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# A Cooperative and Reliable RSU-Assisted IEEE 802.11P-Based Multi-Channel MAC Protocol for VANETs

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**ABSTRACT** Vehicle ad-hoc networks (VANETs), which support various important applications for intelligent transportation systems (ITSs), consist of vehicle-to-vehicle and vehicle-to-infrastructure communications based on vehicles and roadside units (RSUs). Medium access control (MAC) plays a critical role in providing efficient broadcast services for VANETs. Unlike other types of networks, VANETs suffer from rapid changes in topology, resulting in frequent network disconnections caused by the high mobility of nodes. Hence, adaptive MAC protocols, which dynamically adjust the interval according to the traffic conditions, are essential to VANETs. This study proposes a cooperative and reliable RSU-assisted IEEE 802.11p-based multi-channel MAC protocol for VANETs, called RAM. In our proposal, an RSU is used to both calculate the optimized interval and keep track of the safety packet transmission. We also present a cooperative scheme for the retransmission of safety packets that failed to broadcast because of hidden nodes. The simulation results show that the RAM not only allows safety packets to be broadcast more efficiently using the existing MAC protocols, but also outperforms the existing MAC protocols in terms of the packet delivery ratios for safety and control packets.

**INDEX TERMS** VANET, medium access control, adaptive MAC protocol, Markov chain models.

## I. INTRODUCTION

Vehicle ad-hoc networks (VANETs) are designed to provide vehicular safety, reduce the number of traffic accidents and improve transportation efficiency; thus, play an important role in intelligent transportation systems (ITSs) [1]. The equipment used in a VANET topology can be categorized into on-board units (OBUs) and road-side units (RSUs). RSUs are placed along the road to allow for connections to the Internet, while OBUs are installed inside moving vehicles. VANET applications can be grouped into the three following main applications based on the communications between the OBUs and between the OBUs and the RSUs: safety, traffic management, and user-oriented applications [2], [3]. Safety-related applications are related to the safety of the people on the road, such as emergency braking, blind spot warning, and pre-crash sensing. Safety-related applications require reliable and fast broadcasting mechanisms; hence, each vehicle must periodically broadcast information regarding its position, speed, and acceleration [4], [5]. The defining characteristics of safety applications are their reliable and fast broadcast mechanisms. One such safety-related application is beacon packets, which include the vehicle's position, speed, and acceleration [4], [5], and are periodically broadcast by each vehicle. Second, traffic management services consist of intersection management, delay warning, road congestion prevention, toll collection, and cooperative adaptive cruise control. Third, user-oriented services provide information,

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advertisements, and entertainment for users while traveling. User-oriented services have two basic applications: Internet connectivity and peer-to-peer applications [2]. However, safety services require fast access and low delay, while user-oriented services require a large bandwidth [6].

Medium access control (MAC) layers provide solutions for different requirements in VANET applications. MAC protocols for VANETs are specifically designed to provide efficient broadcasting services and fair sharing of the wireless medium. For backward compatibility, MAC protocols are generally designed based on IEEE 802.11 or channelization, such as time division multiple access (TDMA), space division multiple access (SDMA), and code division multiple access (CDMA) [7]. In TDMA schemes, the interval is divided into a time-slotted structure, which is then grouped into frames [7], [8]. The TDMA allows each vehicle to broadcast a packet without any collision. Meanwhile, the SDMA schemes are based on the vehicle location [9]. Similarly, the CDMA is proposed by allocating pseudo noise (PN) codes to different vehicles. The IEEE 802.11p standard [10] is used to provide wireless access in vehicular environments (WAVE). The enhanced distributed channel access (EDCA) mechanism in the IEEE 802.11p standard can provide different levels of quality of service (QoS) requirements. In IEEE 802.11p protocols, if the vehicles have data to transmit, they will access the channel using the carrier sensing mechanism [11]. However, a data packet collision occurs at the destination vehicle when neighboring vehicles sense that the channel is free and simultaneously transmit their data.

VANETs using the existing MAC protocols have several advantages [14], [15]. First, they improve the throughput of non-safety applications and the packet delivery ratio because they can reduce the hidden and exposed terminal problems [14]. Second, they guarantee the QoS for real-time applications by reducing the time delay of service packets. Third, they improve channel utilization because the interval length ratio can be dynamically adjusted between the control channel (CCH) and the service channels (SCHs) according to network conditions [15].

Despite these advantages, VANETs using the existing MAC protocols also face some challenges [15]. First, a VANET has unique characteristics, such as variable vehicle density, large-scale networks, and predictable mobility model; hence, the MAC layer design must include implementation for rapid topology changes. Second, the key performance indicators (KPIs) for the QoS in VANET applications, such as strict end-to-end delay, minimum bandwidth requirement, and guaranteed access to the channel, significantly vary. Hence, MAC protocols need the ability to provide the QoS requirements corresponding to various VANET services [15]. Third, MAC protocols need to efficiently broadcast and utilize the wireless channel depending on whether the traffic is dense or sparse.

The different channel access mechanisms used in a MAC protocol affect its performance. A continuous CCH/SCH access allows vehicles to monitor the incoming data from the CCH/SCH. Alternating CCH and SCH access enables the vehicle nodes to switch between the CCH and SCH intervals. Immediate SCH access allows vehicles to switch to SCH from CCH without waiting for the next SCH interval. An extended SCH access allows vehicles to continue the transmission on the SCH without pausing and switching to the CCH. According to IEEE 1609.4 standard [12], most of the existing MAC protocols use alternating CCH and SCH channel access methods to transmit safety-related messages in the CCH and non-safety messages in the SCHs. This process requires a 100 ms-long sync interval (SI) consisting of a pair of fixed CCH and SCH intervals. Each vehicle broadcasts control messages and safety-related messages (i.e., periodic beacon and event-driven messages) in the CCH interval. Control messages are used to send channel access coordinating messages and WAVE service advertisement (WSA) packets. The sender broadcasts WSA packets which piggyback the service information which the SCHs use. Once the receiver responds to the WSA packet, it will send an acknowledgement (ACK) packet. The fixed CCHI and SCHI affect MAC protocol performance because a fixed interval decreases the throughput under dynamic traffic conditions. The 50 ms CCHI will not be sufficient for disseminating all the safety messages when the vehicle density is high. Furthermore, the restricted CCHI is under-utilized when the vehicle density is low [13].

The multichannel MAC schemes based on the IEEE 802.11p and IEEE 1609.4 standards are designed to calculate the optimized interval based on the vehicle density and data traffic conditions. Multi-channel MAC protocols have a higher performance than single-channel MAC protocols [14]. In addition, adaptive multi-channel MAC protocols can guarantee a bounded transmission delay for real-time safety applications and an increased throughput for non-safety applications [14]. This study focuses on multichannel MAC schemes based on the IEEE 802.11p and IEEE 1609.4 standards. We propose a reliable and adaptive IEEE 802.11p-based multi-channel MAC protocol for VANETs, called RAM. Our contributions are as follows:

- We propose a new IEEE 802.11-based multi-channel MAC protocol that can resolve the limitations of the existing MAC protocols. We divide the CCHI into three main intervals: 1) safety interval, 2) response interval, and 3) contention-based interval. Our proposal guarantees a short delay constraint for safety packets because the collided safety packets can again be broadcasted on the contention-based interval.
- Our proposal can ensure a reliable transmission of the safety packets by confirming information in the response interval.
- We present a Markov chain model to analyze the reliable real-time broadcast of safety packets and WSA unicast on the CCH. We then calculate the optimized CCH interval based on the vehicle density and traffic data conditions by leveraging information from the Markov chains.

