mathcal{V}_j^{\text{c}}$. For a transmitter-receiver pair (v_i, v_j), the indicator of transmission success or not is denoted by $b_{i,j}$, defined by

$$b_{i,j} = \begin{cases} 1, & \text{success} \\ 0. & \text{failure} \end{cases} \tag{5}$$

The packet acknowledgment scheme is executed at the receiver side, as shown in **Algorithm** 1. After one transmission interval, the receiver examines the reception of packets and determines the piggybacked acknowledgment indicators. According to the IFT, the receiver vehicle v_i verifies if it has received the packet from each transmitter v_j in set $\mathcal{V}_i^{\text{T}}$. If the packet is received from v_j, the corresponding acknowledgment indicator $b_{j,i}$ will be set to 1, and it is set to 0 otherwise. Such packet acknowledgment information is contained in set $\mathcal{L}_i^C$, which will be sent out through its own packet in the next transmission interval.

Algorithm 1 Packet Acknowledgment Algorithm

Input: $\mathcal{V}_i^{\text{T}}$: Set of transmitters for v_i based on the IFT; $\mathcal{L}_i^{\text{T}}$: Set of successful transmitters for v_i;
Output: $\mathcal{L}_i^C$: Set of acknowledgment indicators by v_i;

```
Procedure PACKET ACKNOWLEDGMENT (i, V_i^T, L_i^T)
    L_i^C ← ∅
    for v_j in V_i^T do
        if v_j ∈ L_i^T do
            b_{j,i} = 1
        else do
            b_{j,i} = 0
        end if
        L_i^C ← L_i^C + {b_{j,i}}
    end for
return L_i^C
```

After collecting the piggybacked packet acknowledgment information, the transmitter executes the error detection procedure, as shown in **Algorithms** 2. The transmitter v_i scans

Algorithm 2 Error Detection Algorithm

Input: $\mathcal{L}^C = \{\mathcal{L}_j^C | v_j \in \mathcal{L}_i^R\}$: Set of packet acknowledgment indicators received by v_i, where $\mathcal{L}_j^C = \emptyset$ if v_i receives no message from v_j;

Output: B_c: Indicator that represents whether v_i suffers from transmission errors;

Procedure ERROR DETECTION (i, $\mathcal{L}^C$)
  $B_c =$ FALSE
  for s in $\mathcal{L}^C$
    if $s = 0$ **do**
      $B_c =$ TRUE
      break
    else do
      $B_c =$ FALSE
    end if
  end for
return B_c

the acknowledgment indicators provided in the packets from the designated receivers to identify packet loss or reception. If 0 exists among these indicators, $B_{\mathbf{c}}$ is set to TRUE, prompting the transmitter to reserve new resources for future transmissions.

An example is provided in TABLE I to illustrate the advantage of the proposed intra-platoon coordination design. In the example, r and l are both set to 2 and the platoon contains 6 vehicles, which are $v_0, v_1, \dots v_5$. As shown in Fig. 1, we consider the condition that v_1 and v_3 select the same resource for periodic beacon transmission. Each vehicle uses at most 4 bits to indicate whether the required packets from neighbors are successfully received.

During the packet acknowledgment procedure, v_1, v_2, and v_3 all detect the packet loss from neighbors, so 0 is observed in their SCI reserved fields. Note that v_0 successfully receives the packets from v_1 despite the reservation conflict between v_1 and v_3. This is because v_0 is very close to v_1 and far away from the interfering vehicle v_3. For the similar reason, transmissions from v_3 or v_4 to v_5 are also success.

TABLE I
AN EXAMPLE FOR THE PROCEDURE OF INTRA-PLATOON COORDINATION

Platoon vehicle	Reception indicators for neighbors	Information to check from neighbors	Check result
v_0	1, 1	1, 1	Success
v_1	1, 1, 0	1, 0, None	Collision
v_2	1, 0, 0, 1	1, None, None, 1	Success
v_3	0, 1, 1, 1	None, 0, 1, 1	Collision
v_4	1, 1, 1	1, 1, 1	Success
v_5	1, 1	1, 1	Success

After receiving the packets with packet acknowledgment information from neighbors, each vehicle detects whether transmission error occurs during the previous transmission interval. As shown in the TABLE I, v_1 receives the feedback of collision as it finds "0" in the SCI reserved fields after decoding the packet from v_2. v_1 receives no packet from v_3 because of resource reservation conflict, represented by "None" here. Under this circumstance, v_1 selects a new resource for transmission even though its RC has not decreased to 0. For a similar reason, v_3 selects a new resource after error detection. By doing this, v_1 and v_3 are given a second chance to sense and access the channel, which relieves access collision and avoids long delay to successfully receive beacons.

V. Performance Analysis

In this section, Markov chain-based analysis is presented for the 3GPP SPS protocol with and without the proposed error detection procedure.

A. Markov analysis for 3GPP SPS

To evaluate the performance of the 3GPP SPS, we present a Markov chain that models the state transitions during the channel access process. We observe whether the channel access for a vehicle is successful or not, starting from the first try after the vehicle resets its RC. C_i and T_i are the collision state and the successful channel access state for the i-th try, respectively.

According to our preliminary work presented in [12], we can calculate the access collision probability based on the estimated number of vehicles within the interference range. By utilizing this collision probability, we obtained the state transition probability and the steady state distribution $\mathbf{S} = [s_1, s_2, \dots, s_{2q}]^T$. Here, $s_1, s_2, \dots, s_q$ represent the probabilities of collision states C_1 to C_q, while $s_{q+1}, s_{q+2}, \dots, s_{2q}$ denote the probabilities of transmission states T_1 to T_q. To analyze the reliability performance, we also derived the failure probability of platoon communication by summing up all the probabilities of collision states as follow,

$$U_{\mathrm{F}} = \sum_{i=1}^{q} s_i. \tag{6}$$

This subsection extends the analysis in [12] to include the delay distribution, taking into consideration the stringent delay requirements in platoon communication. In addition, the analytical framework is further extended in Section V-B to consider the impacts of the new algorithms proposed in this work on both reliability and delay performances.

Since the age of information contained in beacons increases fast in highly dynamic scenarios like platoon systems, it is significant that beacons of one transmitter are simultaneously received by all designated receivers for close coordination. Therefore, we analyze the delay until beacons are simultaneously received by all designated receivers.

