IEEE Open Journal of
Intelligent Transportation Systems

Received 18 September 2025; revised 17 January 2026; accepted 28 February 2026. Date of publication 6 March 2026; date of current version 13 March 2026.

*Digital Object Identifier 10.1109/OJITS.2026.3671296*

# Cooperative Resource Status Exchange for Reliable Vehicular Sidelink Broadcasts

**MAHMOUD ELSHARIEF [1,2], SAIFUR RAHMAN SABUJ [1,3] (Senior Member, IEEE), SEAN KWON [4] (Member, IEEE), AND HAN-SHIN JO [1] (Member, IEEE)**

[1] Department of Automotive Engineering, Hanyang University, Seoul 04763, South Korea
[2] Department of Electrical Engineering, Al-Azhar University, Cairo 11884, Egypt
[3] Department of Electrical and Electronic Engineering, Brac University, Dhaka 1212, Bangladesh
[4] Department of Electrical Engineering, California State University, Long Beach, CA 90840 USA

CORRESPONDING AUTHOR: H.-S. JO (hsjo23@hanyang.ac.kr)

This work was supported by the National Research Foundation of Korea (NRF) Grants funded by Korean Government through the Ministry of Science and ICT (MSIT) under Grant RS-2024-00409492 and Grant RS-2024-00346319.

**ABSTRACT** Vehicular sidelink communications are essential to autonomous driving, yet broadcast reliability under distributed operation remains constrained by collisions and inefficient resource use. The third-generation partnership project (3GPP) has defined a new radio (NR) for vehicle-to-everything (V2X) Mode 2 for autonomous resource reservation and selection. An important challenge in the design of NR-V2X systems is the efficient allocation of resources. Resource allocation facilitates reliable communication between user equipment (UEs) and other network elements. A cooperative approach among UEs is required to ensure reliable resource allocation and communication in such networks. This paper presents cooperative resource status exchange (CRSE), a cooperative scheme that augments autonomous sidelink broadcasts by disseminating a compact resource status map in each packet. It significantly maximizes the packet reception ratio (PRR) and resource utilization. In addition, CRSE integrates game theory to provide a sophisticated method for analyzing and optimizing resource selection strategies among UEs. The analytical model and simulation results show that CRSE performs better than new radio NR-V2X Mode 2, UE-scheduling, and short-term sensing-based resource selection (STS-RS) in terms of PRR and successful transmission rate. The results show that CRSE improves the PRR by approximately 24.6%, 15.2%, and 12.3% over NR-V2X, UE-scheduling, and STS-RS, respectively. Furthermore, the results demonstrate the possibility of realizing the maximum value of PRR and a successful transmission rate.

**INDEX TERMS** 3GPP, autonomous resource allocation, NR-V2X, sidelink, vehicle-to-everything, connected and automated vehicles, resource status exchange, PRR, game theory.

## I. INTRODUCTION

Vehicle-to-everything (V2X) has become a cornerstone of intelligent transportation systems (ITS). It spans vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) links, along with interactions involving vulnerable road users (VRUs) [1], [2], [3]. By enabling highly reliable exchange of kinematic state, and contextual information between road users, V2X supports a wide range of safety-critical applications. Representative services include cooperative awareness, forward-collision warning, intersection movement assistance, and cooperative perception [4], [5]. In addition to direct safety benefits, these capabilities contribute to smoother traffic flow and eco-driving [6], [7]. Meeting the goals requires a communication substrate that is reliable and scalable under challenging wireless conditions. Although standards have progressed considerably, ensuring reliable communication in dynamic environments remains challenging. Packet collisions, and limited radio resources can severely degrade performance [4], [7].

Standardization has evolved to address these problems. Early deployments used LTE-V2X with Mode 4 distributed resource allocation on the PC5 sidelink [8]. The 3rd generation partnership project introduced new radio for V2X (NR-V2X) in Release 16 [9], [10]. In NR-V2X, resource allocation is an important consideration that may be made centrally by the network (Mode 1) or locally by

The review of this article was arranged by Associate Editor Peter Han Joo Chong.

individual user equipment (UE) via an autonomous selection mechanism (Mode 2) [11], [12].

In Mode 2, UEs are required to adopt a sensing-based semi-persistent scheduling (SPS) scheme [13], [14]. The UEs choose their radio resources without cellular network involvement. The SPS allows UEs to randomly pick a few idle resources [15], [16]. However, the randomness of selecting resources results in a high probability of collision, particularly in a dense network. In addition, when the resource is allocated in a distributed manner, the randomness of choosing the resources broadcasting, NR-V2X Mode 2 has major resource-allocation conflicts, as it has no feedback mechanism [17], [18]. It remains challenging for NR-V2X to achieve the desired reliability levels in all scenarios [14].

Release 17 introduced two schemes (Scheme 1, Scheme 2) to enhance Mode 2. Scheme 1 operates Under coverage. It allows the next-generation node B (gNB) or roadside unit (RSU) to advertise a bitmap of pre-allocated resources [19]. Although Scheme 1 reduces half-duplex conflicts, it does not help when no infrastructure is present. Scheme 2 preserves distributed operation. It shortens the sensing window and introduces an inter-UE coordination (IUC) field in the sidelink control information. IUC carry a candidate resource and priority bits, which helps nearby transmitters avoid selecting resources. Scheme 2, however, is primarily optimized for unicast and groupcast flows. Broadcast safety packets still rely on randomized reselection [4], [20].

Bitmap-based decentralized scheduling provides another path. Periodic packets are augmented with compact resource-usage maps through map-assisted occupancy signaling. In this way, neighbors can make better reselection decisions. Methods like map-based resource reselection procedure (MAP-RP) [21], and reliable self-adaptive medium access control (RSAMAC) [22] send control messages with occupancy bitmaps. However, these methods remain reactive. They capture past or present usage but fail to anticipate future occupancy. As a result, no predictive view of future occupancy is available for look-ahead selection.

The advanced resource management for 6G-V2X (AMR6G) method [7] implements a decentralized resource allocation approach. It incorporates resource-status indicators that dynamically communicate real-time occupancy among UEs. In addition, it applies proactive avoidance of mitigates conflicts. AMR6G significantly lowers collision probabilities compared to traditional NR-V2X Mode 2. AMR6G, however, has not defined a compact bit-level encoding for the resource-status field. In addition, it fails to quantify the control overhead required to keep signaling relatively small.

Motivated by these gaps, to achieve the highest possible reliability performance, advanced resource allocation is required. It is crucial that the UEs exchange resource information throughout the allocation process to enhance packet delivery ratio (PRR) and resource utilization. In this study, we provide a novel approach called cooperative resource status exchange (CRSE). CRSE is based on the NR-V2X standard and AMR6G but has been further tuned for more excellent performance in vehicular networks. This potentially enhances resource allocation by sharing the status of each resource. The resource status shows occupied or idle. The key symbols and parameters used in CRSE are detailed in TABLE 1, providing a reference for the notations and terminologies throughout the protocol. CRSE significantly improves the PRR and successful transmission rate. It provides an optimal method for using resources. The following is a brief outline of our contributions:

- We developed CRSE, a novel protocol designed for the autonomous mode to enhance vehicular sidelink efficiency, focusing on cooperative strategies for resource allocation.
- We created an analytical model based on game theory to optimize the interactions among UEs in resource selection for CRSE. It calculates the probability of collisions, which may occur due to the hidden terminal problem or simultaneous resource selection by multiple users.
- Both the simulation results and the analytical model affirm that CRSE substantially enhances PRR and successful transmission probabilities, underscoring its potential as a foundational technology for next-generation vehicular networks.

The remainder of this paper is structured as follows. Section II introduces an overview of NR-V2X Mode 2 and related work. Section III describes our system model and illustrates the problem statements. Section IV presents the CRSE protocol. Section V demonstrates the theoretical analysis of CRSE. In Section VI, the findings from the simulation and analysis are presented. Finally, in Section VII, the conclusion is given.

## II. OVERVIEW NR-V2X MODE 2 AND RELATED WORK

### A. OVERVIEW NR-V2X MODE 2

In NR-V2X, radio resources (RRs) are extended over the time and frequency spectrum. The RRs are organized into frames, subframes, and slots in the time domain. The lowest time-domain resource-allocation unit for sidelink transmissions is a slot, denoted by $\tau$. RRs are divided into three categories in the frequency domain: resource elements, physical resource blocks, and subchannels $M$. A subchannel, which comprises a collection of subsequent PRBs, is the smallest allocation unit in the frequency domain. Each transmission utilizes a single time slot and one or more contiguous subchannels, the specifics of which are determined by the modulation coding scheme, packet size, and number of PRBs in each subchannel [13], [21].

In NR-V2X Mode 2, UEs make autonomous resource selections for their transmissions through sensing-based semi-persistent scheduling [23]. Choosing the resources to

**TABLE 1.** List of symbols.

| | | | |
|---|---|---|---|
| 3GPP | Third Generation Partnership Project | $N$ | Number of resources |
| 5G | The fifth generation | $N_U$ | Number of utilized resources |
| 6G | The sixth generation | $N_F$ | Number of free resources |
| ACK/NACK | Acknowledgment/negative acknowledgment | $M$ | Number of subchannels |
| BSM | Basic safety message | $\tau$ | Time slot duration |
| BS | Base station | $p$ | Keeping resource probability value (specific range: [0,0.8]) |
| CRSE | Cooperative resource status exchange | $V$ | Vehicles set: $\{v_1, v_2, v_3, \ldots, v_m\}$ |
| HTC | Hidden-terminal collision | $\beta$ | Traffic density (vehicles per meter) |
| ITS | Intelligent transportation system | $\lambda$ | Number of packets per second |
| LTE | Long-term evolution | $P_t$ | Transmission power of each vehicle |
| MAC | Medium access control | $P_{max}$ | Maximum transmission power |
| MCS | Modulation coding scheme | $P_{min}$ | Minimum transmission power |
| NR | New radio | $d_s$ | Sensing range |
| PPR | Packet reception ratio | $P_s$ | Successful transmission probability |
| PRB | Physical resource block | $PRR$ | Packet reception ratio |
| PSCCH | Physical sidelink control channel | $P_c$ | Collision probability |
| PSSCH | Physical sidelink shared channel | $P_n$ | Probability of a resource not being selected |
| PSFCH | Physical sidelink feedback channel | $S$ | Set representing the status of each resource |
| PSBCH | Physical sidelink broadcast channel | $s_m$ | Status value of a specific resource m |
| PCT | Possible collision table | $H$ | Value in CRSE representing UE's high probability of selecting the resource |
| RR | Radio resource | $L$ | Value in CRSE representing UE's low probability of selecting the resource |
| RSSI | Received signal strength indicator | $V(v_x)$ | Set of vehicles in the wireless range of vehicle $v_x$ |
| RE | Resource element | $V(v_y)$ | Set of vehicles in the wireless range of vehicle $v_y$ |
| RSRP | Reference signal received power | $v_i, v_j, v_x, v_y, v_z$ | Variables representing different vehicles in the network |
| RR | Radio resource | $I$ | Set of participants in the game. For a two-point game, $I$ is $\{v_i, v_j\}$For a V-points game, it's $\{1, 2, 3, \ldots, \mathcal{V}\}$ |
| RE | Resource element | $R$ | Strategy where a UE selects resource k |
| RC | Reselection counter | $W$ | Strategy where a UE selects another resource different from $k$ |
| RS | Resource status | $NE$ | Nash equilibrium, a set of probabilities of UEs selecting strategy $R$ |
| SAC | Simultaneous-access collision | $u_s^{v_i}$ | Utility value when successfully selects resource $k$ |
| SPS | Sensing-based semi-persistent scheduling | $u_f^{v_i}$ | Utility value when $v_i$ fails to select resource $k$ |
| SCS | The subcarrier spacing | $u_n^{v_i}$ | Utility value when $v_i$ selects a resource other than $k$ |
| SCI | Sidelink control information | $U_{v_i}$ | Utility function for $v_i$ |
| TB | Transport block | $p_{v_i}$ | Probability of $v_i$ selecting strategy $R$ |
| UE | User equipment | $p_{v_j}$ | Probability of $v_j$ selecting strategy $R$ |
| V2X | Vehicle-to-everything | $I_{-v_i}$ | All participants in the game excluding $v_i$ |
| *RRI* | Resource Reservation Intervals | $\mathcal{V}$ | the set of UEs |
| $\mathcal{G}$ | the game | $\mathcal{S}$ | the UE strategic $\{R, W\}$ |
| U | the utility function | $s_k$ | Status value of a specific resource $k$ |

