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A Novel Capture-Aware TDMA-Based MAC Protocol for Safety Messages Broadcast in Vehicular Ad Hoc Networks

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ABSTRACT Since broadcast communication is considered the highly appropriate technique for the dissemination of safety messages in vehicular ad hoc networks (VANETs), it is vital to design a high-efficient medium access control (MAC) protocol for vehicles accessing wireless channel. However, the characteristics of VANETs, such as high-velocity vehicles, highly dynamic topology and very unstable communication link, lower the performance of existing MAC protocols. In this paper, we propose a novel Capture-aware TDMA-based MAC (CT-MAC) protocol, which can better utilize the channel resource than the existing MAC protocols by setting the optimal frame length with taking capture effect into account. To obtain the realistically optimal frame length, the closed form expression of probability of capture effect is derived under Nakagami-*m* fading channel which is proper to model the small-scale fading channel in VANETs. Besides, a discrete Markov chain is introduced to analyze the impact of capture effect on channel utilization. The theoretical analyses and the simulation results show that the reliability of broadcast and the efficiency of channel utilization are significantly improved.

INDEX TERMS Broadcast, safety message, vehicular ad hoc networks (VANETs), medium access control (MAC), capture effect.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs), an important part of the Intelligent Transportation System (ITS), have drawn great attentions from both academia and industry for the ability to provide safety and non-safety applications for traffic scenarios [1], [2]. VANETs, composed of a set of stationary roadside units (RSUs) and a number of vehicles equipped with on-board units (OBUs) for communication, are special cases of mobile ad hoc networks (MANETs) [2], [3]. The characteristics of VANETs, such as high-velocity vehicles, highly dynamic topology and very unstable communication link, lower the performance of conventional MAC protocols of MANETs [4]. Since the MAC layer is the most critical layer to meet performance criteria for VANETs, to propose a high-efficient VANET MAC protocol is imperative to expedite the application process of VANETs.

Dedicated Short-Range Communication (DSRC), licensed at 5.9GHz with a 75MHz spectrum by the United States Federal Communications Commission, is exclusively used by VANETs [1], [3], [5]. Based on this, the IEEE 802.11p [6] and IEEE 1609.4 [7] standards are established as the main MAC protocols for VANETs. The former is based on IEEE Std 802.11-2007 [8] and the latter is an extension of that about multichannel operation. The 75MHz spectrum is further divided into a 5 MHz guard interval and seven 10 MHz channels with one control channel (CCH) and six service channels (SCHs). The CCH is designed for safety-related applications and system management, whereas the SCHs are dedicated to delivering non-safety data. It has been shown that the above two MAC protocols based on carrier sense multiple access with collision avoidance (CSMA/CA) suffer from the hidden terminal problem and unreliable broadcast service which make it difficult to meet the strict delay requirements for safety messages broadcast especially in highly dense scenarios [9].

In recent years, the MAC protocols employing the TDMA multiple access scheme or employing both TDMA and CSMA multiple access schemes are used to enable vehicles

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to access the channel without interfering with other vehicles. In the TDMA-based MAC protocols and the TDMA-based part of hybrid MAC protocols, time is divided into frames and each frame consists of a number of time slots. Each vehicle can access the channel during its dedicated slot to send safety messages, while it can only receive during the slots reserved by other vehicles and each vehicle usually transmits only once in a frame. In ADHOC MAC [10], A-ADHOC [11], and VeMAC [12], [13], all vehicles need to exchange the slot occupancy information with each other to obtain available slots for transmitting their own safety messages. Therefore, the overhead of each scheme is expensive especially for the dense vehicle scenario. Moreover, since the frame length cannot adaptively be adjusted on the basis of the number of vehicles, the channel utilization is not high. Hence, the RSU-coordinated MAC protocols, VAT-MAC [14], C-MAC [15], and EQM-MAC [16], are proposed to overcome this problem and improve reliability of safety messages broadcast. The overhead can be reduced and the frame length also can be dynamically changed by vehicle density within the coverage of RSU. Although the channel utilization is improved, it is still not optimal for ignoring the so-called capture effect which is a common phenomenon in wireless communication [17]–[19]. As a result, the frame length is not optimal, which lowers the channel utilization and thus the reliability of broadcast.

In this paper, we propose a novel capture-aware TDMA-based MAC (CT-MAC) protocol to improve the reliability in broadcasting safety messages and the efficiency in channel utilization. In CT-MAC, the frame length is optimized by the RSU based on the number of vehicles intending to contend for the slots in each frame. Different from the existing MAC protocols [10]–[16], a slot selected by more than one vehicle can potentially be a successful one due to the capture effect [20]. Moreover, the optimal frame length is announced by transmitting the frame information (FI) by the RSU, which specifies the frame length and the status of each slot at the beginning of the subsequent frame. To our knowledge, it is the first time that the capture effect is taken advantage of designing an RSU-coordinated TDMA-based MAC protocol for VANETs. Our main contributions are as follows:

- A novel capture-aware TDMA-based MAC protocol is designed to provide efficient broadcast service for safety messages, where each frame length is optimized by the RSU based on the estimated number of contending vehicles in its coverage with considering the capture effect.
- The closed form expression of probability of capture effect is derived under the Nakagami-m fading channel which is used to model the small-scale fading in VANETs.
- The impact of capture effect on channel utilization is analyzed by introducing a discrete Markov chain, and the numerical results are illustrated to verify the theoretical analysis.

The rest of this paper is organized as follows. In Section II, we review the related work. Section III mainly describes the proposed CT-MAC protocol. Section IV presents the simulation results to verify the theoretical analyzes and shows that the CT-MAC outperforms the others. Finally, Section V concludes this paper.

II. RELATED WORK

Since the dissemination of safety messages is the key part of VANETs, a variety of researches about MAC protocols have been carried out [4]. The existing MAC protocols can be classified into three categories depending on the channel access methods used, namely the CSMA-based MAC protocols such as IEEE 802.11p and IEEE 1609.4, the TDMA-based MAC protocols, and the hybrid MAC protocols. In the CSMA-based MAC protocols, the vehicles access the channel randomly when they need to transmit. As a result, the transmission collision is inevitable, which leads to poor efficiency in channel utilization and unreliability of safety messages broadcast especially in a high vehicle density scenario. Motivated by it, a variety of Time Division Multiple Access (TDMA)-based MAC protocols have been proposed as well as the hybrid MAC protocols.

In [10], F. Borgonovo et. al proposed ADHOC MAC for inter vehicle communications to solve the hidden-terminal problem and endeavour to broadcast reliably based on reliable reservation ALOHA (RR-ALOHA) [21], which defined a concept of FI (frame information) that contains the status of slots. Each vehicle needs to broadcast its FI to inform other vehicles about the occupied slots by the one-hop neighbors and itself. Finally, each vehicle can obtain the information of slot occupancy about its one- and two-hop neighbors. A vehicle with no reserved slot can select an available slot to transmit only after listening to the channel for a frame. If all one-hop neighbors receive it and add it to their FIs, the vehicle knows that the slot is successfully reserved by itself after receiving these FIs. Otherwise, it fails and tries again. Once a vehicle successfully reserves the slot, it keeps using it at subsequent frames until a collision occurs. Nevertheless, the node mobility significantly impacts on the channel utilization for merging collisions [9]. More importantly, a fixed frame length in ADHOC MAC can either result in inefficient use of channel resource or a network failure [11].

