Future Generation Computer Systems 106 (2020) 55–66

Contents lists available at ScienceDirect

Future Generation Computer Systems

journal homepage: www.elsevier.com/locate/fgcs

VIMAC: Vehicular information medium access control protocol for high reliable and low latency transmissions for vehicular ad hoc networks in smart city ☆

Yuanxin Sun [a,*], Ruoxin Kuai [a], Sa Xiao [a], Wanbin Tang [a], Xiaoping Li [b]

[a] National key lab of communications science, University of electronic science and technology, Chengdu, China
[b] School of mathematical science, University of electronic science and technology, Chengdu, China

ARTICLE INFO

Article history:
Received 10 September 2019
Received in revised form 22 November 2019
Accepted 25 December 2019
Available online 2 January 2020

Keywords:
MAC
TDMA
VANET
Low latency
High reliable

ABSTRACT

The vehicular ad hoc network (VANET) is a promising solution for intelligent transport system in the future smart city. Time division multiple access (TDMA) based VANETs can enhance road safety level through providing safety related applications which pose stringent latency and reliable requirements. In this paper, we provide the mathematical expression to clarify the object of low latency and high reliable communications in TDMA-based VANETs. It can be seen from the object, the transmission collision problem is the biggest obstacle currently. Then, a novel MAC protocol is proposed to overcome the obstacle. The proposed scheme, which is called vehicular information medium access control (VIMAC) utilizes vehicular information, and involves the concepts of multi-hop relaying and temporal central nodes. We develop an analytical model to evaluate performances of the proposed scheme and the baseline protocols. The analytical model shows the advantages of our proposed scheme. At last, we use MATLAB and SUMO to construct a system level simulation platform, the simulation results are consistent with the analytical results.

1. Introduction

As the developing information technologies and increasing requirements, people will enter smart city era [1], where the internet of things [2] is widely deployed. The intelligent transport system, which is mainly implemented by vehicular ad hoc networks (VANETs), is one of the typical form of internet of things. VANETs are designed specifically for vehicular communications [3]. In the near future, with the help of VANETs, moving vehicles can exchange information to each other without causing security issues [4]. Therefore, safety related applications, that are able to boost road safety and prevent losing lives and possessions from crashes, can be realized through exchanging data. Besides, VANETs are capable to improve road throughput, energy efficiency and autonomous driving which are concerned by the smart city.

VANETs guarantee road safety through providing two categories of safety related applications, they are cooperative awareness messages (CAMs) and decentralized environment notifications (DENMs) [5]. The messages of the former service are broadcasted by each vehicle to inform its neighbors of its presence, position, kinematics and basic status. The vehicles broadcast DENMs to alert their neighbors when they encounter hazards. In other words, CAMs are generated periodically, whereas DENMs are triggered by emergency events. Due to the significance of road safety, the required performance of VANETs in terms of latency and reliable is stringent, e.g., the latency requirement is 100*ms* in [6]. The EU project METIS requires that more than 99.999% transmitted packets should be received correctly in 5 ms [7].

An efficient medium access control (MAC) protocol is the key to provide low latency and high reliable communications between vehicles for following reasons: (1) although we can utilize physical layer enhancement technologies (channel coding, diversity, equalization, power control [8] and etc.) to attain near-error-free point-to-point wireless transmissions, MAC layer collisions cannot be ignored. That is, more than two nodes in the network transmit signals simultaneously in the same physical channel, the receivers are not able to demodulate overlapped signals. (2) The transmission latency is solely impacted by the MAC layer protocol. As the development of very large scale integrated digital circuit, physical layer algorithms can be implemented with a negligible latency. On the other hand, if the MAC protocol is improper designed, nodes with data pending cost too much time on waiting for scheduling or contention for radio resources. One of

☆ Fully documented templates are available in the elsarticle package on CTAN.

* Corresponding author.
E-mail address: lakers32_0@163.com (Y. Sun).

https://doi.org/10.1016/j.future.2019.12.041
0167-739X/© 2019 Published by Elsevier B.V.

the most prevalent commercial standards for vehicular communications is IEEE 802.11p, which adopts contention-based backoff MAC scheme. In the scheme, each node that has data sending selects an integer from the contention window with equal probability [9]. Then, the node waits according to the selected integer and trigger to transmit after the waiting time expiring. Collisions happen when more than two nodes choose the same integer. Although the full-duplex mode enables transmitters to sense the channel when they are transmitting and able to detect collisions within one-hop range, it cannot mitigate the hidden terminal problem [10]. The hidden terminal problem occurs while two transmitters cannot hear each other due to the distance, and they transmit at the same time. They cannot detect the collision at their common neighbors through sensing the channel.