use is a two-step process: channel sensing and resource selection. As shown in Fig. 1, the UE observes the sidelink channel during the sensing window. It extracts the sidelink control information (SCI) sent by neighboring UEs. The decoded SCIs, together with reference signal received power (RSRP) values, are stored. This data is then applied to identify the set of resources, $N_U$, that should be excluded from selection. After exclusion, the UE verifies that at least X% of the remaining resources are still available for selection; let us call them $N_F$. If the requirement is not satisfied, the RSRP threshold is increased by 3 dB. The process is repeated until the selection window contains at least X% of candidate resources. The value of X can be 0, 35, or 50 [17], [20]. Finally, one resource is chosen at random from the available set.

The resources corresponding to the selected subchannels are reserved at fixed intervals, known as resource reservation intervals (RRIs). RRIs are constrained by the periodicity of packet generation [24]. Let $N = N_U + N_F$ represent the total number of system resources used in a single *RRI*, which can be calculated as follows:

$$N = \text{RRI} \times \frac{M}{\tau}. \quad (1)$$

Here, $M$ is the number of subchannels, and $\tau$ is the time slot duration. The discrete reselection counter (RC) specifies how many transmission periods occur before resource re-evaluation. Its value is randomly selected from the range [C1, C2] according to the broadcast rate λ. The transmission period is then expressed as, $T_s = \text{RRI} \times \text{RC}$. After each packet transmission, RC decreases by one. Once RC reaches zero, the resource is replaced with probability $(1 - p)$, where $p \in [0, 0.8]$ [8], [13].

### B. RELATED WORK

Designing effective and reliable resource allocation for V2X remains a central research focus. Persistent challenges include hidden-terminal interference, collision avoidance, and efficient use of scarce radio resources. This section reviews representative approaches for reliable resource allocation in NR-V2X Mode 2. It also highlights the gaps that motivate the proposed CRSE method.

Several studies introduce feedback paths to improve resource selection. A receiver grant-based allocation scheme has been proposed for NR-V2X distributed mode. In this scheme, a grant is sent by the receiver through the sidelink feedback channel [14]. The receiver's grant-based design led to improvements in transmission reliability, specifically in terms of the collision ratio, and in inefficient resource utilization [14]. However, this design is only used for unicasting and groupcasting. In [25], Nour et al. showed that packet loss can degrade lane-change safety benefits in work zone scenarios. Their results highlight the importance of improving broadcast reliability in dense vehicular environments. The authors of [15] introduced persistent scheduling with a broadcast feedback scheme. When comparing the persistent scheduling method to the conventional SPS, the authors found that it produced superior performance in terms of packet response time [26]. Under high density, however, repeated collisions can still occur because reselections remain largely reactive.

Saifuddin et al. studied prolonged communication outages in C-V2X Mode 4 caused by SPS [27]. To reduce consecutive packet losses, they proposed a time-controlled one-shot resource scheduling scheme. [28] proposed UE-scheduling resource allocation scheme for NR-V2X Mode 2. It enhances transmission reliability and cluster stability by reducing resource collisions through autonomous clustering. The initial clustering setup, however, can be computationally intensive. In addition, the scheme's success depends on accurate resource detection, which may be challenging in dynamic conditions.

A line of work enhances Mode 2 extended through reservation determined signaling. One approach reserves multiple resources in advance. The reservations are then piggybacks in data packets, which is useful in settings with loose coupling between SCI and data [29]. Subsequent work applied the same principle to LTE-V2X Mode 4. Using a Markov-chain analysis, the study demonstrated gains in throughput and reductions in collision probability [24]. Although these mechanisms improve awareness, it still focuses on current or past occupancy rather than providing explicit look-ahead guidance.

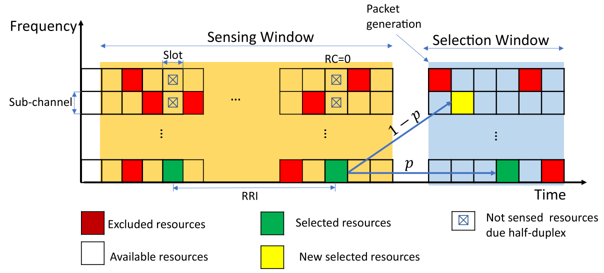


**FIGURE 1.** Resource allocation scheme of NR-V2X Mode 2.

Bitmap-based strategies such as MAP-RP, RSAMAC, and AMR6G expose local resource status to guide reselection. MAP-RP attaches a compact map of recent resource usage to periodic packets. Receivers use this information to skip occupied resources [21]. RSAMAC introduces frame-level control messages that carry resource-usage bitmaps. It adapts frame lengths and scheduling using RSSI and two-hop sensing [22]. Such designs reduce repeated collisions and improve reliability compared with plain SPS. However, they also increase traffic control overhead and packet size. More importantly, the designs remain reactive. They summarize present or past occupancy but offer no predictive view of near-future usage for look-ahead selection. AMR6G applies proactive avoidance to mitigate conflicts. As a result, AMR6G significantly lowers collision probabilities compared to traditional NR-V2X Mode 2. However, a compact bit-level encoding for the resource-status field has not been defined. The control overhead has also not been quantified to demonstrate that signaling remains small.

Deterministic schedules from the time division multiple access (TDMA) research have influenced V2X MAC design. This is because the resource grid in NR-V2X is structurally similar. The hybrid cooperative MAC (HCMAC) [30] and vehicular MAC (VeMAC) [31] exchange detailed frame information that indicates slot occupancy among two-hop neighbors to mitigate hidden terminals. The prediction-based TDMA MAC (PTMAC) further predicts neighbor mobility and adjusts slot assignments in advance to prevent collisions [32]. These approaches can offer strong guarantees but require frequent exchange of neighbor identifiers and slot maps. The resulting overhead burden makes them difficult to sustain in highly dynamic environment.

The authors of [29] proposed a short-term sensing-based resource selection (STS-RS) scheme for C-V2X networks. STS-RS introduces a short sensing phase prior to resource selection to improve PRR. While the scheme effectively enhances the PRR, it does not solve the hidden terminal problem. Specifically, UEs outside the sensing range can still interfere with the selected resources. Re-evaluation mechanisms in NR-V2X Mode 2 can help periodic traffic but are less effective for variable-sized or aperiodic loads, and they increase overhead when reselection is frequent [33]. Opportunistic retransmission policies improve throughput using adaptive blind repeats [16], but they do not predict or deterministically resolve collisions. AoI-aware piggybacking and density-triggered resource expansion improve freshness and reduce drops [34], [35], although they depend on accurate AoI estimates and stable sensing that are difficult to maintain in dense traffic. Learning-based schedulers that rely on Lyapunov optimization can reduce outages in structured scenarios [29], yet they typically do not include explicit predictive collision resolution.

Recent protocols have improved both reliability and utilization. However, most remain reactive and struggle with hidden terminals beyond the sensing horizon. They also lack explicit prediction of short-term future occupancy to guide look-ahead decisions. CRSE addresses these gaps through intelligent resource utilization and proactive tracking of future allocations. It exchanges resource-status information to form near-term occupancy expectations.

## III. SYSTEM MODEL AND PROBLEM DEFINITION

### A. SYSTEM MODEL

We considered a highway scenario with multiple lanes. The UEs are denoted by $V = \{v_1, v_2, v_3, \ldots, v_m\}$ and separated by $\frac{1}{\beta}$ meter. Here, $\beta$ (UEs per meter) is the traffic density. The two-dimensional situation may be reduced to a one-dimensional finite-line scenario by assuming the UEs are uniformly spaced along the line. Every UE consistently broadcasts $\lambda$ packets/s. Thus, all UEs have the same transmission period, RRI. In this work, we do not address the blocking issue caused by nonhomogeneous transmission times. It is assumed that the transmission power of each UE is equal to $P_t$, and all UEs have the same sensing range $d_s$. To isolate the impact of resource selection and collision mechanisms, we assume an ideal, symmetric channel: propagation/fading effects are ignored and any packet not involved in a collision is successfully decoded; hence, two UEs within mutual range can always hear each other in the absence of a collision. We also omit blocking effects arising from non-homogeneous packet durations or aperiodic traffic [37], [38].

### B. PROBLEM STATEMENT

NR-V2X plays a crucial role in vehicular communication, as navigation increasingly relies on real-time data exchange. However, current NR-V2X methods confront paradoxes, as UEs can simultaneously identify free resources and select the same ones, resulting in inefficiency and collisions. This difficulty is exacerbated by the lack of a feedback mechanism in the NR-V2X Mode 2 broadcast system, resulting in the repeated use of conflicting resources. As roads become more intelligent and interconnected, it is necessary to refine systems and strategies to ensure that UEs are safer and more efficient. In this section, we divide the problem statement into two parts.