Let G_k denote the probability of k consecutive collisions. For $k < 2p$, G_k can be derived based on the Markov chain[1], and we have

$$G_k = \begin{cases} \sum_{i=1}^{q} s_{i+q}, & \text{if } k = 0 \\ 0, & \text{if } 0 < k < p \\ \sum_{i=p}^{q} s_{i+q} r_i p_{\mathrm{c}} (u_p + e_p), & \text{if } k = p \\ \sum_{i=p}^{q} s_{i+q} r_i p_{\mathrm{c}} (u_k + e_k) \prod_{i=p}^{k-1} g_i, & \text{if } p < k < 2p \end{cases} \tag{7}$$

[1] G_k can be derived when $k \geq 2p$ with more tedious derivations, which is skipped here since consecutive collisions of $2p$ or more times are typically intolerable in the platoon communication system. For example, if p is set as 10 and the beacon rate is 20 Hz, $2p$ consecutive collisions means delay of 1000 ms.

where p_c is the access collision probability, $r_i = \frac{1-p_0}{q-i+1}$, $u_i = \frac{p_0(1-p_0)}{(q-i+1)^2} + \frac{(1-p_0)(1-p_c)}{q-i+1}$, $e_i = \frac{(1-p_0)(q-i)}{(q-i+1)^2}$, and $g_i = \frac{(q-i)^2}{(q-i+1)^2} + \frac{p_0(q-i)}{(q-i+1)^2}$. Please refer to [12] for derivation details.

In (7), G_k is the probability that delay of $(k+1)t_0$ is caused, where t_0 is the transmission interval, determined by the beacon frequency f, i.e., $t_0 = 1/f$. Channel access with no collision results in delay of t_0, and channel access with k consecutive collisions leads to delay of $(k+1)t_0$, which consists of delay caused by consecutive collisions and delay of new packet transmission. Let D_k denote the delay of kt_0, meaning $(k-1)$ consecutive collisions. Therefore, the delay satisfaction probability that D_k doesn't exceed a given threshold D_{min}, is computed by

$$Prob(D_k \leq D_{\text{min}}) = \sum_{k=0}^{\lfloor \frac{D_{\text{min}}}{t_0} - 1 \rfloor} G_k, k < 2p. \tag{8}$$

B. Markov analysis for the proposed CRR

1) State Transition: Fig. 3 gives the Markov-chain model on condition of our proposed CRR, where SPS is extended with coordinating error detection. When the CRR is adopted, the transition of C_k $(2 \leq k < p)$ will make changes compared to that of the legacy SPS. Besides state C_{k+1}, C_k can also transit to state T_{k+1} thanks to the proposed resource reservation coordination. The coordination takes two transmission intervals and is implemented until $k = p-1$, so transitions from collision to success start from $k = 2$.

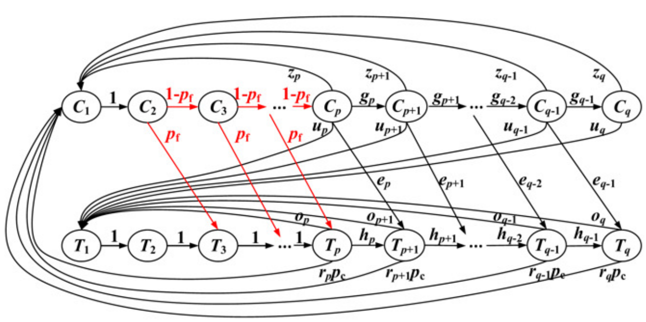


Fig. 3. The state transition diagram for channel access when the proposed CRR protocol is adopted. For one semi-persist period, $C_1, C_2, \ldots, C_q$ represent the collision states, while $T_1, T_2, \ldots, T_q$ represent the transmission states. Directed arcs represent transitions between states, with the corresponding state transition probabilities labeled on.

In case $2 \leq k < p$, state C_k will transit to state T_{k+1} if v_t receives the collision feedback from its neighbor vehicle and reselects a new resource with no further collision. Let p_f denote the transition probability from C_k to T_{k+1}. We have $p_f = (1 - p_c - p_h)(1 - p_c)$, where p_h is the probability of packet loss caused by half-duplex error. p_h is calculated by $p_h = 1/N_t$, where N_t is the number of sub-frames within one beacon transmission interval. N_t is determined by the beacon frequency, i.e., $N_t = 1000/f$, where f is the beacon frequency. Then the transition probability from C_k to C_{k+1} is $(1 - p_f)$.

As a result, $\forall 1 \leq i, j \leq 2q$, the state transition probability is computed by

$$p'_{i,j} = \begin{cases} 1 - p_f, & \text{if } 2 \leq i < p, j = i+1 \\ p_f, & \text{if } 2 \leq i < p, j = q+i+1 \\ p_{i,j}. & \text{otherwise} \end{cases} \tag{9}$$

where $p_{i,j}$ is the transition probability from state i to j when the SPS protocol is implemented [12]. Let $\mathbf{P}' = (p'_{i,j})$ denote the state transition matrix for the channel access of any vehicle when the coordinating resource reservation MAC is adopted. $\mathbf{P}'$ is obtained with (9).

The only difference between the two Markov chains of the SPS and CRR protocols is the transitions of states $C_2, C_3, \ldots, C_{p-1}$. Thanks to the error detection with coordination among neighbor vehicles in the platoon, the number of consecutive collision times may not be as great as p after conflicted reservation occurs.

Let $S' = [s'_1, s'_2, \ldots, s'_{2q}]^T$ denote the steady state distribution, where $s'_1, s'_2, \ldots, s'_q$ are the probabilities of collision states and $s'_{q+1}, s'_{q+2}, \ldots, s'_{2q}$ are the probabilities of transmission states. Since the Markov chain is irreducible and aperiodic, S' can also be obtained by deriving the eigenvector corresponding to the eigenvalue 1 for $\mathbf{P}'$.

2) Reliability Analysis: When the proposed CRR is adopted for vehicle platooning, let U'_S, U'_F denote the success and failure probability, respectively. We have $U'_S = \sum_{i=q+1}^{2q} s'_i$ and

$$U'_F = \sum_{i=1}^{q} s'_i. \tag{10}$$

3) Delay Analysis: Let G'_k denote the probability of k consecutive collisions. For $0 \leq k \leq p$, G'_k can be derived based on the Markov chain, as follow

$$G'_k = \begin{cases} \sum_{i=1}^{q} s_{i+q}, & \text{if } k = 0 \\ 0, & \text{if } k = 1 \\ \sum_{i=p}^{q} s_{i+q} r_i p_c (1-p_f)^{k-2} p_f, & \text{if } 2 \leq k < p \\ \sum_{i=p}^{q} s_{i+q} r_i p_c (1-p_f)^{p-2} (u_p + e_p). & \text{if } k = p \end{cases} \tag{11}$$

Thanks to the proposed error detection, additional transitions from collision states to transition states are observed and analyzed. The time of consecutive collisions can be down to 2 when collision occurs, instead of p with the SPS protocol.

