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Distributed Multi-Channel MAC Protocol for VANET: An Adaptive Frame Structure Scheme

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ABSTRACT The media access control (MAC) layer of the vehicular ad-hoc network (VANET) is designed to provide fast and reliable vehicles to vehicles (V2V) or vehicles to infrastructures (V2I) access. With the development of autonomous driving and intelligent transportation, many sensor information in large-scale vehicles require efficient and reliable transmission with V2V and V2I technologies. In recent years, the demand for various services in VANETs is growing rapidly, which poses great challenges to the design of the MAC protocol. An adaptive scheme for channel frame structure can enhance channel access flexibility to cope with the changing network topologies in vehicular environments. In this paper, we adopt an adaptive frame scheme on the control channel and the service channels, which mainly improves two aspects of channel access performance: improved time slot utilization of the broadcasting period as much as possible while ensuring the vehicle can access the control channel quickly; and increasing the throughput of the service channels without generating excessive overhead. Analysis and simulation results demonstrate the performance of the proposed mechanism.

INDEX TERMS VANET, multi-channel MAC protocol, adaptive frame structure.

I. INTRODUCTION

Since the birth of the car in 1886, driving safety has a point of concern among the government and the public. In particular, the emergence and development of autonomous driving technology in recent years has made safe driving a pertinent issue. According to the Tencent's *2018 Travel Report*, traffic congestion, parking difficulties, and lack of real-time traffic information are three major problems to be addressed for drivers [1]. The vehicular ad-hoc network (VANET) has been recognized by academics and industry as a program that can realize intelligent transportation systems (ITS) [2], thus providing necessary auxiliary functions for driving. However, VANETs involve diverse needs and Quality of Service (QoS) communication requirements differ. To meet the various needs of VANETs, designing a reasonable media access control (MAC) protocol is crucial. Safety-related services, such as collision warnings, and emergency messages, have higher requirements for communication delays; non-safety services, such as video downloads and high-definition maps, have higher throughput requirements.

The new smart car is equipped with a variety of sensors, usually called the onboard unit (OBU). Although these sensors can sense the environment around the vehicle in real time, providing road safety information to the driver, the need to detect potential hazards requires coordinated communication between the vehicle and the infrastructure. In a large-scale vehicle nodes network, the information obtained by the OBU is efficiently and reliably transmitted with surrounding nodes by means of V2V and V2I technologies. The node uses the information from the sensor and collaborative system to reconstruct driving environment in real time to meet the vehicle node's demand for safety applications.

In vehicular communication, the US Federal Communications Commission (FCC) allocates 75M-Hz of bandwidth resources in the 5.9G-Hz band, specifically for inter-vehicle(i.e., V2V or V2I) communication in VANETs, commonly referred to as dedicated short-range communication (DSRC) [3]. DSRC divides the 75M-Hz spectrum into seven frequency bands, including one control channel (CCH) for broadcasting safety or control messages and six service channels (SCHs) for transmitting service messages. Europe, Japan and China have proposed their own standards and communication protocols for vehicular networks. Based on the LTE cellular network, Chen *et al.* [4], [5] proposed LTE-V as a solution for V2X in the VANET environments. The program is considered to be a more suitable vehicular network communication technology in China. Europe has allocated a dedicated channel of 5855-5925MHz for DSRC, while Japan has chosen 755.5-764.5MHz as a dedicated communication band for intelligent transportation systems.

Many scholars have devised single- or multi-channel-based MAC protocols [6], [7], in an attempt to solve transmission requirements for safety messages and non-safety messages in VANETs. In fact, due to communication delays and limited throughput, multiple channels are often required to transmit safety and non-safety messages separately. A primary task of the MAC protocol is to enable many vehicles to share limited spectrum resources and guarantee quality of service for different services.A fundamental characteristic of vehicle communication networks is that network topology changes due to high vehicle mobility; compared to other communication type, the impact on communication performance is mainly reflected in the frequent establishment and disconnection of links. In terms of access technology, a vehicle needs to quickly discover neighboring vehicles and establish communication connections with them to exchange vehicle information; therefore, we must design a reasonable access mechanism to allow vehicles to obtain channel resources more efficiently to send messages. Recently, the adaptive MAC protocol has attracted the attention of many scholars and achieved great progress [8]–[11]. In the VANET environment, the network topology of nodes changes rapidly, and the environment that vehicles encounter is often difficult to predict. Therefore, it is particularly important to improve MAC flexibility and adaptability. Intuitively, an adaptive MAC protocol can select a frame structure more suitable for the current environment according to vehicle density, allowing different vehicle service requirements to be better satisfied.

In this paper, we propose a distributed multi-channel MAC protocol based on an adaptive frame structure. We divide the channel into one CCH and multiple SCHs. On the CCH frame, we adopt a hybrid contention-free and contention-based mechanism. Each CCH frame contains a ‘contention-free’ part and ‘contention-based’ part: the contention-free part adopts time division multiplexing access(TDMA), enabling each car to periodically broadcast messages on its own time slot; and the contention-based part uses the back-off negotiation mechanism to obtain the right to use the SCH. We propose an algorithm, in which time slots can be adaptively changed, to ensure that every vehicle can obtain a slot in time. The number of the time slots on the CCH will adaptively increase(or decrease) according to traffic conditions, and we consider utilization of the number of time slots. Additionally, we use a three-way handshake protocol to negotiate the occupation of the SCHs between vehicles. The SCHs use the TDMA mechanism: when the handshake protocol is completed between vehicles, some or all of the time slots of a certain service channel may be selected; if the time slots on this service channel are still open, then other vehicles that have completed negotiation may continue to use these remaining slots. We will discuss the details of these mechanisms in subsequent sections.

The rest of this paper is organized as follows. In Part-II, we introduce related work. Part-III describes the system model and explains how the schemes work. Model analysis is presented in the part-IV, and the simulation results are discussed in part-V. The last part provides a summary of this work.