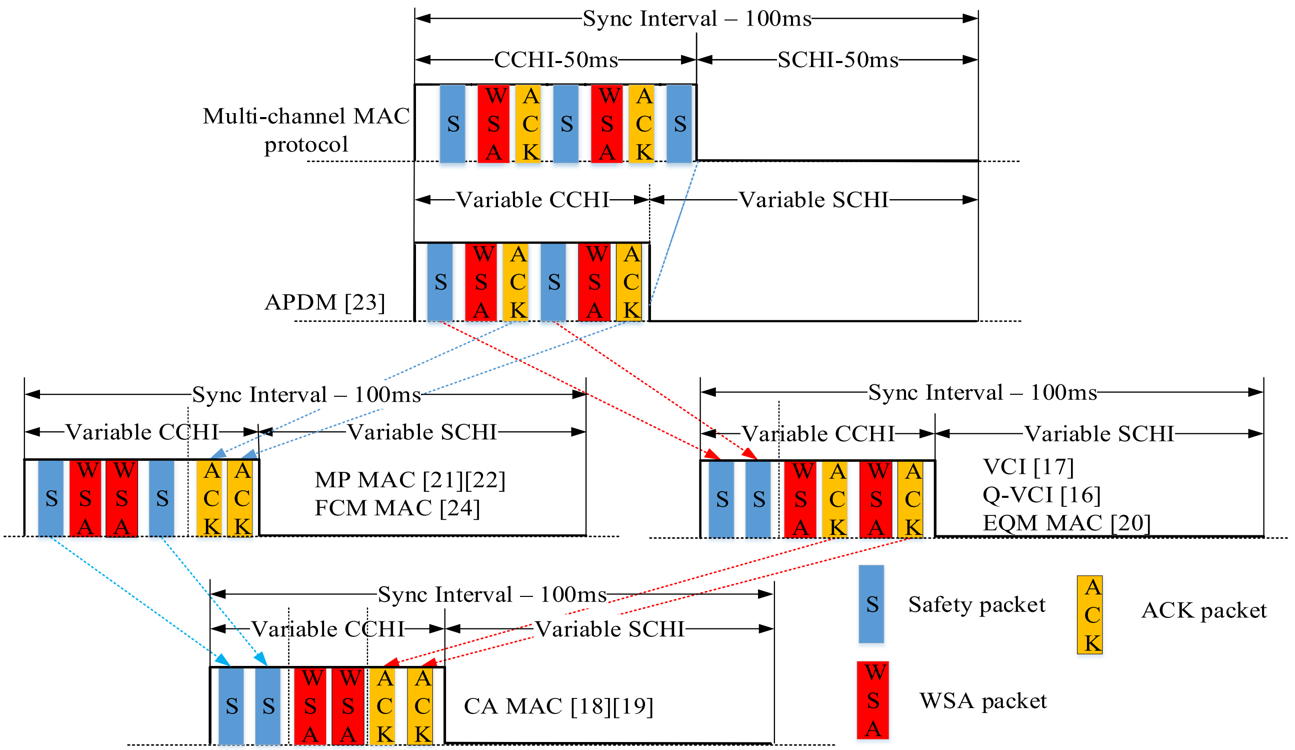


**FIGURE 1. Interactions of adaptive IEEE 802.11p-based multi-channel MAC protocols.**

The rest of this paper is organized as follows: Section II gives a short survey of the adaptive MAC protocol in VANETs; Section III describes the proposed RAM protocol in detail; Section IV presents a theoretical analysis on the optimal interval in the RAM protocol; Section V presents the performance evaluation; and Section VI concludes the paper.

## II. RELATED WORKS

On the CCH, each vehicle transmits three main packets, namely periodic beacon, event-driven, and control packets. First, periodic packets perform cooperative vehicle collision avoidance. Each vehicle updates and disseminates its status via a periodic beacon broadcast. Second, event-driven packets usually contain emergency information such as car accidents and emergency braking. Third, control packets, such as WSA packets, are used to perform SCH negotiation and reservation. Note that safety packets represent the periodic beacon and event-driven messages in adaptive IEEE 802.11p-based multi-channel MAC protocols. Many approaches including MP MAC [21], [22], VCI MAC [17], Q-VCI MAC [16], APDM [23], CA MAC [18], [19], FCM MAC [24] and EQM-MAC [20], has been proposed by arranging these packets (i.e., the control packets and safety packets). Fig. 1 shows the interactions of adaptive IEEE 802.11p-based multi-channel MAC protocols by arranging safety, WSA, and ACK packets. In multi-channel MAC protocols, the safety, WSA, and ACK packets are transmitted in the fixed CCHI. Under the traffic data condition, the APDM calculates the CCHI length to increase the throughput of the non-safety packets while guaranteeing that all packets are successfully transmitted during this optimal CCHI. By separating the ACK packet transmission into a specific interval, MP MAC [21], [22] computes the optimal interval for transmitting all safety and WSA packets. FCM MAC [24] uses an RSU packet in exchange for all the ACK packets. Similarly, VCI MAC [17], Q-VCI MAC [16], and EQM-MAC [20] separate the safety packet transmission in the fixed interval. Finally, CA MAC [18], [19] divides into two fixed intervals for transmitting specific packets (i.e., safety and ACK packets) and a variable interval for transmitting WSA packets.

Moreover, these protocols compute the optimized interval by leveraging information from Markov chain models. Therefore, we classify these protocols into two categories based on Markov chain models used. First, adaptive IEEE 802.11p-based multi-channel MAC protocols use a Markov chain model for the WSA transmission, as shown in Figure 2. VCI [17] optimizes the WSA interval based on the saturation throughput condition. Q-VCI [16] improves the VCI under different applications by calculating the minimum CWs for different service classes, then uses these CWs to access the CCH. In contrast, CA MAC [18], [19] studies a platoon in a highway scenario. EQM-MAC [20] computes the optimized WSA interval based on the data traffic (VCI, Q-VCI and CA MAC used) and the vehicle density (according to the proposed vehicle identification interval). Adaptive IEEE 802.11p-based multi-channel MAC protocols using a Markov

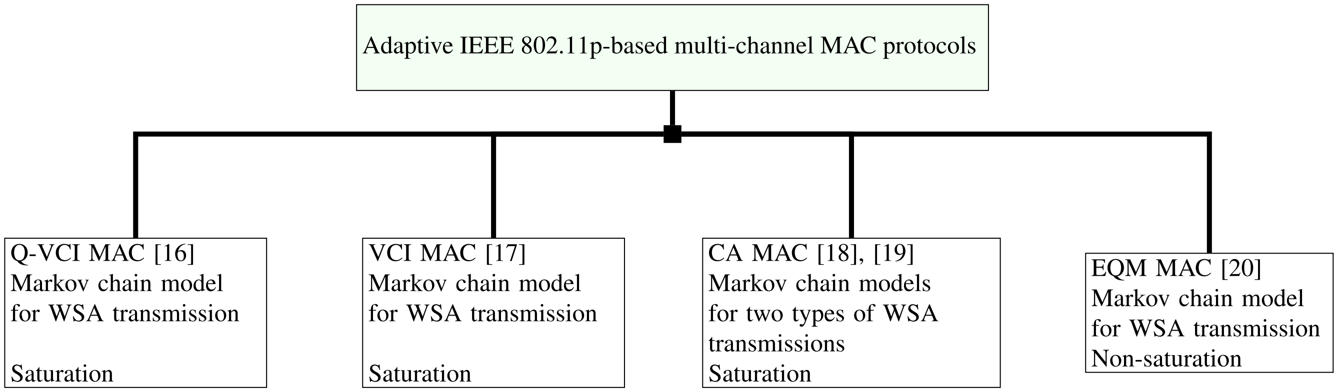


**FIGURE 2.** Adaptive IEEE 802.11p-based multi-channel MAC protocols using a Markov chain model for WSA transmission.

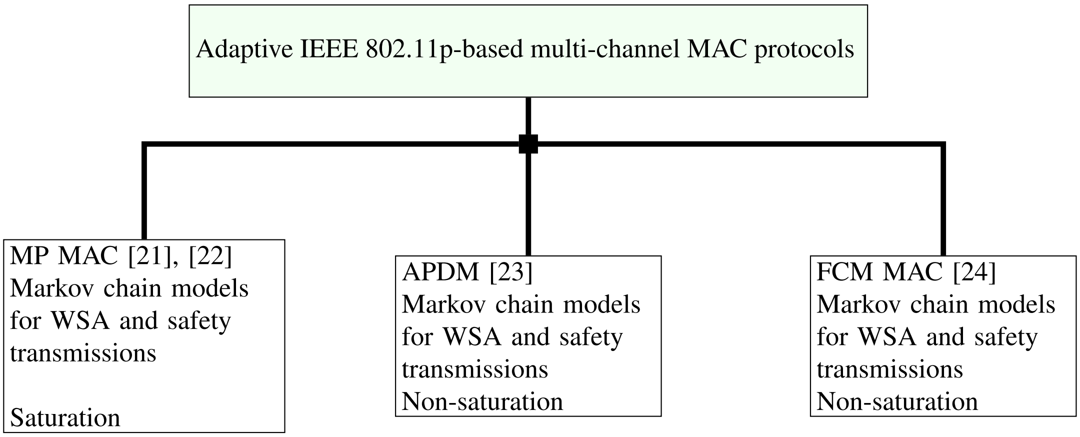


**FIGURE 3.** Adaptive IEEE 802.11p-based multi-channel MAC protocols using Markov chain models for WSA and safety transmissions.

chain model for the WSA transmission can enhance the saturation system throughput and decrease the transmission delay. However, these protocols do not guarantee a bounded transmission delay of safety applications because if a node has a safety packet that arrives in the safety interval, it must wait for the next frame to transmit it [25].