When $k = p+1$, we have

$$G'_k = \sum_{i=p}^{q} s_{i+q} r_i p_c (1-p_f)^{p-2} (u_k + e_k) \prod_{i=p}^{k-1} g_i. \tag{12}$$

When $p+1 < k < 2p$, G'_k is computed by

$$\begin{aligned} G'_k = & \sum_{i=p}^{q} s_{i+q} r_i p_c (1-p_f)^{p-2} (u_k + e_k) \prod_{i=p}^{k-1} g_i \\ & + \sum_{s=p}^{k-2} G'_s z_s (1-p_f)^{k-1-s} p_f. \end{aligned} \tag{13}$$

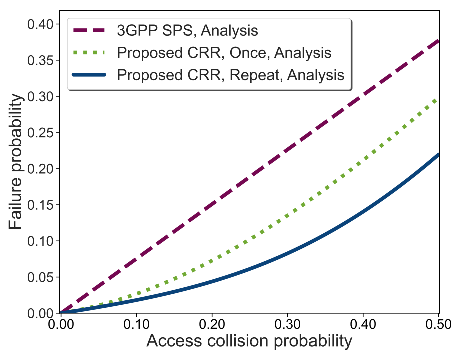
This article has been accepted for publication in IEEE Transactions on Wireless Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TWC.2023.3326852

Similar to the analysis in Section V-A, the delay satisfaction probability with the proposed CRR is computed by

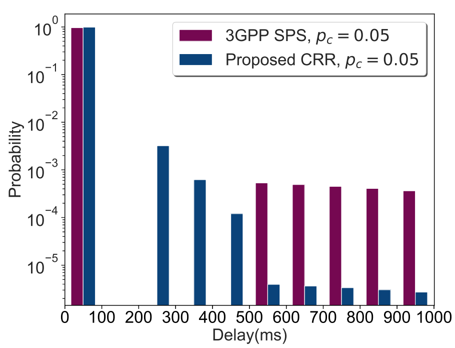
$$Prob(D_k \le D_{\min}) = \sum_{k=0}^{\lfloor \frac{D_{\min}}{t_0} - 1 \rfloor} G'_k, \ k < 2p. \tag{14}$$

C. Numerical Results

Based on the above analysis, the reliability and delay performances of the 3GPP SPS and the proposed CRR are compared with numerical results. The failure probability and delay distribution are taken as the performance metrics to evaluate the two protocols.



(a) Reliability performance comparison.



(b) Delay performance comparison.

Fig. 4. Numerical results of failure probability and delay distribution with the 3GPP SPS and the proposed CRR, based on the proposed analytical framework. The IFT of platooning is specified with $r = 2$ and $l = 2$. (a) Failure probability in platoon communication versus access collision probability. (b) Delay distribution when the access collision probability is 0.05.

Fig. 4 (a) gives the failure probability versus the access collision probability for different MAC protocols when the beacon rate is 10 Hz and the RC range is $[5, 15]$. The failure probability is defined in Section V-A as the probability that at least one designate receiver fails to receive the beacon message due to resource selection conflict. It reflects the reliability of communication for supporting close coordination in platoon. The results of the 3GPP SPS and the CRR are obtained based on (6) and (10), respectively. By changing the access probability p_c from 0 to 0.5 and fixing all other parameters, the failure probability curve is obtained.

Compared with the 3GPP SPS, the proposed CRR brings a substantial reduction in failure probability, thanks to the additional error detection procedure. For example, the failure probability is decreased from 8.2% to 2.3% when the access collision probability is 10%. The failure probability can be reduced by 50% even when the access collision probability is as high as 40%.

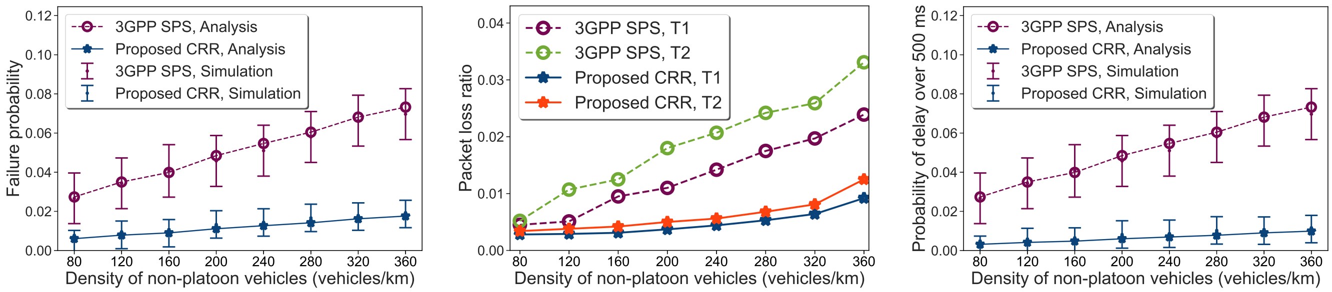
Note that in our CRR MAC design, the error detection procedure is implemented repeatedly before the RC is decremented by C_0. For comparison, we also give the curve when the procedure is implemented only once at the beginning of each semi-persistent reservation period with the green dashed line in Fig. 4 (a). With only once feedback per semi-persistent period, it is possible that the vehicle faces reservation conflicts again upon resource reselection. Thus, the repeated error detection reduces the risk of consecutive collisions. As shown in Fig. 4 (a), a significant reduction in failure probability is observed with repetitive error detection when the access collision probability increases over 0.2.

Fig. 4 (b) gives the delay distribution with the 3GPP SPS and the proposed CRR when $p_c = 0.05$. The delay distribution is obtained based on (7) and (11). For the 3GPP SPS, the probability of delay between 100 ms and 500 ms is 0, so the probability of delay below 500 ms equals the probability of delay below 100 ms, which is 96.23%. However, the probability of delay below 100 ms is increased to 98.67% with the proposed CRR. The probability of delay below 500 ms can also be raised to 99.07%, which is the sum of probabilities of delay in the range of 0∼100 ms, 200∼300 ms, 300∼400 ms, and 400∼500 ms. Therefore, the delay performance of platoon communication is improved thanks to the proposed CRR.

In this paper, the proposed protocol CRR is designed for a system where platoon and non-platoon vehicles coexist in a two-way road scenario. For a more complicated road scenario, the proposed protocol CRR can still be applied to reduce resource reservation collisions between platoon vehicles and any road users, as demonstrated in the simulation study considering both highway and real-world urban scenarios. The proposed Markov chain-based analytical framework can also be extended to more complicated scenarios. In the analytical framework, the state transition probability of the Markov chain is influenced by the access collision probability, which, in turn, relies on the number of vehicles within the interference range. When dealing with a more complicated scenario, this vehicle count can be estimated with the road topology and the density of vehicles on each road. The derived state transition probability can then be utilized within the analytical framework to evaluate performance.

VI. Simulation Results

In this section, extensive simulations are conducted to verify the accuracy of the proposed Markov analysis as well as the effectiveness and superiority of the proposed CRR. The simulations involve two distinct road traffic scenarios, a two-way four-lane highway and a real-world urban scenario with multiple intersections. Furthermore, a range of traffic factors are integrated in the simulation, including vehicle density, platoon inter-vehicle distance, and information flow topology. The wireless dynamics are simulated, including the effects of fast fading and interference caused by resource selection conflicts.



(a) Reliability performance comparison. (b) Packet loss ratio between vehicles. (c) Delay performance comparison.

