



Mobility-Aware Distributed Time-Division Multiple Access for Low-Latency and Collision-Resilient Vehicular Communications

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Abstract: Reliable and timely vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication is essential for safety-critical applications in intelligent transportation systems (ITS). Distributed time-division multiple access (TDMA) supports deterministic channel access in vehicular ad hoc networks (VANETs), but contention during slot reservation and mobility-induced merging collisions remain major obstacles to reliable communication under dense and rapidly changing traffic conditions. This study investigates these limitations and proposes a backoff-based partitioned-reservation medium access control protocol (BPR-MAC), a distributed TDMA protocol that integrates reservation-phase contention control with mobility-aware slot allocation. A mini-slot carrier-sensing backoff mechanism was introduced to resolve competing reservation attempts within individual slots, while an adaptive slot-partitioning mechanism was developed to allocate transmission resources according to driving direction and vehicle speed relative to the surrounding traffic stream. The protocol was evaluated using MATLAB-based discrete-event simulations of a 3 km two-way highway, with vehicle speeds ranging from 40 to 120 km/h. Performance was assessed in terms of slot-reservation delay and merging-collision rate under different traffic densities, slot-occupancy conditions, and protocol parameter settings. At 90% two-hop-neighborhood slot occupancy, BPR-MAC reduced the merging-collision rate from 0.778 for a Vehicular Media Access Control (VeMAC)-like baseline to 0.017, a reduction of 97.8%. For 100 vehicles, the reservation delay decreased from approximately 31 to 2 frames. Ablation results showed that mobility-aware slot partitioning accounted for most of the reduction in merging collisions, while reservation-phase backoff provided complementary collision suppression and faster slot acquisition. Sensitivity analysis further showed that the principal performance trends remained stable under moderate variations in the relative-speed threshold and contention-window size. These findings indicate that combining localized contention control with relative-motion-based slot allocation can improve the predictability of distributed channel access in dense vehicular networks. BPR-MAC provides a communication-layer approach to supporting time-sensitive safety messaging and cooperative V2V/V2I communication in ITS.

Keywords: Vehicular ad hoc networks; Distributed time-division multiple access; Medium access control; Mobility-aware slot allocation; Reservation delay; Merging collision avoidance; V2V/V2I communication

1 Introduction

Intelligent transportation systems (ITS) increasingly depend on timely information exchange among vehicles and roadside infrastructure to support traffic management and safety-critical operations. Vehicular ad hoc networks (VANETs) provide a decentralized communication framework for these applications, enabling inter-vehicle communication (IVC) and roadside-unit-to-vehicle communication (RVC) without continuous reliance on fixed network infrastructure [1]. The reliability of such communication depends on several factors, including network security, channel availability, and the time required to deliver safety information. Recent investigations of cybersecurity in ITS have identified vulnerabilities associated with connected-vehicle communication and the need for dependable V2X operation [2]. At the same time, research on edge computing for autonomous systems has examined the reduction of processing latency in real-time applications [3]. Although communication security, computational latency, and channel-access delay arise at different system layers, each can affect the operation of time-sensitive vehicular services. At the communication layer, the challenge is particularly acute because vehicles must exchange

information while network topology and channel demand change continuously. Basic safety messages typically carry position, speed, and heading information at frequencies of 5–10 Hz, whereas event-driven warnings must be delivered within a limited message lifetime, often no more than 500 ms. The dedicated short-range communications (DSRC) framework provides a control channel for safety-related information exchange, but access to this shared wireless resource becomes increasingly difficult as vehicle density and mobility increase. Consequently, medium access control (MAC) mechanisms must accommodate both competing transmission requests and rapid changes in the relative positions of communicating vehicles.

Carrier sense multiple access with collision avoidance (CSMA/CA), as employed in IEEE 802.11p, provides decentralized channel access without requiring a fixed transmission schedule. Its contention-based operation, however, makes transmission delay less predictable under heavy channel demand [4, 5]. The problem is more pronounced for broadcast safety messages because conventional acknowledgment and retransmission procedures cannot be applied in the same manner as in unicast communication, while hidden terminals may transmit simultaneously without detecting one another [6]. Distributed time-division multiple access (TDMA) offers an alternative by allowing vehicles to reserve transmission slots and subsequently access the channel according to a predetermined schedule. Earlier investigations demonstrated advantages of self-organizing TDMA over CSMA in channel-access fairness and transmission performance [5]. ADHOC MAC and its adaptive extension further established the feasibility of distributed slot reservation for vehicular broadcasting, including adjustments to frame length in response to traffic density [7–9]. Nevertheless, reservation conflicts remain possible when multiple vehicles select the same available slot. Vehicular Media Access Control (VeMAC) introduced direction-based slot separation to reduce collisions between vehicles approaching from opposite directions [10], while preventive allocation methods sought to avoid conflicting reservations before they occurred [11, 12]. These developments established the importance of coordinating slot allocation with traffic conditions, but they also exposed two distinct sources of communication disruption. Access collisions arise when competing vehicles attempt to acquire the same slot, whereas merging collisions occur when vehicles previously separated in space become interfering neighbors while reusing a transmission resource [13]. The latter problem is closely associated with mobile hidden terminals (MHTs) and cannot be resolved solely by improving the initial reservation procedure.