Second, adaptive IEEE 802.11p-based multi-channel MAC protocols using Markov chain models for the WSA and safety transmissions divide the CCHI into two or three main intervals, as shown in Fig. 3. In APDM [23], which consists of two main intervals, the packets transmitted by the RSU or CH use the broadcast interval, while the safety and WSA packets use the contention-based interval. The transmission interval in the case of three main intervals is divided into the broadcast, contention-based, and reliable intervals (e.g., ACK packet in CA MAC [18], [19] and the reservation packet transmitted by the RSU in FCM MAC [24]). Adaptive IEEE 802.11p-based multi-channel MAC protocols using Markov chain models for the WSA and safety transmissions guarantee the requirements for safety applications and allow a simultaneous broadcast of the safety packets when they arrive. An ACK scheme is also designed to confirm a reliable transmission of the safety packets in CA MAC [18], [19]. FCM MAC [24] proposes reservation packets broadcast by the RSU to reduce the length of the ACK interval in CA MAC. A reservation packet carries the SCH assignment and the scheduling order for each link of service data transmission [24]. However, adaptive IEEE 802.11p-based multi-channel MAC protocols with Markov chain models for the WSA and safety transmissions have not yet been used to determine the number of vehicles to compute the optimal interval.

This study proposes a reliable and adaptive IEEE 802.11p-based multi-channel MAC protocol for VANETs, called RAM. RAM ensures the requirements for safety applications and enhances the packet delivery ratio of the WSA packets. The optimized interval is also computed based on both the traffic data conditions and the vehicle density discussed in the next section.

## III. RAM: A COOPERATIVE AND RELIABLE RSU-ASSISTED IEEE 802.11P-BASED MULTI-CHANNEL MAC PROTOCOL

We first propose a reliable transmission for the safety packets in this section. The collided safety packets can re-transmit in the contention-based interval. In contrast, if a node detects

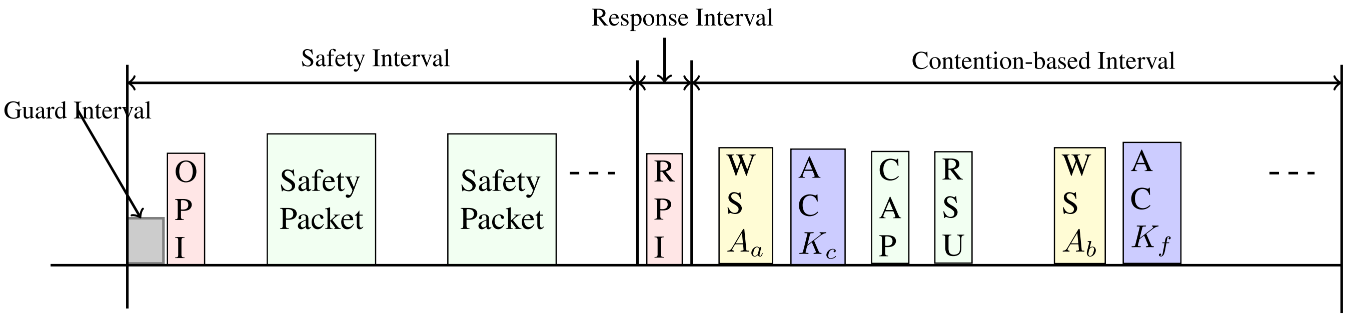


**FIGURE 4.** Operation of RAM in the variable control channel interval.

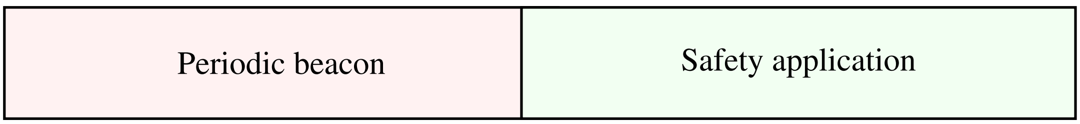


**FIGURE 5.** Format of each safety packet transmitted on the safety interval.

that it did not receive any safety packets sent by a neighbor node, it will request to receive a safety packet, which is sent by an RSU. We then present a Markov chain model to analyze the reliable real-time broadcast of the safety packet and the WSA unicast on the CCH.

We divide the transmission interval into the three following intervals on the CCHI: safety interval, response interval, and contention-based interval, as shown in Fig. 4. First, in RAM, the safety packets represent the event-driven and beacon packets. Each node in the safety interval will attempt to broadcast safety packets. The safety packets have higher priority transmission ($AC_0$) than the WSA packets, which have lower priority transmission ($AC_2$). In addition, safety messages have a bounded delay and no positive ACK. At the start of the safety interval, the RSU will broadcast the optimized protocol information (OPI). According to adaptive IEEE 802.11p-based multi-channel MAC protocols, such as VCI, Q-VCI and CA MAC, each OPI packet will be broadcasted at least twice because it may not be received by some nodes due to the congestion condition.

Second, under its transmission range, the RSU performs the role of a central authority that keeps track of the messages. If the RSU receives a safety packet sent by a sender, it will add the sender's ID to its response protocol information (RPI) packet. Once a sender receives an RPI packet, it will monitor its ID. If the sender detects its ID, it successfully broadcasts its safety packet; otherwise, it will attempt to broadcast its safety packet again in the contention-based interval.

Third, both safety and WSA packet transmissions are happen in the contention-based interval. The WSA packets are used to exchange management information about one or more DSRC services that are offered in an area. A WSA packet requires a positive ACK from the receiver to the sender. During the CCHI, senders wait until the channel is sensed as idle for distributed inter-frame space (DIFS), then broadcast the WSA packets and negotiate the identities of the SCHs to be used [14]. The receiver responds to the WSA packet with a unicast ACK, which is immediately transmitted after a period of time, and is called the short inter-frame space (SIFS), at the end of the corresponding WSA packet. The SIFS is shorter than a DIFS; hence, no other senders can detect the channel as idle for a DIFS at the end of the ACK [26].

### A. RELIABLE TRANSMISSION FOR THE SAFETY PACKETS

The RSU in the safety interval first broadcasts an OPL packet that includes the variable lengths of a different interval. A safety packet contains two main portions: 1) periodic beacon and 2) safety applications, as shown in Fig. 5. Periodic beacon messages are used to inform the surrounding vehicles in the network about the sender's presence and status (e.g., position, speed, and heading) [27]. Whenever a node receives a beacon message from a neighboring vehicle, it stores the node address and position in its neighbor table [28]. The second category is safety applications related to the event-driven messages. A safety application is sent by a vehicle to detect a potentially dangerous situation on the road. This information is disseminated to alarm the other vehicles [27].

The RSU tracks the safety packets sent by all members in its coverage after the safety interval. If the RSU successfully receives a safety packet from sender $x$, it will include $x'$s $ID$ in the RPI packet. The RSU broadcasts the sender's ID information during the response interval. Once a vehicle receives the RPI, it will check its neighbor table information. We assume that node $y$ unsuccessfully receives a safety packet sent by node $z$. Node $y$ will attempt to use the contention-based interval to broadcast a cooperative association packet (CAP). Collision packets comprise access and merging collisions in

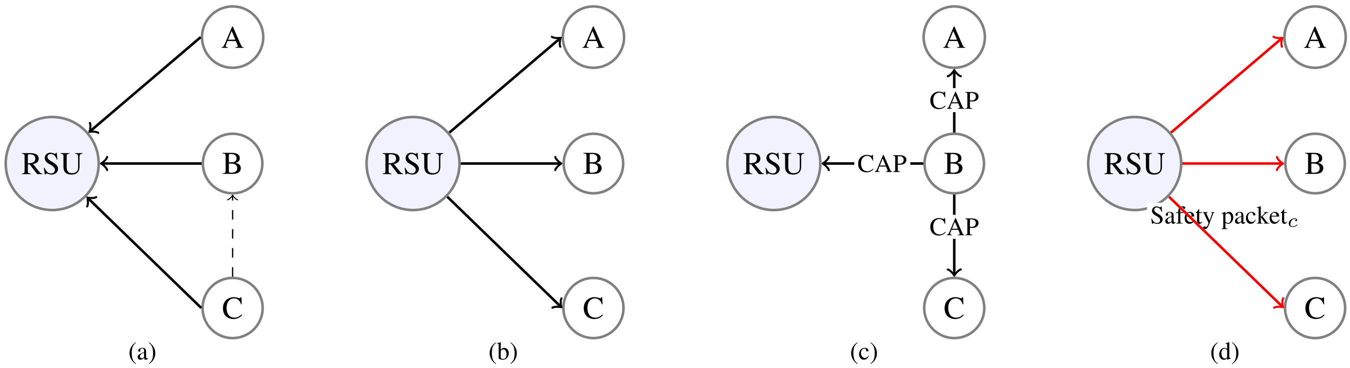


**FIGURE 6.** Operation of a cooperation for the safety packet. (a) Each node periodically broadcasts its beacon packet. (b) An RSU broadcasts an RPI packet to confirm received the safety packets. (c) As node B receives a RIP packet, node *B* knows that it did not receive a safety packet sent by node *C*. Node *B* broadcast a CAP packet. (d) Once an RSU receives a CAP packet sent by node *B*, it will broadcast a safety packet of node *C*, which is stored.