Therefore, H. A. Omar et. al developed VeMAC based on ADHOC MAC for reliable broadcast without hidden terminal problem in [12], [13]. The VeMAC protocol assigns disjoint sets of slots to vehicles moving in opposite directions and to RSUs, and hence decreases the rates of access collision and merging collision in ADHOC MAC caused by the node mobility [22]. Since the frame length is fixed in VeMAC, it does not do well in the channel utilization due to the highly dynamic nature of VANETs [23]. That is, more slots of each frame will be wasted when the frame length does not match the number of vehicles compared with that of the condition that the frame length is optimal.

Like VeMAC, each frame is partitioned into two sets of time slots according to the vehicles moving in opposite directions in ATSA [24]. However, when a vehicle accesses the network, it chooses a frame length based on the number of surrounding neighbors and competes for one of the time slots available for its direction. Moreover, the frame length is dynamically doubled or halved based on the binary tree algorithm, and the ratio of two slot sets is adjusted to decrease the probability of transmission collisions. In fact, the channel utilization can not be optimal for that the frame length is still not optimal.

In order to improve the channel utilization, VAT-MAC based on TDMA is proposed to provide efficient broadcast service for safety applications [14], where the frame length is adjusted frame by frame by the RSU. In order to maximize the channel utilization, the frame length (i.e., the number of slots in each frame) in the contention period is set equal to the number of contending vehicles. Note that this setting method of frame length has also been proved to be the most suitable for ADHOC MAC based on the assumption of ideal channel by literatures [25] and [26]. However, when it is in a real VANET scenario, the setting method cannot optimize the channel utilization for that the frame length is not optimal.

Except for the TDMA-based MAC protocols, a number of hybrid MAC protocols are also proposed to improve the efficiency of safety messages broadcast. In [27], V. Nguyen et. al proposed HER-MAC allowing vehicles to broadcast safety packets twice during both the control channel interval and service channel interval to increase the safety broadcast reliability. In HER-MAC, the control channel is divided into reservation period and contention period. Since many types of packets are broadcasted for handshaking by the vehicles for contending slots in the contention period, the probability of collision is high and thus the channel utilization will be decreased by the overhead.

In [15], Y. Kim et. al proposed C-MAC based on CSMA and TDMA to provide contention-free broadcasting for safety messages by the coordination of RSU. In fact, before being arranged to broadcast without conflict, the vehicles need to contend for the slots so as to be identified by the RSU, where the frame length is also set to be equal to the number of contending vehicles. Similarly, C. Song et. al proposed EQM-MAC in [16], where the vehicles broadcast without conflict only after being identified by the RSU, which means the vehicles need to contend for the slots first like that in C-MAC. Also, the setting method of frame length is the same as that of C-MAC, i.e., the frame length equals to the number of contending vehicles. However, it cannot make the channel utilization optimal when the channel is not ideal.

In fact, all the above-mentioned TDMA-based or hybrid MAC protocols, designed without taking the capture effect into account, result in that the channel utilization cannot be optimized for non-optimal frame length. In this paper, to improve the reliability in broadcasting safety messages and the efficiency in channel utilization, we propose a novel capture-aware TDMA-based MAC (CT-MAC) protocol based on [14]. In CT-MAC, the frame length is optimized by the RSU based on the estimated number of vehicles intending to contend for the slots in each frame. To make each frame length optimal, the closed form expression of capture probability is derived under the Nakagami-*m* fading channel which is proper to model the small-scale fading in VANETs [28]–[30]. Therefore, after setting the optimal frame length, the channel utilization can be optimized. That is, after receiving the FIs broadcasted by the RSU at the beginning of each frame, the vehicles with reserved slots will broadcast safety messages efficaciously, while that with no reserved slots will randomly select a slot for transmission. If a slot is selected by only one vehicle or by more than one but with the capture effect occurring, it is a successful one and will be continually used by the vehicle in the subsequent frames until it leaves the communication coverage of RSU.

III. PROTOCOL DESIGN

In CT-MAC, as shown in Fig.1, the time is divided into frames, and each frame consists of Frame Information Broadcast Phase (FIBP), Slots Allocation Phase (SAP) and Slots Contention Phase (SCP). First of all, the RSU broadcasts FI in FIBP, which specifies the status of each slot of the reserved slots in SAP and contending slots in SCP. After receiving FI, the vehicles with reserved slots will broadcast the safety messages in SAP in sequence, while the vehicles with no reserved slot will contend for the slots in SCP. Besides, the vehicles newly entering without receiving the FI can only randomly choose a slot in the current frame. At the end of each frame, the RSU will acquire the status of each slot. Usually, for a given slot, there are three probable outcomes: no vehicle chooses (an idle slot), only one vehicle chooses (a successful slot) and at least two vehicles choose (a collided slot). In reality, when the capture effect occurs, a collided slot can possibly turn to be a successful one. That is, when the received instantaneous power from one vehicle is greater than the instantaneous joint interference power of others by some threshold value, the RSU can correctly decode the signal from this vehicle in the collided slot [20]. In other word, the vehicle is successfully identified by the RSU in this slot. The detailed explanation can be seen in Appendix A. If the vehicle is successfully identified by the RSU, it will be assigned a fixed slot in SAP of the following frame. On the contrary, if failed, it will contend again in the subsequent frames until

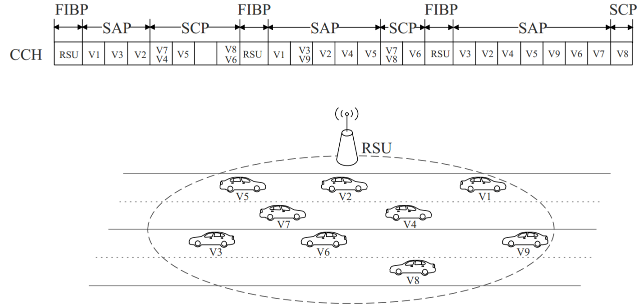

FIGURE 1. The structure of proposed CT-MAC.

it successfully reserves a slot or leaves the communication coverage of the RSU.

In Fig.1, a simple example is given to illustrate the process of CT-MAC. At the beginning of first frame, the RSU broadcasts the FI in FIBP. In the sequel, the vehicles V1-V3, which have reserved slots in previous frame, broadcast safety messages in their own slots of SAP, and the vehicles V4-V8 with no reserved slots randomly choose the slots of SCP. At the end of first frame, V4 and V5 successfully reserve the slots and the former is due to the capture effect. In the second frame, the RSU broadcast the FI first. Afterwards, the vehicles V1-V5 broadcast in SAP while the new coming V9 chooses the slot of V3. Due to the capture effect, the RSU decodes the signal from V9. Then, the vehicles V6-V8 contend for the slots in SCP and V7's signal is captured. Meanwhile, V1 is leaving the communication coverage of RSU. At the end of second frame, the RSU deems that V1 has left its communication range according to V1's velocity. In FIBP of third frame, the RSU still broadcasts FI first. The vehicles V2-V7 and V9 broadcast in SAP and V8 successfully occupies the only slot in SCP.