VANET MAC protocols present a very active field of academic research due to the significance of the VANET MAC protocol and the shortage of the IEEE 802.11p MAC protocol. There are various optimized VANET MAC schemes, including multiple channel MAC [11,12], enhanced contention-backoff scheme [13], and space division multiple access based protocols [14,15] and etc. Among the categories of MAC protocols, the time division multiple access (TDMA) based VANET MAC protocols are proven to achieve near-collision-free performance [16,17]. RR-ALOHA [18] is one of the classical TDMA based Ad Hoc protocols. In the protocol, time is divided into equal duration frames, each frame is divided into equal duration slots. The number of slots in each frame is invariant. Each node occupies a slot within a frame, channel negotiations are not required before transmissions. Furthermore, ADHOC MAC [19] solves hidden terminal problem through forbidding nodes within two hop range to occupy the same slot. Vehicular mobility is one of the features of VANETs [20], which introduces merge collision problem to ADHOC MAC [21]. That is, two nodes occupy the same slot that are out of each other's two hop range. They became two-hop reachable due to the mobility, and their common neighbors cannot hear them due to the collision. Consequently, both of the nodes drop the current slot and select an idle slot (not occupied by any of the two hop neighbors) randomly. We say it is an access collision if more than one nodes choose the same idle slot while they are reserving slots.

As mentioned above, merge collisions and access collisions are reliable issues of TDMA-based VANET MAC protocols. Although there are various modified TDMA-based MAC protocols have been proposed in the recent decade, the collision probability is not satisfactory. Many authors do not concern reducing the collision probability, such as the authors in [22] consider adapting the changing road density through adjustable frame length. Some of the approaches are able to solve merge collision solely, there are not able to alleviate the access collision problem, such as [23] dividing slots in a frame into disjoint sets according to the moving directions of the vehicles. Merge collisions between two vehicles which move in the same direction have been mitigated. The similar idea can be found in [24]. The predictive TDMA MAC (PTMAC) [25] cannot reduce the number of access collisions. Besides, there exists a portion of the studies base on the impractical assumptions, such as in [26], all of the competitors are assume to know other competitors' waiting counters. Therefore, the quality of service of safety application is still unsatisfying, there exists a great potential of improving the performance.

Motivated by the crucial task, in this paper, we propose a high reliable and low latency MAC protocol for TDMA-based VANET, called vehicular information MAC (VIMAC). It is a practical, and can alleviate merge collision and access collision problems simultaneously. The proposed scheme utilizes the upper layer vehicular information, and allows a part of vehicles becoming temporal central nodes in order to allocate slots rather than allows the nodes content for slots autonomously. Our main contribution of the paper can be summarized as follows:

- We propose a vehicular information MAC (VIMAC) protocol that utilize vehicular information (e.g., velocities, positions and headings) to achieve low latency and high reliable inter-vehicle communications. VIMAC can be divided into two processes: prediction and allocation that used to mitigate merge collisions and reduce access collisions respectively.
- We analyze the relationship between reliable and latency of packet transmission in TDMA-based VANET. As analyzed, lower merge and access collision probabilities leads to lower mean latency. The analysis shows that merge and access collisions are critical issues to guarantee low latency and high reliable transmissions.
- We propose two Markov-based analytical models that can be used to evaluate reliable issues for TDMA-based VANETs. One of the Markov models is used to represent the number of vehicles in a two hop set. The other one depicts the state transition for a single vehicle. Furthermore, we use the models to compare the performance of our proposed protocol with the two baseline protocols. It proves that the VIMAC outperforms the two baseline protocols in a theoretical manner. Besides, simulation results demonstrates the same trend as analyzed theoretically.

The rest of the paper is organized as follows: Section 2 provides the general system model for TDMA-based VANET MAC. The proposed scheme is described in Section 3. Section 4 analyzes the relationship between reliable and latency, and presents the analytical model. In Section 5, the simulation parameters, results and discussions are given. We conclude the whole paper in Section 6.

2. System model

In this section we give the scenario and basic framework of TDMA-based VANET MACs.

2.1. Scenario

In this paper, we consider a general scenario that a number of vehicles driving in two opposite directions of a road. The scenario exists in highway, urban and suburb. There are several (e.g., two or three) lanes in each direction. The velocities of vehicles are randomly selected and keep on changing during the driving time. The mean relative velocity between any two vehicles in the same direction is much smaller compared with the mean relative velocity between two vehicles in the opposite directions. Vehicular information (e.g., position, velocity and heading) and the timing can be obtained through the global position system receiver. Therefore, all of the nodes in the network can achieve time synchronization, the have the common sense about the starting points of frames. Each vehicle is equipped with an on board unit (OBU) that can be used for transmit and receive radio signals. Each OBU has an unique identification. Any pair of vehicles can hear each other with negligible physical layer errors if the relative distance is smaller than R and no collisions.

2.2. TDMA-based MAC

In this subsection, we briefly review the basic principle of TDMA-based MAC. In the TDMA-based MAC, time is divided into frames with equal durations. Each frame contains a number of slots, the durations of slots are equal. All of the frames have the same number of slots. Each vehicular node reserves a slot in a frame autonomously, the mechanism guarantees each node access the channel periodically. Each pair of nodes can use the same slot if both of the nodes are out of each other's two hop range. The slot reservation provides high efficiency without incurring hidden terminal problem since they do not have common neighbor.

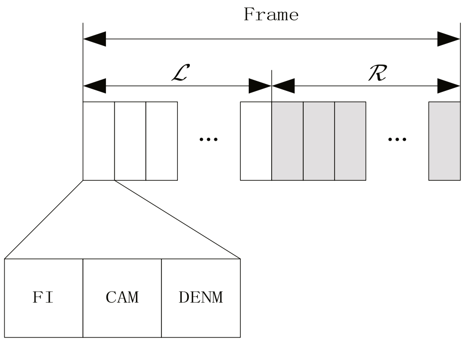


Fig. 1. General frame structure of TDMA-based VANET.