II. RELATED WORKS

The IEEE 802.11p/1609.4 is a relatively mature and widely known vehicle network access protocol, based on carrier sense multiple access/collision avoidance (CSMA/CA) using the Distributed Coordination Function(DCF). The basic idea is that a vehicle node must compete for channel resources before transmitting a message. An advantage of the DCF mechanism is the realization of collision avoidance via random backoff. To support different types of services, 802.11p adopts an enhanced distributed channel access (EDCA) mechanism [12], [13]. By setting different parameters, the mechanism causes different services to have different backoff times to achieve differentiated services for different priority businesses; the detailed operation mechanism is not described in this paper.

Many scholars have conducted extensive research on the MAC protocol in VANETs. Borgonovo *et al.* [14] proposed a TDMA-based distributed access scheme, called ADHOC-MAC, that dynamically establishes a reliable broadcast environment for nodes within one hop. The ADHOC-MAC protocol guarantees that each node can obtain a time slot to broadcast status messages. By sending additional messages, the surrounding nodes (usually within the two-hop communication range) are aware of the time slots occupancy, and can avoid, potential collisions (e.g., hidden terminal problems). VeMAC [15] added a multi-channel operation mechanism based on ADHOC-MAC. This protocol divides the CCH time slot into three parts for communication between vehicles moving in different directions and communication between vehicles and road side unit (RSUs). Moreover, the number of time slots in each part is adaptively adjusted according to different traffic conditions. This solution can reduce transmission collisions caused by vehicle movement.

The scheme proposed in [8], called DMMAC, uses a hybrid TDMA/CSMA access mechanism on the CCH. The author proposed an adaptive broadcasting period, wherein the number of time slots in each frame can be adaptively changed according to vehicle densities, thus, vehicles can smoothly access the channel at different traffic densities, and effectively improve time slot utilization. Similarly, HTC-MAC [16] elaborated on the working mode based on the hybrid TDMA/CSMA access mechanism. The author defined the format of the message packet sent on the control channel, and explained how the vehicle switches the time slot to lower the number of time slots in the reservation period. FMC-MAC [17] involves a flexible adjustment of

CCH and SCHs durations according to traffic conditions. Specially, when the traffic density is high, the SCH duration can be occupied to broadcast the safety message; and when the traffic density is relatively low, the CCH duration can be reduced to improve the SCH throughput.

Study [18] proposed a dynamic interval multi-channel MAC protocol, called VCI-MAC, based on 802.11p. The author divided a synchronization interval into control channel interval (CCHI) and service channel interval (SCHI), and derived the optimal control channel duration by establishing a Markov model. This scheme improves the throughput of the service channel while ensuring a vehicle transmits safety messages. The dynamic interval scheme improves the flexibility of the MAC layer to a certain extent and can adapt to different traffic conditions. Ye and Zhuang [19] proposed an adaptive MAC for z two-hop mobile ad hoc network, called TA-MAC, by adopting a probabilistic token passing scheme. They divides the total time slot of the channel superframe into three parts, which are used for nodes in different communication ranges, and the number of token rotation cycles and superframe duration were optimized and adapted to instantaneous network traffic loads to achieve consistently minimal average end-to-end packet latency. Ye and Zhuang [20] designed a hybrid superframe structure to accommodate packet transmissions from a changed number of mobile nodes generating either delay-sensitive service or best-effort data traffic.

Based on previous studies, we propose a MAC protocol with an adaptive channel frame structure. In a synchronization interval, we divide the channel frame structure into a TDMA-based broadcasting period and a back-off mechanism-based negotiation period, whereas the service channels use a TDMA access mechanism. For this work, our main contributions are as follows:

First, we design an algorithm to allow the number of time slots in the broadcasting period to change adaptively (i.e., increase or decrease) based on traffic densities. The algorithm maximizes the time slots utilization to ensuring that a vehicle can successfully obtain time slots and broadcast messages periodically.

Second, we consider SCH throughput and design an inter-channel switching mechanism based on the three-way handshake protocol. In our proposed scheme, the SCH duration is changed dynamically according to the negotiation outcome between vehicles, and the time slot on the channel is multiplexed by the TDMA mechanism to improve SCHs throughput.

Third, we use the Markov model to analyze the vehicle access process (i.e., broadcasting period and negotiation period) and present the simulation results.

III. SYSTEM MODEL

The application requirements in VANETs are increasingly abundant. Therefore, when considering the design of the MAC layer, one must consider the low-latency and high-reliability transmission requirements of safety messages, as well as the high-throughput requirements for entertainment messages and service messages. For example, real-time video transmission, vehicle edge cloud computing, and traffic offloading applications are research hot-spots that require a large amount of transmitted data [21]–[23].

In this paper, we adopt a TDMA-based access mechanism to provide contention-free transmission for vehicles and ensure the reliability of message transmission. We also adopt a contention-based negotiation mechanism to ensure the fairness of vehicles using service channels. Before introducing the channel frame structure, we must make a few assumptions about the model: First, each vehicle is equipped with a half-duplex transceiver, which can only work on the CCH or SCHs simultaneously. Second, GPS will provide a precise UTC clock signal for inter-vehicle synchronization.

A. CHANNEL FRAME STRUCTURE

Fig.1 depicts a schematic diagram of the channel frame structure of one synchronization period. The CCH frame is divided into broadcasting period and negotiation period. The broadcasting period is composed of time slots of equal duration, and the number of slots will change adaptively with traffic densities to allow the vehicle to broadcast status messages periodically. The negotiation period is based on the back-off access mechanism to ensure fairness among vehicles accessing SCHs.

The three-way handshake protocol is used in the negotiation period; each time a handshake protocol is completed, the vehicle can choose to access an available service channel. Therefore, the SCHs duration will adaptively change according to negotiation outcomes. Compared to the traditional fixed-duration service channel scheme(e.g., [3], [8], and [16]), our scheme can improve the throughput of SCH to some extent.

Regarding the other parameter settings of the frame structure, we follow several provisions of the 802.11p/1609.4 standard [3], [24]; specially, the synchronization interval duration is equal to 100ms, and the number of available channels includes 1 CCH and 6 SCHs.