Recent research has extended vehicular resource coordination beyond conventional distributed TDMA to cellular V2X and more flexible scheduling architectures. In NR-V2X sidelink communication, reuse-distance-aware resource selection and sensing-based scheduling have been investigated to reduce resource conflicts under autonomous operation [14, 15]. Related studies have addressed resource allocation for vehicle platoons, congestion control in cellular-V2X, and cooperative scheduling under changing traffic conditions [16–18]. Hybrid multichannel MAC protocols have also been developed to reduce local access delay in VANETs [19], while broader investigations of V2X resource allocation have emphasized the continuing difficulty of coordinating wireless resources under high mobility [20]. Although these approaches differ in their communication architectures and resource-selection procedures, they illustrate a common tension between rapid channel acquisition and stable resource reuse. Mechanisms that reduce contention during initial access do not necessarily prevent interference when vehicle neighborhoods change. Conversely, mobility-based resource separation may reduce subsequent conflicts but can restrict the number of slots available to vehicles competing within the same traffic group. For distributed TDMA, this distinction is especially important because reservation and transmission are separate operational phases. A protocol must therefore limit repeated reservation attempts without sacrificing the collision resistance of the established transmission schedule. Existing direction-based and mobility-aware allocation strategies provide useful foundations, but the combined treatment of reservation-phase contention and relative-motion-induced merging collisions warrants further investigation within a unified distributed TDMA framework.

To address this problem, a backoff-based partitioned-reservation medium access control protocol (BPR-MAC) is proposed for vehicular communication. The protocol combines two mechanisms operating at different stages of channel access. During slot reservation, a mini-slot carrier-sensing backoff procedure allows competing vehicles to detect ongoing reservation attempts and withdraw before transmitting conflicting requests. Unlike hybrid approaches that retain contention during regular data transmission, this procedure is restricted to the reservation phase, after which channel access follows the TDMA schedule. To address merging collisions, the available slots are partitioned according to vehicle driving direction and speed relative to the surrounding two-hop neighborhood. This relative-speed representation distinguishes vehicles whose motion differs from the local traffic stream, rather than relying exclusively on fixed absolute-speed categories. The capacities of the resulting slot subsets are adjusted according to observed traffic conditions, and a fallback procedure permits access to alternative subsets when the preferred allocation becomes exhausted. The two mechanisms are intended to perform complementary functions: reservation-phase backoff reduces competing access attempts, while mobility-aware partitioning limits the reuse of transmission slots by vehicles with potentially conflicting motion patterns. Their combined operation was examined using MATLAB-based discrete-event simulations of a two-way highway. Comparisons with a VeMAC-like baseline and configurations containing only one of the proposed mechanisms were used to evaluate reservation delay, merging-

collision behavior, and sensitivity to selected protocol parameters.

The significance of this approach lies in treating slot acquisition and mobility-induced interference as related but distinct problems in distributed vehicular communication. For safety-oriented ITS applications, delayed channel access can prevent a vehicle from obtaining transmission resources when information must be exchanged promptly, while merging collisions can interrupt communication after a slot has already been reserved. Addressing both mechanisms is therefore relevant to periodic safety broadcasting, cooperative vehicle communication, and event-driven warning services. The present study evaluates these effects at the MAC layer through reservation-delay and merging-collision metrics rather than through end-to-end safety-message delivery or field measurements. Within this scope, BPR-MAC provides a mobility-aware distributed channel-access design intended to support more predictable communication under dense and rapidly changing vehicular conditions.

2 System Model

In distributed TDMA protocols such as ADHOC MAC and VeMAC, a node randomly selects a slot that it perceives to be idle for reservation, and the reservation outcome is confirmed from the frame information (FI) reported by neighboring nodes after one frame has elapsed. As node density increases, access collisions become more frequent, causing the reservation delay to increase and become less predictable [7, 10]. One approach to addressing this limitation is to introduce contention mechanisms into the TDMA frame. The hybrid TDMA/CSMA multichannel MAC [21], the hybrid MAC combining scalable CSMA with self-organizing TDMA [22], and CTMAC, which switches between CSMA-style random access and TDMA-style reservation according to vehicle density [23], are representative examples. In these schemes, however, contention-based backoff generally governs channel access across transmission cycles. BPR-MAC instead confines backoff to candidate slots during the reservation phase, while retaining deterministic TDMA operation during the transmission phase. MPTDMA reduces the reallocation delay after slot collisions by employing a fast conflict-resolution strategy based on the rate of change in the number of neighbor nodes [24]. Abid et al. [11, 12] developed a preventive time-slot allocation framework that assigns slots before collisions occur. SMDP-MAC partitions the slot set according to driving direction and dynamically selects slots by jointly considering vehicle speed and acceleration [25]. BPR-MAC differs from these approaches by incorporating mini-slot carrier-sensing backoff exclusively into the candidate-slot reservation process and combining it with relative-speed-adaptive slot partitioning within a distributed TDMA framework.