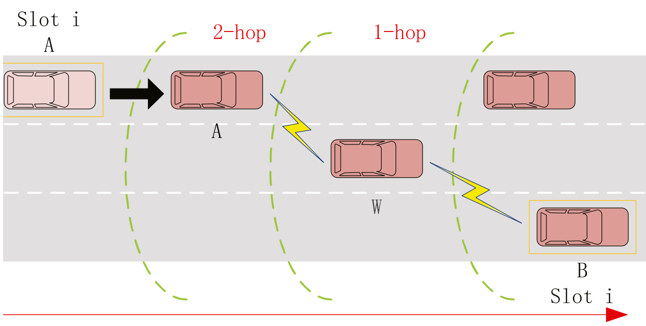


Fig. 2. A merge collision.

The frame structure of the TDMA based MAC can be given by Fig. 1. There are two disjoint sets of slots within the frame, denoted by the sets $\mathcal{L}$ and $\mathcal{R}$. First half of the slots within a frame are included in the set $\mathcal{L}$ whereas the rest of the slots belong in the set $\mathcal{R}$. Each vehicle senses the channel all the time, it would change its slot to new one that belongs to the other set if it has realized the fact that more than half of its one hop neighbors that drive in the same direction occupy slots in the other set. The mechanism guarantees that slots in the same set are occupied by the vehicles that drive in the same direction.

There are three fields in a slot: frame information (FI), CAM and DENM [6]. FI is presented as a vector, where the elements are nonnegative integers. The length of the vector equals to the number of slots within a frame. The identifications of OBUs are positive integers, thus, if the ith element in the vector is positive, it reflects the identification of the vehicle that occupy the ith slot. Otherwise, there are no one-hop neighbor occupy the slot if the corresponding element is zero. It is worth to note that the jth element should be the identification of the transmitter that occupies the current slot if the current slot number is j. Vehicular information (position, velocity and heading) of the transmitter is included in the CAM field, the interval of two adjacent CAM equals to a frame duration in the collision-free case. The DENM field carries event-driven emergency messages which is not occurs frequently. Therefore, most of the time, the DENM field is empty.

Each node keeps occupying the same slot after reserving a slot corresponding to its direction. It drops its occupied slot and find another idle slot to reserve if and only if the node encounter a collision. There are two types of collisions in TDMA-based VANETs: merge collision and access collision. A merge collision can be depicted in Fig. 2. Initially, the nodes A and B which occupy the same slot, are out of each other's two hop range, they become two hop reachable due to the mobility. Both of the nodes broadcast simultaneously, the common neighbor W receives the signals. This is called a merge collision. After encountering the merge collision, the nodes A and B drop their slots and select an idle slot to reserve. There may be other neighbor nodes that lost their slot due to previous merge collisions, we call the nodes which do not occupy slots competitors. Thus, it can be viewed as A and B contend slots with other competitors. It is an access collision if more than one node choose the same idle slot to reserve.

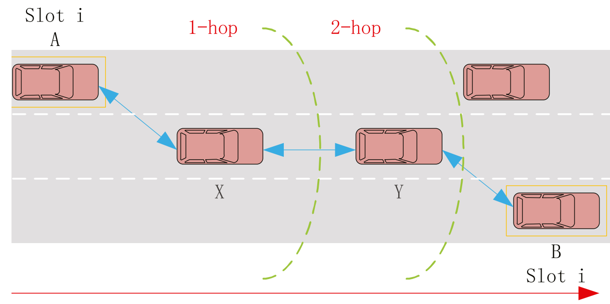


Fig. 3. An example of prediction process.

3. Proposed scheme

As aforementioned, our proposed scheme contains two processes: prediction and allocation, which are used for solving merge collision and access collision problems, respectively.

The prediction process can be depicted by Fig. 3, vehicular nodes A, B, X and Y are moving in the same direction. X and Y locate between A and B. We use t_A and t_B to denote the slots which are occupied by A and B respectively. Similarly, X and Y occupy slots t_X and t_Y in each frame, respectively. In the specific condition, t_A equals to t_B. Initially, the node A and B are out of each other's two hop range. We do not need to predict the potential merge collision in the moment. Then, A and B becomes each other's two hop reachable. The change of the distance between A and B can be depicted as $(d(A,B) > 2R) \rightarrow (d(A,B) = 2R) \rightarrow (d(A,B) < 2R)$. The prediction process is activated when the distance between A and B equals to $2R$. There are two intermediate vehicles X and Y that can mitigate the potential merge collision. An example of the process can be described as follows:

- The nodes A and B broadcast in slot i simultaneously without collision due to there are no common neighbor.
- The nodes X and Y update their one hop neighbor information according to the received packets from A and B respectively. Besides, X stores vehicular information of A and Y stores vehicular information of B.
- The node X broadcasts in its occupied slot and the node Y receives the packet.
- The node Y finds that the FI from node X is not coincidence with one hop neighbor information of Y. In other words, the FI of X indicates the ith slot is occupied by A; however, according to one hop neighbor information of Y, B occupies the slot. It implies that there probably exists a potential merge collision between A and B.
- The node Y include the stored vehicular information B in the packet that to be send in the next time. Since the hazards do not occur frequently, the DENM is idle in most of the time. Thus, the DENM field carries the vehicular information of B.
- The node Y broadcasts in its slot, X receives the packet and obtain the vehicular information of B. The current position of B contains the longitude x_B and the latitude y_B. The heading of B is denoted as θ_B, and the velocity of B is v_B. The node X has stored vehicular information of A, i.e., the longitude x_A, the latitude y_A, the heading θ_A and the velocity v_A. Here, we

use T_f to denote the duration of a frame. Then, the position of A in the next frame can be predicted as

$$\begin{cases} x\prime_A = x_A + v_A T_f \cos\theta_A, \\ y\prime_A = y_A + v_A T_f \sin\theta_A, \end{cases} \tag{1}$$

where $x\prime_A$ and $y\prime_A$ are the predicted longitude and latitude of A, respectively. It is worth noting that we made an assumption that the change of the velocity can be ignored in a short duration, such as a frame duration in TDMA VANET, typically, the duration of a frame is 100 ms. Here we set the initial velocity of the node B is v_0, the time variant acceleration is $\alpha(t)$, after experiencing a time duration t_0, the velocity is

$$v(t_0) = v_0 + \int_0^{t_0} \alpha(\tau)d\tau. \tag{2}$$

Considering the case $t_0 \to 0$, we have

$$\lim_{t_0\to 0} v(t_0) = v_0 + \lim_{t_0\to 0}\int_0^{t_0} \alpha(\tau)d\tau = v_0. \tag{3}$$

Therefore, it can be viewed that the velocity keeps constant in a frame duration.

Similarly, predicted position of B, i.e., the longitude $x\prime_B$ and the latitude $y\prime_B$, which are given by

$$\begin{cases} x\prime_B = x_B + v_B T_f \cos\theta_B, \\ y\prime_B = y_B + v_B T_f \sin\theta_B. \end{cases} \tag{4}$$

Now, the node X predicts the potential merge collision based on the following inequality

$$\sqrt{(x\prime_A - x\prime_B)^2 + (y\prime_A - y\prime_B)^2} < 2R. \tag{5}$$

There exists a merge collision if the inequality holds. Otherwise, we can ignore it. In the current example, the inequality holds.

- The node X broadcasts, in the DENM field of the packet, there is a notification message that tells A there is an upcoming merge collision.
- The node A drops the occupied slot and select another idle slot to reserve. A merge collision has been avoided.

In the above example, the node Y is responsible for finding potential conflicts and the node X is responsible for informing slot change. The responses of the nodes A and B depends on the relationship between the slots t_X and t_Y. To be specific, the node Y is responsible for finding potential conflicts since $t_X < t_Y$.

- **Becoming the node** A
  In the above example, A dropped its slot and chose another idle slot to reserve. Essentially, A become a competitor to compete with other nodes that lost their slots. The node A is possible to encounter access collisions after the prediction process. Therefore, we say that A encountered a merge collision. It can be observed that A drops its slot due to the node X broadcasts earlier than Y.
- **Absence of intermediate nodes**
  The merge collision is possible to be avoided only if there exists two intermediate nodes, i.e., X and Y. Two conditions should be satisfied if there are two intermediate nodes: (1) There are more than two nodes between A and B; (2) The locations of nodes between A and B are proper. $d(A, B)$ is defined as the distance between the nodes A and B. Here we consider the case which there are two nodes (X and Y) between A and B. The nodes X and Y become intermediate nodes only if the following inequality holds:

$$\begin{cases} d(A, X) < R, \\ d(X, Y) < R, \\ d(B, Y) < R. \end{cases} \tag{6}$$

In the rest of this section, we provide the other process in VIMAC to reduce access collisions in the case of no proper intermediate nodes.

3.1. Allocation process

The allocation process is available in the scenario that is illustrated in Fig. 2. Initially, A and B are out of each other's two hop range and occupy the same slot within a frame. The node W is a one hop neighbor of B. Then, A drives into the two hop range of B and they encounter unpredictable merge collision due to the absence of intermediate nodes. In the slot i, A and B broadcast simultaneously. Although W cannot demodulate the overlapped signals from A and B, it recognizes that there exists merge collision through energy detection.

Here we describe the energy detection process. Let us begin to interpret the energy detection with the basic model for communication signals. In the allocation example, let us assume the signals transmitted by A and B in the slot t_A (note that $t_A = t_B$) are $s_A(t)$ and $s_B(t)$ respectively. It is obvious that they are random processes. The time duration of one slot is denoted by T_{slot}, and the starting time of the slot t_A is t_A^s. Then, $s_A(t)$ and $s_B(t)$ are possible to get non-zero values if and only if $t_A^s < t < t_A^s + T_{slot}$. The instantaneous power of $s_A(t)$ can be represented by the variance of $s_A(t)$, var$[s_A(t)]$, similarly, the instantaneous power of $s_B(t)$ is var$[s_B(t)]$. The channel fading coefficient from the node A to W is denoted by h_A, whereas the coefficient from the node B to W is denoted by h_B. If a slot with the time duration $[t_I^s, t_I^s + T_{slot}]$, is not occupied by any one hop neighbor of W, then W receives nothing but noise in the slot. The signal can be given by

$$r_0(t) = n(t), t_I^s < t < t_I^s + T_{slot}. \tag{7}$$

where $n(t)$ is the white Gaussian noise, the mean is zero and the variance is σ^2. We can calculate the energy of the signal which is received by W in the slot

$$P_0 = \int_{t_A^s}^{t_A^s+T_{slot}} \mathrm{var}(h_A s_A(t) + h_B s_B(t) + n(t))dt. \tag{8}$$