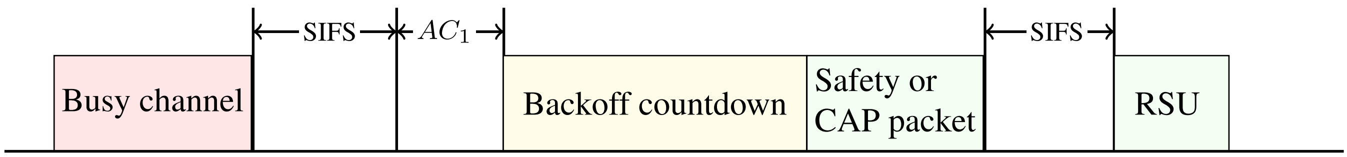


**FIGURE 7.** Operation of reliable transmissions for safety packets in the contention-based interval.

the safety interval [7]. The RSU will broadcast the safety packet of node $z$ when it hears the CAP packet sent by node $y$. For instance, in Figure 6(**a**), nodes A, B and C alternately broadcast their safety packets. Assume that nodes B and C are a one-hop neighbor set, and node B did not receive the safety packet sent by node C. The RSU will broadcast to inform all vehicles in its coverage in Fig. 6(**b**) after it collects all safety packets. Node B receives the RPI packets sent by its corresponding RSU and knows that node C has a safety application; hence, it will attempt to broadcast a CAP packet in the contention-based interval, as shown in Fig. 6(**c**). The RSU will immediately send the safety packet of node C in Figure 6(**d**) once it receives the CAP packet. If another node also did not receive the safety packet of node C, both nodes terminate their CAP packets and wait to broadcast and update the safety packet of node C.

Meanwhile, if a node receives the RPI packets broadcasted by its corresponding RSU and knows that its safety packet was not successfully sent, it will attempt to transmit in the contention-based interval (CI) to broadcast its safety packet again. Once the RSU receives that safety packet, it will broadcast the RSU packet including the sender's ID, to confirm the successful transmission. Fig. 7 shows the reliable transmissions of the safety packets in the CI.

### *B. SCH SELECTION SCHEMES*

Each vehicle maintains a service channel status (SCHS) to reduce collisions on SCHs, as shown in TABLE 1. In a one-hop neighbor set, a vehicle will update its SCHS corresponding to an index of the used service channel and an index of the used time slots if it receives an ACK packet. The operation of the SCH access reservation is as follows:

**TABLE 1.** Service channel status.

| Service channel | Busy slots |
|---|---|
| 1 | 1, 2 |
| 2 | 1, 5 |
| 3 | 3, 4, 8 |
| 4 | 4 ,6 ,7 |
| 5 | 2, 3 |
| 6 | 5, 6 |

1) The sender will attempt to broadcast a WSA packet on the CI if it has a service packet to deliver. The WSA packet includes the sender's ID, receiver's ID, service information, its SCHS, and other information [12].
2) A receiver will compare the received WSA packet with its own SCHS once it receives the WSA packet, including the sender's SCHS. The receiver will also randomly choose the SCH and time slots based on the common information of the SCHSs from both the sender and the receiver. The receiver will broadcast the ACK, including the selected SCH and time slots to the sender to respond to the WSA packet.
3) The sender and the receiver switch to the identified SCH and time slots to transmit the packets after the end of the CI.
4) Neighboring nodes overhear the ACK messages, then update their SCHSs.

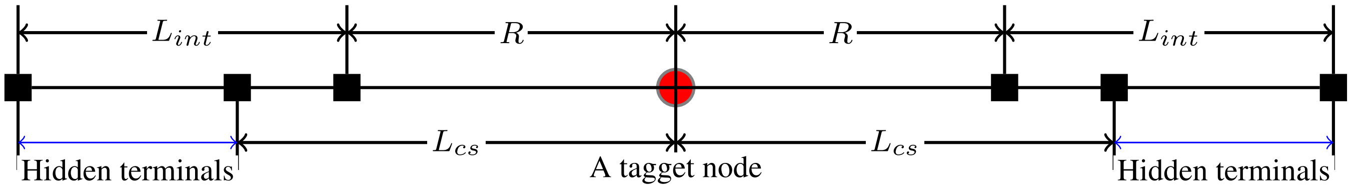


**FIGURE 8.** One-dimensional VANET model for a highway scenario.

**TABLE 2.** Main parameters used in the model analysis.

| Parameters | Description |
|---|---|
| $\beta$ | Density of the vehicles in the highway (nodes per meter) |
| $P(i,l)$ | Probability of finding $i$ nodes in a length of $l$ |
| $R$ | Transmission range of a given node |
| $L_{int}$ | Interference range of a given node |
| $L_{cs}$ | Carrier-sensing range of a given node |
| $\lambda$ | Arrival rate of the WSA packets |
| $p_c$ | Collision probability of the transmission of a CAP packet |
| $p_s$ | Collision probability of the transmission of a WSA packet |
| $p_b$ | Probability that the channel is busy |
| $P_{s,\emptyset}$ | Probability that the type of WSA queue is empty |
| $I_{s,\emptyset}$ | State with an empty queue belongs to the type of WSA packet |
| $W_{c,i}$ | CW size for the CAP packets in the $i^{th}$ backoff stage |
| $W_{s,i}$ | CW size for the WSA packets in the $i^{th}$ backoff stage |
| $\tau_c$ | Transmission probability that a node transmits a CAP packet in a generic slot time |
| $\tau_s$ | Transmission probability that a node transmits a WSA packet in a generic slot time |
| $T_{CCHI}$ | Time duration of the variable CCHI |
| $T_{SCHI}$ | Time duration of the variable SCHI |
| $T_{CAP}$ | Time duration for transmitting a CAP packet |
| $T_{safe}$ | Time duration for transmitting a safety packet |
| $T_{WSA}$ | Time duration for transmitting a WSA packet |
| $T_{ACK}$ | Time duration for transmitting an ACK packet |
| $T_{CAP}$ | Time duration for transmitting an CAP packet |
| $T_{OPI}$ | Time duration for transmitting an OPI packet sent by an RSU |
| $T_{RPI}$ | Time duration for transmitting an RPI packet sent by an RSU |
| $T_{total}$ | Time duration of a synchronization interval |
| $N_{SCH}$ | Number of available SCHs in VANETs |
| $DIFS$ | Duration of a DCF interframe space |
| $SIFS$ | Duration of a short interframe space |
| $\sigma$ | Backoff slot time duration |
| $\delta$ | Channel propagation delay |

## IV. MODEL ANALYSIS

This section presents an analytical model to compute the optimized CI. First, we provide some definitions and assumptions used to perform the RAM protocol. TABLE 2 shows the main parameters analyzed in this section.

### A. DEFINITIONS AND ASSUMPTIONS

Adaptive IEEE 802.11p-based multi-channel MAC protocols occur under highway scenarios within the presence of an RSU. We simplify the network in each direction as a one-dimensional VANET model [32], [33] because the transmission range is much larger than the highway′s width.

*Assumption 1:* Considering highway vehicle traffic, the exponential model is a good tool for simulating and evaluating VANETs and vehicular applications [34]. We assume herein that when the vehicles are distributed along a line according to a Poisson process [32] with a single parameter, the vehicle density $\beta$. The probability of finding $j$ nodes along a length of $l$ is given as

$$P(j,l) = \frac{(\beta l)^j e^{-\beta l}}{j!}\cdot \quad (1)$$

*Assumption 2:* All vehicles have an equal transceiving range, same carrier-sensing range, and same interference range.

*Definition 1:* The average number of nodes on the line within the transmission range[1], $R$, of a given node is given as

$$N_{tr} = 2\beta R\cdot \quad (2)$$

*Definition 2:* The average number of nodes within the carrier-sensing range[2], $L_{cs}$, of the given node on the line is given as

$$N_{cs} = 2\beta L_{cs}\cdot \quad (3)$$

*Definition 3:* The interfering range, $L_{int}$, is defined as the range in which nodes in a receiving operation interferes with the transmission of the other nodes [33]. The hidden terminal range is the range in which the transmitting nodes, which exist in the range of $[L_{cs}, R + L_{int}]$ and $[-L_{cs}, -R - L_{int}]$, cannot be detected by a tagged node, but can still interfere with the receiving packets of the nodes in $[-R, R]$ from the tagged node, as shown in Fig. 8. Hence, the average number of potential hidden nodes for the tagged node on the line is given as

$$N_{int} = 2\beta(R + L_{int} - L_{cs})\cdot \quad (4)$$

An analytical model for understanding periodic broadcasting of safety and WSA packets on the control channel of IEEE 802.11p VANETs with multichannel architecture was proposed in [29], [30]. The model calculated the packet delivery probability as a function of the contention window and the number of vehicles. The effects of EDCA's differentiated access priorities on the network performance under

[1]The range where a packet can be successful transmitted or received.
[2]The range where a node can detect another node′s transmission