According to the previous description, the optimal frame length is related to the number of contending vehicles. To derive the expression of optimal frame length, the following hypotheses are made. The length of i-th frame is L_i (i.e., the number of slots) and the number of slots of SAP and SCP are L_i^{SAP} and L_i^{SCP}, respectively. Furthermore, the number of contending vehicles in SAP and SCP are N_i^{SAP} and N_i^{SCP}, respectively.

In SAP, a slot has two possible states: successful with/without capture or collided without capture, and their probabilities can be respectively calculated by

$$P_i^{SAPsuc} = \frac{L_i^{SAPsuc}}{L_i^{SAP}} = 1 - P_i^{SAPcol} \quad (1)$$

$$P_i^{SAPcol} = \frac{L_i^{SAPcol}}{L_i^{SAP}} = \sum_{j=1}^{N_i^{SAP}} \binom{N_i^{SAP}}{j} \left(\frac{1}{L_i^{SAP}}\right)^j \times \left(1 - \frac{1}{L_i^{SAP}}\right)^{N_i^{SAP}-j} \left[1 - p_{cap}(j+1)\right] \quad (2)$$

where L_i^{SAPsuc} (the number of successful slots in SAP) consists of N_i^{SAPone} (the number of slots with only one vehicle transmitting) and N_i^{SAPcap} (the number of newly coming vehicles identified due to capture effect), and $p_{cap}(\cdot)$ is the probability of capture effect derived in Appendix A. Since L_i^{SAPsuc}, L_i^{SAPcol} (the number of collided slots in SAP) and L_i^{SAP} are all known to the RSU, $\hat{N}_i^{SAP}$ can be estimated by (1) or (2). An example is given in Fig.2, where the estimation error is defined as the ratio of the absolute value of the difference between the actual and estimated number of vehicles to the actual number. As shown in Fig.2, the estimation errors of the number of vehicles in SAP are given when $L_i^{SAP} = 50$ and N_i^{SAP} varies from 10 to 50 and the values of estimation error are all less than 2%.

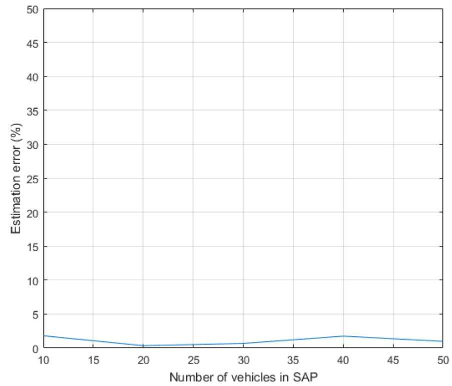

FIGURE 2. Estimation errors of the number of vehicles in SAP on the basis of (2).

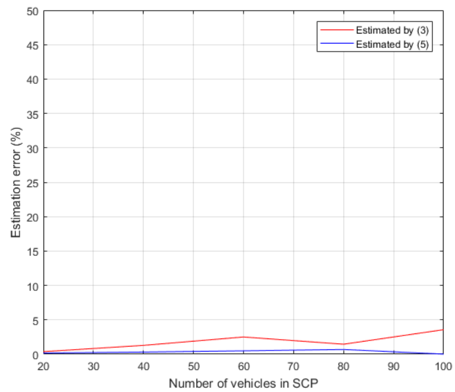

FIGURE 3. Estimation errors of the number of vehicles in SCP on the basis of (3) and (5).

In SCP, a slot has three possible states: idle, successful or collided. The slot utilization of SCP is calculated by

$$P_i^{SCPsuc} = \frac{L_i^{SCPsuc}}{L_i^{SCP}} = \sum_{j=1}^{N_i^{SCP}} \binom{N_i^{SCP}}{j} \left(\frac{1}{L_i^{SCP}}\right)^j \times \left(1 - \frac{1}{L_i^{SCP}}\right)^{N_i^{SCP}-j} p_{cap}(j) \quad (3)$$

where L_i^{SCPsuc} is the number of successful slots in SCP. Since L_i^{SCPsuc} and L_i^{SCP} are known to the RSU, the number of contending vehicles $\hat{N}_i^{SCP}$ can be obtained by (3). In fact, $L_i^{SCPidle}$ (the number of idle slots in SCP) is irrespective of the capture effect, the probability of idle slots in SCP can be calculated by

$$P_i^{SCPidl} = \frac{L_i^{SCPidle}}{L_i^{SCP}} = \left(1 - \frac{1}{L_i^{SCP}}\right)^{N_i^{SCP}} \quad (4)$$

Since $L_i^{SCPidle}$ and L_i^{SCP} are known to RSU, $\hat{N}_i^{SCP}$ can be briefly estimated by [15]

$$\hat{N}_i^{SCP} = \frac{\ln\left(\frac{L_i^{SCPidle}}{L_i^{SCP}}\right)}{\ln\left(1 - \frac{1}{L_i^{SCP}}\right)} \tag{5}$$

Note that $\hat{N}_i^{SCP}$ can be obtained by (5) iff $L_i^{SCPidle} \neq 0$. An example is as shown in Fig.3, the estimation errors of the number of vehicles in SCP are given when $L_i^{SCP} = 100$ and N_i^{SCP} varies from 20 to 100, and the estimation errors by (3) are slightly higher than that by (5) with all values no more than 4%.

Hence, the number of vehicles within the communication coverage at the end of frame i is

$$\hat{N}_i = L_i^{SAP} + \hat{N}_i^{SAP} + \hat{N}_i^{SCP} \tag{6}$$

Here, we assume that the vehicles of each lane follow a Poisson point process with vehicle density β (vel/km) in a two-way, four-lane highway. Then, the probability of finding $\hat{N}_i$ vehicles in the communication coverage of RSU during i-th fame is given by [31]–[33]

$$P\left(\hat{N}_i, 4R\right) = \frac{(4\beta R)^{\hat{N}_i} e^{-4\beta R}}{\hat{N}_i!} \tag{7}$$

where R is the communication coverage of RSU. Under the hypothesis of perfect power control mechanism like literature [34], the communication coverages of both RSU and vehicles can be the same constant R. Then, the average vehicle density can be given by

$$\beta = \frac{\hat{N}_i}{4R} = \frac{L_i^{SAP} + \hat{N}_i^{SAP} + \hat{N}_i^{SCP}}{4R} \tag{8}$$

Based on the above analysis, the number of contending vehicles in $(i+1)$-th frame includes three parts: a) the number of unidentified vehicles without receiving FI in SAP is $\left(\hat{N}_i^{SAP} - N_i^{SAPcap}\right)$; b) the number of vehicles contending abortively in SCP is $\left(\hat{N}_i^{SCP} - N_i^{SCPsuc}\right)$; c) the number of vehicles entering into the communication range during the $(i+1)$-th frame is

$$N_{i+1}^{new} = 4 \cdot \beta \cdot L_{i+1} \cdot \bar{V} \tag{9}$$

where $\bar{V}$ is the average velocity of vehicles and L_{i+1} is the $(i+1)$-th frame length. Furthermore, the length of SCP in the following frame can be given by

$$L_{i+1}^{SCP} = \lambda \cdot \left[\left(\hat{N}_i^{SAP} - N_i^{SAPcap}\right) + \left(\hat{N}_i^{SCP} - N_i^{SCPsuc}\right) + N_{i+1}^{new} \cdot \frac{L_{i+1}^{SCP}}{L_{i+1}}\right] \tag{10}$$

where λ is the coefficient defined in Appendix B. Combine (9) and (10), we can obtain

$$L_{i+1}^{SCP} = \frac{\hat{N}_i^{SAP} - N_i^{SAPcap} + \hat{N}_i^{SCP} - N_i^{SCPsuc}}{\lambda^{-1} - 4 \cdot \beta \cdot \bar{V}} \tag{11}$$

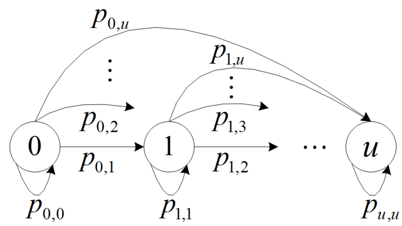

FIGURE 4. Discrete Markov chain for X_f.