Compared with existing approaches, BPR-MAC has three distinguishing characteristics. First, contention-based backoff is applied only to candidate slots during the reservation phase, whereas the transmission phase remains deterministic TDMA, distinguishing the protocol from whole-frame hybrid contention mechanisms [21]. Second, vehicle mobility states are classified according to the difference between a node's speed and the average speed of its neighboring nodes rather than by predefined absolute-speed tiers. This relative-speed representation makes it possible to distinguish vehicles moving faster or slower than the surrounding traffic stream, including vehicles within a platoon whose absolute speeds may otherwise appear similar. Third, BPR-MAC employs a two-level coarse-grained slot-partitioning structure in which subset sizes are adaptively adjusted according to the measured directional traffic ratio. This structure incurs lower partitioning overhead than the three-level speed ranges adopted by CFR-MAC [26] and the lane-based division used by MoMAC [27], while reducing the risk that excessively fine-grained partitioning aggravates slot contention under high-density conditions.

The VANET system model assumes that all nodes share a common synchronization source. The carrier-sensing range of each node is assumed to be equal to its communication range, with identical transmission radii and symmetric wireless links. Consistent with the assumptions commonly adopted in protocols such as VeMAC, balanced two-way traffic is considered in the basic system model; the effects of unbalanced traffic are subsequently addressed through the fallback strategy and simulation experiments. Time is organized into periodic frames containing N slots, with each slot representing the minimum transmission unit. Vehicles reserve slots on the control channel for the transmission of safety messages and FI. Each node maintains the slot-occupancy state of its two-hop neighbor set, denoted by THS, and selects an available slot for channel access. Spatial reuse is permitted for nodes separated by at least three hops.

3 Problem Statement

Under conventional distributed slot reservation, a vehicle first listens to the channel for one complete frame and then randomly selects a slot perceived as idle. When multiple nodes independently select the same slot, an access collision can occur. As traffic density increases, the probability of simultaneous reservation attempts rises, which in turn increases slot-reservation delay. After a collision is detected, the affected node must repeat the reservation procedure until a slot is successfully acquired. Because the outcome of each reservation attempt can only be confirmed after a frame-sliding interval, the node cannot immediately compete for another slot during this period, further increasing the time required for successful access. Existing studies have identified reservation delay as an important limitation on the practical deployment of distributed TDMA protocols in high-density vehicular

networking environments. The reservation-phase delay, expressed in frames under different traffic densities, is illustrated in Figure 1.

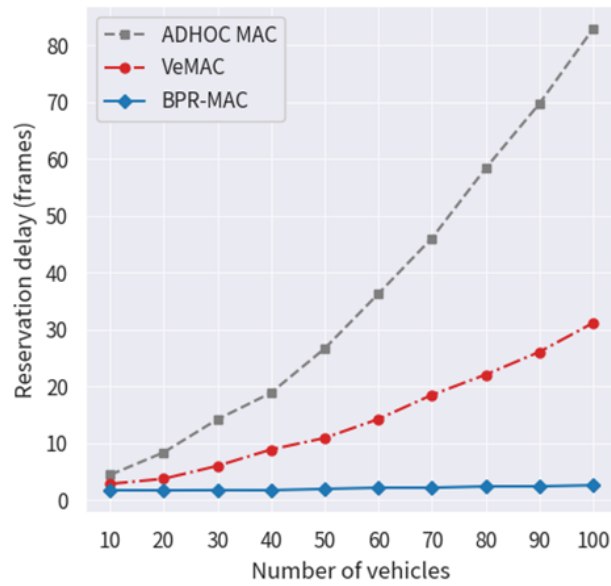


Figure 1. Reservation delay required for all vehicles to successfully reserve slots

Note: ADHOC MAC—Ad Hoc Medium Access Control; VeMAC—Vehicular Media Access Control; BPR-MAC—backoff-based partitioned-reservation medium access control protocol.

As shown in Figure 2, the probability of merging collisions increases with traffic density and with the number of MHTs. Increasing the total number of available slots can alleviate this problem to some extent. However, under highly dynamic VANET conditions, frequent merging collisions force vehicles to leave the stable transmission phase, release their occupied slots, and repeatedly re-enter the reservation process. This behavior reduces wireless-resource utilization and degrades the reliability of periodic vehicular communication. Merging collisions are particularly likely to occur between vehicles traveling in opposite directions or exhibiting high relative speeds.