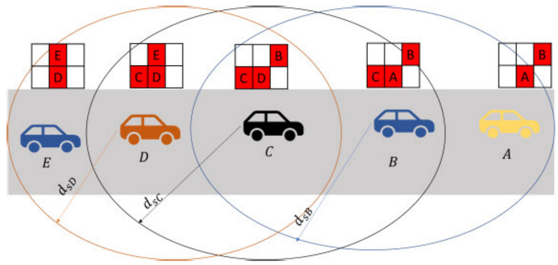


**FIGURE 2.** An example of vehicular network. Each UE can only communicate with UEs within its wireless range.

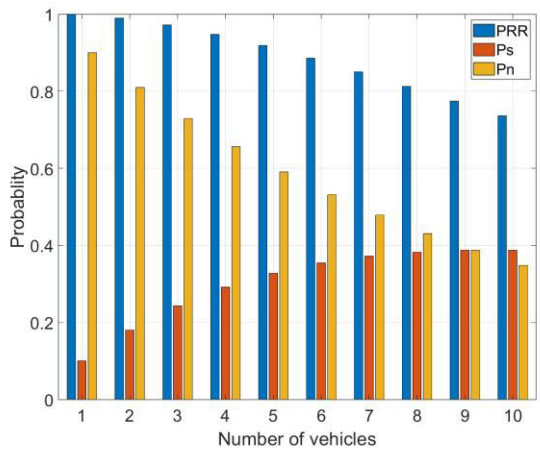


**FIGURE 3.** PRR, $P_s$, and $P_n$ of NR-V2X Mode 2. Number of free resources is 10.

**Resource selection dynamics:** As described in Section II, in NR-V2X Mode 2, each UE builds a list of free resources, $N_F$, after excluding the utilized resources, $N_U$. Considering Fig. 2, let us assume that the value of RC of UEs $B$ and $C$ simultaneously goes to zero. In addition, for simplicity, let us consider that the resource-keeping probability, $p$, of $B$ and $C$ is equal to 0. As shown in Fig. 3, $B$ and $C$ have the same free resource list: $N_F\ (B) = N_F\ (C) = 3$. Therefore, each UE independently and randomly selects a new resource from each free-resource list with a probability of $1/N_F$. Here, we assume that each UE chooses one resource. Therefore, for example, the successful transmission probability of $B$ that attempts to access each resource $P_s$ is given [39] as follows:

$$P_s = \frac{|V|}{N_F}\left(1 - \frac{1}{N_F}\right)^{|V|-1}. \tag{2}$$

With $|V| = 2$ and $N_F = 3$ in (2), then $P_s = 0.44$. Here, $P_s$ can be used as a representation of a successful utilization. In addition, in the majority of cases, the PRR is determined by the following step:

$$PRR = 1 - P_c. \tag{3}$$

Here, $P_c$ is the collision probability. To determine $P_c$, we first determine the probability of a resource not being selected, i.e., $P_n$. $P_n$, which is given by

$$P_n = \left(1 - \frac{1}{N_F}\right)^{|V|}. \quad (4)$$

On considering $|V| = 2$ and $N_F = 3$, we get $P_n = 0.44$. Next, we used the following equation to calculate $P_c$ :

$$P_c = 1 - P_s - P_n. \quad (5)$$

On substituting (2), (4), and (5) into (3), we obtain the following equation, which demonstrates PRR as a function of $|V|$ and $N_F$:

$$\text{PRR} = \frac{|V|}{N_F}\left(1 - \frac{1}{N_F}\right)^{|V|-1} + \left(1 - \frac{1}{N_F}\right)^{|V|}. \quad (6)$$

To generalize the problem, Fig. 3 presents the values of PRR, $P_s$, and $P_n$ for $N_F = 10$ and $|V| = 1 : 10$. The maximum value of $P_s$ is approximately 0.4 at $|V| = N_F$. Hence, we rewrite (2) as Max $(P_s) = \left(1 - \frac{1}{|V|}\right)^{|V|-1}$. Although the number of UEs is equal to the number of resources, $P_s$ is small, and PRR is not considerably large. In contrast, $P_n$ is significantly large. In Fig. 3, at $N_F = 10$ and $|V| = 5$, the value of PRR is enhanced; however, the $P_s$ does not exceed 0.4. The enhancement of PRR is related to the increasing value of $P_n$. Therefore, there are many unused resources, which results in inefficient resource utilization.

**Feedback mechanisms and collision challenges:** In NR-V2X Mode 2, to improve reliability, the receiver transmits feedback (ACK/NACK) to the transmitter in the case of unicast and multicast. However, in the case of broadcast, NR-V2X Mode 2 does not provide a feedback scheme to enhance reliability. For example, in Fig. 2, let us assume that the RC value of UE $A$ goes to zero, and the same resource as UE $C$ is selected for the next transmission. $C$ (hidden UE) is out of the range of $A$. The collision will happen at $B$, and UE $B$ cannot hear any $A$ or $C$. As there is no feedback mechanism, UEs $A$ and $C$ continue using the same resource, which can cause a severe problem.

Based on the preceding analysis, we concluded that maximizing the utilization in NR-V2X while satisfying reliability under constrained resources is challenging. Therefore, a significant paradigm is needed for the highly dynamic vehicular network. To take this approach further, in the following sections, we propose the CRSE. The CRSE is an attempt to find a solution to the challenging issue of providing techniques to maximize $P_s$ and PRR. In addition, it provides a feedback mechanism to enhance the system's reliability.

## IV. CRSE PROTOCOL

In this section, we present our proposed technique, CRSE. The CRSE is an innovative protocol developed to be used as a technology that shapes next-generation vehicular networks. Each UE in CRSE obtains its resources in a decentralized manner. In the following subsections, we explore: (a) the configuration of the resource status (RS) field, a newly introduced type of control information incorporated into the packet, and the data exchanged among nearby UEs; (b) the resource selection procedure for a UE whose RC goes to zero or a new UE entering the network; (c) the dual-state feedback mechanism which points out the innovative approach taken in the protocol to manage collisions.

### A. RESOURCE STATUS FORMAT

In CRSE, each transport block (TB) has an associated SCI message that carries control information. The CRSE modifies the structure of the packet and adds a new field of control information called RS. Importantly, CRSE carries the RS field without enlarging the SCI. The RS vector is encapsulated as a variable-length sidelink MAC control element (SL-MAC-CE) and placed directly after the MAC header at the start of the physical sidelink shared channel (PSSCH) payload, which keeps the PSCCH format unchanged.

RS represents the status of each resource, $S = \{s_1, s_2, s_3, \ldots, s_{N-1}, s_N\}$. For example, let us consider Fig. 4; the resources have a status value, $s_m$. $s_m \in [1, 2, H, L] | sm \in [1 : N]$. $s_m = 1$ means that the resource is used by a UE within the wireless range of the transmitted UE (within the one-hop range). $s_m = 2$ indicates that the resource is used by a UE located within a range larger than $d_s$ and smaller than $2d_s$ from the transmitted UE (within a two-hop range).

The available resources, which may be selected, have different status values (high $H$, and low $L$). The values of $H$ and $L$ can be determined based on the required reliability level. When $s_m$ indicates $L$, the probability of collision increases if it is selected, and vice versa. Based on multiple parameters, $s_m$ was determined for each UE. In this study, a UE uses the density and status of other UEs that share the same resource to determine its own status. However, other parameters such as RC, $p$, mobility, and the location of other UEs can be used. Within the sensing window, a UE monitors the sidelink channel and receives packets from others, including the RS field. Next, the UE builds its own $S$ based on the received information. In addition, the information received allows the UE to discover $S$ for UEs not located in its wireless range. Hence, resource duplication and hidden UE problems can be avoided.

### B. RESOURCE SELECTION PROCEDURE

By employing the structure of the RS shown in Fig. 4, and exchanging the RS among UEs, the UEs can discover $S$ for UEs at a distance of $2d_s$. Let $v_x$ be the current UE that recently joins the network, or its RC goes to 0. Within the sensing window, $v_x$ receives packets from each neighbor $v_i \in V(v_x)$ in its wireless range. The received packets include the $S(v_i) | v_i \in V(v_x)$ .$S(v_i)$ includes the $s_m$ of $v_j \in V(v_i)$, $v_j \notin V(v_x)$, $\forall v_i \in V(v_x)$. After receiving the $S(v_i)$, $v_x$ updates its value of S$(v_x)$. ALGORITHM 1 illustrates the

**Algorithm 1** CRSE resource selection process

Input:
$S(v_x)$, Receiving $S(v_i)\,|v_i \in V(v_x)$ . // $V(v_x)$ neighbors of $v_x$

Output:
Building a new $S(v_x)$. Selecting a resource for the transmission: $k$.

1. ■ **Upon receiving** $\boldsymbol{S(v_i \in V(v_x))}$
2. **for** (*each* $m \in S(v_i)$) **do**
3. **if** ($s_m(v_i) == 1$) **Then**
4. **if** ($m == v_i$ *resource*) **Then**
5. $s_m(v_x) \leftarrow 1$ // Resources used by first hop neighbor.
6. **else**
7. $s_m(v_x) \leftarrow 2$ // Resources used by second hop neighbor.
8. **end if**
9. **if** ($s_m(v_i) == 2$) **Then**
10. $s_m(v_x) \leftarrow (HorL)$ // Third hop has no effect on transmission.
11. **end if**
12. **if** ($s_m(v_i) == H$) **Then**
13. $s_m(v_x) \leftarrow L$ // High impact collision possibility.
14. **end if**
15. **if** ($s_m(v_i) == L$) **Then**
16. $s_m(v_x) \leftarrow (HorL)$ // Low impact collision possibility
17. **end if**
18. $S(\boldsymbol{v_x}) \leftarrow s_m(v_x)$
19. **end for**
20. ■ **Building excluding resources list**
21. $N_U(\boldsymbol{v_x}) \leftarrow s_m \in [1, 2, -1], \forall s_m \in S(\boldsymbol{v_x})$
22. ■ **Building available resources list**
23. $N_F(\boldsymbol{v_x}) \leftarrow \forall m \in S(\boldsymbol{v_x}), s_m \in [H, L]$
24. ■ **Choosing a resource for the transmission**
25. $v_x$ chooses $k \in N_F(v_x)$ for the transmission, $s_k \in [H, L]$, $s_k$ almost equals $H$ as the it has a low collision impact.

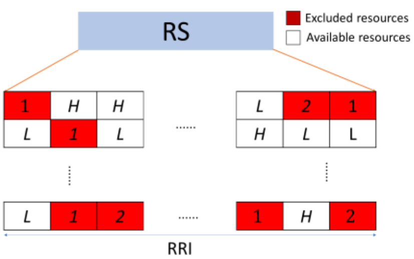


FIGURE 4. RS structure. The resource in red indicates the occupied resource, and the resource in white indicates the available resource which can be used.

construction process for S($v_x$). $v_x$ checks the status of each resource $s_m \in S(v_i)$, $m \in N$.

Here, $s_m$ has four possible values. First, if $s_m \in S(v_i)$ equals 1 and $m$ is the resource utilized by $v_i$, $v_x$ considers $m$ to be a resource utilized by a direct neighbor and sets $s_m \in S(v_x)$ equal to 1. However, if $m$ is not utilized by $v_i$, $v_x$ considers $m$ as a resource utilized by $v_j$ and sets its $s_m \in S(v_x)$ equal to 2 (line: 3:8). Second, $s_m \in S(v_i) = 2$, which means that $m$ is utilized $v_z \in V(v_j)$, $v_z \notin (V(v_x), V(v_i))$. $v_z$ has no effect on the $v_x$; therefore, $v_x$ sets its $s_m \in S(v_x) = (H$ or $L)$, (line: 9:11). Subsequently, we show how the UE sets its $s_m$ to H or L values. Third, $s_m \in S(v_i) = H$. This implies that the neighboring $v_x$ has a high likelihood of utilizing $s_m$. Therefore, $v_x$ sets $s_m \in S(v_x)$ equals $L$ to reduce the chance that $v_x$ and another UE will both choose this resource simultaneously, hence minimizing the possibility of a collision (line: 12:14). Fourth, $s_m \in S(v_i) = L$. This indicates that the neighboring $v_x$ has a low likelihood of utilizing $s_m$. In this case, $v_x$ has the flexibility sets its $s_m \in S(v_x)$ equal to $H$ or $L$, based on its own assessment and strategy (line: 15:17). This decision could be influenced by additional network information, the density of UEs as we show in the next example. Finally, $v_x$ can successfully construct its own $S(v_x)$.