Fig. 5. Performance evaluation of the 3GPP SPS and the proposed CRR protocol for vehicle platooning, with the information flow topology as $r = l = 2$, the beacon rate as 10 Hz, and the RC range as $[5, 15]$. (a) Comparison of simulations and analytical values of failure probability under different non-platoon vehicle densities for both the 3GPP SPS and the proposed CRR. (b) Packet loss ratio for transmission to the closest platoon vehicle (T1) and the second closest one (T2). (c) Comparison of simulations and analytical values of delay outage probability under different non-platoon vehicle densities for both the 3GPP SPS and the proposed CRR.

In the simulation, the simulator SUMO is used to generate road traffic [29]. To achieve the MAC protocol, a discrete-event simulator is developed, where vehicle location and packet transmission states change over time. In the simulator, we take into account the vehicle mobility, packet transmission requirements, the channel model, and the sensing-based resource selection and reservation process. The open-source version of the developed simulator is now accessible[2]. The reliability and delay performances are evaluated given the information flow topology. Parameters regarding road condition and the communication network are given in TABLE II. In particular, this paper focuses on providing high-reliability communications for platoon vehicles that travel closely to achieve high energy efficiency and emission reduction, so the inter-vehicle distance is set from 5 to 25 meters following [30] and [31].

TABLE II
PARAMETER SETTINGS

Parameters	**Value**
Road length l	4 km
Inter-vehicle distance in platoon d_{g}	5∼25 m
Vehicle length d_{v}	4 m
Maximal vehicle speed v_{s}	30 m/s
Density of non-platoon vehicles λ	80∼360 vehicles/km
Number of platoon vehicles	10
Carrier frequency	5.9 GHz
Transmit power P^{t}	23 dBm
Path-loss exponent γ	3.68
Path-loss constant K_0	$10^{-4.38}$
Channel Bandwidth B	10 MHz
Noise PSD N_0	-174 dBm/Hz
Minimum SINR $SINR_{\mathrm{T}}$	2.76 dB
Beacon frequency f	10 Hz, 50 Hz
Beacon size b	300 bytes
Number of subchannels	2
Number of predecessors in the IFT r	1∼3
Number of followers in the IFT l	1∼3
Delay threshold D_{min}	500 ms
RC range $[p, q]$	$[5, 15]$, $[25, 75]$
Probability of resource keep p_0	0

[2]https://github.com/xinuvic/V2XPlatoonScenario

A. Verification of Analysis

First of all, we verify the correctness of the Markov chain-based models exploited in Section V. The failure probability and delay outage probability are numerically solved given various densities of non-platoon vehicles, and then compared with simulation results.

Fig. 5 gives the reliability and delay performance of both the 3GPP SPS and the proposed CRR for platoon communication. In the simulation, there is a 10-vehicle platoon and several non-platoon vehicles, on a 4-km 4-lane two-way road. All vehicles have the same length as 4 m. Each platoon vehicle acts based on the information of 2 predecessors and 2 follower, i.e., $r = 2$ and $l = 2$. Within the platoon, the inter-vehicle distance is 10 m, and the vehicle length is 4 m. For the platoon safety with such an inter-vehicle distance, the delay threshold is set as 500 ms, which is approximately the satisfying time for a vehicle to react when driving at the speed of 20 m/s. In the simulation, the density of non-platoon vehicles varies from 80 vehicles/km to 360 vehicles/km.

Fig. 5 (a) shows the comparison between simulation and theoretical results of failure probability. As defined in Section V, the failure probability is the probability that the beacon message of a platoon vehicle is not received by all designated receivers simultaneously. Since $r = 2$ and $l = 2$, the designated receivers are two predecessors and two followers. The simulation results are an average of 30 times, and each run lasts for 20 s. For either the 3GPP SPS or the proposed CRR algorithm, the theoretical values are basically within one standard deviation from the mean. Therefore, the correctness of the presented analytical model is verified. Moreover, when the vehicle density increases, the failure probability has a dramatic increase. This is because more crowded vehicles lead to more intense resource contention. By comparison, the proposed CRR is superior to the 3GPP SPS since a much lower failure probability is obtained for all densities.

To analyze the transmission performance between two platoon vehicles, we also observe the packet loss ratio between two pairs of transmission, denoted by T1 and T2. T1 represents the transmission between one platoon vehicle and its closest neighbors, T2 represents the transmission between one platoon vehicle and its second closest neighbors. Fig. 5 (b). Compared

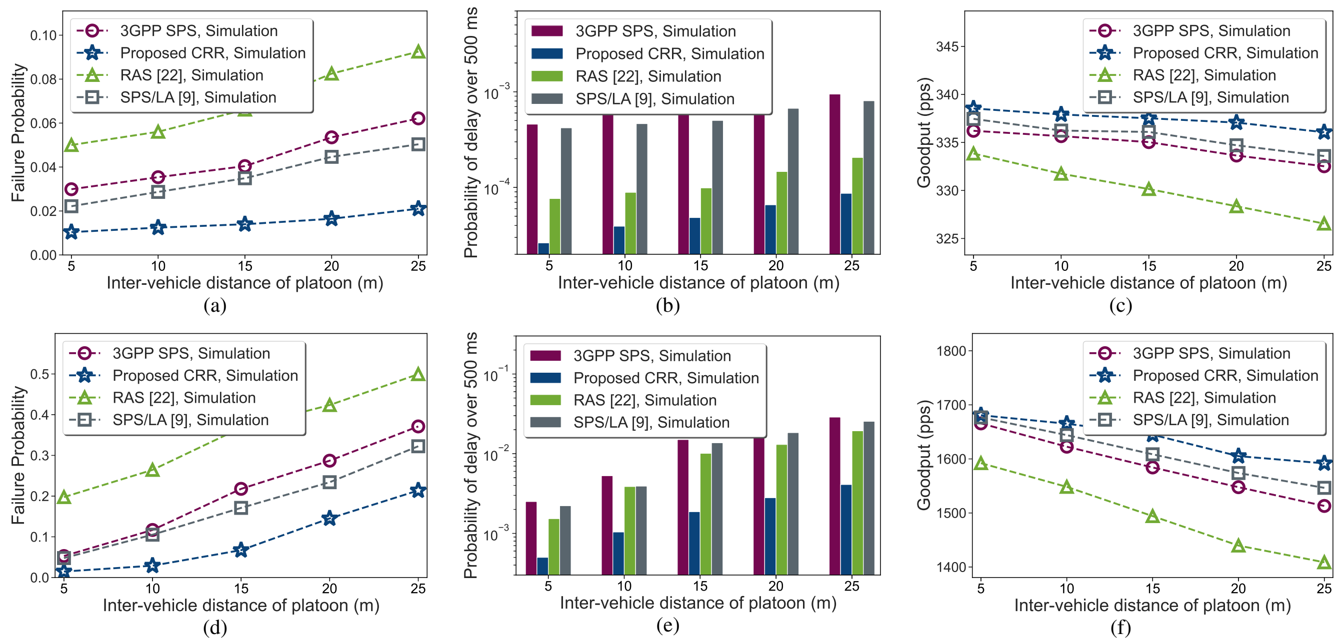


Fig. 6. Performance comparison between the proposed CRR, the 3GPP SPS, the RAS algorithm [22] and the SPS/LA [9] for different inter-vehicle distances in platoon, with the information flow topology as $r = 2$ and $l = 2$. The beacon rate is set as 10 Hz in (a)-(c) and 50 Hz in (d)-(f). (a) and (d) show the failure probability of platoon communication versus the inter-vehicle distance for the four MAC protocols. (b) and (e) show the comparison of delay outage probability among the four MAC protocols under different inter-vehicle distances in platoon. The delay threshold is 500 ms. (c) and (f) show the goodput of platoon communication versus the inter-vehicle distance obtained with the four MAC protocols.

with T1, the packet loss ratio of T2 is higher due to more path-loss and larger interference range caused by the longer transmission distance. In addition, it is found that our proposed CRR leads to a lower packet loss ratio for both T1 and T2.