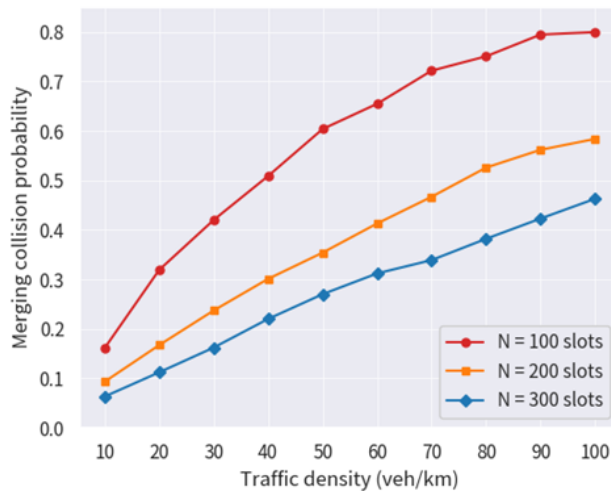


Figure 2. Severity of the merging-collision problem

These characteristics indicate that a distributed TDMA protocol for highly mobile vehicular networks must address two related requirements: slot-reservation delay should remain predictable as node density increases, and mobility-induced collisions should be suppressed during subsequent transmission. BPR-MAC is designed to satisfy these requirements by applying mini-slot backoff during the reservation phase to accelerate slot acquisition and by introducing relative-speed-adaptive slot partitioning to reduce merging collisions before conflicting vehicles occupy

the same transmission resource.

4 Algorithm Description

The BPR-MAC protocol consists of three coordinated components: (1) a mini-slot backoff reservation mechanism operating within candidate slots to accelerate slot acquisition and reduce access collisions; (2) a relative-speed-adaptive slot-partitioning mechanism designed to prevent merging collisions among MHTs; and (3) a transmission-phase monitoring and recovery mechanism for detecting and resolving residual merging collisions.

In existing distributed TDMA protocols such as VeMAC, nodes competing for transmission slots must collect the FI of their two-hop neighbors over a complete frame before the outcome of a reservation attempt becomes known. If an access collision occurs, an entire frame may therefore elapse before another reservation can be attempted, making reservation delay sensitive to traffic density. BPR-MAC introduces carrier-sensing backoff into the candidate-slot reservation phase so that an unsuccessful attempt can be detected within one slot rather than after an entire frame. Hybrid TDMA/CSMA mechanisms, by comparison, generally allow contention over the transmission frame [21], whereas the backoff process in BPR-MAC is restricted to candidate slots during reservation; once a slot has been successfully acquired, data transmission proceeds according to deterministic TDMA. The reservation procedure for node i is defined as follows.

Step 1—Slot-state learning.

When node i joins the network or releases its currently occupied slot, it listens to the control channel for one complete frame and collects the FIs transmitted by neighboring nodes. Any slot reported as occupied by a member of $THS(i)$ is marked as busy, and the corresponding available-slot set S_i is constructed.

Step 2—Candidate-slot selection.

Node i uniformly and randomly selects a candidate slot s^* from $S_i \cap F(d_i, l_i)$.

Step 3—Backoff-counter initialization.

Node i initializes its backoff counter B_i using an integer selected uniformly at random from $[0, CW - 1]$, where CW denotes the contention-window size.

Step 4—Carrier sensing and backoff.

At the beginning of a candidate slot s^* , node i senses the channel. If the channel remains idle, B_i is decremented by one after each mini-slot of duration δ . If the channel becomes busy, indicating that another node within the carrier-sensing range is attempting to reserve the same slot, node i immediately terminates the current attempt, returns to Step 2, and selects another available candidate slot. Because this decision relies on physical carrier sensing rather than subsequent FI decoding, an unsuccessful reservation attempt can be identified within at most one slot duration. This contrasts with VeMAC, in which confirmation may require an entire frame.

Step 5—Reservation-request transmission.

When B_i reaches zero and the channel remains idle, node i transmits a reservation request in slot s^* . The request contains the node identifier, the candidate-slot index s^* , and the current FI.

Step 6—Reservation confirmation.

Node i verifies the reservation outcome during the next sliding frame. If the FIs received from all members of $THS(i)$ indicate that slot s^* is occupied by node i , the reservation is considered successful and the node enters the transmission phase. Otherwise, the procedure returns to Step 2.

The following notation is used:

- N : number of slots in each frame;
- $F = \{1, 2, \dots, N\}$: set of slot indices within one frame;
- $THS(i)$: two-hop set of node i , consisting of the nodes within two hops of i , including node i itself;
- $FI(j)$: fi broadcast by node j , containing the occupancy state of each slot in F as perceived by node j ;
- S_i : set of slots perceived by node i as available, i.e., not occupied by any member of $THS(i)$;
- CW : contention-window size, expressed in mini-slots;
- δ : duration of one mini-slot and the carrier-sensing granularity of the backoff process;
- v_i, d_i : speed and driving direction (heading) of node i , obtained from its onboard GPS receiver;
- $\bar{v}(i)$: average speed of the THS neighbors of node i ;
- Δ : threshold used to classify the relative-speed level.