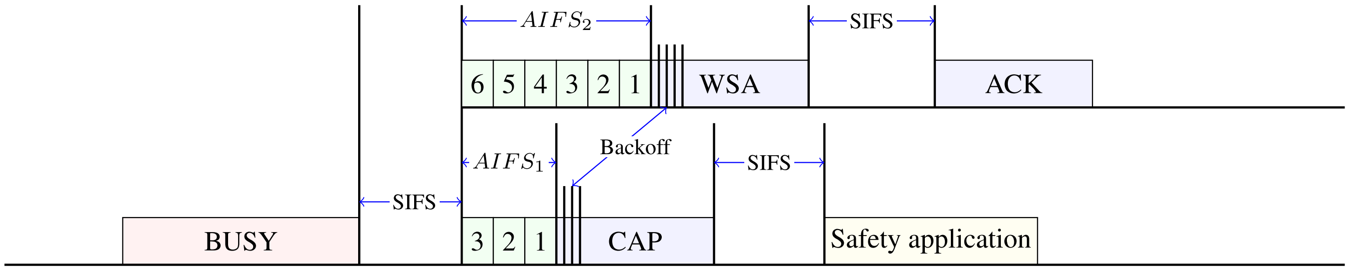


**FIGURE 9.** The access mechanisms of CAP and WSA packets.

**TABLE 3.** Difference between $AC_1$ and $AC_2$ according to the EDCA parameter used [12].

| $AC_i$ | $CW_{min}$ | $CW_{max}$ | $AIFS$ |
|---|---|---|---|
| $AC_1$ | 3 | 7 | 3 |
| $AC_2$ | 7 | 15 | 6 |

various traffic loads were analyzed, and large AIFS windows were found to reduce collision, but increase packet loss [31]. Vehicle transmission of the safety and WSA packets of the broadcast scheme is out of the scope of this study. In our proposal, two main types of handshaking are used on CI: 1) CAP (safety packets)/RSU and 2) WSA/ACK packets. Therefore, considering different priority levels between WSA and CAP and referring to [29], [30], the CAP packet transmission needs to use $AC_1$, which has a higher priority than the WSA packet transmission. The WSA packet transmission is used for $AC_2$. TABLE 3 shows the different parameters used for the access control channel between $AC_1$ and $AC_2$. The access mechanisms of the CAP and WSA packets are presented in Fig. 9 based on these different values. Furthermore, all potentially hidden nodes will have CAP packets that exist at the MAC queues. The CAP packet is only deleted when that node hears the corresponding safety packet broadcast by an RSU. Hence, we will use a 2-D Markov chain model [14] to perform CAP/RSU and WSA/ACK packet transmission under a saturation throughput, as will be described in the next section.

Let $s$ and $c$ be the WSA and CAP packet transmissions. The $m_a$ and $CW_{a,i}$ values represent the maximum retransmission number and the contention window $CW_a$ in the $i^{th}$ backoff stage, respectively, where $a = [s, c]$. In the first stage, $CW_a$ is set to be the minimum value of $CW_{a,0}$. According to [12], [23], if the packet is collided, the $CW_a$ is doubled, and the packet is retransmitted during the [0, m′] step; otherwise, the CW remains unchanged for the $(m - m')$ steps. We summarize $W_{a,i}$ as the $CW_a$ size in the $i^{th}$ step as follows:

$$W_{a,i} = \begin{cases} 2^i W_{a,0}, & i \le m' \\ 2^{m'} W_{a,0}, & m' \le i \le m \end{cases}. \tag{5}$$

### B. MARKOV CHAIN MODEL FOR THE CAP/WSA PACKET

Let $b_{a,i,k} = \lim_{t\to\infty}\{a\{t\} = i, b(t) = k\}$, $0 \le i \le m$, $0 \le k \le W_{c,i} - 1$ be the station distribution of the chain of traffic in Fig. 10, where $a = [s, c]$. $b_{c,i,k}$ represents the backoff state. The non-null one-step transition probabilities of this Markov chain model are

$$\begin{cases} P\{i,k|i,k\} = p_b, & 0 \le k \le W_{a,i}-1, \quad 0 \le i \le m \\ P\{i,k-1|i,k\} = p_b, & 0 \le k \le W_{a,i}-1, \quad 0 \le i \le m \\ P\{i,k|i-1,k\} = & \\ \begin{cases} \dfrac{p_c}{W_{a,i}}, & 0 \le k \le W_{a,i}-1, \quad 0 \le i \le m' \\ \dfrac{p_c}{W_{a,m'}}, & 0 \le k \le W_{a,m'}-1, \quad m' \le i \le m \end{cases} & \\ P\{0,k|i,0\} = & \\ \begin{cases} \dfrac{(1-p_a)}{W_{a,0}}, & 0 \le k \le W_{a,i}-1, \quad 0 \le i \le m-1 \\ \dfrac{1}{W_{a,0}}, & 0 \le k \le W_{a,i}-1, \quad i = m \end{cases} & \end{cases}. \tag{6}$$

The operation of each line in Eq.(6) means the following.

1) The backoff timer is frozen if the channel is sensed as busy,.
2) The backoff timer subtracts one if the channel is sensed as idle,.
3) Within the $[0, m']$ backoff stage, if a packet is collided, the backoff stage increases, and the CW is doubled; otherwise, the CW remains as $2^{m'} W_{c,0}$ for the collided packet.
4) The node will reset the backoff stage when a packet is successfully transmitted or a packet reaches its maximum retransmission number $m$.

The stationary probability $\tau_c$ that a node transmits an WSA or CAP packet in an arbitrary time slot is presented as

$$\tau_a = \frac{1 - p_a^{m+1}}{1 - p_a} b_{a,0,0}. \tag{7}$$

Note that $P_b = 0$ implies that the slot time $i$ is idle, and the backoff timer is decremented. This corresponds to the stationary state probability $b_{a,0,0}$ found by Chatzimisio [35].

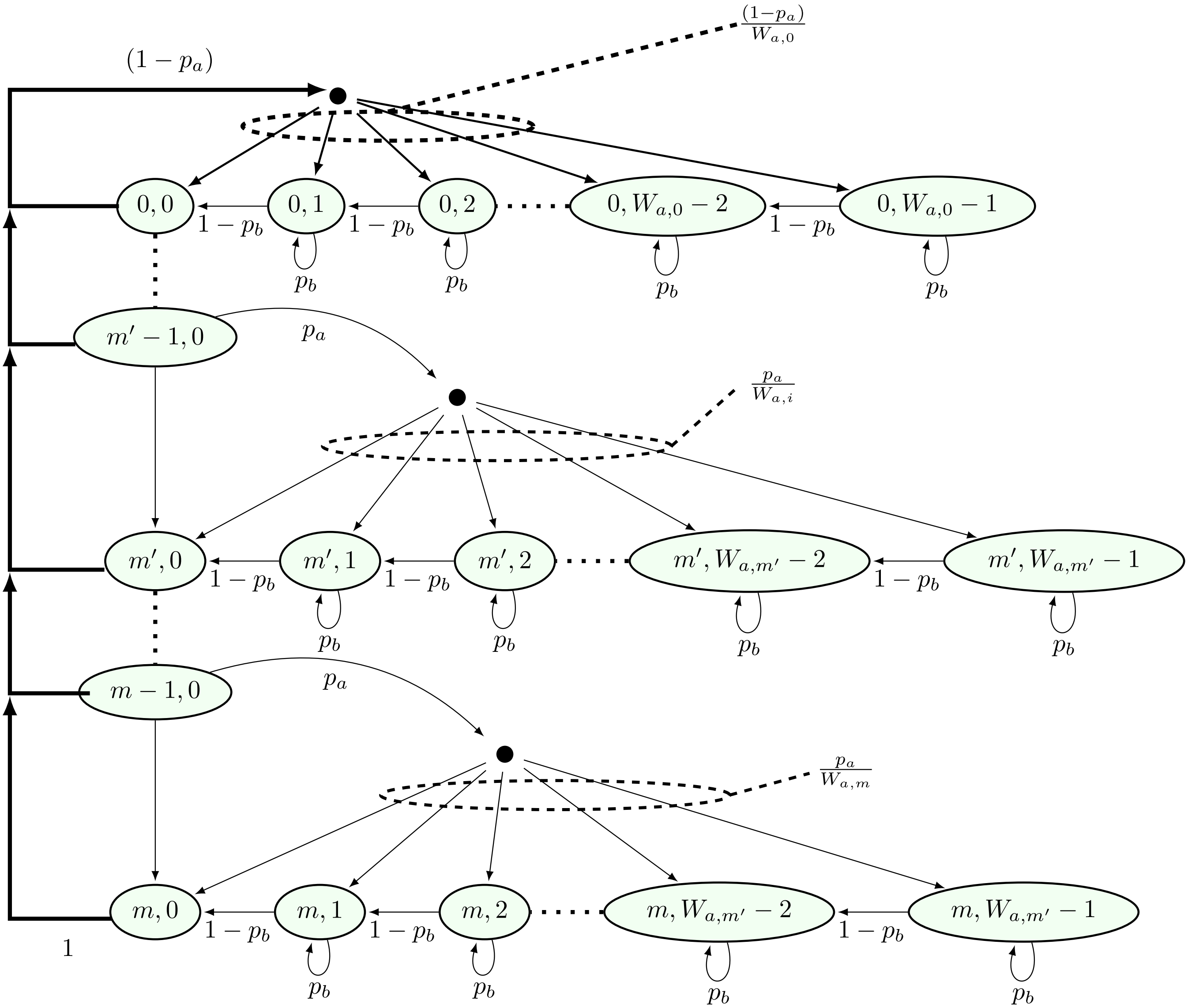


**FIGURE 10.** **Markov chain used for WSA or CAP message broadcast.**

Let $p_c$ and $p_s$ be the collision probability when more than one node transmits CAP and WSA packets at the same time slot, respectively. We then obtain:

$$\begin{cases} p_c = 1-(1-\tau_c)^{N_{int}-1}(1-\tau_s)^N \\ p_s = 1-(1-\tau_c)^{N_{int}}(1-\tau_s)^{N-1} \end{cases}. \tag{8}$$