Fig. 5 (c) shows the performance comparison between the 3GPP SPS and our proposed CRR in terms of delay outage probability in a platoon system. For each algorithm, both the theoretical and simulation results are given. Here the delay threshold is set as 500 ms. The probability of delay over 500 ms means the number of consecutive collisions is no less than 5 since the beacon messages are transmitted per 100 ms. As shown in the figure, for both the 3GPP SPS and the proposed CRR, the theoretical values of delay outage probability are within one standard deviation from the mean of simulation results, which verifies the correctness of the delay analysis in Section V. According to Section V, the consecutive collisions follow different rules for the SPS and the proposed CRR. Specifically, the number of consecutive collisions is at least 5 once collision occurs. However, our proposed CRR implements the error detection procedure, with which the collision can be checked after two transmission opportunities. As a result, the probabilities of delay over 500 ms is dramatically reduced, verified in Fig. 5 (c). For example, when the density of non-platoon vehicles is 120 vehicles/km, the probability of delay over 500 ms is over 0.03 for the SPS but less than 0.005 for the proposed CRR. Thus, the delay outage probability is reduced by over 80% thanks to the proposed CRR.

B. Performance Comparison

To evaluate the superiority of our proposed CRR for vehicle platooning, we conduct simulations to compare it with three other MAC protocols including the legacy 3GPP SPS, the resource alternation selection (RAS) and the SPS with lookahead (SPS/LA). The RAS algorithm was designed in [22] as an enhancement of SPS to relieve the consecutive packet collision problem by reserving and allocating multi-resources alternatively. It has been regarded as a simple and efficient enhanced reservation MAC protocol. SPS/LA was proposed in [9]. Similar to our design, it used the SCI reserved fields to piggyback information on the periodic message. The difference is that SPS/LA exchanges the lookahead information to eliminate most message collisions arising from the ignorance of other vehicles' internal decisions, where the hidden terminal issue still exists. Our proposed CRR piggybacks the packet reception/loss information as transmission feedback among platoon vehicles. By doing this, collision and delay caused by the hidden terminals and simultaneous resource selection are both reduced. Meanwhile, packet losses caused by deep channel fading can also be mitigated by switching to another sub-channel.

In a highly automated and coordinated platoon system, the inter-vehicle distance can be very short without considering the reaction time of humans. In the simulation, the inter-vehicle distance of the platoon is increased from 5 to 25, stepped by 5. The information flow topology is set as $r = 2$ and $l = 2$, i.e., each vehicle uses the information from the nearest two predecessors and two followers. The density of non-platoon vehicles is 120 vehicles/km. Both slow fading and fast fading are considered in the simulations. In particular, we use the well-known Nakagami-m channel model to simulate the statistical fading channel, where the parameter m can reflect the fading severity and $m = 1$ yields the Rayleigh distribution. Following [32], m is set to 5 for the transmissions between two adjacent vehicles while $m = 1$ for non-adjacent pairs considering the existence of blocking vehicles between the transmitter and the receiver. The comparison results are presented in Fig. 6, where the beacon rate is set as 10 Hz in (a-c) and 50 Hz in (d-f), respectively.

For a communication-based platoon system, the coordination among platoon vehicles depends highly on the reliability of information exchange. According to the principle of our proposed CRR, neighbor platoon vehicles can remind each other of packet delivery success/failure with the error detection procedure. Once transmission error feedback is received from any of the designated receivers, the transmitter will immediately select a new resource for the following transmissions. The failure probability is plotted in Figs. 6 (a) and (d). Overall, the higher beacon rate leads to a higher failure probability. Among the four MAC protocols, the proposed CRR brings about the lowest failure probability, which is more than 50% lower than that obtained by the 3GPP SPS and about 80% lower than that obtained by the RAS algorithm. Owing to the reselection lookahead exchange, the SPS/LA also achieves low failure probability too. For the RAS when compared with the legacy SPS, the delay performance is improved at the cost of worse reliability.

Figs. 6 (b) and (e) show the delay outage probability obtained by the four MAC protocols when the beacon rate is set as 10 Hz and 50 Hz, respectively. In Figs. 6 (b), the delay outage probability obtained by our proposed CRR is less than 1/10 of that obtained with the 3GPP SPS. In Fig. 6 (e), the delay outage probability can also be reduced by adopting our proposed CRR. Compared with the RAS and SPS/LA protocols, our proposed CRR has the advantage of achieving both low failure probability and low delay. Meanwhile, it is found that the probability of delay over 500 ms when the beacon rate is set as 10 Hz is much lower than that when the beacon rate is 50 Hz. Although increasing the beacon rate benefits the delay reduction, it leads to more intense contention with fewer accessible resources. Therefore, limiting the beacon rate in congestion scenarios is significant for reliable and timely packet delivery.

To compare the data rate performance of the four MAC protocols, Figs. 6 (c) and (f) show the comparison results of goodput in the scenarios of 10 Hz and 50 Hz, respectively. Given the information flow topology, the goodput is the number of beacons successfully received per second for vehicles in the platoon. With the information flow topology $r = l = 2$ for a platoon consisting of 10 vehicles, the expected received packets within one transmission interval is 34. Therefore, the upper bound of goodput is 340 packets per second (pps) in the case of 10 Hz and 1700 pps in the case of 50 Hz. As shown in Figs. 6 (c) and (f), the proposed CRR achieves the highest goodput among the four MAC protocols, thanks to the reduction in packet losses caused by resource selection conflicts and fading channel. Moreover, with the increase of the inter-vehicle distance, the goodput has a decreased trend and the RAS protocol performs worst among the four solutions.

In summary, the above comparison results show that the proposed CRR protocol is superior to other three MAC protocols in terms of failure probability, delay outage probability and goodput. The proposed protocol has the potential to provide high-rate and high-reliability communications for platoon vehicles traveling closely in close coordination.

C. Discussion on Information Flow Topology

Next, the communication reliability for various information flow topologies is studied, and the results are presented in Fig. 7. We evaluated the three MAC protocols mentioned in Section VI-B, which are the legacy SPS, the proposed CRR and the RAS. Based on the above analysis, although the SPS/LA is inferior to the proposed CRR and the RAS in terms of delay performance, so it is not analyzed in this subsection. The inter-vehicle distance is set as 10 m in the platoon. In Fig. 7 (a), the information flow topology is set as $r = 1$ and $l = 1$, meaning that each vehicle acts based on the information from its closest predecessor and follower. When more vehicles are involved in the information flow topology, it becomes more difficult to guarantee the simultaneous reception of all messages.