Merging collisions arise when nodes occupying the same slot become mutually interfering MHTs as their relative positions change. Their likelihood is therefore governed not only by absolute vehicle speed or position, but also by the relative motion between vehicles sharing a transmission resource. CFR-MAC classifies vehicles according to absolute speed and may therefore be unable to distinguish vehicles that move faster or slower than the surrounding traffic stream when their absolute speeds fall within the same predefined range. BPR-MAC instead adopts relative-speed-based classification. For node i , the relative-speed indicator is calculated from the difference between its own speed and the average speed of the vehicles in its two-hop neighborhood:

$$v_{rel}(i) = |v_i - \bar{v}(i)|$$

The relative-speed level is denoted by $l \in \{L, H\}$. When $v_{\text{rel}}(i) < \Delta$, the vehicle is assigned to level L ; otherwise, it is assigned to level H . The variable $d \in \{+, -\}$ represents the driving direction relative to the road axis. The complete frame F is accordingly partitioned into four mutually exclusive subsets:

- $F(+, L)$: slots assigned to vehicles traveling in the positive direction with low speed deviation from their neighboring traffic stream;
- $F(+, H)$: slots assigned to vehicles traveling in the positive direction with a comparatively high relative speed;
- $F(-, L)$: slots assigned to vehicles traveling in the negative direction with low speed deviation from their neighboring traffic stream;
- $F(-, H)$: slots assigned to vehicles traveling in the negative direction with a comparatively high relative speed.

A node with mobility state (d, l) is initially allowed to compete only for slots belonging to the corresponding subset $F(d, l)$ during Step 2. Vehicles traveling in opposite directions are therefore separated into different slot subsets, substantially reducing the probability that oncoming vehicles become conflicting MHTs. The additional relative-speed classification further separates vehicles whose motion differs substantially from that of the surrounding traffic stream, enabling more stable spatial reuse of transmission slots. Unlike schemes based solely on driving direction, this mechanism incorporates mobility information without requiring acceleration measurements.

The capacities of the four slot subsets are configured adaptively. Their initial sizes are determined from the measured two-way traffic ratio and the observed proportions of the two relative-speed levels, and the configuration is updated every K frames according to the most recent traffic statistics. VeMAC partitions slots only according to direction, while MoMAC relies on lane-based division; both can encounter resource imbalance when traffic demand becomes concentrated in one direction while slots allocated to the opposite direction remain unused. CFR-MAC allows the number of slots to vary but relies on three absolute-speed classes. BPR-MAC instead adopts a two-level coarse-grained relative-speed structure and adjusts only the subset capacities, reducing configuration overhead while limiting the additional contention that can arise from excessive partition granularity under dense traffic conditions.

When the slot subset corresponding to the current mobility state becomes exhausted, a graded fallback mechanism is activated. The vehicle first attempts to access the subset associated with the opposite relative-speed level but the same driving direction. If no slot is available there, access is extended to the subset with the same relative-speed level in the opposite direction. This fallback procedure can moderately increase the risk of merging collisions, but it prevents reservation deadlock under severely unbalanced traffic conditions.

Once a slot has been successfully reserved, the corresponding slot in each subsequent frame remains dedicated to that node until a merging collision is detected. Each node continuously examines the received FI to determine whether another node in its THS reports the same slot as being occupied by a different node identifier. When such a conflict is detected, a merging collision is declared. The colliding nodes then release the conflicting slot and re-enter the reservation procedure. The complete protocol is summarized in Algorithm 1.