Before making a resource selection, $v_x$ eliminates any resources from the consideration that are marked with a status of 1 or 2, (line: 23) to get $N_F(v_x)$. From $N_F(v_x)$, $v_x$ randomly chooses a resource $k \in N_F(v_x)$ to use for the next transmission (line: 25). Although the resource selection process is performed randomly, it is biased towards resources marked as $H$ in $N_F(v_x)$. In CRSE, for any given resource, we set the sum of the probabilities represented by $H$ and $L$ is equal to $(H + L = 1)$. The value of $H$ is constrained to the range between 0.5 and 1 $(0.5 \leq H \leq 1)$. This means that resources with a status of $H$ are more likely to be selected. The idea is that resources marked as $H$ are deemed to have a low risk of collision based on the network's current state. By preferentially selecting these resources, $v_x$ aims to minimize its chances of encountering a collision during transmission. In contrast, resources marked as $L$ are less likely to be selected. This is intentional, as a resource marked as $L$ has a higher perceived risk of collision. By rarely selecting these resources, $v_x$ further reduces its collision risk.

Fig. 5 demonstrates an example of building the $S$ and illustrates the resource selection procedure for UE $E$. For simplicity and to make the process easily understandable, we use the UE's name to represent the status of the occupying resource. For example, UE $D$ has six resources. Three resources are free, and three resources are occupied (indicated in red). The occupied resources are used by UEs $C$ (one-hope neighbor), $D$ (UE itself), and $B$ (two-hope neighbor). $C$ and $D$ are equivalent to $s_k = 1$, whereas $B$ is equivalent to $s_k = 2$.

Initially, as illustrated in Fig. 5 (a), $E$ joins the network and senses its channels. $E$ receives RS from $D$. Then, $E$ configures $D$'s RS and constructs its $S$ as depicted in Fig. 5 (b). $E$ ignores $D$'s two-hop neighbors (such as $B$) and considers the corresponding resource to be free. On the other hand, $E$ considers $D$'s one-hop neighbors (such as $C$) as its two-hop neighbors and makes its corresponding resource equal to 2. Next, $E$ checks its free resources and assigns their status as $H$ or $L$. As shown in Fig. 5 (b), $E$ assigns $L$ to the resource, which corresponds to $H$ in $D$. For the remaining three resources, $E$ choose one as $H$ which has no conflicts with other UEs and sets the remaining resource to $L$. In fact, a UE can set multiple resources to $H$. However, the UE's density should be considered. In this study, if the number of

UEs equals the number of resources, the UE sets one resource to $H$. On the other hand, if the number of UEs equals half the number of resources, the UE sets two resources to $H$, and so on.

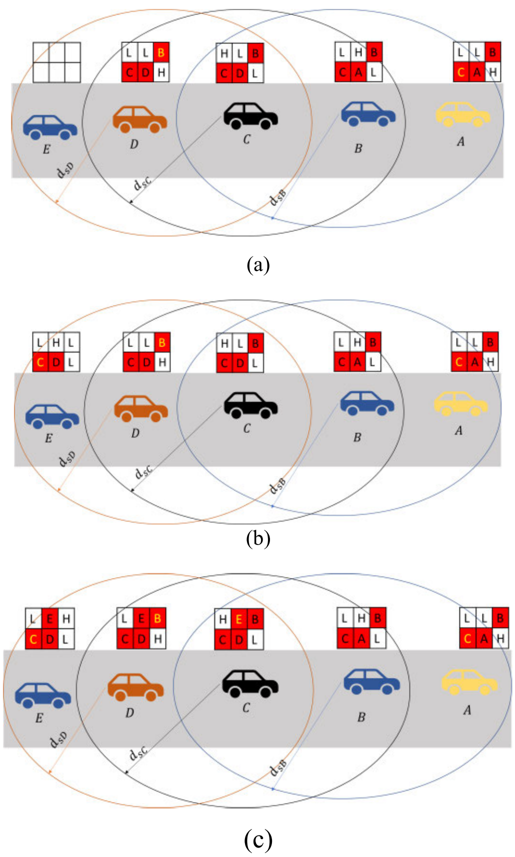

FIGURE 5. Resource-building status and resource-selection process. (a) E joins the network and senses the channel. (b) E gathers resource statuses from its neighbors and creates its own. (c) E selects a resource for transmission and marks it as occupied.

Subsequently, as shown in Fig. 5 (c), $E$ selects a resource of $H$ value for transmission and marks it as occupied. In addition, for future transmission, it chooses another resource and sets it to $H$. It then broadcasts the new RS to its neighbors. Each neighbor receives the RS from $E$ and updates its resource as $D$.

To analyze the complexity of the CRSE protocol and ensure its implementation in time, we consider the following:

### C. DUAL-STATE FEEDBACK MECHANISM

To understand the collision-avoiding mechanism in CRSE, we first illustrate how previous methods identify the collision, as in [22], [30], and [31]. Subsequently, we propose a CRSE-avoiding mechanism. Generally, collisions are classified into two types: simultaneous-access collisions (SACs) and hidden-terminal collisions (HTCs) [26]. A SAC occurs when two or more UEs are within the same wireless range and transmit simultaneously. This SAC often occurs when the UEs' RC goes to 0 simultaneously and randomly acquires the same resource. In contrast, the HTC occurs when a UE receives a packet from two or more transmitters in different wireless ranges. In previous methods [30], [31], each UE determines its neighbors and builds a neighbor list with the associated resources, $NL$. The UE then transmits $NL$ with its message. Let $v_x \in V(v_x)$ and $v_i \in V(v_x), \forall v_i \in V(v_x)$. $v_i$ builds its $NL(v_i)$ and transmits it. $v_x$ receives feedback from $v_i$. By inspecting the feedback, $NL(v_i)$, $v_x$ can determine the resource used by each of its two-hop neighbors, $v_j \in V(v_i)$, $v_j \notin V(v_x), \forall v_i \in V(v_x)$. $v_x$ can check whether its packet was successfully delivered. Although the prior method is useful for avoiding many collisions, it usually requires a significant overhead, particularly in a dense network.

In CRSE, we propose a new feedback mechanism to avoid collisions and carry only a relatively small overhead compared to the previous method. As in [7], each resource status is encoded using a two-bit binary format. When set to 0, the first bit signifies that the resource is free, while a value of 1 indicates that the resource is currently occupied. The second bit, contingent on the first, conveys additional information about the resource's state. If the first bit is 0, the second bit discriminates between $L$ state (bit set to 0) and $H$ state (bit set to 1). Conversely, if the first bit is 1, the second bit distinguishes whether the resource is utilized by a UE within a one-hop range (state 1, bit set to 0) or within a two-hop range (state 2, bit set to 1). This compact binary representation offers a concise means of digitally representing resource status and is valuable in applications that require efficient resource management and status monitoring. Therefore, we can map the resource status as follows: $L \leftarrow 00, H \leftarrow 01$, $1 \leftarrow 10$ and $2 \leftarrow 11$. Accordingly, the added overhead is $\frac{2N}{8}$ bytes.

### D. HYBRID UPDATE STRATEGIES

Although the overhead with CRSE's method is relatively small, especially when compared to previous techniques, it can still consume a significant amount of bandwidth as the number of resources scales up, potentially leading to inefficient use of network capacities. To combat this, we advocate for a hybrid strategy that not only retains the robustness and reliability required for next-generation vehicular networks communications but also minimizes overhead. This strategy incorporates both delta updates and periodic full-state updates.

#### 1) DELTA UPDATES

These updates only transmit changes or differences from the last known states of the resources rather than the complete state information. Initially, this approach required sending the indices along with the states of changed resources, which, while reducing the data payload compared to full updates, still incurred substantial overhead. For example, with a 20% change rate among 100 resources, where each resource state is represented by 2 bits and each index by approximately

8 bits, the required overhead for one update cycle using this naive delta update method would be around 200 bits (25 bytes).

Implementing a binary mask (bitmask) method, where a bit set to 1 indicates a changed resource state, significantly reduces this overhead. Employing a bitmask where each bit corresponds to one resource, this method efficiently flags changes: a bit is set to 1 if the corresponding resource's state has changed since the last update and is set to 0 otherwise. Only the new states of the changed resources are transmitted following the bitmask. For instance, consider a scenario with 100 resources where changes occur randomly at about 20% of the resources per update cycle. A bitmask of 100 bits is created, with bits set to 1 at positions corresponding to changed resources. If the changes are at indices 10, 20, and 90, for example, the bitmask would be 000…001…001…001…000 (simplified), and the subsequent data transmission would only include the new values for these indices, such as 01, 10, …, etc. The total data transmitted would thus be the 100-bit bitmask plus 40 bits for the new values, totaling 140 bits (around 18 bytes). This marks a significant reduction from the 200 bits previously required. The percentage of reduction is 30%. Consequently, the overhead can be calculated as $\frac{N(1+2\mu)}{8}$ bytes, where $\mu$ is change rate. In addition, the bitmask can use algorithms like Huffman coding, which could further reduce the overhead. However, the detailed exploration of such compression techniques is beyond the scope of this paper.

#### 2) FULL STATE UPDATES

Due to the highly dynamic nature of vehicular networks, UEs frequently enter or leave the network, and environmental conditions rapidly change. Therefore, relying only on delta updates might lead to inconsistencies and errors in state information. Although the delta update method significantly reduces overhead by transmitting only the changes, full state updates are required to ensure that each UE in the network gets synchronized. Therefore, full state updates are scheduled at regular intervals to address these challenges. Full state updates are transmitted at regular intervals, such as every 1 second, determined based on network dynamics, such as the frequency of topology changes or critical environmental updates, such as mobility. It ensures all nodes in the network are accurately synchronized and addresses any discrepancies that may arise from incomplete or missed incremental updates.

Although the overhead of CRSE is relatively small, it is helpful to contextualize its efficiency against other state-of-the-art protocols. Bitmap-based designs such as MAP-RP [21] and AMR6G [7] encode each resource with 2 bits, which yields an overhead of $\frac{2N}{8}$ bytes. For $N = 100$, this is 25 bytes per transmission. RSAMAC [22] uses either full or simplified frame-information messages, with sizes that range from 36 to 100 bytes depending on the mode. HCMAC [30] and VeMAC [31], which allocate 1 byte per neighbor ID and 1 bit per slot status, introduce density-dependent overhead. With 70% resource utilization, this corresponds to about 35 neighbor IDs and 35 status bits, for a total of 35+35/8≈39.4 bytes.