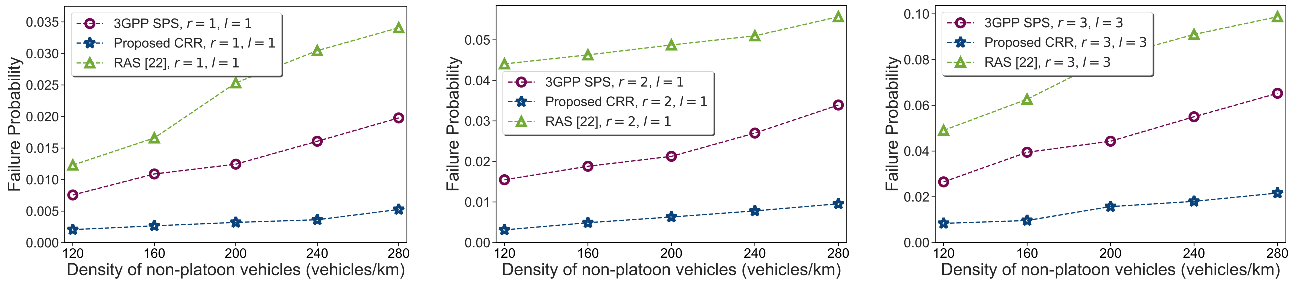
Figs. 7 (b) and (c) show the results obtained in the scenarios where $r = 2$ and $l = 1$, and $r = l = 3$, respectively. For any MAC protocol, it is found that the failure probability rises when more vehicles are involved in the information flow topology. When information from three predecessors and three followers is needed for advanced platoon coordination, the legacy 3GPP SPS leads to low reliability with the failure probability above 0.05 for 120 vehicles/km and nearly 0.1 for 280 vehicles/km. To better support advanced information flow topology, efficient collision and delay reduction approaches or relaying technologies are in need. Compared to the 3GPP SPS, the proposed CRR is beneficial for reliability improvement, where the failure probability is controlled below 0.02 when the density is as high as 280 vehicles/km. However, the RAS obtains the highest failure probability because reserving multiple resources increases the collision risk.

The delay performance in the above simulations is observed and the results are presented in Figs. 7 (d)-(f), which correspond to different information flow topologies. The delay threshold is set as 500 ms, which is the reference delay bound for a platoon with an inter-vehicle distance of 10 m when moving at the speed of 20 m/s. The delay outage probability obtained by the 3GPP SPS is above 10^{-2} for $r = 2, l = 1$ and $r = l = 3$. Compared to this, the RAS algorithm leads to a reduction of 50% on delay outage probability. Moreover, our proposed CRR can further lower the delay outage probability thanks to the error detection procedure using only two transmission intervals, i.e., 200 ms in the scenario of 10 Hz. To conclude, the proposed CRR is superior to the other two MAC protocols in terms of both reliability and delay of platoon communication.

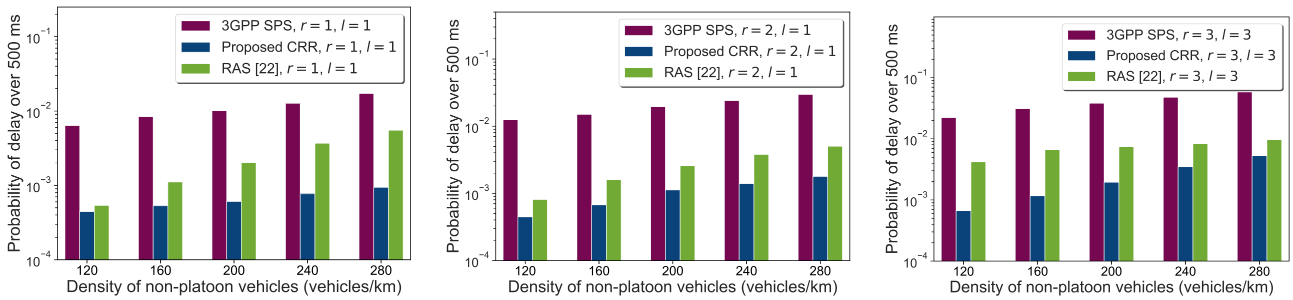
D. Verification on Real-world Roadmap

Finally, the performance of the three MAC protocols is evaluated in the simulation based on part of the roadmap of

This article has been accepted for publication in IEEE Transactions on Wireless Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TWC.2023.3326852

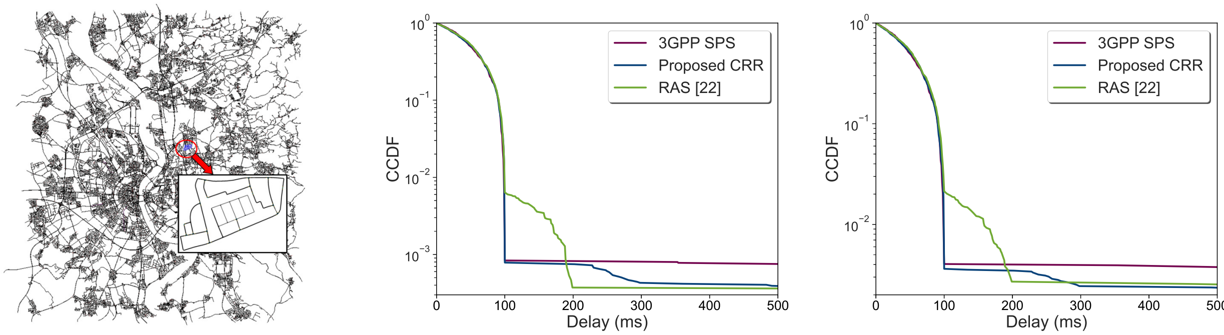


(a) $r = l = 1,\ f = 10\,\text{Hz}$. (b) $r = 2,\ l = 1,\ f = 10\,\text{Hz}$. (c) $r = l = 3,\ f = 10\,\text{Hz}$.



(d) $r = l = 1,\ f = 10\,\text{Hz}$. (e) $r = 2,\ l = 1,\ f = 10\,\text{Hz}$. (f) $r = l = 3,\ f = 10\,\text{Hz}$.

Fig. 7. Performance comparison of the three MAC protocols for different flow topologies. The beacon rate is 10 Hz. (a)-(c) show the failure probability versus the density of non-platoon vehicles. (e)-(f) show the delay outage probability versus the density of non-platoon vehicles, with the delay threshold set as 500 ms. The information flow topology for (a)-(f) is set as follows: In (a) and (d), $r = 1$, $l = 1$. In (b) and (e), $r = 2$, $l = 1$. In (c) and (f), $r = l = 3$.