B. CCH ACCESS PROCESS

Before introducing the mechanism of vehicle access to the CCH, it is necessary to explain the format of the message packet sent by vehicles during the broadcasting period, as shown in Fig.2. This message packet consists of three parts. The header contains the basic state information of the vehicle, including vehicle identification(ID), the basic time slot(N_{basic}, the time slot occupied by the vehicle for transmitting data packets); and N_{ts} and N_{ava} denote the total number of time slots and number of available time slots in the broadcasting period, respectively. Part "$ID + N_{rcmd}$" of the header is dedicated to one situation: when $N_a va$ is relative large, the vehicle will reduce a part of slots to improve slot utilization; but if one of the slot in this part is occupied by nodes, the vehicle will recommend this node to switch to another slots (usually in more advanced position) and then

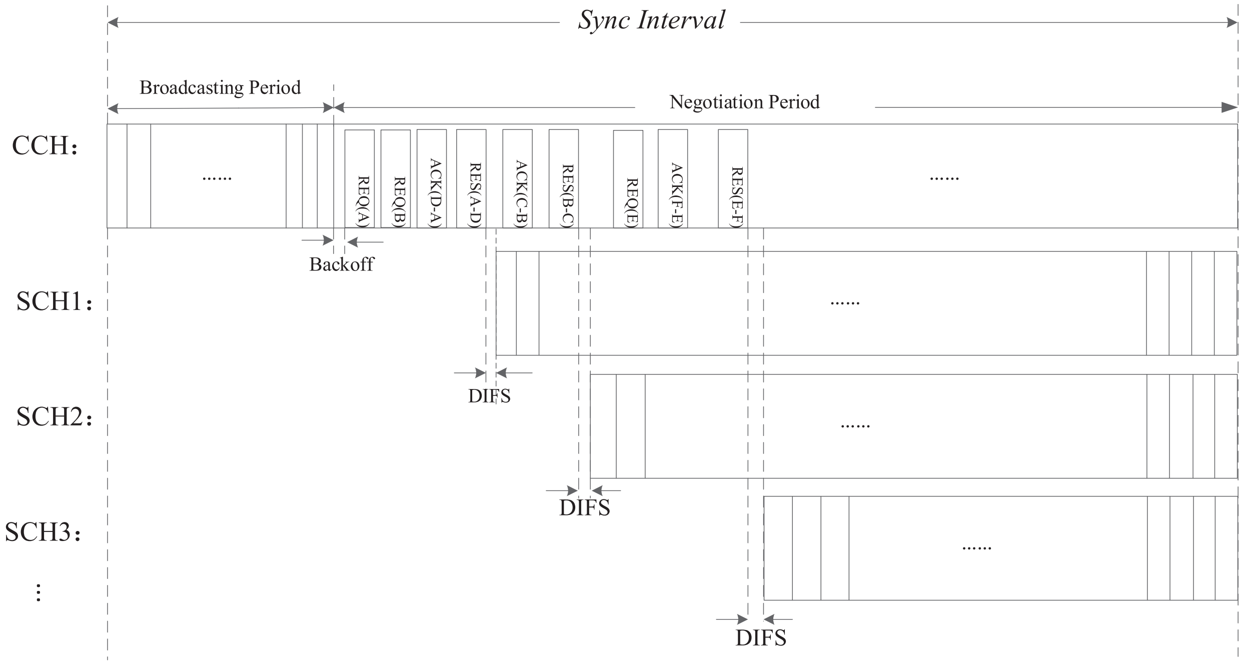


FIGURE 1. Frame structure of MAC layer.

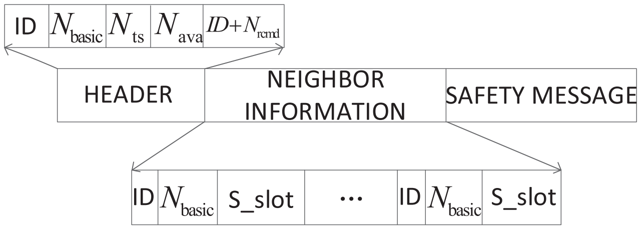
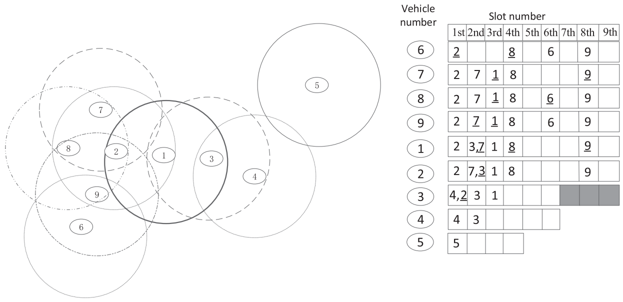


FIGURE 2. Format of message packet sent by vehicles during broadcasting period.

reduce the slots in next synchronization interval. The second part is the neighbor information, which records the time slot occupancy of vehicle nodes within the two-hop communication range. There are two slot states ($S_s lot$) in the message packet: 0 indicates the slot is occupied by a node within the one-hop communication range, and 1 indicates the slot is occupied by a node within the two-hop communication range but outside of the one-hop communication range. The third part is the safety message, which is added to the message packet when the vehicle needs it.

Next, we introduce the mechanism of the vehicle access to the CCH. Because the vehicle outside the two-hop communication range can reuse the time slot (shown in Fig.3, and discussed later), we generally consider network time slot occupancy within the two-hop communication range. When a new node (a vehicle that has not yet obtained a basic time slot) enters the network, it must first listen to the channel for a synchronization interval. By receiving and parsing the message packet from the neighbor node, the vehicle can learn the time slot occupancy of nodes within the two-hop communication range. Then, the vehicle can randomly select



Slot number

Vehicle number	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
6	2			8		6		9	
7	2	7	1	8				9	
8	2	7	1	8		6		9	
9	2	7	1	8		6		9	
1	2	3,7	1	8				9	
2	2	7,3	1	8				9	
3	4,2	3	1				▨	▨	▨
4	4	3							
5	5								

FIGURE 3. Specific network topology and corresponding time slot occupancy.

an idle time slot as the basic time slot, and broadcast its status message to surrounding vehicles in the next synchronization interval broadcasting period.