The probability $p_b$ that the channel is sensed as busy is given by

$$p_b = 1-(1-\tau_c)^{N_{int}}(1-\tau_s)^N. \tag{9}$$

where $N_{int}$ is shown in Eq. (4).

From Eqs. (7) - (9), we can solve for the unknowns $\tau_c$ and $\tau_s$ using several numerical methods, as in [17]. Note that $0 < \tau_c, \tau_s < 1$ and $0 < p_c, p_s < 1$.

Let $p_{c,suc}$ and $p_{s,suc}$ be the probabilities of the successful CAP and WSA packets transmission, respectively; otherwise, $p_{c,col}$, $p_{s,col}$ and $p_{cs,col}$ represent the collided transmission of only the CAP, and WSA packets, and both packets, respectively. We have:

$$\begin{cases} p_{c,suc} = N_{int}\tau_c(1-\tau_c)^{N_{int}-1}(1-\tau_s)^N \\ p_{s,suc} = N\tau_s(1-\tau_c)^{N_{int}}(1-\tau_s)^{N-1} \\ p_{c,col} = (1-\tau_s)^N(1-(1-\tau_c)^{N_{int}} - N_{int}\tau_c(1-\tau_c)^{N_{int}-1}) \\ p_{s,col} = (1-\tau_c)^{N_{int}}(1-(1-\tau_s)^N - N\tau_s(1-\tau_s)^{N-1}) \\ p_{cs,col} = p_b - p_{c,suc} - p_{s,suc} - p_{c,col} - p_{s,col} \end{cases}. \tag{10}$$

Let $\sigma$, $T_{c,col}$, $T_{c,suc}$, $T_{s,col}$, and $T_{s,suc}$, denote the duration of a free time slot, the duration for a transmission collision, and the duration for a successful reservation of the CAP and WSA packets, respectively. Hence, we have:

$$\begin{cases} T_{c,suc} = T_{CAP} + T_{safe} + 2\delta + 2.SIFS + AIFS_1 \\ T_{c,col} = T_{CAP} + \delta + AIFS_1 \\ T_{s,suc} = T_{WSA} + T_{ACK} + 2\delta + 2.SIFS + AIFS_2 \\ T_{s,col} = T_{WSA} + \delta + AIFS_2 \end{cases} \cdot \quad (11)$$

The average length of a slot time, which is sensed as idle or successful transmission or a collision status, is given as

$$T_{cs} = (1-p_b)\sigma + p_{c,suc}T_{c,suc} + p_{s,suc}T_{s,suc} + p_{c,col}T_{c,col} + p_{s,col}T_{s,col} + p_{cs,col}\max(T_{c,col}, T_{s,col}) \cdot \quad (12)$$

The average total service time interval $X_s$ under the condition of saturated traffic loads is given as

$$E[X_s] = \begin{cases} \frac{(1-p_s)T_{cs}}{2}\left(\frac{2-2^{m+1}p_s^m}{1-2p_s}W_{s,0} - \frac{1-p_s^m}{1-p_s}\right) + T_{s,suc}, \ (m \le m') \\ \frac{(1-p_s)T_{cs}}{2}\left(\frac{2-2^{m'+1}p_s^{m'}}{1-2p_s}W_{s,0} + \frac{2^{m'}W_{s,0}(p_s^{m'} - p_s^m) - 1 + p_s^m}{1-p_s}\right) \\ +T_{s,suc}, \ (m > m'). \end{cases} \quad (13)$$

### C. OPTIMAL RATIO OF THE CCHI AND THE SCHI

We define some notations to compute the optimal ratio of CCHI and SCHI:

- Let $N_{SCH}$ be the number of available SCHs.
- Let $T_{SI}$ denote the safety interval and response interval. Note that the $T_{SI}$ length is fixed according to the number of vehicles in the RSU′s coverage. According to Figure 4, we have:

$$\begin{cases} T_{CCHI} = T_{SI} + T_{CI} \\ T_{total} = T_{CCHI} + T_{SCHI} = T_{SI} + T_{CI} + T_{SCHI} \end{cases} \cdot \quad (14)$$

  where $T_{CI}$ is the length of the CI.
- Let $\beta$ be the ratio of $T_{CCHI}$ and $T_{SCHI}$, $\beta = \frac{T_{CCHI}}{T_{SCHI}}$.
- Let $G_1$ denote the number of WSA reservations made on CI.

$$T_{CI} = G_1 E[X_s] \cdot \quad (15)$$

- We assume that the service packet length is constant, and the duration to transmit a service packet on the SCH is given as follows:

$$T_{data} = T_h + T_{service} + T_{SIFS} + T_{ACK} + T_{DIFS} + 2\delta \cdot \quad (16)$$

  where $T_h$ is the cost of the MAC and PHY header of the service data packet, $T_{service} = \frac{L}{R_{data}}$, and $R_{data}$ and $L$ denote the data transmission rate and payload, respectively, of a service packet on the SCHs.
- Let $G_2$ denote the number of service packets delivered on $N_{SCH}$ during the SCHI given as

$$T_{SCHI} = \frac{G_2 E[T_{data}]}{N_{SCH}} \cdot \quad (17)$$

According to the adaptive IEEE 802.11p-based multi-channel MAC protocols using a Markov chain model (e.g., VCI [17], CA MAC [18], [19], APDM [23]), the number of reservations made on the CCH is equal to the number of service packets transmitted on $N_{SCH}$ (i.e., $G_1 = G_2$).

The ratio $\beta$ between $T_{CCHI}$ and $T_{CCHI}$ in the optimal condition is given as

$$\beta = \frac{T_{data}T_{SI} + N_{SCH}E[X_s]T_{total}}{T_{data}(T_{total} - T_{SI})} \cdot \quad (18)$$

The saturation throughput is given by

$$S_{SCH} = \frac{T_{SCH}}{E[T_{data}]}.N_{SCH}.L \cdot \quad (19)$$

## V. SIMULATION RESULTS

In this section, we simulated the RAM protocol and compared it with other schemes (i.e., the VCI MAC [17] and CA MAC [18], [19] protocols). We set the sending frequency of the safety packets, $f_e$ and $\alpha$, to 1 and 0.5, respectively. The calculation of the safety interval ($T_{si}$) is shown in [17], [36] given as:

$$T_{si} = \frac{\alpha \cdot f_e \cdot N}{R} \cdot 1000 \cdot \quad (20)$$

### A. SIMULATION ENVIRONMENT

We first created a highway scenario to simulate the RAM, VCI MAC, and CA MAC protocols, as shown in Fig. 11. TABLE 4 summarises the system parameters used in both the theoretical analysis and simulations. Note that the vehicles were placed on the line according to a Poisson process with the vehicle density, $\beta$. The RSU was placed in the middle of the highway scenario.