Algorithm 1. BPR-MAC

```

1: while node  $i$  has not acquired a dedicated slot do
2:   Listen for one frame and construct  $S_i$  from the FIs of neighboring nodes;
3:    $s^* \leftarrow \text{RandomSelect}(S_i \cap F(d_i | l_i))$ ;
4:    $B_i \leftarrow \text{UniformInteger}(0, CW - 1)$ ;
5:   while  $B_i > 0$  do
6:     if channel  $s^*$  is busy then
7:       Abort the current reservation attempt;
8:       break;
9:     else
10:      Wait for one mini-slot of duration  $\delta$ ;
11:       $B_i \leftarrow B_i - 1$ ;
12:    end if
13:  end while
14:  if  $B_i = 0$  and channel  $s^*$  remains idle then
15:    Transmit a reservation request in slot  $s^*$ , carrying the node ID, slot index, and FI;
16:    if the FI in the next frame confirms the reservation of  $s^*$  then
17:      Enter the transmission phase;
18:    end if
19:    end if
20:  end while
21:  while node  $i$  remains in the transmission phase do
22:    Transmit the safety message and FI in the dedicated slot;
23:    if FI indicates a slot conflict then
24:      Release the dedicated slot;
25:      break;
26:    end if
27:  end while

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5 Simulation Analysis

The performance of BPR-MAC was evaluated using a MATLAB-based discrete-event simulator. The simulated transportation environment consisted of a 3 km two-way highway with balanced traffic flows in both directions. Vehicles traveled at speeds uniformly distributed between 40 and 120 km/h, periodically broadcast beacon messages over the control channel, and reserved transmission slots according to the BPR-MAC procedure. The principal simulation parameters are summarized in Table 1. To reduce the influence of stochastic variation, each reported result represents the average of 10 simulation runs conducted with different random seeds.

Table 1. Simulation parameters

Parameter	Value
Highway length	3 km (two-way)
Frame length (N)	100 slots
Slot duration	10 ms
Communication range	300 m
Vehicle speed	40–120 km/h (uniform distribution)
Beacon transmission frequency	10 Hz
Relative-speed threshold Δ	30 km/h
Contention window (CW)	8 mini-slots

A sensitivity analysis was conducted to examine whether the performance of BPR-MAC remained stable under moderate variations in its two principal protocol parameters. Table 2 reports the average reservation delay and merging-collision rate, defined as the average number of merging-collision events per reserved vehicle per frame, for $\Delta = 20, 30$, and 40 km/h with CW = 8, and for CW = 4, 8, and 16 with $\Delta = 30$ km/h.

Table 2. Sensitivity of reservation delay and merging-collision rate to Δ and CW

Setting	Reservation Delay (Frames)	Merging-Collision Rate ($\times 10^{-3}$)
$\Delta = 20$ km/h (CW = 8)	2.11	1.44
$\Delta = 30$ km/h (CW = 8)	2.11	1.55
$\Delta = 40$ km/h (CW = 8)	2.11	1.65
CW = 4 ($\Delta = 30$ km/h)	2.11	1.57
CW = 8 ($\Delta = 30$ km/h)	2.11	1.55
CW = 16 ($\Delta = 30$ km/h)	2.10	1.61

Note: CW—contention window; Δ —relative-speed threshold. 100 vehicles on the 3 km two-way highway; merging-collision rate = average events per reserved vehicle per frame; average of 10 runs.

Three observations can be drawn from these results. First, the average reservation delay remained approximately 2.1 frames across all six parameter settings, indicating that moderate variations in Δ and CW had little influence on slot-acquisition delay under the simulated conditions. Second, as Δ increased from 20 to 40 km/h, the merging-collision rate changed from 1.44×10^{-3} to 1.65×10^{-3} , corresponding to a relative variation of approximately 15%. This limited variation can be attributed to the direction-based component of the partitioning mechanism, which provides the primary separation between vehicles traveling in opposite directions and operates independently of Δ . Third, when CW increased from 4 to 16, the merging-collision rate remained within a narrow range of 1.55×10^{-3} to 1.61×10^{-3} , while the reservation delay remained essentially unchanged. Under the evaluated density and frame configuration, access collisions were therefore already infrequent with 100 slots per frame, leaving limited scope for a larger contention window to improve performance. A larger CW may instead increase the backoff time within an individual slot. Overall, the results indicate that the main performance trends of BPR-MAC are insensitive to moderate variations in Δ and CW within the tested ranges.

The baseline values of $\Delta = 30$ km/h and CW = 8 mini-slots in Table 1 were selected to provide a coarse distinction between relative-motion states while maintaining a short reservation interval. In urban and highway traffic, vehicles traveling within the same lane or platoon typically exhibit lower relative speeds, often below 20–30 km/h, whereas larger relative speeds are more commonly associated with oncoming traffic on two-way roads or overtaking maneuvers. Accordingly, $\Delta = 30$ km/h provides a practical threshold for separating the two relative-speed states used by the coarse-grained partitioning mechanism. The contention window CW = 8 is selected to balance reservation contention and access delay within a 10 ms slot. A very small contention window of only one or two mini-slots provides limited separation between simultaneous reservation attempts and consequently increases their collision risk, whereas an excessively large window unnecessarily extends the backoff process. A window of

eight mini-slots maintains the backoff interval within a small fraction of the slot duration while providing sufficient differentiation among competing reservation attempts.

Figure 3 compares the merging-collision rates of the evaluated TDMA MAC configurations under different THS occupancy rates in the two-way highway scenario. The VeMAC-like baseline (V-0) exhibited the highest merging-collision rate, whereas the complete BPR-MAC configuration combining reservation-phase backoff with relative-speed-adaptive slot partitioning consistently produced the lowest values. The difference became particularly pronounced as THS occupancy increased. At a 90% occupancy rate, the merging-collision rate decreased from 0.778 for V-0 to 0.017 for the complete BPR-MAC configuration, corresponding to a reduction of approximately 97.8%.