In contrast, CRSE employs a hybrid update strategy that combines delta and full-state updates. The delta path contributes $\frac{N(1+2\mu)}{8}$ bytes per cycle, while full updates contribute $\frac{2N}{8}$ bytes every second. With a 100 ms update cycle and $\mu = 0.2$, the average per-cycle overhead for CRSE is about 20 bytes, which is lower than the typical values for RSAMAC, VeMAC, and HCMAC, and comparable to MAP-RP and AMR6G. This comparison shows that CRSE offers competitive overhead while providing stronger coordination and reliability, as illustrated in Fig. 6.

### E. COMPLEXITY AND TIMELINESS ANALYSIS

To analyze the complexity of the CRSE protocol and ensure its timely implementation, we consider two critical aspects: the resource selection procedure and the feedback mechanism of the hybrid update strategies. The resource selection procedure involves multiple steps. It includes receiving packets, constructing the RS, and selecting a resource for transmission. The process of receiving packets and updating the resource status from neighbors has a complexity of $O(n)$. $n$ represents the number of neighbors. On the other hand, as a UE selects one or more resources that have a status value of $H$, the selection of a resource for transmission exhibits a complexity of $O(1)$. The complexity of receiving messages and selecting resource processes ensures that each UE has up-to-date information on resource utilization, enabling efficient resource management.

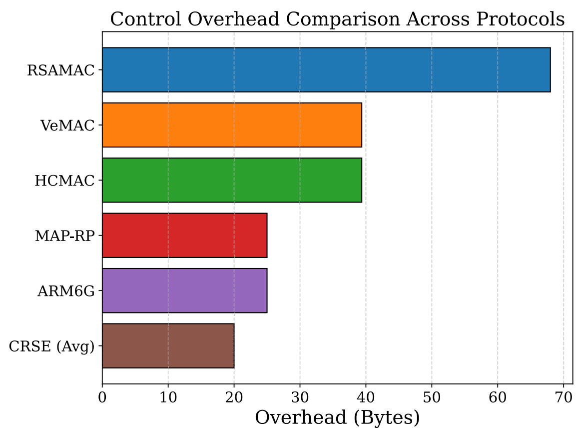


**FIGURE 6. Comparison of control message overhead for decentralized V2X protocols, $N = 100$. CRSE achieves lower average overhead than other protocols while maintaining cooperative reliability.**

The hybrid update strategies feedback mechanism incorporates both delta updates and full-state updates. The delta updates based on the bitmask method are regularly sent to every RRI. It introduces a minimal overhead calculated as $\frac{N(1+2\mu)}{8}$ bytes. On the other hand, the full state updates, which are transmitted at regular intervals at every 1 second, introduce $\frac{2N}{8}$ bytes. Therefore, the hybrid update strategies ensure that the overhead can remain manageable, supporting the scalability of CRSE. Generally, the combination of efficient resource selection and minimal feedback overhead illustrates that the CRSE can be implemented promptly and support the real-time requirements of next-generation vehicular networks.

## V. THEORETICAL MODEL ANALYSIS

In this section, we propose an analytical model for CRSE. The model aims to enhance the likelihood of successful transmissions and improve PRR. We utilize game theory to analyze and optimize strategic interactions among UEs. In CRSE, UEs independently select resources based on their local observations. Consequently, this leads to a highly decentralized decision-making process. Game theory, which effectively models decentralized decision-making, is well-suited to represent the analytical model of CRSE [40].

Game theory provides a mathematical framework to analyze and optimize the interactions between multiple UEs in a competitive environment [41]. By modeling each UE as a player aiming to maximize its utility, we establish a robust foundation for designing resource allocation strategies. We discuss the game-theoretical framework employed to analyze the strategy resource selection by the UEs. Leveraging an advanced probabilistic model referenced in [42], [42], we have utilized an extended version of this model to develop our analytical framework.

In addition, to improve the consistency of strategy updates, we integrate the dual-state feedback mechanism of CRSE into the game-theoretic model to ensure that UEs have accurate information about resource status. The scenario is formulated as a finite game of mixed strategies. In game theory, the existence of at least one Nash Equilibrium (NE) is guaranteed according to established literature [40]. In addition, by adopting the assumptions described in Section III and considering our new parameters, we can construct a formulation that is mathematically controlled.

### A. GAME MODEL DEFINITION

Initially, consider that ($v_i$ and $v_j \in \mathcal{V}|\mathcal{V} \subseteq \mathcal{V}$) intend to choose resource $k$, where $\mathcal{V}$ is the set of UEs. $v_i$ and $v_j$ should play a game to choose a resource. According to established game-theoretical principles, the UE strategic states, $\mathcal{S}$, are either "$R$" or "$W$." $R$ indicates that $v_i$ and $v_j$ select $k$, and $W$ indicates that $v_j$ selects another resource. We aim to derive the NE, which represents the set of probabilities of the UEs' selecting strategy $R$. Based on their game-based probability calculations, the UEs select either the $R$ or $W$ approach. We define the game $\mathcal{G} = (\mathcal{V}, \mathcal{S}, \mathcal{U})$, where $U$ denotes the utility function [22].

### B. TWO-PLAYER GAME

The following are the parameters of the game: Participants $I = \{v_i, v_j\}$ for a two-point game. Later, we consider $I = \{1, 2, 3, \ldots, |\mathcal{V}|\}$ for a $\mathcal{V}$-points game; strategy status: $\{R, W\}$; and utility value: based on the strategies used. There are three possible outcomes for node $v_i$'s utility value. $u_s^{v_i}$ is the utility value of $v_i$ when $v_i$ successfully selects $k$, and $v_j$ selects another resource. $u_f^{v_i}$ is the utility value of $v_i$ when $v_i$ fails to select $k$ because $v_j$ selects $k$. $u_n^{v_i}$ is the utility value of $v_i$ when $v_j$ selects $k$ and $v_i$ selects another resource. To simplify the calculation, we set $u_s^{v_i} = 1$, $u_f^{v_i} = 0$, and $0 < u_n^{v_i} < 1$. Hence, $\left(u_s^{v_i} > u_n^{v_i} > u_f^{v_i}\right)$. $U_{v_i}$ is $v_i$'s utility function $P_s$ is the successful transmission probability in the game; $p_{v_i}$ is the probability of $v_i$ selecting the $R$ strategy.

The utility function of $v_i$ is formulated in (7).

$$U_{v_i} = p_{v_i}\left[p_{v_j}u_f^{v_i} + \left(1 - p_{v_j}\right) u_s^{v_i}\right] + \left(1 - p_{v_i}\right) u_n^{v_i}. \tag{7}$$

The objective is to maximize $U_{v_i}$. Hence, we compute the partial derivative of $U_{v_i}$ with respect to $p_{v_i}$. The NE is attained when no player can unilaterally deviate from their strategy to improve their utility and make it equal to 0. Let $\frac{\partial U_{v_i}}{\partial p_{v_i}} = 0$, then

$$p_{v_j}u_f^{v_i} + \left(1 - p_{v_j}\right) u_s^{v_i} - u_n^{v_i} = 0. \tag{8}$$

Simplifying (8), then

$$p_{v_j} = \frac{u_n^{v_i} - u_s^{v_i}}{u_f^{v_i} - u_s^{v_i}}, \tag{9}$$

where $p_{v_j}$ represents the probability with which $v_j$ chooses strategy $R$ in the NE of the game. Similarly, we can compute $p_{v_i}$ as follows:

$$p_{v_i} = \frac{u_n^{v_j} - u_s^{v_j}}{u_f^{v_j} - u_s^{v_j}}. \tag{10}$$

Mathematically, a strategy profile $(p_{v_i}, p_{v_j})$ is NE. From (9) and (10) we can conclude that the NE solution of the two-points game is $\left\{\frac{u_n^{v_j}-u_s^{v_j}}{u_f^{v_j}-u_s^{v_j}}, \frac{u_n^{v_i}-u_s^{v_i}}{u_f^{v_i}-u_s^{v_i}}\right\}$. This derivation is aligned with the conventional best-response correspondence in game theory, where the fixed points represent the NE solution.

#### 1) EXTENSION TO MULTI-PLAYER GAME

Here, we extend the model to a $\mathcal{V}$-points game. Let $v_i$ play the game with each UE in set $I_{-v_i}$. $I_{-v_i}$ is all the participants excluding $v_i$. The utility function of $v_i$ is given in (11).

$$U_{v_i} = p_{v_i}\left\{u_s^{v_i} \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} \left(1 - p_{v_j}\right) + u_f^{v_i}\left[1 - \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} \left(1 - p_{v_j}\right)\right]\right\} + \left(1 - p_{v_i}\right) u_n^{v_i}. \tag{11}$$

On taking the partial derivative of (11) and equating it to 0, we obtain

$$u_s^{v_i} \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} (1 - p_{v_j}) + u_f^{v_i} \left[ 1 - \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} (1 - p_{v_j}) \right] - u_n^{v_i} = 0. \tag{12}$$

Simplifying (12), we get

$$p_{v_j} = 1 - \left( \frac{u_n^{v_i} - u_s^{v_i}}{u_f^{v_i} - u_s^{v_i}} \right)^{\frac{1}{(|\mathcal{V}|-1)}}. \tag{13}$$

Similarly, we can compute $p_{v_i}$ as follows:

$$p_{v_i} = 1 - \left( \frac{u_n^{v_j} - u_s^{v_j}}{u_f^{v_j} - u_s^{v_j}} \right)^{\frac{1}{(|\mathcal{V}|-1)}}. \tag{14}$$

To successfully select resource $k$ and maximize the successful transmission rate, only one UE should select $k$, and the others should choose another resource. Therefore, the successful transmission rate is

$$P_s = \sum_{v_i=1}^{|\mathcal{V}|} \left[ p_{v_i} \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} (1 - p_{v_j}) \right]. \tag{15}$$

The probability of a resource not being selected is

$$P_n = \prod_{v_j=1,}^{|\mathcal{V}|} (1 - p_{v_j}). \tag{16}$$

On substituting (15) and (16) into (5), we obtain the following equation for $P_C$:

$$P_C = 1 - \sum_{v_i=1}^{|\mathcal{V}|} \left[ p_{v_i} \prod_{v_j=1, v_j \neq v_i}^{|\mathcal{V}|} (1 - p_{v_j}) \right] - \prod_{v_j=1,}^{|\mathcal{V}|} (1 - p_{v_j}). \tag{17}$$

### 2) PROBABILISTIC TRANSMISSION METRICS IN CRSE

In the CRSE, either the $H$ or $L$ values of $s_k$ can be used to represent the UE's probability of selecting the resource. On substituting $p_{v_i} = H, p_{v_j} = L, \forall v_j \in |\mathcal{V}|$, and $H + L = 1$, in (15) and (17), We obtain $P_s$ as

$$P_s = H^{|\mathcal{V}|} + (|\mathcal{V}| - 1) L^2 H^{|\mathcal{V}|-2}, \tag{18}$$

and $P_C$ is

$$P_C = 1 - H^{|\mathcal{V}|} - (|\mathcal{V}| - 1) L^2 H^{|\mathcal{V}|-2} - L H^{|\mathcal{V}|-1}. \tag{19}$$

Next, to obtain the PRR of the CRSE, we substitute (19) into (3).

$$\text{PRR} = H^{|\mathcal{V}|} - (|\mathcal{V}| - 1) L^2 H^{|\mathcal{V}|-2} - L H^{|\mathcal{V}|-1}. \tag{20}$$

(18), (19), and (20) show that when $H \to 1$, $P_s \to 1$, $P_C \to 0$, and PRR $\to 1$. We can then conclude that the maximum value of $P_s$, minimum value of $P_c$, and maximum value of PRR occur at $H = 1$.