Since the number of reserved slots in SAP of $(i+1)$-th frame is $L_{i+1}^{SAP} = L_i^{SAP} - N_i^{SAPlea} + N_i^{SAPcap} + N_i^{SCPsuc}$, the $(i+1)$-th frame length $L_{i+1} = L^{FIBP} + L_{i+1}^{SAP} + L_{i+1}^{SCP}$ can be easily obtained. Note that N_i^{SAPlea}, the number of vehicles leaving the communication coverage during frame L_i, can be calculated by the RSU based on the velocities of vehicles.

IV. PERFORMANCE ANALYSIS

A. IMPACT OF CAPTURE EFFECT ON CHANNEL UTILIZATION

To show the impact on channel utilization from capture effect, we give the following mathematical analysis based on [35] with considering the capture effect. Let $P(k, u, v)$ be the probability of k successful slots given u contending vehicles and v available slots in a frame ($u \leqslant v$), which can be given by

$$P(k,u,v) = \begin{cases} 0, \\ \quad (k=0,\ u=1,\ v \geqslant 0) \text{ or } k > u \text{ or } k > v \\ 1, \\ \quad (k=0,\ u=0,\ v \geqslant 0) \text{ or } (k=1,\ u=1,\ v>0) \\ 1 - p_{cap}(u), \\ \quad k=0,\ u>1,\ v=1 \\ \sum_{j=0}^{u} p_b(j)\left[1-p_{cap}(j)\right]P(0,u-j,v-1), \\ \quad k=0,\ u>1,\ v>1 \\ \sum_{j=0}^{u} p_b(j)\left\{\left[1-p_{cap}(j)\right]P(k,u-j,v-1) \right. \\ \qquad \left. + p_{cap}(j)P(k-1,u-j,v-1)\right\}, \\ \quad u \geqslant k > 0,\ v > 0. \end{cases} \tag{12}$$

where $p_b(\cdot)$ and $p_{cap}(\cdot)$ are the binominal probability and the capture probability given in Appendix A, respectively.

Define X_f to be the number of the successful slots after the f-th frame ($f = 1, 2, 3 \ldots$). Then, X_f forms a discrete Markov chain illustrated in Fig.4. Based on above expressions of probabilities, the initial probability of k successful slots after the first frame's contention can be given by

$$Pr\{X_1 = k\} = P(k,u,v), \quad 0 \leqslant k \leqslant u \tag{13}$$

With the distribution of X_1, we can compute the distribution of X_f $(f \geqslant 2)$ iteratively by

$$Pr\left\{X_f = k | X_{f-1} = j\right\} = P_{j,k} = P(k-j, u-j, v-j), \quad 0 \leqslant j \leqslant k \leqslant u \tag{14}$$

By unconditioning on X_{f-1}, the probability of successes after the f-th frame's contention can be given by

$$Pr\left\{X_f = k\right\} = \sum_{j=0}^{k} Pr\left\{X_{f-1} = j\right\} \times P(k-j, u-j, v-j), \quad 0 \leqslant k \leqslant u \tag{15}$$

Then, the cumulative distribution function of the system stabilization time $SST(u, v)$ (i.e., the number of the frames that elapse until each vehicle in the system has successfully reserved a slot for u vehicles and v slots) is

$$Pr\left\{SST \leqslant f\right\} = Pr\left\{X_f = u\right\}, \quad f \geqslant 1 \tag{16}$$

With the distribution of SST, the mean values can be computed numerically. Alternatively, literature [35] provides another fast way to get the mean values. Therefore, the average number of successful vehicles in f-th frame can be calculated by

$$\bar{A}_{suc}(f) = \sum_{k=0}^{u} k Pr\left\{X_f = k\right\}, \quad f \geqslant 1 \tag{17}$$

Then, the channel utilization (i.e., average normalized throughput) of frame f can be expressed as

$$\eta_{suc}(f) = \frac{\bar{A}_{suc}(f)}{L_f} \tag{18}$$

where L_f is the length of frame f.

In order to verify the accuracy of above theoretical analyzes, we implement the following simulation by Monte Carlo method. Here, we follow the parameter settings in [35] and assume that the number of vehicles is $u = 9$, and the number of slots in a frame is $v = 16$. Besides, we assume that the receiver can successfully decode the signal when a slot is selected by only one vehicle or two (or more) vehicles with capture ratio $z = 2$. In addition, we assume that the shape parameter of Nakagami-m fading channel is $m = 1.5$. In Fig.5 and Fig.6, the average number of vehicles acquiring their slots and the average normalized throughput since the first frame are given and the analytical results are in accord with the simulation results. As seen from the figures, in the first several frames, if the capture effect is considered, larger average number of successful vehicles and higher average normalized throughput can be obtained than that of ignoring it. In addition, Fig.7 shows the performance indices (i.e., the distribution and mean value of SST), where the analytical results are in accord with the simulation results. In fact, the mean value of SST with capture (≈ 2.220) is smaller than that without capture (≈ 2.411), which means that the capture effect makes the success probability that the vehicles contend for slots increased. That is to say, compared with the case without capture, fewer frames (i.e., slots) are required for all vehicles acquiring slots when the capture effect is taken into account.