Using the fact that $s_A(t)$, $s_B(t)$ and $n(t)$ independent to each others, and there is no direct current components in the signals, we have

$$\begin{aligned} &\mathrm{var}(h_A s_A(t) + h_B s_B(t) + n(t)) \\ &= \mathrm{var}(h_A s_A(t)) + \mathrm{var}(h_B s_B(t)) + \sigma^2, \end{aligned} \tag{9}$$

substituting (9) into (8), yielding

$$\begin{aligned} P_1 &= T_{slot}\mathrm{var}(h_A s_A(t)) + T_{slot}\mathrm{var}(h_B s_B(t)) + T_{slot}\sigma^2 \\ &= T_{slot}\mathrm{var}(h_A s_A(t)) + T_{slot}\mathrm{var}(h_B s_B(t)) + P_0. \end{aligned} \tag{10}$$

It is obviously that $P_1 > P_0$. We just need to set an energy threshold $\frac{P_0+P_1}{2}$, we say there is a transmission collision if the energy of the current slot exceeds the threshold and the received signal cannot be demodulated successfully. Otherwise, the slot is idle if the energy is less than the threshold and the signal cannot be demodulated successfully.

In the slot t_A of the last frame, W stored the vehicular information from B, i.e., longitude x_B, latitude y_B, heading θ_B and velocity v_B. The current vehicular information of the node W, i.e., $(x\prime_W, y\prime_W, \theta\prime_W, v\prime_W)$, can be obtained from the global positioning system receiver that is equipped on W. Based on vehicular information of B and W, the node W can check whether B is still in the one hop range of W through the following conditions:

$$\begin{cases} \sqrt{(x\prime_W - x\prime_B)^2 + (y\prime_W - y\prime_B)^2} < R, \\ x\prime_B = x_B + T_f v_B \cos\theta_B, \\ y\prime_B = y_B + T_f v_B \sin\theta_B. \end{cases} \tag{11}$$

The node B is still the one hop neighbor if the above inequality holds. In this case, W sets the ith element of its FI as the negative value of B's identification. For example, the identification of B is 6, W sets the t_Ath element as -6 and broadcasts the FI with other fields of the packet in the occupied slot in the next frame. Upon receiving the FI from W, both of A and B detect merge collision and the ith slot is allocated to B.

In the above process, the nodes A and B encountered inevitable merge collision. The node B experienced zero times of access collisions with the help of its old neighbor W. Although A have to be a competitor, access collision probability can be reduced since the number of competitors is reduced by one.

In the considered scenario, there is only one common neighbor of A and B. In the rest of this section, we extend the scenario into more complex conditions. At the first step, we consider a scenario that there are multiple common neighbors, we denote them as W_i, $1 \leq i \leq I$, all of them are old neighbors of B. In the considered condition, the number of old neighbors of B is I. After A and B broadcasting at the same slot, all of the common neighbors set the ith element in their FIs as negative value of B's identification and plan to broadcast at the next time. Here, we assume that the node W_j is the first node among the common neighbors to broadcast its FI. In this circumstance, A drops its slot and selects an idle slot to reserve once A receives the FI from W_j, the node B is notified of keep the previous slot. Other FIs from the rest of common neighbors are ignored by A and B. We can see that the allocation process can work well in extended scenario.

At the second step, we consider a more practical scenario. The common neighbors of A and B can be divided into three sets $\mathcal{W} = \{W_i\}_{i=1}^{I}$, $\mathcal{U} = \{U_j\}_{j=1}^{J}$ and $\mathcal{V} = \{V_k\}_{k=1}^{K}$. The vehicles in the set $\mathcal{W}$ and $\mathcal{U}$ are the old neighbors of B and A respectively, the vehicles in the set $\mathcal{V}$ are neither old neighbors of A nor old neighbors of B. Vehicles in the set $\mathcal{W}$ plan to allocation the ith slot to B through setting the ith element to negative value of the identification of node B. On the other hand, vehicles in the set $\mathcal{U}$ allocate the ith slot to A, the actions of vehicles in the set $\mathcal{V}$ are reporting the collision rather than allocation. The FIs from vehicles in $\mathcal{V}$ will be ignored by A and B, the two nodes only pay attention to the FIs from vehicles in the set $\mathcal{W}$ and $\mathcal{U}$. The node A drops the occupied slot if W_j is the first node among vehicles in the sets $\mathcal{W}$ and $\mathcal{U}$. Otherwise, the node B insists and A quits. When merge collision happens, we can find a node similar to A and B in the analyzed scenario, and common neighbors belong to one of the sets (i.e., $\mathcal{W}$, $\mathcal{U}$ and $\mathcal{V}$). The above analysis cover all of the conditions in TDMA-based VANETs, the allocation process is possible to reduce access collisions.