It is important to be emphasized that the number of time slots in the broadcasting period can be adaptively adjusted based on vehicle densities. We specify the total number of slots in the broadcasting period $N_{ts} \in [N_{min}, N_{max}]$, when the number of vehicles in the network is K, then $N_{ava} = N_{ts}$-K. Intuitively, the larger the value of N_{ava}, the more quickly a new vehicle entering the network gets an available time slot. However, time slots utilization is relatively low. If we stipulate that the number of available time slots per broadcasting period is not less than N_{thre}, then when $N_{ava} \leq N_{thre}$, the vehicle will increase the number of time slots in the broadcasting period in the next synchronization interval. As the vehicle keeps leaving the network, the occupied time slot will be gradually released, and N_{ava} will increase accordingly, making $N_{ava} = N_{thre}$. To ensure the reliability that the vehicle acquires a time slot, we will not immediately reduce the number of time slots in the broadcasting period when N_{ava} is greater than N_{thre}. The process of vehicle access and time slot changes is shown in Algorithm 1.

Algorithm 1 Process of Channel Access and Time Slot Changes

```
// The process of vehicle $V_i$ accessing CCH
// assuming there are $K$ vehicles in the network
// Indicates that the time slot is not obtained,
// i.e, the vehicle that newly enters the network
if $N_{basic} = -1$ then
    Monitor a synchronization interval duration and randomly select an idle slot
else
    Send the message on time slot $N_{basic}$ and receive messages from the neighbors
    if $V_i$'s information is included by all neighbors then
        Continuous use of time slot $N_{basic}$
    else    // deem that the time slot has collided
        Abandon slot $N_{basic}$ and restart the access process

// Time slot change process
// $N_{tsi}$ represents the number of time slots of the broadcasting period of the $i$-th vehicle
initialization: $N_{tsi} = max\{N_{ts1}, N_{ts2}, \dots, N_{tsi}, \cdots, N_{tsK}\}$
$N_{ava} = N_{ts} - K$;
if $N_{ava} \geq 2N_{thre}$ then
    if The time slot will be recycled is not occupied by the vehicle then
        $N_{ts} = K + N_{thre}$    // decrease slots
    else
        using part "$ID + N''_{rcmd}$ to recommend the node to switch to another slot
else if $N_{ava} < N_{thre}$ then
    $N_{ts} = K + N_{thre}$    // increase slots
else
    stays $N_{ts}$
```

Fig.3 presents a schematic diagram of vehicles occupying a time slot in a particular topology to visually depict time slot occupancy and its change process throughout the broadcasting period. In this image, the circle represents the communication range of the vehicle. Taking Vehicle 1 as an example, Vehicles 2 and 3 are in the one-hop communication range, and the vehicles 7, 8, and 9 are in the two-hop communication range. Correspondingly, in the slot occupancy graph, the vehicle numbers that are not underlined denote one-hop node, and those that are underlined is denoted two-hop nodes. It is easy to notice that vehicles 3 and 7 use the second time slot together because the communication range between these vehicles is a three-hop range; therefore, they can send messages on the same time slot without generating message collisions with other vehicles. Fig.3 also indicates the broadcasting period parameters. For example, the parameters of Vehicle 1 are $N_{ts} = 9$, $N_{ava} = 4$ and we set the parameter $N_{thre} = 3$. The time slot occupancy diagram of the Vehicle 3 represents the process by which the vehicle reclaims the time slot, where the gray portion represents the time slot to be recovered. Initially, the broadcasting period parameters of the Vehicle 3 are: $N_{ts} = 9$, $N_{ava} = 6$. Because $N_{ava} = 2N_{thre}$ and the part of the time slot that was recovered is not occupied by vehicles, the Vehicle 3 can smoothly reduce the slots to improve the utilization.

C. SCHs ACCESS PROCESS

In a conventional scheme using a half-duplex transceiver, a synchronization interval is usually divided into a CCHI and a SCHI (generally 50ms each); however, the transceiver can only work alternately on one of the channels, leading channel utilization to reach up to 50%. In fact, since the SCHs data transmission is usually point-to-point communication, in the multi-channel MAC protocol, the vehicle can switch to the SCHs without waiting for the CCHI to end. Our solution design is based on this idea.

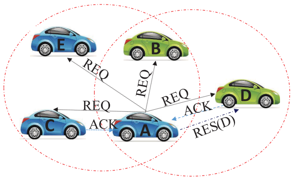


FIGURE 4. Process of three-way handshake protocol.

We illustrate the process of the handshake protocol in Fig.4. When Vehicle A needs service, it will broadcast a request (REQ) message to the network. Assuming that Vehicles C and D can each meet the needs of Vehicle A, then they will send an acknowledgment (ACK) message to Vehicle A. Then, Vehicle A decides whether to accept service from Vehicle D by sending a respond (RES) message. Note that the negotiation process starts after the broadcasting period ends, and messages received by a vehicle during this period are the signaling message of the handshake process. Therefore, when two vehicles complete a handshake agreement, they choose to switch to an available SCH (instead of waiting for the CCHI to end) and thus do not miss important neighbor information. Frame structure diagram of Fig.1, we can see that in the negotiation period, we adopt a contention-based back-off access mechanism. Each node will randomly select a back-off number within the range [0, CW-1] before sending the message. Since the data of the signaling message is relatively small and can be transmitted in a relatively short time (e.g., within one time slot), the mechanism of "freeze backoff time when the channel is detected as busy" in the distributed coordination function (DCF) is not adopted in our backoff mechanism.

The SCH duration will is also divided into equal duration time slots. When a pair of vehicles completes a negotiation and switches to an available SCH, the pair may not fully use all time slots in the service channel in a one-time transmission; hence, other vehicles can continue to use the remaining time slots on the SCH to transmit data. To implement our solution, we must design a special RES message format, as shown in Fig.5. The RES message includes the source vehicle ID (ID_{sour_veh}, indicating the vehicle that needs service, such as Vehicle A); the destination vehicle ID (ID_{dest_veh}, such as Vehicle D); the SCH number (N_{sch}, from 1 to 6); the SCH duration (T_{sch}), and the required set of time slots (O_{set_ts}). When vehicles in the network received the RES signal, they update the SCH occupancy information, and when the negotiation period in the current synchronization interval ends, the vehicle clears these information.

ID_{sour_veh}	ID_{dest_veh}	N_{sch}	T_{sch}	$O_{(Set\_ts)}$

FIGURE 5. Format of RES message.