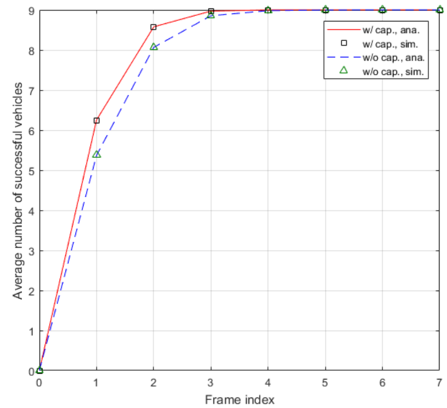

FIGURE 5. **Average number of vehicles acquiring their slots.**

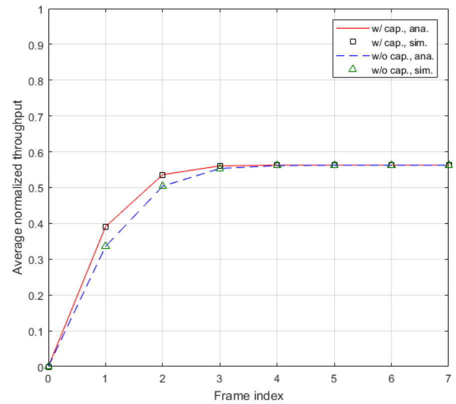

FIGURE 6. **Average normalized throughput.**

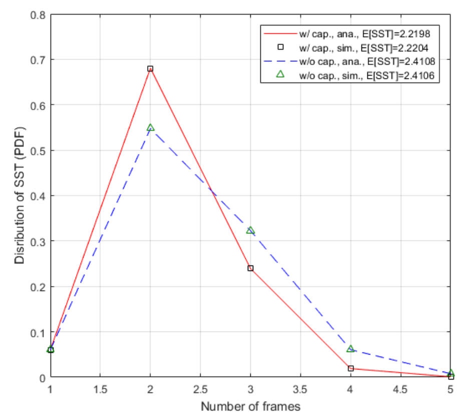

FIGURE 7. **The probability distribution of SST.**

Note that the above analyzes are based on the assumption that the frame length is fixed for simplicity, where the frame length actually does not match the number of vehicles. As a matter of fact, if the frame length is optimal in each frame, the channel utilization can be optimized. According to Appendix B, if the capture ratio is $z = 2$ and the shape parameter of Nakagami fading is $m = 1.5$, the calculation of coefficient is $\lambda^* = 0.725$. Therefore, the optimal frame length can be obtained according to the number of contending vehicles. As shown in Fig.8, the optimal frame lengths in SCP of CT-MAC are shorter than that of VAT-MAC when the number of vehicles is larger than 2.

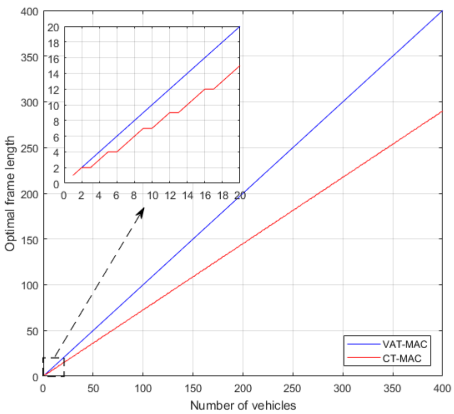

FIGURE 8. Comparison of optimal frame lengths of VAT-MAC and CT-MAC.

The average number of vehicles successfully acquiring slots within frames is shown in Fig.9, where three cases of ratio u/v are 10/15, 15/15, and 15/20, respectively. In the case of 10/15, all vehicles can acquire slots in a few frames for the frame length is larger than the number of vehicles, i.e., the slots are sufficient. Since the capture effect is taken into account and each frame length of CT-MAC is less than that of VeMAC and VAT-MAC, fewer slots but more frames are needed in CT-MAC and thus the curve of CT-MAC is below that of VeMAC but slightly above that of VAT-MAC. In the case of 15/15, since the frame length equals to the number of contending vehicles, the curves of VeMAC and VAT-MAC are overlapping. The reason why the curve of CT-MAC is above the others is the same as the first case. In the case of 20/15, since the frame length in VeMAC cannot be adaptively adjusted to match the number of contending vehicles, some vehicles cannot acquire the slots and thus the curve of VeMAC is below that of VAT-MAC and CT-MAC. Meanwhile, the curve of CT-MAC is on the top of that of VAT-MAC just like the previous two cases. As a matter of fact, the curve of VeMAC in the third case is even below that in the second case due to that more vehicles contend for slots resulting in more collisions.

Fig.10 gives the average normalized throughput of each frame. From Fig.9, not all the vehicles can be assigned to slots when u is larger than v in VeMAC. But in CT-MAC and VAT-MAC, all vehicles can acquire their slots in a few frames since both of them dynamically adjust the frame length in each frame according to the number of contending vehicles. In fact, the average normalized throughput of both VeMAC and VAT-MAC ignoring the capture effect is lower than that

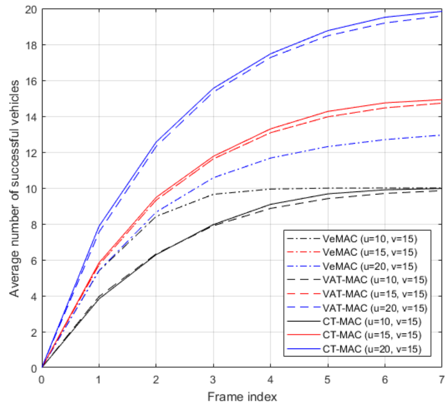

FIGURE 9. Average number of vehicles acquiring their slots within *f* frames.

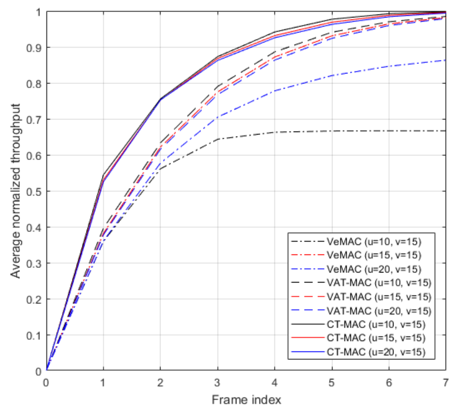

FIGURE 10. Average normalized throughput of frame *f*.

of CT-MAC for no real optimal frame length. Fortunately, the proposed CT-MAC protocol optimizes the frame length by taking the capture effect into account, which means fewer slots of each frame in CT-MAC are included than that of the other two. Therefore, the proposed CT-MAC outperforms VeMAC and VAT-MAC.

B. PERFORMANCE RESULT AND ANALYSIS

In this section, the simulations are performed in MATLAB to verify our proposed CT-MAC protocol. The simulated scenario is a two-way, four-lane highway with one RSU and a number of vehicles as shown in Fig.1, where the free-flow traffic model is considered as in [37]. At the beginning of simulation, the vehicles choose their velocities following a truncated normal distribution, with mean velocity 100 km/h, standard deviation of velocity 20 km/h, maximum velocity 130 km/h and minimum velocity 90 km/h. Besides, the velocities of vehicles keep unchanged when they move in the communication coverage of RSU.

The maximum frame length is limited to 100 ms by the QoS requirement of safety messages [3], [7]. The safety message size for CT-MAC is set to be 200 bytes like that in VAT-MAC. Since the proposed CT-MAC is a RSU-coordinated MAC protocol like VAT-MAC [14], each safety message does not need to include an additional 100-byte time slot occupancy information field like VeMAC [12], [13]. Consider a transmission rate of 8 Mbps like that in [14], the transmission time of 200 bytes and 300 bytes safety message packets is 0.2 ms and 0.3 ms, respectively. By adding guard periods and taking account of the physical layer overhead, additional 0.05 ms duration in each time slot can be assumed [13]. Monte Carlo method is also used in the simulation and the simulation parameters are shown in TABLE 1.

TABLE 1. Simulation parameters.