4. Performance analysis

In this section, we propose an analytical model to evaluate the performances of TDMA-based VANETs. Firstly, we tag a packet, analyze the behavior of the tagged packet in order to find the way to obtain the analytical results of the latency performance. Once the tagged packet is generated, it enters to the queue and waiting for the former packets being served. The tagged packet becomes the head of line of the queue if all of the former packets have departed, and then, it is served to be transmitted. Therefore, it can be observed that there are two latency components which constitute the total latency, i.e., queueing latency and service latency. The queueing latency is defined as the time interval between the tagged packet entering the queue and becoming the head of line, whereas the service latency is the time interval between the tagged packet becoming the head of line and being transmitted successfully.

As analyzed in [27], the latency performances for CAMs and DENMs depend on the service latency components. Mean service latencies equal to frame length if we ignore merge collisions and access collisions. Indeed, it is infeasible to design a MAC protocol that can get rid of collisions. The vehicles have to retransmit the packets after collisions.

Let us tag a packet to analyze the service latency in the best case. Firstly, there exists other packets in the queue when the tagged packet enters the queue, therefore, the tagged packet has to wait for the other packets be transmitted. Then, we assume that the former packet is transmitted in the slot $t_A^{(1)}$, that is, the tagged packet becomes head of line in the following slot, i.e., $t_A^{(1)} + 1$. We use t_{HOL} to denote the slot where the tagged packet becomes head of line, thus, we have $t_{HOL} = t_A^{(1)} + 1$. The tagged packet is transmitted successfully in the next frame, i.e., in slot $t_A^{(1)} + M$, since there are M slots in a frame. According to the definition of the service latency, it is the interval between the packet becoming head of line and the departure of the packet. Hence,

$$T_s = (t_A^{(1)} + M) - (t_A^{(1)} + 1) + 1 = M. \tag{12}$$

It can be observed in the above equation, in the best case, the service latency is M (slots) if the tagged packet is fortunate enough and does not encounter any collision.

Given the tagged packet transmitted successfully after k collisions (1 merge collision and $k-1$ access collisions) the service latency is $(k+1)M$ slots, where M is the frame length. Here, we use T_s to denote the service latency. Merge collision probability and access collision probability are represented by p_m and p_a, respectively. The probability of service latency equaling to $(k+1)M$ can be given by

$$P(T_s = (k+1)M) = \begin{cases} 1 - p_m, & k = 0, \\ p_m(1 - p_a), & k = 1 \\ p_m p_a^{k-1}(1 - p_a), & k > 1 \end{cases} \tag{13}$$

Thus, we can obtain the mean service latency

$$\begin{aligned} \overline{T}_s &= \sum_{k=0}^{+\infty}(k+1)MP(T_s = (k+1)M) \\ &= M(1 - p_m) + 2Mp_m(1 - p_a) + Mp_m(1 - p_a)\sum_{k=2}^{+\infty} kp_a^{k-1} \end{aligned} \tag{14}$$

where

$$kp_a^{k-1} = \frac{1}{dp_a}p_a^k. \tag{15}$$

Therefore, we have

$$\sum_{k=2}^{+\infty} kp_a^{k-1} = \frac{1}{dp_a}\sum_{k=2}^{+\infty} p_a^k = \frac{1}{dp_a}\frac{p_a^2}{1 - p_a} = \frac{2p_a - p_a^2}{(1 - p_a)^2} \tag{16}$$

Substituting (16) into (14), we have

$$\begin{aligned} \overline{T}_s &= M(1 - p_m) + 2Mp_m(1 - p_a) + \\ &\quad Mp_m(1 - p_a)\frac{2p_a - p_a^2}{(1 - p_a)^2}. \end{aligned} \tag{17}$$

Fig. 4 provides the relationship between mean service latency and collision probabilities. It is obviously that mean service latency increases as both of the collision probabilities. Merge collision and access collision probabilities are critical issues to be optimized in order to guarantee low latency and high reliable transmissions for TDMA-based VANETs. In the following subsections, we analyze the collision probabilities to verify the advantages of the proposed scheme.

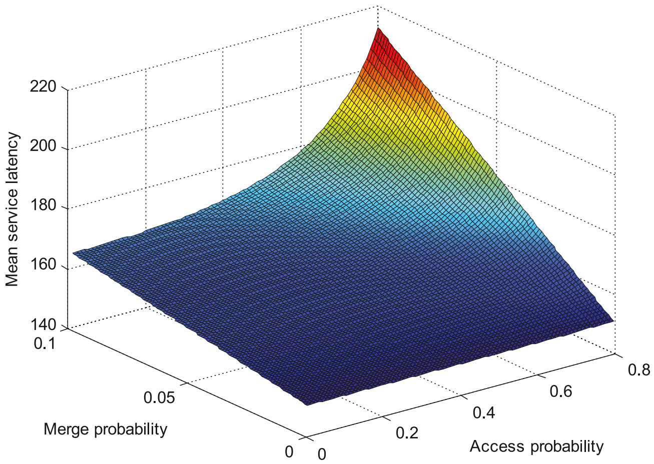


Fig. 4. Mean service latency as a function of merge collision and access collision probabilities.

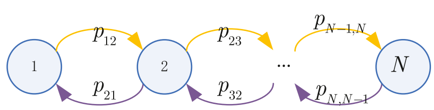


Fig. 5. 1D-CTMC to describe the behavior of vehicles in tagged two hop set.