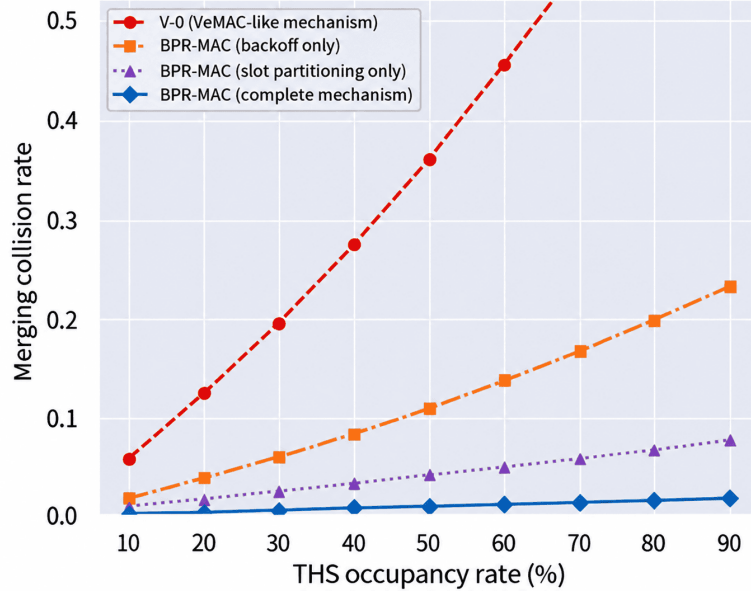


Figure 3. Merging-collision rates under different THS occupancy rates

Note: THS—two-hop neighbor set; VeMAC—vehicular medium access control; BPR-MAC—backoff-based partitioned-reservation medium access control.

The four configurations also clarify the distinct functions of the two mechanisms incorporated into BPR-MAC. V-0 does not differentiate vehicles according to driving direction or relative-speed level, allowing vehicles within the two-hop neighborhood to draw from the same available-slot space. Consequently, MHTs with high relative motion, particularly vehicles approaching from opposite directions, are more likely to occupy the same slot and subsequently interfere when they enter one another's two-hop neighborhoods.

Relative-speed-adaptive slot partitioning directly addresses this source of merging collisions by separating vehicles according to driving direction and relative-motion state before slot acquisition. Vehicles with substantially different mobility states are therefore less likely to share the same transmission slot, reducing mobility-induced conflicts during subsequent encounters and supporting more stable spatial slot reuse. The results in Table 3 show that slot partitioning alone reduced the merging-collision rate from 0.778 to 0.074 at 90% THS occupancy, accounting for most of the improvement achieved by the complete protocol.

Table 3. Merging-collision rates under different THS occupancy rates

THS Occupancy Rate (%)	10	20	30	40	50	60	70	80	90
V-0	0.058	0.124	0.196	0.276	0.362	0.456	0.556	0.664	0.778
BPR-MAC (backoff only)	0.017	0.037	0.059	0.083	0.109	0.137	0.167	0.199	0.233
BPR-MAC (slot partitioning only)	0.009	0.015	0.022	0.029	0.037	0.045	0.054	0.064	0.074
BPR-MAC (complete mechanism)	0.002	0.003	0.005	0.007	0.008	0.010	0.012	0.014	0.017

Note: THS—two-hop neighbor set; V-0—VeMAC-like baseline mechanism; VeMAC—Vehicular Media Access Control; BPR-MAC—backoff-based partitioned-reservation medium access control.

The mini-slot backoff mechanism serves a different purpose. It operates exclusively during slot reservation and primarily suppresses access collisions. When multiple unreserved vehicles compete for the same candidate slot, a node with a larger backoff counter can detect an ongoing reservation attempt and withdraw before transmitting its own request. This mechanism reduces simultaneous reservation attempts and shortens the repeated contention process.

Its contribution to merging-collision reduction is therefore indirect: more orderly slot acquisition reduces the period during which unreserved nodes repeatedly contend for and change candidate slots. Consistent with this mechanism, the backoff-only configuration yielded a merging-collision rate of 0.233 at 90% THS occupancy, substantially higher than the 0.074 obtained with slot partitioning alone. The combined configuration produced the lowest value of 0.017, indicating that the two components perform complementary functions in stabilizing distributed channel access under dense vehicular conditions. These trends are consistently reflected in both Table 3 and Figure 3.

Beyond comparison with the VeMAC-like baseline, BPR-MAC can also be considered in relation to more recent V2X resource-allocation approaches. NR-V2X Mode 2 employs sensing-based semi-persistent scheduling, in which vehicles autonomously sense sidelink resources and perform resource selection. Recent developments include reuse-distance-aided resource selection [14], comparative investigations of semi-persistent and dynamic scheduling [15], congestion-control mechanisms [17], machine-learning-based resource allocation [28], and low-delay hybrid multichannel MAC designs [19]. These approaches primarily address cellular sidelink resource allocation and rely on mechanisms such as sidelink control information and resource-reselection procedures, whereas BPR-MAC is formulated for the DSRC control channel and retains deterministic TDMA operation after slot reservation.

A VeMAC-like mechanism was retained as the principal baseline because it provides a technically consistent basis for isolating the effects of the proposed mechanisms. In particular, VeMAC and BPR-MAC share fundamental distributed TDMA assumptions, including two-hop FI and GPS-based driving-direction classification. Their comparison therefore allows the effects of reservation-phase backoff and relative-speed-adaptive slot partitioning to be examined without introducing differences associated with fundamentally different physical-layer or frame structures. A full PHY-level implementation of NR-V2X Mode 2 falls outside the scope of the present MATLAB-based discrete-event simulation and was therefore not used as a direct numerical baseline.

In terms of protocol overhead, BPR-MAC retains the per-frame FI broadcast used by VeMAC and additionally piggybacks only the relative-speed level and current slot-subset configuration, requiring a small number of additional information bits per frame. The mini-slot backoff process is confined to the reservation phase and occupies only a fraction of the 10 ms slot. By comparison, sensing-based sidelink approaches rely on continuous resource sensing and associated sidelink control information during autonomous resource selection. These architectural differences mean that the present results should not be interpreted as a direct performance comparison between BPR-MAC and NR-V2X Mode 2. Rather, BPR-MAC represents a distributed TDMA approach to mobility-aware resource coordination within the DSRC-based VANET framework. Direct cross-platform evaluation under a unified physical-layer and mobility model remains an important direction for future investigation. Integrated simulation environments for connected automated vehicles offer a practical basis for such unified cross-platform evaluation [29].