Based on the information table of SCH occupancy, when selecting available service channel resources, the vehicle will first check whether the remaining time slots in the occupied service channels can meet the vehicle's transmission requirements. If not, then the vehicle will switch to an unoccupied service channel (if spare service channel resources are available); otherwise, the remaining time slots of occupied service channels will be used preferentially. An extreme case in this scheme may occur when, according to SCH occupancy, the amount of data a vehicle needs to transmit cannot be satisfied (i.e., no SCH resources may be available, or the remaining time slots of the occupied SCH maybe insufficient to transmit all data, or the remaining time in the current synchronization interval maybe insufficient to transmit all data). in this case, we adopt the principle of "try the best to transmit". such that we aim to transfer as much data as possible in the current synchronization interval.

IV. MODEL ANALYSIS

A. PACKET DELAY

As shown in Fig.2, packets transmitted in the CCH broadcasting period include three parts: the Header, Neighbor Information, and Safety Messages. If the maximum number of slots in the broadcasting period is N_{max}, then we need at least $\lceil \log_2 N_{max} \rceil$ bits to represent, where $\lceil . \rceil$ indicates the ceiling function. When the number of vehicles in the network is N_{nei}, in this case, the number of vehicles in the network cannot exceed the maximum number of slots N_{max}, that is, $N_{max} \geq N_{nei}$. Therefore, the packet size can be expressed as:

$$\begin{aligned} S_{packet} &= S_{HEADER} + S_{nei} + S_{safety} \\ &= b_{ID} + \lceil \log_2 N_{basic} \rceil + \lceil \log_2 N_{ts} \rceil + \lceil \log_2 N_{ava} \rceil \\ &\quad + N_{nei} * (b_{ID} + \lceil \log_2 N_{basic} \rceil + \log_2 status) + S_{safety} \end{aligned} \tag{1}$$

Since $\lceil \log_2 N_{max} \rceil \geq \lceil \log_2 N_{basic} \rceil or \lceil \log_2 N_{ts} \rceil or \lceil \log_2 N_{ava} \rceil$, we can simplify (1) to

$$\begin{aligned} S_{packet} \leq S_{packet}^{max} &= b_{ID} + 3 * \lceil \log_2 N_{max} \rceil \\ &\quad + N_{max} * (b_{ID} + \lceil \log_2 N_{max} \rceil) + \log_2 status + S_{safety} \end{aligned} \tag{2}$$

As in [19] and [20], we make the following assumptions: for the 5.9 GHz band, the IEEE 802.11p OFDM physical layer supports data rates of $R = 12$ Mbps. If $N_{max} = 100$, $b_{ID} = 1$byte, $S_{safety} = 200$bytes, and there are two slot states (either idle or occupied), then $\log_2\ status = 1$. According to 2, we obtain $S_{packet}^{max} = 3332\ bits$; therefore, the duration of each time slot in the broadcasting period should be $t = \frac{S_{packet}^{max}}{R} = \frac{3332bits}{12Mbps} \approx 0.28ms$. Considering the header information of the physical layer, we set the duration of each time slot to 0.3ms($t_{dua} = 0.3ms$) to meet the requirement that the data packet is transmitted.

B. TIME SLOT ACQUISITION PROCESS IN THE BROADCASTING PERIOD

In [15], the process of vehicles accessing the broadcasting period is described as a one-dimensional *Markov* model. Suppose there are K vehicles in the network. After n frames (i.e., n synchronization intervals), the number of vehicles that successfully obtain time slots is X_n. Then

$$\begin{aligned} &P\{X_n = x_n | X_{n-1} = x_{n-1}, X_{n-2} = x_{n-2}, \cdots, X_1 = x_1, X_0 = x_0\} \\ &\quad = P\{X_n = x_n | X_{n-1} = x_{n-1}\} \end{aligned} \tag{3}$$

This formula holds because if the total number of vehicles that successfully obtain time slots in the $n-1$-th frame is X_{n-1}, then X_n is based on the number X_{n-1}, plus the number of vehicles that oblain time slots at the n-th frame, and independent of the number of vehicles in the previous n-2 frame. This arrangement is consistent with the definition of a *Markov* chain, shown in Fig.6.

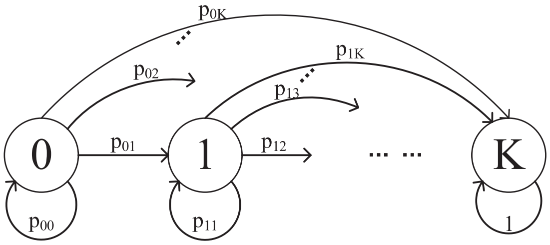


FIGURE 6. ***Markov*** **process of time slot acquisition in the broadcasting period.**

Assuming the number of vehicles in the network is K, and the number of slots in the broadcasting period is N, then we can know that $N_{ava} = N_{ts} - K$. The process of obtaining time slots can be described as placing K balls in N_{ava} boxes. When there are two or more balls in one box, we assume a collision has occurred. At this time, the ball should be removed and another box should be selected for replacement next time.

Hence, the transition probability of the *Markov* chain can be expressed as follows:

$$p_{ij}=\begin{cases}\dfrac{P(j-i,K-i,N_{ava})}{(N_{ava})^{K-i}}, & i\le j,\ i\in[0,K-1]\\ & j\in[i,K]\\ 1, & i=j=K\\ 0, & others\end{cases} \tag{4}$$

In (4), the expression $P(x, y, z)$ represents the probability that there are y nodes competing for z time slots, and x nodes successfully obtain a slot. Compared to VeMAC [15], because we are considering a variable number of time slots (i.e., as the vehicle continuously acquires time slots), the number of time slots in the broadcasting period will increase accordingly. Therefore, within a certain range, our solution will enable vehicles in the network to obtain time slots more quickly. We discuss this concept further in Section V.