4.1. Merge collision probability

In this subsection, we provide the analysis of the merge collision probabilities for the proposed VIMAC protocol and baseline protocols. VeMAC and PTMAC are considered as the baseline schemes since VeMAC is one of the most typical TDMA-based VANET MACs and PTMAC is the only one TDMA-based MAC that utilizes vehicular information. Analyzing the merge collision of our proposed scheme is a difficult task, however, we can find the mathematical expression of the merge collision probability VeMAC and get the merge collision probability of the proposed VIMAC through the relationship between the merge collision probability of VeMAC and that of VIMAC. In order to get the mathematical expression for the merge collision probability of VeMAC, we develop a one dimensional continuous time Markov chain (1D-CTMC) analytical model.

4.1.1. 1D-CTMC analytical model

The considered scenario contains a number of vehicles moving on the road. We tag vehicular node, named A, to analyze merge collision probability. The priorities of vehicles in the network are equally, that is, there does not exist a vehicle whose priority is higher than that of others. Therefore, we only need to analyze merge collision probability of the node A. The result is also available for all of the vehicles in the network.

In order to avoid hidden terminal, the vehicles within a two hop range are not allowed to occupy the same slot. The communication range is R, we define the two hop ranges of A as a circle with the radius of $2R$, the center of the circle is the node A. All of the vehicles within the circle constitute the two hop set of the node A. We call it as tagged two hop set. Vehicles enter tagged two hop range and depart tagged two hop range all the time. A slot is a sufficient short time duration, typically $1ms$ or even shorter. Therefore, the number of vehicles in tagged two hop set is a random process and can be modeled as a one dimensional continuous Markov chain (1D-CTMC). We use $p_{i,j}$, $1 \leq i, j \leq N$ to denote one-step transfer probability, which means the probability of the number of vehicles changing from i to j in the slot, where N is the allowable maximum number of vehicles in a two hop set. In practical, spaces of two hop sets are limited, the number of vehicles in each two hop set cannot be infinitely. In 1D-CTMC models, the transfer probabilities $p_{i,j}$ where $|i-j| > 1$ can be approximate to zero. Therefore, the 1D-CTMC can be sketched as Fig. 5. We define $p_{i,i+1}$, $1 \leq i \leq N-1$ as the arrival rate λ.

4.1.2. Merge collision probability for VeMAC

It is difficult to analyze the merge collision probability of our proposed scheme directly. However, we can get the mathematical expression of the merge collision probability of VeMAC, then, we can evaluate our proposed scheme through the relationship between the merge collision probability of VeMAC and that of our proposed scheme. Besides, as one of the most classical TDMA-based VANET MAC, VeMAC is considered as one of the baseline schemes in this paper. Analyzing the merge collision probability of VeMAC is useful for comparing the proposed VIMAC protocol and VeMAC.

The event of the node A encountering a merge collision is denoted by F_m, and the event F_B is defined as there is only one new comer (the node B) of the tagged two hop set. In the two hop set of B, there are n_o^B occupied slots. Given the event F_B occurring and the number of occupied slots being n_o^B, the conditional probability of the event F_m is $\mathbb{P}(F_m|F_B, n_o^B)$.

Let us consider the node B, it is one of the nodes which occupy slots in the tagged two hop set. Therefore, it selects one of the slots among the n_o^B occupied slots to reserve. It is worth noting that, the tagged two hop set and the two hop set of B are not the same, since the center of the tagged two hop set is A whereas the center of the two hop set of B is not the node A. The two hop sets have different elements although there are some common two hop neighbors of A and B. The slot that is occupied by B is randomly chosen from the n_o^B slots. We denote the slots that are occupied by A and B as t_A and t_B respectively. A merge collision occurs if and only if t_A equals to t_B. The first condition which is to be satisfied is the n_o^B occupied slots covering t_A. We denote the event as F_c. Before analyzing $\mathbb{P}(F_m|F_B, n_o^B)$, we have to obtain $\mathbb{P}(F_c|F_B, n_o^B)$, which is defined as the conditional probability of event F_c by given the event F_B occurring and n_o^B occupied slots in the two hop set of the node B. The conditional probability $\mathbb{P}(F_c|F_B, n_o^B)$ can be viewed as throwing n_o^B balls into M empty boxes, each box is allowed to have zero ball or one ball in the trial. There are $A_{n_o^B}^M$ different ways, where $A_n^M = \frac{M!}{(M-n)!}$. If the box which corresponds to t_A is not empty, we have A_n^{M-1} different ways. Thus, the conditional probability is

$$\mathbb{P}(F_c|F_B, n_o^B) = 1 - \frac{A_{n_o^B}^{M-1}}{A_{n_o^B}^M} = \frac{n_o^B}{M}. \tag{18}$$

In the case that n_o^B slots cover slot t_A, node B selects a slot among n_o^B slots randomly. Hence,

$$\mathbb{P}(F_m|F_B, F_c, n_o^B) = \frac{1}{n_o^B}. \tag{19}$$

Use the fact that $F_c \in F_m$, yielding,

$$\mathbb{P}(F_m|F_B, n_o^B) = \mathbb{P}(F_m, F_c|F_B, n_o^B)$$
$$= \mathbb{P}(F_m|F_B, F_c, n_o^B)\mathbb{P}(F_c|F_B, n_o^B) = \frac{1}{M}. \tag{20}$$