## VI. SIMULATION RESULTS

In this section, we evaluate the performance of the CRSE and compare it with that of the conventional NR-V2X, UE-scheduling resource allocation scheme [28], and STS-RS [32]. We verified the accuracy of the CRSE model by comparing it to the results obtained from a simulator built in MATLAB using extensive Monte Carlo simulations. We measure the performance of the model by considering the PRR, $P_s$ and $P_n$. In addition, we illustrated how the various traffic densities impact the system's PRR. The traffic density directly determines the number of simultaneously transmitted UEs and thus reflects different V2X penetration ratios.

The following parameters were used for the simulation. The deployment comprises multiple lanes with an inter-lane distance of 4 meters, and the highway road is 2.5 km. The packet size was 300 bytes with QPSK modulation. We used the numerology of 15 kHz SCS with a bandwidth of 10 MHz, which resulted in five subchannels and a slot duration of 1 ms. Although NR-V2X supports higher numerologies, this configuration is commonly adopted baseline configurations for comparison with other schemes. In addition, higher numerologies reduce slot duration, which can limit resource availability under QPSK, which makes BSM packet sizes are infeasible [8], [13]. We used the numerology of 15 kHz SCS with a bandwidth of 10 MHz, which resulted in five subchannels and a slot duration of 1 ms. We set the transmission power to 23 dBm, the sensitivity power level at the receiver to −91 dBm, the RRI to 100 ms, and the probability of keeping the resource, $p$ to 0. Since CRSE focuses on sidelink resource coordination at the MAC level, its performance is primarily governed by the number of UEs that transmit at the same time. For periodic broadcast traffic, therefore, the instantaneous UE speed has a limited impact on CRSE.

To test the CRSE over a wide range of distances between transceivers, we used a different set of ranges, starting from 0 m to 500 m, and then calculated the average number of UEs using the formula $\mathcal{V} = 2d_s\beta - 1$. In addition, we selected the $H$ value as 0.9. Subsequently, we illustrate how the $H$ value can affect the system's performance.

Initially, we checked the accuracy of the analytical model of the CRSE presented in Section V and compared it with the simulation results. Fig. 7, Fig. 8, and Fig. 9 show the simulation and analytical results of $P_s$, $P_n$, and PRR, respectively. The figures clearly show that the simulated and analytical results of the CRSE and NR-V2X using the proposed analytical model are in good agreement Fig. 7 compares the $P_s$ of the CRSE and NR-V2X over various distances, derived from both analytical and simulation methods. At a distance of 500 meters, the CRSE significantly outperforms the NR-V2X. The $P_s$ of NR-V2X does not exceed 0.4. However, when the $P_s$ of the CRSE was more than 0.8, the CRSE outperformed NR-V2X by a factor of approximately 2. In addition, as shown in Fig. 8, CRSE reduces the number of idle resources by approximately 25% compared with NR-V2X.

Fig. 9 demonstrates the PRR as a function of distance for three models: CRSE, NR-V2X, UE-scheduling, and STS-RS. Both analytical and simulation results are presented for each model. The UE-scheduling and STS-RS results are taken from [28], and [32], respectively. At 500 meters, the CRSE model demonstrates superior performance with a PRR of 0.91 in simulation, compared to 0.73 for NR-V2X, 0.79 for UE-scheduling, and 0.81 for STS-RS. The improvement, computed as a relative increase with respect to each baseline scheme, was approximately 24.6%, 15.2%, and 12.3% over NR-V2X, UE-scheduling, and STS-RS, respectively. The results indicated that CRSE maintains a higher PRR over extended distances.

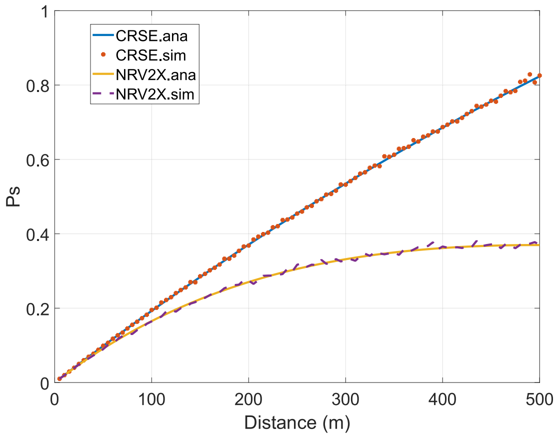


**FIGURE 7.** $P_S$ as a function of distance for CRSE, and NR-V2X. The traffic density is 0.1.

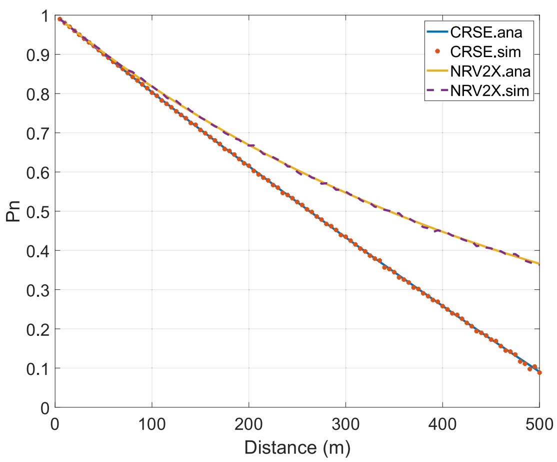


**FIGURE 8.** $P_n$ as a function of distance for CRSE, and NR-V2X. The traffic density is 0.1.

To quantify the performance of CRSE beyond PRR, we evaluated both collision probability reduction and throughput improvement at different distances (150 m, 300 m, and 500 m). Fig. 10 shows the collision reduction achieved by CRSE as the relative decrease with respect to each other protocols. At a distance of 500 m, CRSE reduces packet collisions by approximately 68% compared

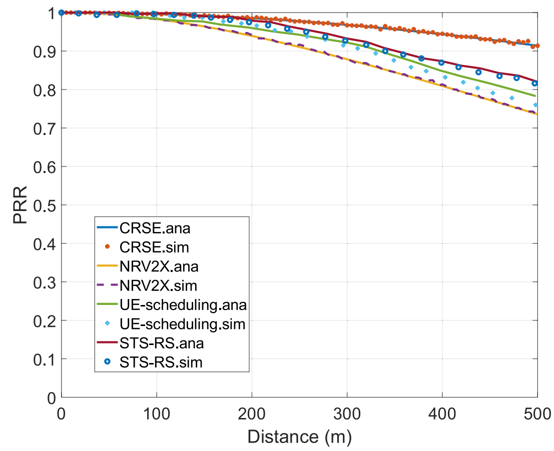


**FIGURE 9.** PRR as a function of distance for CRSE, NR-V2X, UE-scheduling, and STS-RS. The traffic density is 0.1.

with NR-V2X, 65% compared with UE-scheduling, and by around 55% compared with STS-RS. On the other hand, Fig. 11 illustrates the throughput gain achieved by CRSE relative to other protocols., At 500 m, CRSE provides a throughput gain approximately 4.3 kbps, 3.7 kbps, and 2.4 kbps over NR-V2X, UE-scheduling, and STS-RS, respectively.

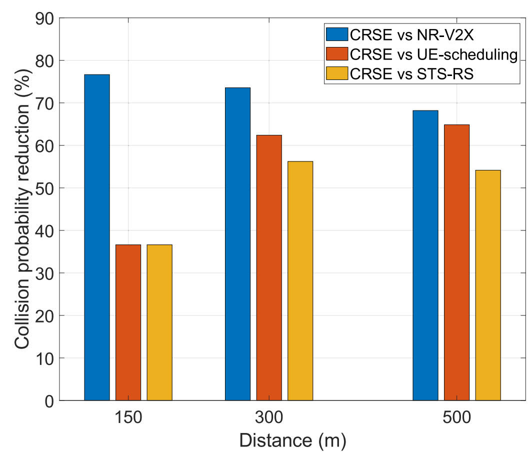


**FIGURE 10.** Collision probability reduction of CRSE relative to NR-V2X, UE-scheduling, and STS-RS at different distances. The traffic density is 0.1.

To further investigate the impact of wider bandwidth, we doubled the bandwidth to be 20 MHz. Fig. 12 illustrates the PRR performance of NR-V2X and CRSE for bandwidths of 10 and 20 MHz. As expected, increasing the bandwidth improves PRR for both schemes due to the larger number of available resources. At 500 m and with 20 MHz, CRSE achieves a PRR of about 0.97, outperforming NR-V2X by 6.5%. In addition, CRSE operating at 10 MHz achieves PRR performance comparable to NR-V2X operating at 20 MHz across all distances.

To evaluate the performance of four models under varying traffic loads, which represent congested conditions

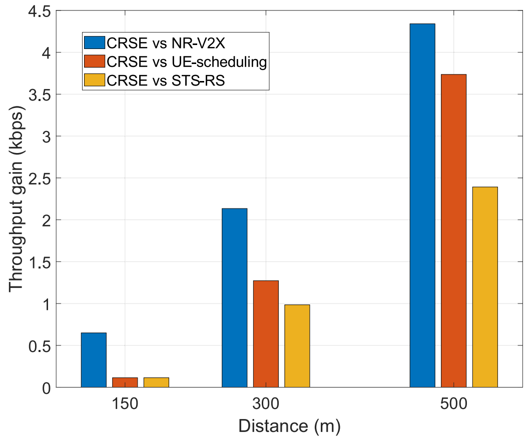


**FIGURE 11.** **Throughput gain of CRSE relative to NR-V2X, UE-scheduling, and STS-RS at different distances. The traffic density is 0.1.**

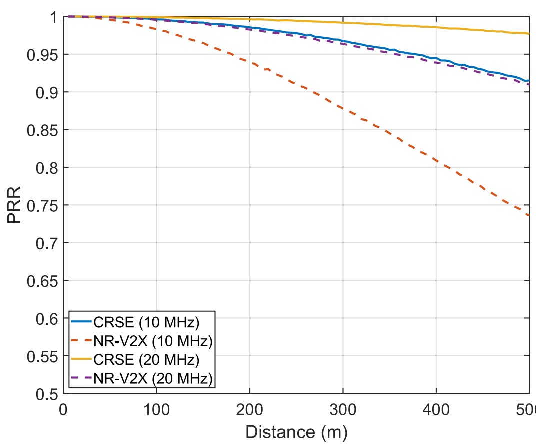


**FIGURE 12.** **PRR comparison of NR-V2X and CRSE under 10 MHz and 20 MHz bandwidth configurations. The traffic density is 0.1.**