The solution process of transition probability $P(x, y, z)$ is a problem of permutation and combination. Relevant literature [25] used a recursive method to solve the probability $P(x, y, z)$:

$$P(x,y,z)=\begin{cases}C_y^x A_z^x((z-x)^{y-x}\\ -\sum_{i=1}^{y-x}P(i,y-x,z-x)), & 0\le x\le y\\ A_z^x, & x=y\\ 0, & x>y\end{cases} \tag{5}$$

The homogeneous *Markov* chain satisfies the $C-K$ equation in that the n-step transition probability is equal to the nth-power of the one-step transition probability.

$$P\{X_n=x_n|X_0=x_0\}=P^n\{X_i=x_i|X_{i-1}=x_{i-1}\} \tag{6}$$

Accordingly, where $0\le i\le n\le K$, and $P\{X_0=x_0\}=1$. If we use P_1 to represent the one-step transition probability, from the above formula we can determine the average number of nodes that obtain a slot within the n-frame:

$$\mu_0=\sum_{i=0}^{n} iP\{X_i=x_i\}=\sum_{i=0}^{n} iP_1^i \tag{7}$$

Section V presents scenarios of several vehicles that successfully obtained time slots in n frames based on our simulation.

C. AVERAGE SCH DURATION

Many research studies have included performance analysis of the binary backoff process [26]–[28]. We calculate the average SCH length to supplement these results. We adopted a backoff-based competitive access mechanism in the negotiation period. Before a vehicle accesses the service channel, it must compete for the right to use the channel, which ensures the fairness of using the service channel to a certain extent. Compared to the DCF mechanism in the 802.11 protocol, the mechanism we adopted simplifies the mechanism of "freeze backoff time when the channel is detected as busy". Each signaling message (REQ/ACK/RES) transmission process in the negotiation period can be represented by a *Markov* chain, as shown in Fig.7. During the negotiation process, if the node needs to send a message, it first randomly selects a backoff number within [0, CW-1]. When the number is reduced to 0, the node attempts to send a message in the channel. If the transmission fails, the backoff process will be restarted. Thus, we can represent the negotiation process based on the three-way handshake protocol with a *Markov* chain, as shown in Fig.8.

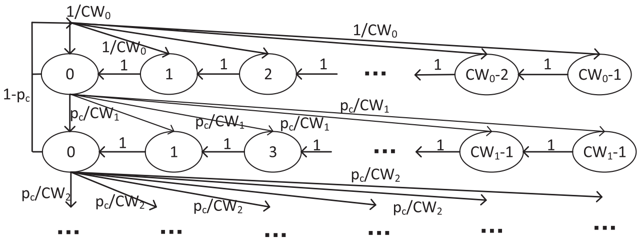


FIGURE 7. ***Markov*** **process of signaling message transmission based on backoff mechanism.**

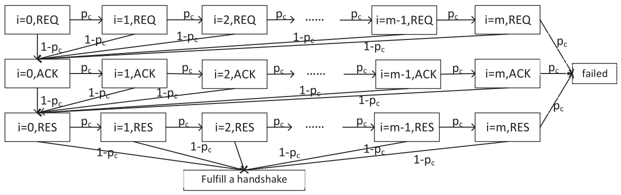


FIGURE 8. ***Markov*** **chain of negotiation process based on three-way handshake.**

From Fig.7 and Fig.8, we can acquire a comprehensive understanding of the three-way handshake-based negotiation process. Fig.7 presents the backoff process required before a message transmission. When the backoff number equals zero, the node will try to send a message to the channel; if a collision occurs, then the backoff process will be restarted with twice the contention window size. During the negotiation process, if the packet fails to be transmitted twice, the message will be discarded, and the handshake process will end in failure. Fig.8 illustrates the *Markov* process for completing a handshake process, where i represents the i-th backoff before the node sends the message (i.e., the previous $i-1$ transmissions collided). The three types of signaling messages in the handshake protocol are sequential; the first is the REQ message, followed by the ACK message, and finally the RES message. However, the backoff process of these three messages is independent of each other. We depict the transition probability of the *Markov* chain on the arrow line in Fig.7 and Fig.8.

The p_c in Fig. 7 and Fig. 8 indicates the probability that the node will encounter a collision when transmitting a message. Articles [26] and [27] pointed out that the collision probability p_c is related to the size of the contention window (CW) and the number of active nodes (n); thus, we obtain the expression of the collision probability p_c, as follows:

$$\begin{cases} p_c = 1-(1-p_t)^{n-1} \\ p_t = \dfrac{2(1-rp_c)}{CW(1-p_c)+1-rp_c} \end{cases} \quad (8)$$

where p_t denotes the probability that a given node will send a message at an arbitrary time, and r denotes the backoff factor. When $r = 2$,it represents binary exponential backoff. According to the above formula, we can get the $p_c - n$ numerical result curve, as indicated in Fig.9.

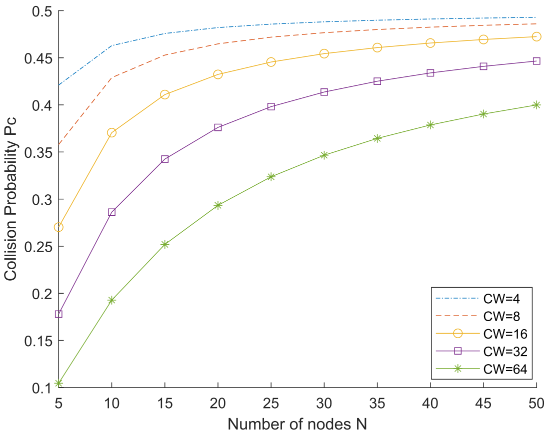


FIGURE 9. **Message transmission collision probability under node number N.**

A delay in three-way handshake protocol can be expressed as the total number of backoffs required during the three type message transmission. Assuming that the contention window selected by the node before sending the message is D, we use D_1, D_2, and D_3 to represent the contention window of the REQ/ACK/RES message respectively, where $D \in [0, CW - 1]$. Then according to [26], we determine the mathematical expectation of D:

$$\overline{D_i} = \frac{1}{2}\left(\frac{1}{1-p_c} + \frac{CW_0}{1-rp_c}\right) - 1 \quad (9)$$

Because the backoff process of the three signaling messages in the three-way handshake protocol is independent, the average delay that the three-way handshake protocol needs is:

$$\overline{D_\Sigma} = \overline{D_1} + \overline{D_2} + \overline{D_3} + t_{DIFS} = 3\overline{D} + t_{DIFS} \quad (10)$$

At this point, we can calculate the average duration of the SCH:

$$\overline{T}_{SCH} = T_{SyncInterval} - (\overline{N}_{ts} * t_{dua1} + \overline{D}_\Sigma * t_{dua2}) \quad (11)$$

where $T_{SyncInterval}$ indicates the duration of a synchronization interval, usually equals to 100ms, and $\overline{N}_{ts}$ indicates the average number of slots in the broadcasting period. $\overline{N}_{ts}$ and $\overline{D}_\Sigma$ must be multiplied by the width of the time slot, because the granularity of time in the broadcasting period is $t_{dua1} = 0.3ms$, but the granularity of time in the negotiation period is $t_{dua2} = 0.1ms$ in our proposed scheme. The reason why we use the different value of t_{dua1} and t_{dua2} is that, according to the analysis in part IV-A, we find that the time slots duration of the broadcasting period is 0.3ms, and the data of the REQ/ACK/RES message are relatively small, (usually between 100-300 bytes), and it only takes 0.1ms to ensure that the message will be sent completely in one time slot.