Parameter	Value
RSU coverage range	300, 500 meters
Number of lanes	4
Maximum and minimum vehicle velocities	130 km/h and 90 km/h
Average vehicle velocity	100 km/h
Average vehicle density	0.05-0.3 veh/m
Channel fading model	Nakagami-*m* (*m*=1.5)
Data rate	8 Mbps
Safety message size for CT-MAC, VAT-MAC	200 bytes
Safety message size for VeMAC, ATSA	300 bytes
Time slot duration for CT-MAC, VAT-MAC	0.25 ms
Time slot duration for VeMAC	0.35 ms
Frame information size for CT-MAC, VAT-MAC	1000 bytes
Number of slots in initial frame for all protocols	285
Maximum frame length	100 ms
Simulation time	1000 s

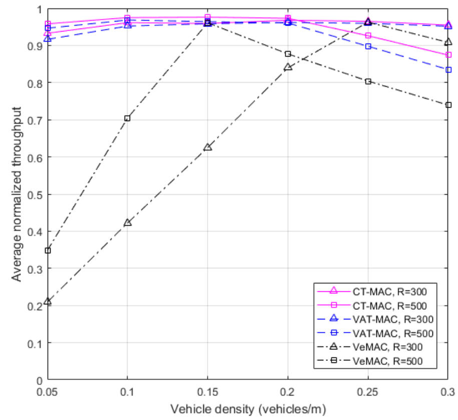

FIGURE 11. Average normalized throughput versus vehicle density.

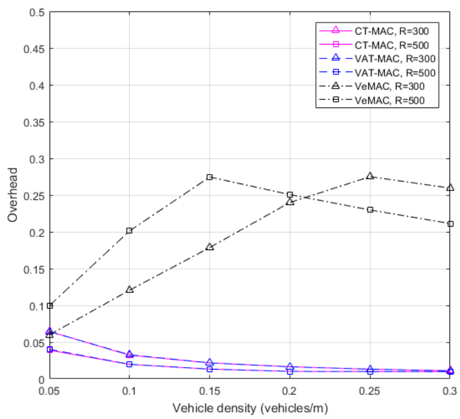

FIGURE 12. Coordination overhead versus vehicle density.

Fig.11 shows the average normalized throughput for different vehicle densities when the RSU coverage ranges are 300 and 500 meters, respectively. Since CT-MAC and VAT-MAC adjust the frame length adaptively, their curves almost are above that of VeMAC and the curve of VAT-MAC are slightly below that of CT-MAC. That is, the VeMAC protocol fixes the length of different frames, which results in the waste of slots. The reasons are as follows: a) a lot of slots will be wasted when the number of vehicles is much smaller than the frame length, and b) plenty of collisions will come out when the number of vehicles is much larger than the frame length. In fact, we take the capture effect into account in the proposed CT-MAC protocol, and the optimal frame length is derived. Therefore, combine Fig.10 and Fig.11, CT-MAC outperforms VAT-MAC which ignores the capture effect. As seen from the case of that the RSU coverage range is 500 meters in Fig.11, the average normalized throughput declines when the vehicle density exceeds 0.2 veh/m. As a matter of fact, when the RSU coverage range is large and the vehicle density is high, more vehicles will join in the process of contending their own slots than that of the case with small RSU coverage range and low vehicle density. As a result, when the number of vehicles reaches a certain level, no optimal frame length can be obtained for the frame length is finite and at most 100 ms. Finally, more collisions come out and the average normalized throughput falls off.

In Fig.12, the coordination overheads, defined as the throughput wasted by coordination related messages, are given for CT-MAC, VAT-MAC and VeMAC when the RSU coverage ranges are 300 and 500 meters, respectively. Obviously, the curves of the first two MAC protocols, below that of the third one, are very close to each other for the frame length can be adaptive to the number of vehicles in the first two protocols. Since the proposed CT-MAC protocol is an RSU-coordinated MAC protocol like VAT-MAC in [14], its overhead is also less than that of VeMAC. Because as described before, VeMAC is a non-RSU-coordinated protocol, and it needs additional 100 bytes in each safety message for coordination purpose [12]–[14]. Nevertheless, the only coordination-related overhead of the proposed CT-MAC protocol is the FI message transmitted just once at the beginning of each frame. Therefore, the number of available slots for the same frame length in VeMAC is less than that of VAT-MAC and CT-MAC, while that of the latter two are close to each other.

In Fig.13, the success ratio performance of delivering safety messages of VeMAC, VAT-MAC, and CT-MAC for different vehicle densities are given. The success ratio is the ratio of the number of vehicles successfully delivering safety messages to the number of vehicles in the RSU coverage in each frame, which is different from "the ratio of the number of vehicles that are allocated time slots to the total number

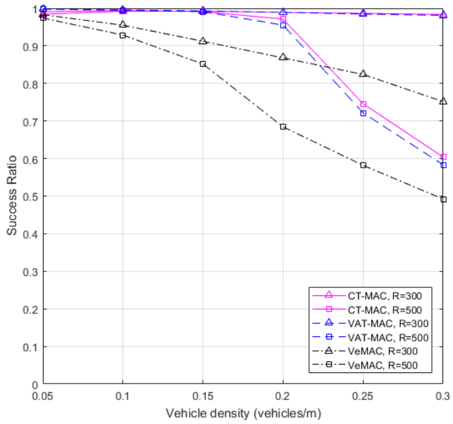

FIGURE 13. **Success ratio versus vehicle density.**

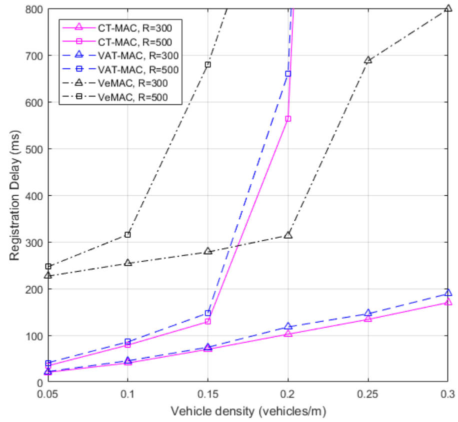

FIGURE 14. **Average registration delay versus vehicle density.**

of vehicles" defined in [13]. The reason is that the vehicles with reserved slots maybe interfered by the newly coming vehicles missing the FI messages from the RSU. In addition, the vehicles with reserved slots will be also interfered by the vehicles with the same slots from the adjacent two-hop cluster in VeMAC (i.e., the merging collision defined in [8]). As seen from Fig.13, when the RSU coverage is 300 meters, the curves of VAT-MAC and the Proposed CT-MAC are close to each other and the curve of VeMAC is below the former. Since the overhead of VeMAC is higher than that of VAT-MAC and CT-MAC, the number of vehicles with allocated slots in VeMAC is less than the other two for the same frame length. Besides, the merging collision occurs more frequently as the vehicle density increases, which results in more vehicles broadcasting abortively and reserving slots again. Likewise, the curve of VeMAC declines for the same reason as above when the RSU coverage is 500 meters. While the curves of VAT-MAC and CT-MAC are still above that of VeMAC but decline for the reason that the available slots of the frame are not sufficient. Besides, the success ratio of CT-MAC is slightly bigger than that of VAT-MAC when the vehicle density is greater than 0.20 veh/m. The reason is that the former takes the capture effect into account which increases the possibility of reserving slots. Since the vehicles delivering safety messages normally will be interfered by more newly coming vehicles missing the FI messages broadcasted by the RSU as the vehicle density increases, the curves of both VAT-MAC and CT-MAC decline as the vehicle density increases.