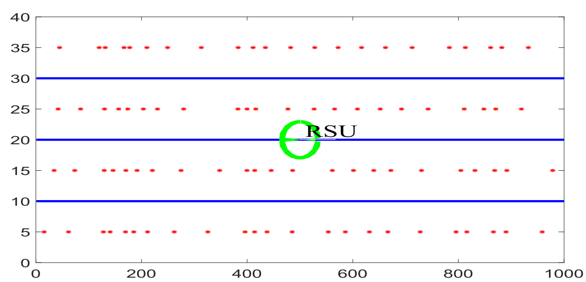


**FIGURE 11.** Snap shot of the simulated highway segment.

### B. OPTIMAL INTERVALS

Figs. 12 and 13 show the optimum CCH intervals obtained from the model analysis under different network conditions. We performed the experiments for two cases of contention windows: 1) Fig. 12 with $m = m' = 5$ and 2) Fig. 13 with $m' = 5, m = 10$. In Fig. 12. with vehilce increases, a longer

**TABLE 4. Main parameters used in the model analysis.**

| Parameter | Value |
|---|---|
| Number of SCHs | 4 |
| Number of CCH | 1 |
| Data rate for each channel | 3 Mbps |
| R | 500 m |
| $L_{cs}$ | 500 m |
| $L_{int}$ | 500 m |
| Wc | 8 |
| Ws | 32 |
| m | 5 |
| MAC header | 256 bits |
| PHY header | 192 bits |
| WSA | 160 bits + PHY header |
| ACK | 112 bits + PHY header |
| $L_{RSU}$ | 112 bits + PHY header |
| CAP | 112 bits + PHY header |
| Safety packet length | 80 bits + PHY header |
| Slot time | 20 $\mu s$ |
| SIFS | 10 $\mu s$ |
| DIFS | 50 $\mu s$ |
| Service packet length | 2000 bytes |
| Sending frequency of safety packets | 1 |
| Number of nodes | 20:100 |

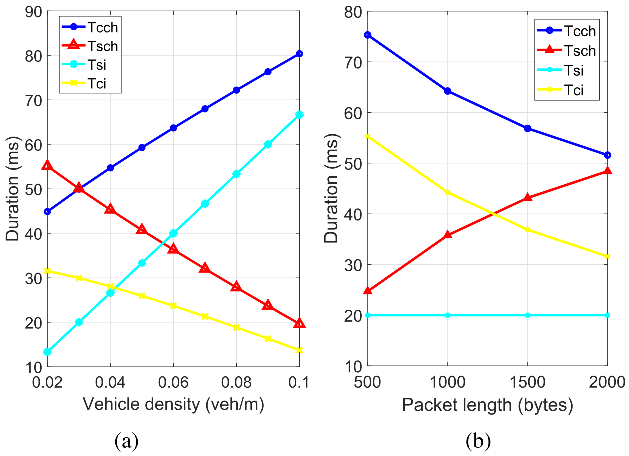


**FIGURE 12.** **Optimum CCH intervals with $m = m' = 5$ in terms of. (a) the vehicle density. (b) the packet length.**

CCHI was required to guarantee a reliable transmission of the safety packets; hence, the SCHI decreased with an increase in the number of vehicles. In addition, the probability of channel collision increased as the number of vehicle increased. Consequently, the time for service reservations on the CCH was longer. Comparing Figs. 12(a) and 13(a), the CCHI in Fig. 12(a) increased faster than that in Fig. 13(a) because in the $m'$ backoff stage, if a packet collided in $m' = 5$, the backoff stage increases and $CW'_m + 1$ remains as $2^{m'}CW$, while the vehicles reset the backoff stage and CW in $m' = m = 5$. In Fig. 12(a), the intervals of the CCH and the SCH are approximately equal to 50$ms$ when the vehicle density is 0.03 vehicle/m. Meanwhile, in Fig. 13(a), the intervals of the CCH and the SCH are equally divided in 0.1 vehicle/m.

Figs. 12(b) and 13(b) show the optimum intervals in terms of the length of the service packets. According to Eq. (16), the duration to transmit a service packet

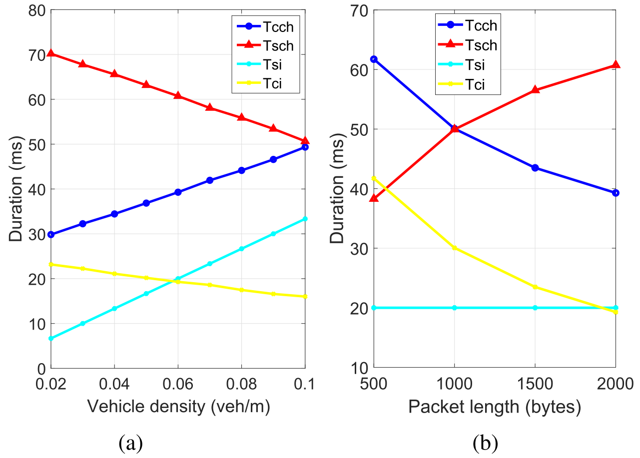


**FIGURE 13.** **Optimum CCH intervals with $m' = 5$, $m = 10$ in terms of. (a) the vehicle density. (b) the packet length.**

increases with the increase in the packet length. Therefore, in Figs. 12(b) and 13(b), when the SCHI, $T_{sch}$, increases, $T_{SI}$ and $T_{cch}$ decrease; on the other hand, according to Eq. (20), the length of the safety interval, $T_{si}$, remains constant. The intervals of the CCH and the SCH were approximately equal to 50 $ms$ when the service packet length was approximately 1300 bytes in Fig. 12(b) and 600 bytes in Fig. 12(b).

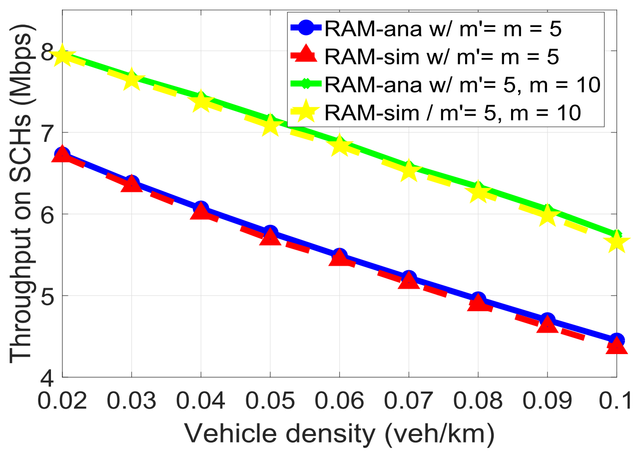


**FIGURE 14.** **Saturated throughput on the SCHs: Analytical versus simulation results with $m = m' = 5$ and $m' = 5$, $m = 10$.**

## C. THROUGHPUT ON THE SCHS

Fig. 14 shows the analytical and simulation results of the saturated throughput on the SCHs with $m' = m = 5$ and $m' = 5, m = 10$. We computed the throughput on the SCHs using Eq. (19). The analytical results matched well the simulation curve, thereby validating the proposed analytical model for the RAM scheme. The saturated throughput decreased when the vehicle density increased because according to Figs. 12(a) and 13(a), the vehicles only have little chances of making reservations when the SCHI is small with the increase in the number of nodes. In contrast, many reservations are made during the CI when the SCHI is large; hence, the smaller the vehicle density, the higher the saturated throughput.

Fig. 14 shows that the RAM protocol with $m' = 5$, $m = 10$ had a higher saturated throughput than that in case of $m' = m = 5$ because the SCHI using RAM protocol with $m' = 5, m = 10$ was longer than using RAM protocol with $m' = m = 5$ as shown in Figs. 12(a) and 13(a). Another reason for this result is that the channel collision probability increases with the number of nodes. However, according to Eqs. (7) - (9), the channel collision probability slowly increases when it uses $m' = 5, m = 10$. Consequently, the number of service reservations will increase. Moreover, this is similar to the conclusion in [30] that increasing the window size is successful in terms of the frame loss probability reduction.

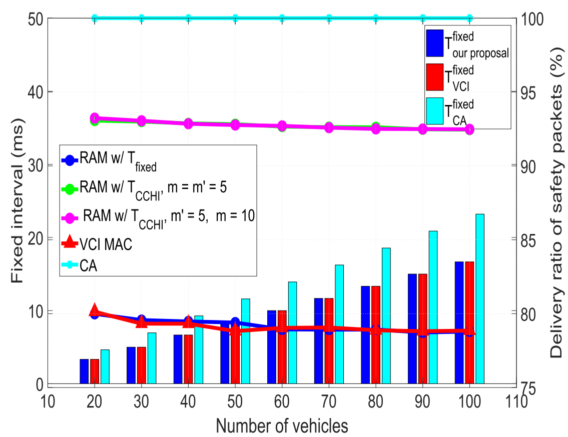


**FIGURE 15. Fixed interval and delivery ratio of the safety packets vs the number of nodes.**

### D. PACKET DELIVERY RATIO OF THE SAFETY PACKETS

Compared with the VCI MAC [17] protocol, the RAM protocol used the same fixed interval. The fixed interval in the CA MAC [18] protocol consisted of two intervals: safety interval and ACK interval. Hence, the fixed length used in CAMAC is greater than both the VCI MAC and RAM protocols. However, the CA MAC protocol allowed all vehicles to broadcast their safety packets in their time slots assigned by an RSU without any collision. In the safety interval, the RAM and VCI MAC protocols had the same delivery ratio of the safety packets. Nevertheless, the RAM protocols allowed unsuccessful safety packets obtained by receiving information from the RPI packet sent by an RSU to be retransmitted in the CI. The delivery ratio of safety packets was higher than the VCI MAC protocol in both cases of $m = m' = 5$ and $m' = 5$, $m = 10$, as shown in Fig. 15. Note that the CA MAC protocol required strict synchronization schemes between the vehicles to broadcast the safety and ACK packets in their time slots, while both the RAM and VCI MAC protocols allowed vehicles to randomly broadcast their safety packets. In addition, the CA MAC examined the role of platoons[3] and the RSU in the highway. In our protocol, the role of an RSU was used to calculate the optimized interval similar to the VCI MAC protocol and track the packets.