V. SIMULATION RESULTS

This section presents simulation results of the proposed model. In this simulation, we consider a two-way lane and assume that the channel is ideal, meaning that we do not consider the error generated in the transmission. The simulation scenario is illustrated in Fig.10. Table 1 lists several key parameters in the simulation. It is worth mentioning that the duration of the time slot has three different values, which are 0.3, 0.1, and 1ms. Because the amount of data transmitted on the SCHs is large, it is usually impossible to transmit in a short time slot. Therefore, setting too small a time slot does not improve the performance of the system. The reason we set it to 1ms is also for convenience.

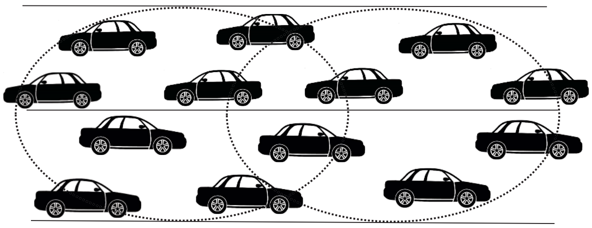


FIGURE 10. **Simulation scenario.**

TABLE 1. **Simulation parameters.**

Parameter	Value
N_{min}	10
N_{max}	100
N_{thre}	5
Slot Duration(t_{dua})	0.3, 0.1, 1(ms)
Packet Size(REQ/ACK/RES)	100byte
Contention Window Size	32
Communication Range	150m
Vehicle Speed	40-80km/h
Vehicle Number	10-100(step=10)
Contention Windows(CW)	4-48(step=4)
Data Transmission Rate(R)	12Mbps
Simulation Time	2minute

In Fig.11 (where K represents the number of vehicles in the network), when available time slot resources are sufficient for the nodes, our scheme and the VeMAC can allow the nodes in the network access control in a relatively short time. However, because the number of slots in the VeMAC is fixed, when the number of nodes and number of available slots are relatively similar, the VeMAC cannot guarantee that all vehicles in the network will obtain a basic time slot (e.g., when $N = 20$, $K = 20$). In our proposed scheme, when the number of available time slots in the broadcasting period is insufficient

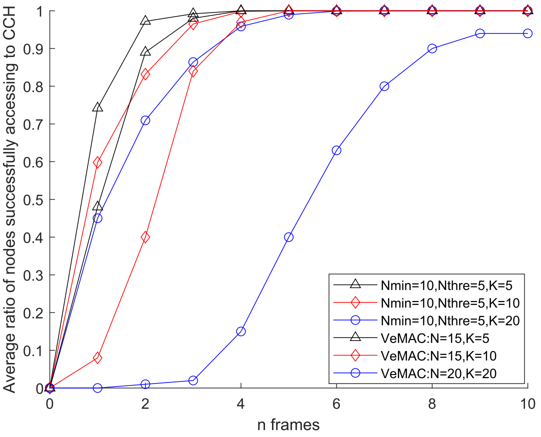


FIGURE 11. Average ratio of nodes successfully accessing control channel.

(i.e., when it is less than the set threshold), the slots will be adaptively increased to satisfy the needs of the node to obtain a basic time slot and broadcast its safety messages. This is also a mechanism to adaptively increase the number of time slots, allowing new vehicles relatively more available time slots for access, therefore, the average time for nodes to obtain basic time slots is relatively short.

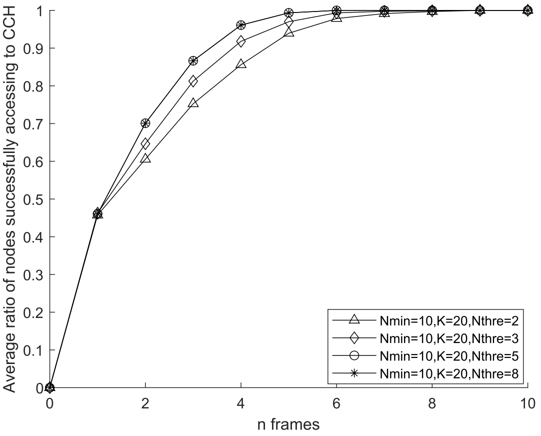


FIGURE 12. Average ratio of nodes successfully accessing control channel.

Fig.12 shows the proportion of nodes obtaining slots in n frames with the change in N_{thre} given that $K = 20$ and the initial time slot $N_{min} = 10$. N_{thre} can represent the number of available time slots in the broadcasting period to a certain extent. The value of N_{thre} is not the better when it is higher; rather when N_{thre} is relatively small, appropriately increasing the value of N_{thre} can actually improve the rate at which the vehicle acquires the time slot. Yet when N_{thre} is too large, vehicle access performance cannot improved, and the time slot utilization rate can decline. As shown in fig.12, the curves of $N_{thre} = 5$ and $N_{thre} = 8$ nearly coincide, indicating that their performance is equivalent.

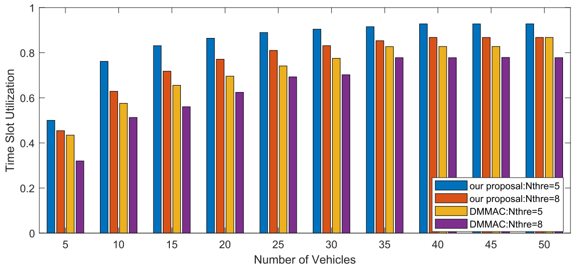


FIGURE 13. Time slot utilization of the broadcasting period.