In Fig.14, the average registration delays of VeMAC, VAT-MAC, and CT-MAC are given. In VeMAC, one vehicle just powered on randomly chooses an available slot after listening to the channel for L_f (i.e., the frame length) successive slots (not necessarily in the same frame), and then determines whether its attempt is successful or not by observing the $L_f - 1$ slots following the chosen slot. Therefore, the average registration delay (i.e., the average duration before the concerned vehicle marked by all of its one-hop neighbors) in VeMAC consists of the listening duration, the duration until the chosen slot elapsing, and the observing duration. While in both VAT-MAC and the proposed CT-MAC, the average registration delay is the average time form the beginning that one vehicle comes into the RSU coverage to the end that the vehicle affirms that it has been identified by the RSU. As seen from Fig.14, the curves of VeMAC are on the top of the other two for different vehicle densities when the RSU coverage is 300 meters (named Case 1) or 500 meters (named Case 2). Besides, the average registration delay of the proposed CT-MAC is less than VAT-MAC for setting the optimal frame length with considering the capture effect. As a matter of fact, even though the vehicle densities are the same in both cases, the average registration delays of each protocol of Case 2 are larger than that of Case 1 for more vehicles need to register. Moreover, the average registration delay of different protocols increase as the vehicle density increases in both cases.When the vehicle density gets larger, the contention of reserving slots becomes very fierce and even some vehicles always reserve abortively for that the slots available in each frame are not sufficient. Therefore, the registration delay gets larger and larger and some vehicles even cannot register. Note that the average registration delays of different protocols are calculated by the average time that the vehicles needed for successfully registering.

In Fig.15, the delays of safety message deliveries of VeMAC, VAT-MAC, and CT-MAC are given. According to literature [22], the delivery delay of a safety message consists of five components: upper layers delay, queueing delay, access delay, transmission duration and propagation delay, while it is dominated by the access delay component (around one half the duration of a frame). For simplicity, we only take the access delay into account. In addition, we assume that the safety message generates at the beginning of a frame and its lifetime is the duration of current frame. Since some vehicles may always fail to reserve the slots in VeMAC, they cannot broadcast the safety messages. That is to say, the delay of safety message delivery is infinite. Therefore, to show the delay curves of the three protocols integrally, the delays of safety message deliveries are calculated based

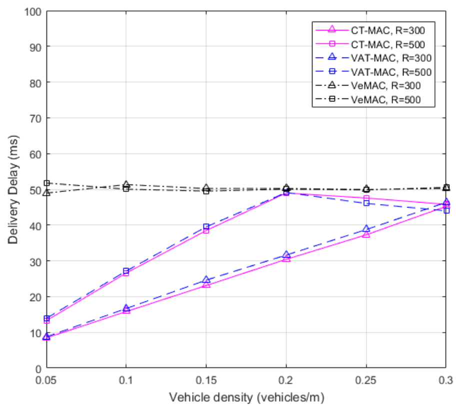

FIGURE 15. Delay of safety message delivery versus vehicle density.

on the vehicles broadcasting successfully. Since the frame length is fixed in VeMAC and equals to 99.75 ms here (because the maximum slot amount is 285), the delivery delay is around 49.875 ms [22]. While in both VAT-MAC and the proposed CT-MAC, the frame lengths can be adaptively adjusted by the vehicle amount in the RSU coverage and the delivery delays of both two protocols depend on the vehicle density. As seen from Fig.15, the delivery delay increases as the vehicle density increases in Case 1 but decreases when the vehicle density is larger than 0.20 veh/m in Case 2 for both VAT-MAC and CT-MAC. The reason is that plenty of attempts for reserving slots lead to more contending failure. As a result, the number of vehicles delivering safety messages normally becomes smaller, while the average access delay decreases for the front part of a frame (i.e., the shots allocated to vehicles) becomes shorter. In a word, the delay requirement of safety messages (i.e.,100 ms) can be meet in Case 1 with different vehicle densities and in Case 2 with low vehicle density (less than 0.20 veh/m to ensure that the slots for reservation are sufficient).

V. CONCLUSION

In this paper, we propose a novel VANET MAC protocol called CT-MAC for efficient broadcast service for safety messages in VANETs. By setting the optimal frame length with taking the capture effect into account, the proposed CT-MAC protocol outperforms the existing MAC protocols (such as VeMAC and VAT-MAC) in terms of the normalized throughput, the registration delay, and the delay of safety message deliveries. The closed form expression of probability of capture effect is derived under the Nakagami-m fading channel which is proper to model the small-scale fading channel in VANETs. Besides, the impact of capture effect on channel utilization is analyzed by introducing a discrete Markov chain and then we draw a conclusion that the channel utilization can be improved by taking advantage of the capture effect. The theoretical analyses and the simulation results show that the proposed CT-MAC can significantly improve the reliability in safety messages broadcast and the efficiency in channel utilization of VANETs. In the future, we plan to further increase the slot utility by using the successive interference cancellation technique and extend the CT-MAC protocol by allowing each vehicle to access more than one slot per frame in different scenarios if necessary.

APPENDIX A

We assume that u vehicles contend for v slots (i.e., the frame length) and each vehicle can only try to access the channel once in a frame. For a particular slot, it can be idle, successful or collided. The binominal probability that n out of u vehicles randomly choose a particular slot with probability $\frac{1}{v}$ can be given by

$$p_b(n) = \binom{u}{n}\left(\frac{1}{v}\right)^n\left(1-\frac{1}{v}\right)^{u-n} \tag{19}$$

where $\binom{u}{n} = \frac{u!}{n!(u-n)!}$. Then, the probabilities that the slot is idle, successful or collided are $p_b(n = 0)$, $p_b(n = 1)$ and $p_b(n \geqslant 2)$, respectively. But when the capture effect occurs, a collided slot possibly becomes a successful one. Then, the successful probability of the slot can be calculated by

$$p_{suc}(u,v) = \begin{cases} 0, & u=0, v\geqslant 0 \\ \frac{1}{v}, & u=1,\ v\geqslant 1 \\ \sum_{n=1}^{u} p_b(n)p_{cap}(n), & u\geqslant 2, v\geqslant 1 \end{cases} \tag{20}$$

where $p_{cap}(\cdot)$ is the probability of capture effect.

According to the literatures [20], [36], [38], [39], a signal is captured by the receiver when its power level exceeds the sum of the power of all the other interfering signals by capture ratio z, which reflects the capture performance of the applied receiver, modulation and coding techniques. We consider n (an integer greater than one) vehicles transmitting simultaneously, which means that they choose the same slot for transmission. The compound signal power at the receiver is the superposition of the overlapping signals, which equals to

$$\Lambda = \sum_{k=1}^{n} P_k + N_0 \tag{21}$$

where N_0 is the noise power. For simplicity, we omit it like that in literatures [20], [34]. Here, we assume the concerned signal t is the most strongest among all the signals, and the condition for capture is given by [20], [34], [38]

$$\frac{\frac{P_t}{N_0}}{\frac{\Lambda}{N_0}-\frac{P_t}{N_0}} = \frac{\gamma_t}{\sum\limits_{k=1,k\neq t}^{n}\gamma_k} > z, \quad t\in[1,n] \tag{22}$$

Then, if the interference power is due to incoherent accumulation of $n-1$ independently fading signals, the capture probability can be calculated by [20]

$$p_{cap}(n) = n\int_0^{\infty} f_{\gamma_t}(\gamma_t)\left[\int_0^{\frac{\gamma_t}{z}} g_{\gamma_{n-1}}(\gamma_{n-1})d\gamma_{n-1}\right]d\gamma_t \tag{23}$$

where $f_{\gamma_t}(\gamma_t)$ is the probability density function (PDF) of individual signal power, and $f_{\gamma_{n-1}}(\gamma_{n-1})$ is the compound PDF resulting from $(n-1)$-fold convolution of the PDF of individual signal power.