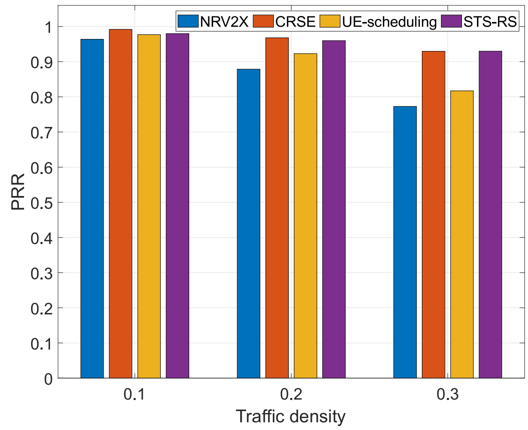


**FIGURE 13.** **PRR as a function of traffic density for CRSE, NR-V2X, UE-scheduling, and STS-RS. The distance is 150 m.**

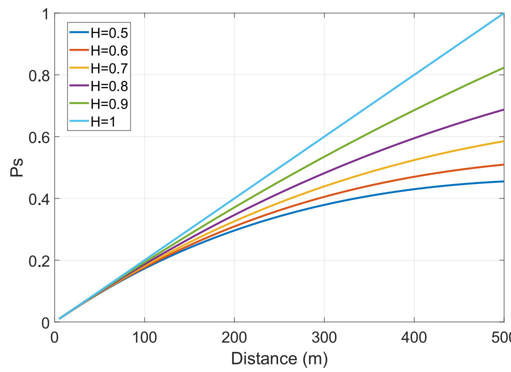


**FIGURE 14.** **$P_S$ for the CRSE as a function of distance($H = 0.5 : 1$).**

encountered in dense urban environments, the PRR is measured at traffic densities of 0.1, 0.2, and 0.3, with the distance set to 150 meters. These traffic density levels also correspond to different V2X penetration ratios. Fig. 13 compares the PRR across different traffic densities for NR-V2X, UE-scheduling, and STS-RS. CRSE consistently outperforms both NR-V2X and UE-scheduling across all traffic densities. It maintains a higher PRR and demonstrates better resilience under increasing traffic loads. At the highest traffic density of 0.3, CRSE achieves the highest PRR, indicating its robustness in high-traffic scenarios. On the other hand, CRSE with $H = 0.9$ shows similar performance to STS-RS in all traffic densities.

Although the CRSE with $H = 0.9$ enhances the performance of the system compared to the conventional other protocols, particularly at long distances, it still needs to satisfy the highest possible performance in terms of reliability and utilization. For example, if the resources are 100 and the number of UEs is 100, the maximum performance in terms of the PRR and $P_s$ is 1 and 1, respectively. However, if the number of UEs exceeds the number of free resources, a collision occurs and degrades the system's performance. Here, we demonstrate how the $H$ value can affect the system performance and show the optimum value of $H$ that maximizes the PRR and $P_s$. Fig. 14 illustrates $P_s$ as a function of distance for the CRSE with varying values of $H$. The curves show $P_s$ for $H$ values ranging from 0.5 to 1.0. As the distance increases from 0 to 500 meters, the $P_s$ generally improves with higher $H$ values, demonstrating the impact of $H$ on the system's reliability. The highest $H$ value achieves the maximum $P_s$, indicating optimal performance in terms of reliability. Furthermore, as shown in Fig. 15, $P_n$ is decreased as the value of $H$ increases and reaches a minimum value at $H = 1$.

Fig. 16 presents the PRR as a function of distance for the CRSE model with different $H$ values, ranging from 0.5 to 1.0. The results show that as the distance extends from 0 to 500 meters, PRR improves with increasing $H$. The highest reliability and optimal performance are observed at $H = 1$, demonstrating the significant influence of $H$ on system performance. To evaluate the performance of the CRSE system under different traffic densities, the PRR is measured at traffic densities of 0.05, 0.1, 0.15, 0.2, 0.25, and 0.3, as shown in Fig. 17. The highest $H$ value (1.0) consistently achieves the highest PRR across all traffic densities, indicating optimal performance. This configuration maintains robust PRR even under higher traffic densities, showcasing its effectiveness in high-traffic scenarios. Thus, the best system reliability is achieved with $H = 1$.

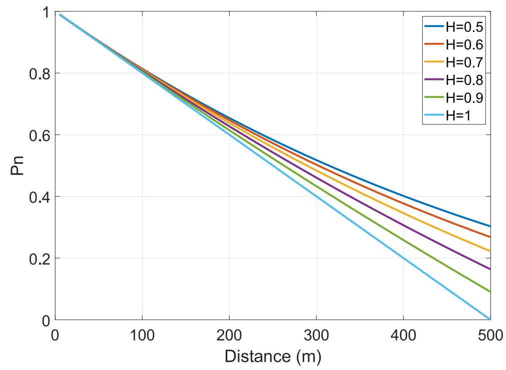


**FIGURE 15.** $P_n$ for the CRSE as a function of distance($H = 0.5 : 1$).

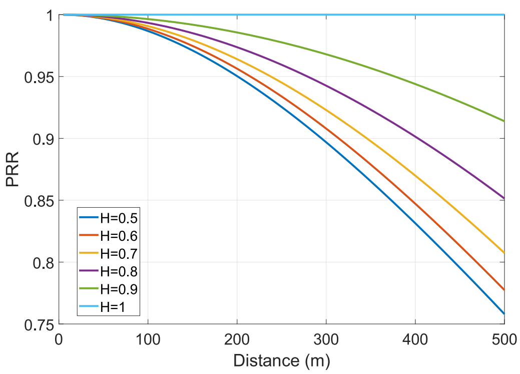


**FIGURE 16.** PRR for the CRSE as a function of distance($H = 0.5 : 1$).

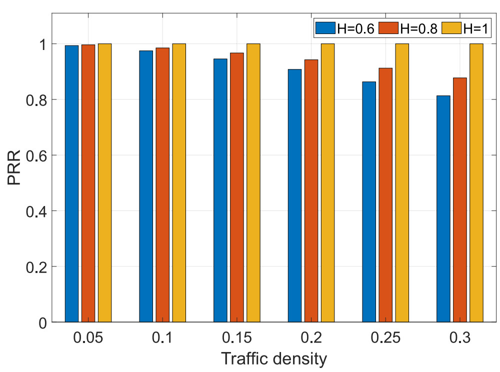


**FIGURE 17.** PRR as a function of traffic density for CRSE($H = 0.6, 0.8, 1$).

According to the preceding findings, it is evident that the CRSE model significantly enhances the performance of resource allocation compared to other schemes. Although the CRSE utilized a modest overhead to share the status of the resources, it consistently outperforms the other models in terms of PRR, especially over extended distances and varying traffic densities. In this study, we only focused on the performance evaluation of CRSE, verifying its accuracy. Our goal is to ensure that CRSE can deliver the highest possible performance in terms of reliability and utilization, making it a robust solution for next-generation vehicular communication systems.

## VII. CONCLUSION

In this study, we presented the CRSE protocol, a novel approach designed to address resource allocation challenges in next-generation vehicular networks. By employing a cooperative approach among UEs to exchange resource status information, CRSE significantly enhances the PRR and resource utilization compared to existing protocols. We utilized game theory to optimize the strategic interactions among UEs. Through comprehensive analytical modeling and simulation results, CRSE demonstrates a remarkable improvement in PRR compared to NR-V2X Mode 2, UE-scheduling, and STS-RS. The dual-state feedback mechanism and hybrid update strategy embedded in CRSE ensure minimal overhead while maintaining high reliability in dynamic vehicular environments. The results from this study are promising.

## REFERENCES

[1] Md. Noor-A-Rahim et al., “6G for vehicle-to-everything (V2X) communications: Enabling technologies, challenges, and opportunities,” *Proc. IEEE*, vol. 110, no. 6, pp. 712–734, Jun. 2022.

[2] J. Kim, Y. Wang, D. Yan, K. Guan, and H. Chung, “Sidelink evolution toward enhanced data rate: Experimental and simulation validation,” *IEEE Trans. Veh. Technol.*, vol. 74, no. 9, pp. 14331–14342, Sep. 2025, doi: 10.1109/TVT.2025.3566265.

[3] R. Viterbo et al., “A 5G roadside infrastructure assisting connected and automated vehicles in vulnerable road user protection,” *IEEE Open J. Intell. Transp. Syst.*, vol. 6, pp. 346–362, 2025, doi: 10.1109/OJITS.2025.3552849.

[4] A. Annu and P. Rajalakshmi, “Towards 6G V2X sidelink: Survey of resource allocation—Mathematical formulations, challenges, and proposed solutions,” *IEEE Open J. Veh. Technol.*, vol. 5, pp. 344–383, 2024.

[5] Q. Liu, R. Luo, H. Liang, and Q. Liu, “Energy-efficient joint computation offloading and resource allocation strategy for ISAC-aided 6G V2X networks,” *IEEE Trans. Green Commun. Netw.*, vol. 7, no. 1, pp. 413–423, Mar. 2023.

[6] R. Shrivastava, S. Hegde, and O. Blume, “Sidelink evolution toward 5G-A/6G future considerations for standardization of group communications,” *IEEE Commun. Standards Mag.*, vol. 7, no. 1, pp. 24–30, Mar. 2023.

[7] M. Elsharief, S. R. Sabuj, and H.-S. Jo, “Advanced resource management strategies for next-generation 6G autonomous vehicular networks,” in *Proc. 15th Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2024, pp. 607–608.

[8] V. Todisco, S. Bartoletti, C. Campolo, A. Molinaro, A. O. Berthet, and A. Bazzi, “Performance analysis of sidelink 5G-V2X mode 2 through an open-source simulator,” *IEEE Access*, vol. 9, pp. 145648–145661, 2021, doi: 10.1109/ACCESS.2021.3121151.

[9] 3GPP, *5G; NR; NR and NG-RAN Overall Description; Stage-2 (Release 16)*, document TS 38.300 V16.11.0, Jan. 2023. [Online]. Available:. https://www.etsi.org/standards-search

[10] W. Yang and H.-S. Jo, “Deep-reinforcement-learning-based range-adaptive distributed power control for cellular-V2X,” *ICT Exp.*, vol. 9, no. 4, pp. 648–655, Aug. 2023.

[11] H. Tran-Dang and D.-S. Kim, “Digital twin-empowered intelligent computation offloading for edge computing in the era of 5G and beyond: A state-of-the-art survey,” *ICT Exp.*, vol. 11, no. 1, pp. 167–180, Feb. 2025.

[12] X. Gu et al., "Performance analysis and optimization for semi-persistent scheduling in C-V2X," *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 4628–4642, Apr. 2023, doi: 10.1109/TVT.2022.3223414.

[13] M. Elsharief, S. R. Sabuj, and H.-S. Jo, "Advancing NR-V2X: Evaluating mode 2 performance through analytical modeling and simulations," *IEEE Access*, vol. 13, pp. 141636–141650, 2025, doi: 10.1109/ACCESS.2025.3596946.

[14] W.-D. Shen and H.-Y. Wei, "Distributed V2X sidelink communications with receiver grant MAC design," *IEEE Trans. Veh. Technol.*, vol. 71, no. 5, pp. 5415–5429, May 2022.