In Fig.13, the slot utilization of the broadcasting period is compared with the DMMAC; slot utilization is defined as the number of vehicles in the network (also the occupied time slots) divided by the total number of slots in the broadcasting period (i.e., N_{ts}). Because the speed of the basic time slot obtained in our proposed scheme and DMMAC is not substantially different given the same parameters, we compare the performance of these schemes on the aspect of time slot utilization. As shown in Fig.13, the time slot utilization exhibits an increasing trend with an increase in the number of vehicles, presumably because the proposed scheme and the DMMAC each consider that some time slots are reserved for new vehicles. But as the number of vehicles accessing the CCH increases, the difference between the number of vehicles and the number of slots tends to be stable (approximately equal to N_{thre}); as such, time slot utilization will increase first and eventually stabilizing. Compared with these two schemes, the performance of our proposed scheme is slightly better than DMMAC in the case of $N_{thre} = 5$ and $N_{thre} = 8$. The value of different N_{thre} affects the performance of time slot utilization. Compared with the values of $N_{thre} = 5$ and $N_{thre} = 8$, the time slot utilization rate at $N_{thre} = 5$ is higher irrespective of the scheme.

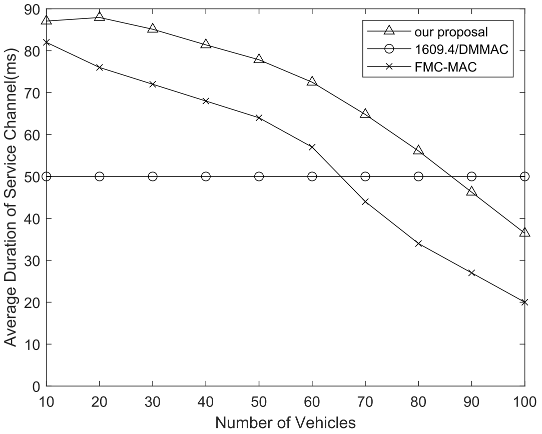


FIGURE 14. Average duration of service channels.

Fig.14 illustrate the trend in average SCHs duration as the number of vehicles changes. With an the increase in the number of vehicle nodes in the network, collisions between signaling messages of the handshake protocol intensify, resulting in an increase in handshake delay; the SCH duration declines accordingly. The SCH duration of our proposed scheme is higher than 50ms for a wide range of

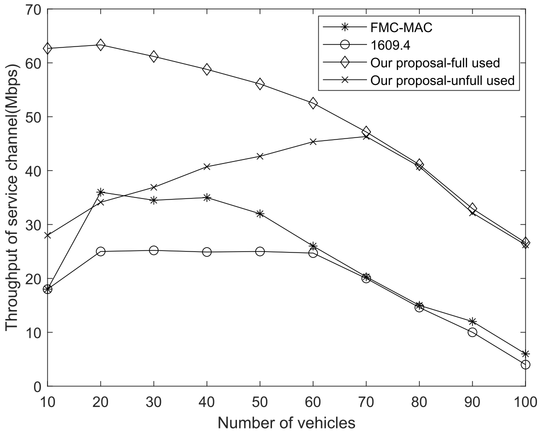


FIGURE 15. **Throughput of service channel.**

vehicle numbers. However, when the number of vehicles exceeds 85, the SCH duration tends to be less than 50ms. In the scheme adopted by FMC-MAC, as the vehicle density increases, the SCH duration reduces to a larger extent because the scheme essentially adopts a competitive-based access approach. Therefore, as the vehicle density increases, the downward trend becomes more obvious. Note that we use the TDMA mechanism for SCH access; this allows the vehicle to use SCH in a contention-free manner, whereas the 1609.4/FMC-MAC uses contention-based message transmission after accessing the service channel. In the latter case, SCHs throughput declines sharply under a large vehicle density. Therefore, even if the SCH duration is less than 50ms, the throughput remains relatively high. We will discuss this in Fig.15.

Fig.15 depicts the SCHs throughput between schemes. Because the SCH in our scheme adopts the TDMA mechanism, it can provide non-contention message transmission for nodes. Assuming that the SCH throughput reaches a saturation condition (i.e., all time slots are used), the system throughput of our solution will be much larger than the other two solutions. This performance improvement is due to node negotiation when using the service channel. Signaling overhead caused by the negotiation period is completely worthwhile compared to the improvement in SCH throughput. FMC-MAC will make the system's throughput slightly better than 1609.4 due to the RSU coordination, although both approaches adopt competitive access mechanisms. We also conducted a simulation based on the following hypothesis: when the vehicle negotiates to use the service channel, it will randomly select the required number of time slots; that is, the SCH time slot may not be fully used. The vehicle selects the number of time slots according to need (here, we consider the number of random time slots to be the number of time slots required by the vehicle). The result is shown in the ''unfull used'' curve. When the number of vehicles is relatively small, even if the SCH duration is long, the usage rate of the time slot is low (in the case of low throughput). As the vehicle density gradually increases, the number of time slots in the service channel approaches full usage such that the throughput is nearly saturated.

VI. CONCLUSION AND FUTURE WORK

In this scheme, we adopt an adaptive frame structure scheme, wherein the number of slots of the broadcasting period of the CCH and the SCH duration can be adaptively changed based on traffic densities. This solution improves the flexibility of the MAC protocol in the VANET environment. Under the premise of ensuring that the vehicle obtains time slots efficiently, our solution improves the slot utilization rate by nearly 23% in the best case compared to DMMAC. For transmission of non-secure messages, we increase the average SCH duration in a synchronization interval by nearly 40%, and because the SCH adopts the TDMA access mechanism, the vehicle can use the service channel without competition, and the throughput is also greatly improved.

Despite our revelations, the proposed scheme has several areas for improvement that will be examined in the future. First, considering the RSU assistance, overhead caused by the negotiation period can be reduced to some extent. The RSU will also contribute some communication resources, computing resources and energy costs. Second, in the VANET environment, if we consider the role of the vehicle or its inherent properties, then we can apply prior knowledge to the MAC protocol design to further improve the protocol performance.

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