In Nakagami-m fading channel, the PDF of instantaneous received power is given by [40]

$$f_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}}}, \quad \gamma \geqslant 0 \tag{24}$$

where m is the shape parameter, which ranges from $\frac{1}{2}$ to ∞. For simplicity, we disregard the effect of propagation path loss and assume that all signals transmitted by vehicles have same average power value $\bar{\gamma}$ by performing perfect power control mechanism [34]. According to the Laplace transform method, we can obtain

$$f_\gamma(\gamma) \leftrightarrow F_\gamma(s) = \frac{m^m}{\bar{\gamma}^m} \frac{1}{\left(s + \frac{m}{\bar{\gamma}}\right)^m} \tag{25}$$

Next, by applying the convolution property of Laplace transform, we can obtain

$$f_\gamma(\gamma)^{\otimes n-1} \leftrightarrow G_{\gamma_{n-1}}(s) = \frac{m^{m(n-1)}}{\bar{\gamma}^{m(n-1)}} \frac{1}{\left(s + \frac{m}{\bar{\gamma}}\right)^{m(n-1)}} \tag{26}$$

Then, by applying the inverse Laplace transformation, we can obtain

$$G_{\gamma_{n-1}}(s) \leftrightarrow g_{\gamma_{n-1}}(\gamma_{n-1}) = \frac{m^{m(n-1)}}{\bar{\gamma}^{m(n-1)} \Gamma(mn-m)} \times \gamma_{n-1}^{m(n-1)-1} e^{-\frac{m\gamma_{n-1}}{\bar{\gamma}}} \tag{27}$$

To simplify the writting, we let $\frac{m}{\bar{\gamma}} = a$, and then the capture probability can be written as

$$p_{cap}(n) = \frac{na^{mn}}{\Gamma(m)\Gamma(mn-m)} \int_0^\infty \gamma_t^{m-1} e^{-a\gamma_t} \times \left[\int_0^{\frac{\gamma_t}{z}} \gamma_{n-1}^{mn-m-1} e^{-a\gamma_{n-1}} d\gamma_{n-1} \right] d\gamma_t \tag{28}$$

According to [41], i.e., $\gamma(\alpha, x) = \sum_{k=0}^{\infty} \frac{(-1)^k x^{\alpha+k}}{k!(\alpha+k)}$, we can obtain

$$\begin{aligned} &\int_0^{\frac{\gamma_t}{z}} \gamma_{n-1}^{mn-m-1} e^{-a\gamma_{n-1}} d\gamma_{n-1} \\ &= \frac{1}{a^{mn-m}} \gamma\left(mn-m, \frac{a\gamma_t}{z}\right) \\ &= \frac{1}{a^{mn-m}} \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{a\gamma_t}{z}\right)^{mn-m+k}}{k!(mn-m+k)} \end{aligned} \tag{29}$$

After substituting (29) into (28), we can obtain

$$\begin{aligned} p_{cap}(n) &= \frac{na^m}{\Gamma(m)\Gamma(mn-m)} \int_0^\infty \gamma_t^{m-1} e^{-a\gamma_t} \\ &\quad \times \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{a\gamma_t}{z}\right)^{mn-m+k}}{k!(mn-m+k)} d\gamma_t \\ &= \frac{na^m}{\Gamma(m)\Gamma(mn-m)} \left[\frac{\Gamma(mn)}{(mn-m)a^m z^{mn-m}} \right. \\ &\quad - \frac{\Gamma(mn+1)}{(mn-m+1)a^m z^{mn-m+1}} \\ &\quad + \frac{\Gamma(mn+2)}{2!(mn-m+2)a^m z^{mn-m+2}} - \cdots \\ &\quad \left. + \frac{(-1)^k \Gamma(mn+k)}{k!(mn-m+k)a^m z^{mn-m+k}} - \cdots \right] \\ &= \frac{n}{\Gamma(m)\Gamma(mn-m)} \\ &\quad \times \sum_{k=0}^{\infty} \frac{(-1)^k \Gamma(mn+k)}{k!(mn-m+k) z^{mn-m+k}} \end{aligned} \tag{30}$$

Therefore, the probability of capture effect in Nakagami-m fading channel can be expressed as

$$p_{cap}(n) = \begin{cases} 0, & n = 0 \\ 1, & n = 1 \\ \dfrac{n}{\Gamma(m)\Gamma(mn-m)} \\ \quad \times \displaystyle\sum_{k=0}^{\infty} \frac{(-1)^k \Gamma(mn+k)}{k!(mn-m+k) z^{mn-m+k}}, & n \geqslant 2 \end{cases} \tag{31}$$

APPENDIX B

According to the analysis in Appendix A, the channel utilization can be expressed as

$$\begin{aligned} \eta &= \frac{v \cdot p_{suc}(u, v)}{v} \\ &= \sum_{j=1}^{u} p_{cap}(j) \frac{u!}{j!(u-j)!} \left(\frac{1}{v}\right)^j \left(1 - \frac{1}{v}\right)^{u-j} \end{aligned} \tag{32}$$

For simplicity, we only take a linear model into account, i.e., $L = \lambda u$ with $0 < \lambda \leqslant 1$. Since $\lim_{u \to +\infty} \frac{u-1}{u} = 1$ and $\lim_{u \to +\infty} \left(1 - \frac{1}{\lambda u}\right)^u = e^{-\frac{1}{\lambda}}$, (32) can approximatively be expressed as

$$\eta \approx \sum_{j=1}^{u} p_{cap}(j) \frac{\lambda^{-j}}{j!} e^{-\frac{1}{\lambda}} \tag{33}$$

Let (33) be the maximum, we can obtain

$$\lambda^* = arg \max_{0<\lambda\leqslant 1} \left[\sum_{j=1}^{u} p_{cap}(j) \frac{\lambda^{-j}}{j!} e^{-\frac{1}{\lambda}} \right] \tag{34}$$

Then, the optimal frame length can be given by

$$L_{opt} = [\lambda^* u] \tag{35}$$

where $[\cdot]$ is a function rounding to the nearest integer. That is, if the number of vehicles contending for slots in a frame is known, the optimal frame length can be determinate.In fact, the precise number of contending vehicles including unidentified vehicles in the RSU coverage and upcoming vehicles is hard to obtain. Fortunately, the number of unidentified vehicles in the RSU coverage can be estimated by (1) (or (2)) and (4) (or (5)), and the predicted number of upcoming vehicles can be obtained by (9).

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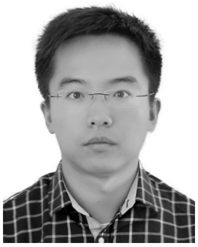

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