[15] Y. Yoon and H. Kim, "Resolving persistent packet collisions through broadcast feedback in cellular V2X communication," *Future Internet*, vol. 13, no. 8, p. 211, Aug. 2021.

[16] C. Brady and S. Roy, "Opportunistic retransmissions: A novel distributed adaptive algorithm for NR C-V2X mode 2," *IEEE Syst. J.*, vol. 18, no. 2, pp. 881–892, Jun. 2024.

[17] M. Elsharief, S. R. Sabuj, and H.-S. Jo, "Insights into sidelink resource allocation: A performance study in 5G NR-V2X," in *Proc. 14th Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2023, pp. 743–744.

[18] D. Hyeon, C. Lee, H. Kim, S. Cho, J. Paek, and R. Govindan, "Probabilistic resource rescheduling for C-V2X based on delivery rate estimation," *J. Commun. Netw.*, vol. 26, no. 2, pp. 239–251, Apr. 2024.

[19] 3GPP, *5G; NR; NR and NG-RAN Overall Description; Stage-2 (Release 17)*, document TS 38.300 V17.1.0, Aug. 2022. [Online]. Available: https://www.etsi.org/standards-search

[20] M. H. C. Garcia et al., "A tutorial on 5G NR V2X communications," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1972–2026, 3rd Quart., 2021.

[21] G. Cecchini, A. Bazzi, B. M. Masini, and A. Zanella, "MAP-RP: Map-based resource reselection procedure for autonomous LTE-V2V," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.

[22] J. Wu, Y. Guo, and S. Zhou, "A reliable self-adaptive scheduling control protocol for cellular V2X mode 4," *IEEE Access*, vol. 10, pp. 63991–64003, 2022.

[23] A. Bazzi, A. O. Berthet, C. Campolo, B. M. Masini, A. Molinaro, and A. Zanella, "On the design of sidelink for cellular V2X: A literature review and outlook for future," *IEEE Access*, vol. 9, pp. 97953–97980, 2021, doi: 10.1109/ACCESS.2021.3094161.

[24] K. Sehla, T. M. T. Nguyen, G. Pujolle, and P. B. Velloso, "Resource allocation modes in C-V2X: From LTE-V2X to 5G-V2X," *IEEE Internet Things J.*, vol. 9, no. 11, pp. 8291–8314, Jun. 2022, doi: 10.1109/JIOT.2022.3159591.

[25] M. Nour, M. H. Zaki, and M. Abdel-Aty, "Assessing the impact of vehicle-to-vehicle communication on lane change safety in work zones," *IEEE Open J. Intell. Transp. Syst.*, vol. 6, pp. 832–847, 2025, doi: 10.1109/OJITS.2025.3578872.

[26] Y. Yoon, J. Kang, and H. Kim, "Persistent scheduling with broadcast feedback for cellular V2X communication," in *Proc. IEEE 93rd Veh. Technol. Conf. (VTC-Spring)*, Apr. 2021, pp. 1–5.

[27] M. Saifuddin, M. Zaman, Y. P. Fallah, and J. Rao, "Addressing rare outages in C-V2X with time-controlled one-shot resource scheduling," *IEEE Open J. Intell. Transp. Syst.*, vol. 5, pp. 208–222, 2024, doi: 10.1109/OJITS.2024.3361473.

[28] X. He, X. Yang, J. Lv, J. Zhao, T. Luo, and S. Chen, "A cluster-based UE-scheduling scheme for NR-V2X," *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 4538–4552, Apr. 2023.

[29] S. Jung, J.-H. Kim, and J. Kim, "Intelligent extra resource allocation for cooperative awareness message broadcasting in cellular-V2X networks," *IEEE Trans. Netw. Service Manage.*, vol. 22, no. 2, pp. 1677–1689, Apr. 2025.

[30] M. A. A. El-Gawad, M. Elsharief, and H. Kim, "A cooperative V2X MAC protocol for vehicular networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 65, Mar. 2019, doi: 10.1186/s13638-019-1382-8.

[31] H. A. Omar, W. Zhuang, and L. Li, "VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Trans. Mobile Comput.*, vol. 12, no. 9, pp. 1724–1736, Sep. 2013.

[32] X. Jiang and D. H. C. Du, "PTMAC: A prediction-based TDMA MAC protocol for reducing packet collisions in VANET," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9209–9223, Nov. 2016, doi: 10.1109/TVT.2016.2519442.

[33] X. He, J. Lv, J. Zhao, X. Hou, and T. Luo, "Design and analysis of a short-term sensing-based resource selection scheme for C-V2X networks," *IEEE Internet Things J.*, vol. 7, no. 11, pp. 11209–11222, Nov. 2020.

[34] A. Molina-Galan, L. Lusvarghi, B. Coll-Perales, J. Gozalvez, and M. L. Merani, "On the impact of re-evaluation in 5G NR V2X mode 2," *IEEE Trans. Veh. Technol.*, vol. 73, no. 2, pp. 2669–2683, Feb. 2024.

[35] F. Peng, Z. Jiang, S. Zhang, and S. Xu, "Age of information optimized MAC in V2X sidelink via piggyback-based collaboration," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 607–622, Jan. 2021.

[36] T. Sahin, R. Khalili, M. Boban, and A. Wolisz, "Scheduling out-of-coverage vehicular communications using reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 71, no. 10, pp. 11103–11119, Oct. 2022.

[37] J.-Y. Choi, H.-S. Jo, C. Mun, and J.-G. Yook, "Deep reinforcement learning-based distributed congestion control in cellular V2X networks," *IEEE Wireless Commun. Lett.*, vol. 10, no. 11, pp. 2582–2586, Nov. 2021, doi: 10.1109/LWC.2021.3108821.

[38] H. Mosavat-Jahromi, Y. Li, Y. Ni, and L. Cai, "Distributed and adaptive reservation MAC protocol for beaconing in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 20, no. 10, pp. 2936–2948, Oct. 2021, doi: 10.1109/TMC.2020.2992045.

[39] A. S. Tanenbaum and D. J. Wetherall, *Computer Networks*. Upper Saddle River, NJ, USA: Prentice-Hall, 2011.

[40] G. Owen, *Game Theory*. Bingley, U.K.: Emerald Group Publishing, 2013.

[41] Y. Chen, J. Zhao, Y. Wu, J. Huang, and X. Shen, "QoE-aware decentralized task offloading and resource allocation for end-edge-cloud systems: A game-theoretical approach," *IEEE Trans. Mobile Comput.*, vol. 23, no. 1, pp. 769–784, Jan. 2024, doi: 10.1109/TMC.2022.3223119.

[42] Z. Tianjiao and Z. Qi, "Game-based TDMA MAC protocol for vehicular network," *J. Commun. Netw.*, vol. 19, no. 3, pp. 209–217, 2017, doi: 10.1109/JCN.2017.000038.


**MAHMOUD ELSHARIEF** received the B.S. degree in communications and electronics engineering from Al-Azhar University, Egypt, in 2010, the M.S. degree in communications and electronics engineering from Ain Shams University, Cairo, Egypt, in 2014, and the Ph.D. degree in electronics engineering from Chungbuk National University, South Korea, in 2020. From 2012 to 2016, he was a Researcher and a Teaching Assistant at the Communications and Electronics Engineering Department, Al-Azhar University. In 2020, he joined the School of Electrical Engineering, Korea University, South Korea, as a Research Fellow. He was a Research Fellow at the Department of Electronic Engineering, Hanbat National University, Daejeon, South Korea, from 2021 to 2023. He has been an Assistant Professor with the Department of Electrical Engineering, Al-Azhar University. He is currently a Research Fellow with the Department of Automotive Engineering, Hanyang University, Seoul, South Korea. His research interests include wireless sensor networks, wireless vehicular communications, intelligent transportation systems, and reinforcement learning for autonomous wireless industry 4.0 applications.

**SAIFUR RAHMAN SABUJ** (Senior Member, IEEE) was born in Bangladesh. He received the Ph.D. degree from the Graduate School of Engineering, Kochi University of Technology, Japan, in 2017. From 2020 to 2022, he was a Post-Doctoral Research Fellow with the Electronic Engineering Department, Hanbat National University, South Korea. He has been an Associate Professor at the Department of Electrical and Electronic Engineering, Brac University, Bangladesh, since September 2017. From 2008 to 2013, he was a Faculty Member at the Green University of Bangladesh, Metropolitan University, Sylhet, and Bangladesh University. He is currently a Brain Pool Fellow with the Automotive Engineering Department, Hanyang University, Seoul, South Korea. His research interests include MIMO-OFDM/OTFS/NOMA, satellite communication, cognitive radio, the Internet of Things, relay networks, drones, machine learning, artificial intelligence, and vehicular communications for wireless communications.

**SEAN (SEOK-CHUL) KWON** (Member, IEEE) received the B.Sc. degree from Yonsei University, Seoul, South Korea, in 2001, the M.Sc. degree from the University of Southern California, Los Angeles, USA, in 2007, and the Ph.D. degree from Georgia Institute of Technology, Atlanta, USA, in December 2013. He performed research at Intel's Next Generation and Standards Division, Communication and Devices Group, from 2015 to 2017, where he contributed to 5G MIMO standards, associated system design, and patents. He is currently an Associate Professor with California State University, Long Beach, and the Chief Director/the Founder of the Wireless Systems Evolution Laboratory (WiSE Lab). He also conducted post-doctoral research at the Wireless Devices and Systems Group, University of Southern California, from 2014 to 2015. He worked on CDMA common air interface, focusing on layer-three protocols at the Research and Development Institute, Pantech Company Ltd., Seoul, from 2001 to 2004. He was involved in several projects, including a DARPA project, the U.S. Army Research Laboratory project, the Aerospace Corporation projects, and six mobile station projects for Motorola and Sprint, which were successfully brought to market. His current research interests include 6G and future wireless system/network design, satellite communications, polarization diversity and multiplexing, body area networks such as wearable computing, wireless channel modeling and its applications, and the application of machine learning for wireless communications and signal processing. He was a recipient of five best paper awards from the IEEE International Conference on Green Energy and Smart Systems (IEEE GESS, previously IGESSC).

**HAN-SHIN JO** (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and electronics engineering from Yonsei University, Seoul, South Korea, in 2001, 2004, and 2009, respectively. He was a Professor at the Department of Electronic Engineering, Hanbat National University, Daejeon, Republic of Korea, from 2012 to 2023. He was a Post-Doctoral Research Fellow with the Wireless Networking and Communications Group, Department of Electrical and Computer Engineering, University of Texas at Austin, from 2009 to 2011. He developed a long-term evolution base station at Samsung Electronics from 2011 to 2012. He was a Visiting Scholar with the Wireless Devices and Systems Group, University of Southern California, from 2018 to 2019. He is currently a Professor with the Department of Automotive Engineering, Hanyang University, Seoul. His current research interests are in coexistence study and spectrum sharing, and applications of stochastic geometry, optimization theory, and machine/reinforcement learning to wireless communications and connected and autonomous mobility. He has been a member of Korea ITU-R Working Party 5D Committee since 2016.