(a) (b) (c)

Fig. 8. Simulation results in real-word roadmap. (a) Roadmap of Bologna partially used in the simulation. (b) and (c) show the delay comparison of the three MAC protocols when used for platoon communication simulated on the roadmap of Bologna. The information flow topology is $r = l = 3$ and the beacon rate is 10 Hz. (b) shows the complementary cumulative distribution function (CCDF) of delay between the designated transmitter and receiver in the information flow topology. (c) shows the CCDF of delay till beacons are simultaneously received by all designated receivers in the information flow topology.

Bologna[3] with the generated traffic of platoon and non-platoon vehicles in SUMO. The roadmap is presented in Fig. 8 (a).

The complementary cumulative distribution function (CCDF) of delay is shown in Fig. 8, where the delay between any two platoon vehicles and the delay for any transmitter with all designated receivers are given in Figs. 8 (b) and (c), respectively. As a result of consecutive collisions, the CCDF of delay obtained by SPS has a rare change when the delay is increased from 200 ms to 500 ms, in both Figs. 8 (b) and (c). However, our proposed CRR leads to decreased CCDF when the delay is increased over 200 ms. With the alternative resource allocation, the RAS results in a decrease of CCDF when delay is increased above 100 ms, while there is a high proportion of delay above 100 ms. Compared to the RAS, our proposed CRR and the 3GPP SPS limits the proportion of delay above 100 ms within a smaller range.

[3]https://sumo.dlr.de/docs/Data/Scenarios.html#bologna

VII. Conclusion

In this paper, a MAC protocol of resource reservation coordination is proposed to enhance the communication performance of vehicle platooning. To reduce collisions and delay caused by reservation conflict in the legacy SPS, intra-platoon coordination is utilized to enhance vehicles' awareness of collisions. By doing this, vehicles can inform each other of packet loss in the neighborhood using their own transmission opportunities, without causing additional channel load. Both the theoretical analysis and simulation results verify the advantage of the proposed protocol in terms of reliability and delay performance. In the future, we will investigate more adaptive distributed resource scheduling to handle varying platoon construction and traffic conditions.

References

[1] A. Sarker, C. Qiu and H. Shen, "Connectivity Maintenance for Next-Generation Decentralized Vehicle Platoon Networks," *IEEE ACM Trans. Netw.*, vol. 28, no. 4, pp. 1449–1462, Aug. 2020.

[2] K. Xiong, S. Leng, X. Chen, C. Huang, C. Yuen and Y. L. Guan, "Communication and Computing Resource Optimization for Connected Autonomous Driving," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 12652–12663, Nov. 2020.

[3] S. Chen, J. Hu, Y. Shi, L. Zhao and W. Li, "A Vision of C-V2X: Technologies, Field Testing, and Challenges With Chinese Development," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 3872–3881, May 2020.

[4] M. Segata, L. C. Renato, H. Tobias, H. Julian, S. Max, B. Bastian, S. Christoph and D. Falko, "Multi-Technology Cooperative Driving: An Analysis Based on PLEXE," *IEEE Trans. Mob. Comput.*, to be published, doi: 10.1109/TMC.2022.3154643.

[5] C. Zhao, X. Duan, L. Cai and P. Cheng, "Vehicle Platooning With Non-Ideal Communication Networks," *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 18–32, Jan. 2021.

[6] H. Mosavat-Jahromi, Y. Li, Y. Ni and L. Cai, "Distributed and Adaptive Reservation MAC Protocol for Beaconing in Vehicular Networks,' *IEEE Trans. Mob. Comput.*, vol. 20, no. 10, pp. 2936–2948, Oct. 2021.

[7] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (Release 17) TS 36.321 V17.1.0, June 2022.

[8] X. Gu, J. Peng, L. Cai, Y. Cheng, X. Zhang, W. Liu and Z. Huang, "Performance Analysis and Optimization for Semi-Persistent Scheduling in C-V2X," *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 4628-4642, Apr. 2023.

[9] Y. Jeon, S. Kuk and H. Kim, "Reducing Message Collisions in Sensing-Based Semi-Persistent Scheduling (SPS) by Using Reselection Lookaheads in Cellular V2X." *Sensors*, vol. 18, no. 12, 4388, Dec. 2018.

[10] A. Bazzi, C. Campolo, A. Molinaro, A. O. Berthet, B. M. Masini and A. Zanella, "On Wireless Blind Spots in the C-V2X Sidelink," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 9239–9243, Aug. 2020.

[11] S. Gyawali, S. Xu, Y. Qian and R. Q. Hu, "Challenges and Solutions for Cellular Based V2X Communications," *IEEE Commun. Surv. Tutor.*, vol. 23, no. 1, pp. 222–255, Oct. 2021.

[12] X. Gu, J. Peng, L. Cai, X. Zhang and Z. Huang, "Markov Analysis of C-V2X Resource Reservation for Vehicle Platooning," in *Proc. IEEE Veh. Technol. Conf. (VTC-Spring)*, pp. 1–5, June 2022.

[13] M. Hoffmann, P. Kryszkiewicz and A. Kliks, "Frequency Selection for Platoon Communications in Secondary Spectrum Using Radio Environment Maps," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 3, pp. 2637–2650, Mar. 2022.

[14] G. Giambene, M. S. Rahman and A. Vinel, "Analysis of V2V Sidelink Communications for Platoon Applications," *Proc. IEEE Int. Conf. Commun. (ICC)*, Dublin, Ireland, pp. 1–6, Jul. 2020.

[15] P. Wang, B. Di, H. Zhang, K. Bian and L. Song, "Platoon Cooperation in Cellular V2X Networks for 5G and Beyond," *IEEE Trans. Wirel. Commun.*, vol. 18, no. 8, pp. 3919–3932, Aug. 2019.

[16] L. Wang, H. Ye, L. Liang and G. Y. Li, "Learn to Compress CSI and Allocate Resources in Vehicular Networks," *IEEE Trans. Commun.*, vol. 68, no. 6, pp. 3640–3653, June 2020.

[17] X. Luo, Y. Liu, H. H. Chen and Q. Guo, "Physical Layer Security in Intelligently Connected Vehicle Networks," *IEEE Netw.*, vol. 34, no. 5, pp. 232–239, Sept./Oct. 2020.

[18] V. Vukadinovic, K. Bakowski, P. Marsch,I. D. Garcia, H Xu, M. Sybis, P. Sroka, K. Wesolowski, D. Lister and I. Thibault. "3GPP C-V2X and IEEE 802.11 p for Vehicle-to-Vehicle Communications in Highway Platooning Scenarios." *Ad Hoc Netw.*. vol. 74, pp. 17–29, May 2018.

[19] M. Gonzalez-Martin, M. Sepulcre, R. Molina-Masegosa and J. Gozalvez, "Analytical Models of the Performance of C-V2X Mode 4 Vehicular Communications," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1155–1166, Feb. 2019.

[20] G. P. Wijesiri N.B.A., J. Haapola and T. Samarasinghe, "A Discrete-Time Markov Chain Based Comparison of the MAC Layer Performance of C-V2X Mode 4 and IEEE 802.11p," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2505–2517, Apr. 2021.