### E. PACKET DELIVERY RATIO OF THE WSA PACKETS

We define herein the two following KPIs to evaluate the different protocols:

1) Packet delivery ratio of the WSA packets: This is the ratio of the number of successful WSA packet transmissions to all the transmitted WSA packets. The WSA packet transmission is considered successful if a sender successfully receives the ACK packet sent by a receiver.
2) Packet loss ratio: This is the ratio of the number of lost packets to all packets. The number of lost packets consists of four cases: 1) lost WSA packets caused by collisions between the WSA packets; 2) lost WSA packets caused by collisions between the WSA and ACK packets; 3) lost ACK packets caused by collisions between the ACK packets; and 4) lost ACK packets caused by collisions between the WSA and ACK packets.

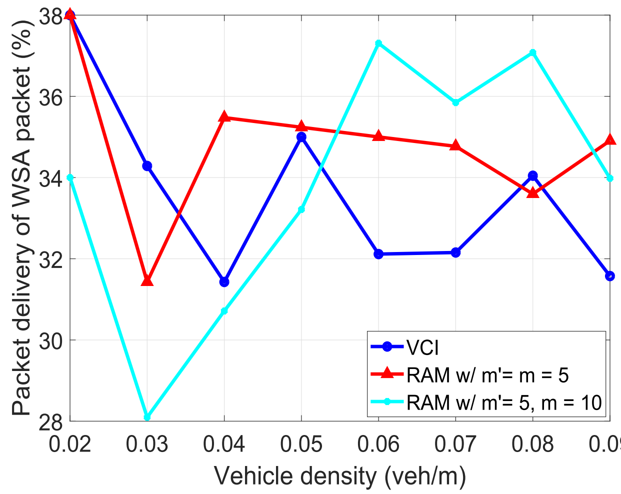


**FIGURE 16. Packet delivery ratio of the WSA packets under the same highway scenarios.**

First, we considered the same highway scenario to evaluate the performance of different protocols. Fig. 16 shows the packet delivery ratio (PDR) of the WSA packets ($PDR_{WSA}$) in terms of the vehicle density when the service packet length is 2000 bytes. For low vehicle densities (i.e., 0.02 to 0.03 vehicle/m), the VCI MAC has a higher $PDR_{WSA}$ than the RAM protocol in the case of $m = m' = 5$ and $m' = 5, m = 10$. For average vehicle densities from 0.035 to 0.055 vehicle/m (veh/m), $PDR_{WSA}$ using the RAM protocol with $m = m' = 5$ was greater than using the VCI MAC

[3] A platoon is a train of vehicles composed of a leading vehicle and a number of followers traveling at highway speeds with only a few meters between them [18]

and RAM protocols with $m' = 5$, $m = 10$. Meanwhile, $PDR_{WSA}$ using the RAM protocol with $m' = 5, m = 10$ was greater than using the VCI MAC and RAM protocols with $m = m' = 5$ when the vehicle density is high (i.e., from 0.055 to 0.1 veh/m) because unlike the VCI MAC protocol, the RAM protocol with $m' = 5, m = 10$ can offer the chance for a more contention-free transmission for service packets.

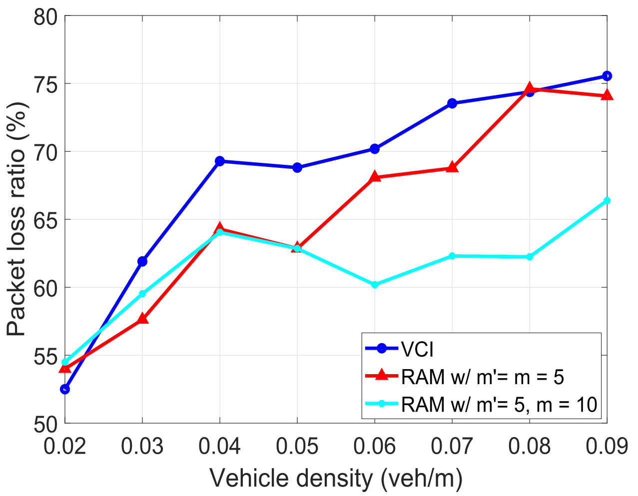


**FIGURE 17.** **Packet loss ratio of the packets under the same highway scenarios.**

Fig 17 shows the packet loss ratio (PLR) under the same highway scenario. The PLR using the VCI MAC protocol was higher than that using RAM protocol because the length of the CI in the VCI MAC protocol did not consider the hidden terminal problem. Hence, the length of the CI in the VCI MAC protocol was not sufficient for all the WSA packet transmissions. In addition, the occurrence of hidden nodes was high when all the vehicles transmitted in the small interval.

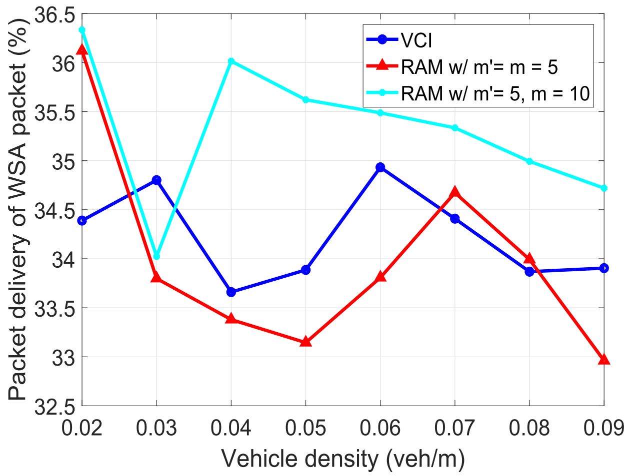


**FIGURE 18.** **Average packet delivery ratio of the WSA packets under 100 different highway scenarios.**

Second, we considered 100 different highway scenarios to evaluate the performance of different protocols. Fig. 18 shows

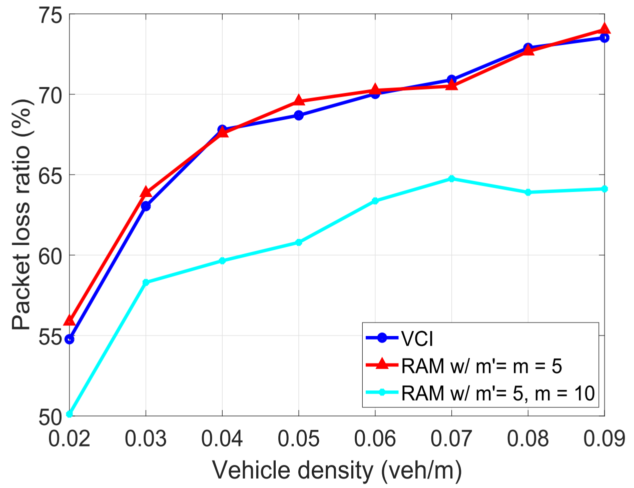


**FIGURE 19.** **Average packet loss ratio of the packets under 100 different highway scenarios.**

that when the vehicle density was greater than 0.032 veh/m (average to high vehicle density), $PDR_{WSA}$ using the RAM protocol with $m' = 5, m = 10$ was greater than that obtained using the VCI MAC and RAM protocols with $m = m' = 5$. Meanwhile, Fig. 18 also depicts that the PLR using the RAM protocol with $m' = 5, m = 10$ was the lowest compared with those using the VCI MAC and RAM protocols with $m = m' = 5$ because the RAM protocol with $m' = 5, m = 10$ considered not only the hidden terminal problem, similar to the RAM protocol with $m = m' = 5$, but also a larger number of contention-free transmissions for service packets being exchanged compare to that when using $m = m' = 5$, as shown in Fig. 12(a) and Fig. 13(a).

## VI. CONCLUSION

This study propose a reliable and adaptive IEEE 802.11p-based multi-channel MAC protocol for VANETs. Our proposal guarantees a reliable transmission of the safety packets via a CAP packet, which includes information on the status of the safety packet transmission in an RSU. In our proposal, the RSU plays a role in not only calculating the optimized interval, but also in tracking the safety packet transmission. The collided safety packets will be broadcasted in the contention-based interval. In addition, the optimized interval is computed based on the vehicle density and data traffic conditions considering the hidden terminal problem. Our proposed protocol outperformed the VCI MAC protocol in terms of the packet delivery ratio of safety and WSA packets. We will extend this research to satisfy various requirements for applications in the Internet of Vehicles as a future work.

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