6 Discussion and Limitations

BPR-MAC operates under several assumptions that should be considered when interpreting the simulation results and assessing its applicability to practical vehicular communication environments. First, relative-speed classification relies on vehicle speed and driving-direction information obtained from onboard GPS receivers. Errors in GPS-derived speed estimates may lead to occasional misclassification when the relative speed of a vehicle lies close to the threshold Δ . The two-level coarse-grained partitioning structure limits the effect of such errors to the selection of the corresponding slot subset; nevertheless, the influence of positioning and speed-estimation errors on protocol performance requires further evaluation under realistic mobility and sensing conditions.

Second, the protocol relies on FI representing the two-hop neighborhood observed during the preceding frame. Rapid changes in vehicle density or neighborhood topology may therefore cause temporary discrepancies between the current traffic state and the information used for slot allocation. Similarly, because the capacities of the slot subsets are updated every K frames, short-term changes in traffic demand may temporarily produce an imbalance between available slot resources and actual reservation demand. The graded fallback mechanism provides an alternative reservation path when the preferred subset is exhausted, but its effectiveness under rapidly varying and strongly asymmetric traffic conditions remains to be examined systematically.

Third, as with distributed TDMA schemes such as VeMAC, BPR-MAC requires time synchronization among participating vehicles. The mini-slot backoff mechanism additionally requires sufficiently accurate slot-level alignment to support carrier sensing within a transmission slot. In principle, the required synchronization can be supported by Global Navigation Satellite System (GNSS)-based timing available in vehicular communication systems; however, synchronization errors, clock drift, and intermittent GNSS availability were not explicitly modeled in the present simulations and may affect reservation performance in practical deployments.

Fourth, BPR-MAC introduces additional signaling information for mobility-aware slot coordination. Each vehicle broadcasts its FI once per frame, as in VeMAC, while the relative-speed level and current slot-subset configuration are piggybacked onto the FI message. The resulting additional information is limited to a small number of bits per frame under the present protocol design. Nevertheless, the current evaluation focuses primarily on reservation

delay and merging-collision behavior rather than a detailed analysis of communication, computational, and energy overhead. These implementation-related costs should therefore be quantified in future evaluations.

Finally, the present simulation considers a balanced two-way highway with a single control channel and a simplified wireless communication model. Although this setting provides a controlled environment for isolating the effects of reservation-phase backoff and relative-speed-adaptive slot partitioning, it does not represent the full diversity of real transportation environments. Unbalanced directional flows, heterogeneous traffic densities, urban intersections, lane-changing behavior, complex mobility patterns, physical-layer fading, and channel impairments may affect both the absolute performance of BPR-MAC and its relative gains over existing distributed TDMA mechanisms. Evaluation under these conditions, followed by hardware-in-the-loop or field-based validation, represents an important direction for future work.

7 Conclusion

This study addressed two persistent challenges in distributed TDMA-based vehicular communication: reservation delay caused by access collisions and mobility-induced merging collisions associated with MHTs. A backoff-based partitioned-reservation MAC protocol, BPR-MAC, was developed by combining mini-slot carrier-sensing backoff during the reservation phase with relative-speed-adaptive slot partitioning based on vehicle driving direction and relative motion. The former mechanism was designed to improve the slot-acquisition process, whereas the latter separates vehicles with different mobility states before transmission resources are shared.

Simulation results demonstrated substantial improvements over the VeMAC-like baseline under the evaluated highway conditions. With 100 vehicles, the reservation delay decreased from approximately 31 frames to approximately 2 frames. At a 90% two-hop-set occupancy rate, the merging-collision rate decreased from 0.778 to 0.017, corresponding to a reduction of approximately 97.8%. The sensitivity analysis further showed that the principal performance trends remained stable under moderate variations in the relative-speed threshold and contention-window size.

These findings indicate that reservation-phase contention control and mobility-aware slot partitioning can perform complementary functions in distributed vehicular resource coordination. By reducing slot-acquisition delay and suppressing mobility-induced transmission conflicts, BPR-MAC provides a more predictable communication mechanism for latency-sensitive vehicular applications, including highway safety-message exchange, cooperative vehicle communication, emergency warning, and V2V/V2I information exchange. The present conclusions are limited to the simulated highway conditions considered in this study. Future work should evaluate BPR-MAC under unbalanced and urban traffic conditions, more realistic physical-layer and mobility models, and hardware-in-the-loop or field-based vehicular communication environments.

Author Contributions

Conceptualization, L.Z. and R.M.M.; methodology, L.Z.; software, L.Z.; validation, L.Z.; formal analysis, L.Z.; investigation, R.M.M.; data curation, R.M.M.; writing—original draft preparation, R.M.M. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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