[21] S. Heo, W. Yoo, H. Jang and J. M. Chung, "H-V2X Mode 4 Adaptive Semipersistent Scheduling Control for Cooperative Internet of Vehicles," *IEEE Internet Things J.*, vol. 8, no. 13, pp. 10678–10692, July 2021.

[22] S. Jung, H. Cheon and J. Kim, "Reducing Consecutive Collisions in Sensing Based Semi Persistent Scheduling for Cellular-V2X," in *Proc. IEEE Veh. Technol. Conf. (VTC-Fall)*, pp. 1–5, Sept. 2019.

[23] A. González, N. Franchi and G. Fettweis, "A Feasibility Study of LTE-V2X Semi-Persistent Scheduling for String Stable CACC," in *Proc. IEEE Wirel. Commun. Netw. Conf. (WCNC)*, pp. 1–7, Apr. 2019.

[24] W. Gao, C. Wu, L. Zhong and K. -L. A. Yau, "Communication Resources Management Based on Spectrum Sensing for Vehicle Platooning," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 2, pp. 2251–2264, Feb. 2023.

[25] P. Wendlend, G. Schaefer. "Feedback-Based Hidden-Terminal Mitigation for Distributed Scheduling in C-V2X," in *Proc. IFIP Netw. Conf.*, pp. 549–553, June 2020.

[26] H. Mosavat-Jahromi, Y. Li, L. Cai and L. Lu, "NC-MAC: Network Coding-based Distributed MAC Protocol for Reliable Beacon Broadcasting in V2X," in *Proc. IEEE Glob. Commun. Conf. (GLOBECOM)*, pp. 1–6, Dec. 2020.

[27] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures, document 3GPP TS 36.213 V17.5.0, Mar. 2023.

[28] W. J. Stewart, *Introduction to the Numerical Solution of Markov Chains*, Princeton, NJ, USA:Princeton Univ. Press, 1994.

[29] P. A. Lopez, B. Michael, B. -W. Laura, E. Jakob, F. Yun-Pang, H. Robert, L. Leonhard, R. Johannes, W. Peter and W. Evamarie, "Microscopic Traffic Simulation using SUMO," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, pp. 2575–2582, Nov. 2018.

[30] J. Wang, J. Liu and N. Kato, "Networking and Communications in Autonomous Driving: A Survey," *IEEE Commun. Surv. Tutor.*, vol. 21, no. 2, pp. 1243–1274, Dec. 2019.

[31] T. Zeng, O. Semiari, W. Saad and M. Bennis, "Joint Communication and Control for Wireless Autonomous Vehicular Platoon Systems," *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 7907–7922, Nov. 2019.

[32] J. Kim, Y. Han and I. Kim, "Efficient Groupcast Schemes for Vehicle Platooning in V2V Network," *IEEE Access*, vol. 7, pp. 171333–171345, Nov. 2019.

Xin Gu (Graduate Student Member, IEEE) received her B.S. degree in 2015 in Communication Engineering from Central South University, Changsha, China. She is currently a Ph.D. candidate in the School of Automation, Central South University, Changsha, China. From 2021 to 2023, she was a visiting Ph.D. student with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada. Her research interests include cellular vehicle-to-everything (C-V2X), wireless resource management and protocol design.

Jun Peng (Senior Member, IEEE) received the B.S. degree from Xiangtan University, Xiangtan, China, in 1987, the M.Sc. degree from the National University of Defense Technology, Changsha, China, in 1990, and the Ph.D. degree from Central South University, Changsha, in 2005. In April 1990, she joined Central South University. From 2006 to 2007, she was with the School of Electrical and Computer Science, University of Central Florida, USA, as a Visiting Scholar. She is a Professor with the School of Computer Science and Engineering, Central South University. Her research interests include cooperative control, cloud computing, and wireless communications.

This article has been accepted for publication in IEEE Transactions on Wireless Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TWC.2023.3326852

Lin Cai (S'00-M'06-SM'10-F'20) received her M.A.Sc. and Ph. D. degrees (awarded Outstanding Achievement in Graduate Studies) in electrical and computer engineering from the University of Waterloo, Waterloo, Canada, in 2002 and 2005, respectively. Since 2005, she has been with the Department of Electrical & Computer Engineering at the University of Victoria, and she is currently a Professor. She is an NSERC E.W.R. Steacie Memorial Fellow, an Engineering Institute of Canada (EIC) Fellow, a Canadian Academy of Engineering (CAE) Fellow, and an IEEE Fellow. In 2020, she was elected as a Member of the Royal Society of Canada's College of New Scholars, Artists and Scientists, and a 2020 "Star in Computer Networking and Communications" by N2Women. Her research interests span several areas in communications and networking, with a focus on network protocol and architecture design supporting emerging multimedia traffic and the Internet of Things. She has co-founded and chaired the IEEE Victoria Section Vehicular Technology and Communications Joint Societies Chapter. She has been elected to serve the IEEE Vehicular Technology Society Board of Governors, 2019 - 2024, and served its VP Mobile Radio, 2023. She has been a voting Board Member of IEEE Women in Engineering (2022-23). She has served as an Associate Editor-in-Chief for IEEE Transactions on Vehicular Technology, a member of the Steering Committee of the IEEE Transactions on Mobile Computing, IEEE Transactions on Big Data and IEEE Transactions on Cloud Computing, an Associate Editor of the IEEE Internet of Things Journal, IEEE/ACM Transactions on Networking, IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technology, IEEE Transactions on Communications, etc., and as the Distinguished Lecturer of the IEEE VTS Society and the IEEE Communications Society.

Weirong Liu (Member, IEEE) received the B.E. degree in computer software engineering and the M.E. degree in computer application technology from the Central South University, Changsha, China, in 1998 and 2003, respectively, and the Ph.D. degree in control theory and control engineering from the Institute of Automation, Chinese Academy of Sciences, Beijing, China, in 2007. Since 2008, he has been a Faculty Member with the School of Computer Science and Engineering, Central South University, where he is currently a Professor. His main research interests include cooperative control, energy storage management, reinforcement learning, neural networks, wireless sensor networks, network protocol, and microgrids.

Xiaoyong Zhang (Member, IEEE) received the master's and Ph.D. degrees in computer application technology from Central South University, Changsha, China, in 2005 and 2009, respectively. He is currently a Professor with the School of Computer Science and Engineering, Central South University. His current research interests include intelligent transportation, train network control, and prognostics and health management.

Zhiwu Huang (Member, IEEE) received the B.S. degree in industrial automation from Xiangtan University, Xiangtan, China, in 1987, the M.S. degree in industrial automation from the University of Science and Technology Beijing, Beijing, China, in 1989, and the Ph.D. degree in control theory and control engineering from Central South University, Changsha, China, in 2006. In October 1994, he joined the Staff of Central South University. From 2008 to 2009, he was with the School of Computer Science and Electronic Engineering, University of Essex, Colchester, U.K., as a Visiting Scholar. He is currently a Professor with the School of Automation, Central South University. His research interests include fault diagnostic technique and cooperative control.