The above result is independent to n_o^B, hence, the above equation can be rewritten as

$$\mathbb{P}(F_m|F_B, n_o^B) = \mathbb{P}(F_m|F_B) = \frac{1}{M}. \tag{21}$$

The conditional probability $\mathbb{P}(F_m|F_B)$ can be viewed as given that there is only one new comer (the node B) in one frame, the probability of the node A encountering a merge collision. Here, we use a random variable k_n to denote the number of new comers during a frame, the probability is

$$\mathbb{P}(k_n) = C_{k_n}^{M}\lambda^{k_n}(1-\lambda)^{M-k_n}, 0 \le k_n \le M, \tag{22}$$

where $C_n^m = \frac{A_n^m}{n!}$. The conditional probability of the event F_m by given $k_n = 1$ (i.e., $\mathbb{P}(F_m|k_n = 1)$) can be also expressed as (21). We denote $\overline{F_m}$ as the complementary event of F_m, that is, the event of tagged vehicle encountering no merge collision in a frame. Then, we have the conditional probability of tagged vehicle encountering a merge collision by given k_n new comers,

$$\mathbb{P}(F_m|k_n) = 1 - \mathbb{P}(\overline{F_m}|k_n) = 1 - \left(1 - \frac{1}{M}\right). \tag{23}$$

From (22) and (23), we can obtain merge collision probability of VeMAC

$$p_m^V = \mathbb{P}(F_m) = \sum_{k_n=0}^{M} \mathbb{P}(k_n)\mathbb{P}(F_m|k_n)$$
$$= \sum_{k_n=0}^{M} C_{k_n}^{M}\lambda^{k_n}(1-\lambda)^{M-k_n}\left(1 - \left(1 - \frac{1}{M}\right)^{k_n}\right), \tag{24}$$

4.1.3. Merge collision probability of VIMAC

Our proposed scheme can reduce the number of merge collisions through utilizing vehicular information (e.g., positions, headings and velocities). However, considering Fig. 3, there are a portion of merge collisions cannot be eliminated for following two reasons: (1) becoming the node A, and (2) absence of intermediate nodes. We denote the ratio of unavoidable merge collisions and all of the merge collisions as β. We use p_m^I and p_m^V to denote the probabilities of VIMAC and VeMAC respectively, Then, we have

$$p_m^I = (1-\beta)p_m^V. \tag{25}$$

To obtain β, we define the following events:

- F_I: There are intermediate nodes between A.
- F_D: Tagged node becomes the node A and drops occupied slot.

An unavoidable merge collision happens if intermediate nodes do not exist, or intermediate nodes present, but tagged node becomes the node A. Thus,

$$\beta = (1 - \mathbb{P}(F_I)) + \mathbb{P}(F_I, F_D)$$
$$= 1 - \mathbb{P}(F_I) + \mathbb{P}(F_I)\mathbb{P}(F_D|F_I), \tag{26}$$

where it is obviously that $\mathbb{P}(F_D|F_I) = \frac{1}{2}$, the above equation can be rewritten as

$$\beta = 1 - \frac{\mathbb{P}(F_I)}{2}. \tag{27}$$

Here, we try to obtain the probability of the event F_I. Let us consider the scenario that is depicted in Fig. 3. The prediction of potential merge collision occurs if and only if the distance between A and B equals to $2R$. For the case of $d(A, B) > 2R$, A and B are out of each other two hop range, they are allowed to reserve the same slot without introducing merge collisions, it is unnecessary to predict merge collisions when $d(A, B) > 2R$. Considering the case $d(A, B) < 2R$, the prediction or the merge collision has happened already, it is too late to predict potential merge collision in the situation. Therefore, we only need to consider the special situation, $d(A, B) = 2R$, when we analyze the absence of intermediate nodes. We can simplify the problem as the form that there is a line segment with the length of $2R$. There are two nodes, X and Y that are randomly placed in the line segment, the locations of X and Y are independent. We use L to denote the distance between a node (i.e., X or Y) and A, we have the probability

$$\mathbb{P}(L < l) = F_L(l), \tag{28}$$

and probability density function

$$f_L(l) = \frac{\partial}{\partial l}F_L(l). \tag{29}$$

If X and Y form the intermediate nodes, we have to consider two cases. The first case is

$$\begin{cases} d(A, X) < R, \\ d(X, Y) < R, \\ d(B, Y) < R, \end{cases} \tag{30}$$

and the second case is

$$\begin{cases} d(A, Y) < R, \\ d(X, Y) < R, \\ d(B, X) < R. \end{cases} \tag{31}$$

The nodes X and Y become intermediate nodes only if the positions of the two nodes are proper, we have

$$\mathbb{P}(F_I) = \mathbb{P}(d(A, X) < R, d(X, Y) < R, d(B, Y) < R) +$$
$$\mathbb{P}(d(A, Y) < R, d(X, Y) < R, d(B, X) < R)$$
$$= \mathbb{P}(F_I^{(1)}) + \mathbb{P}(F_I^{(2)}), \tag{32}$$

where events $F_I^{(1)}$ and $F_I^{(2)}$ represents the events that satisfy the conditions in (30) and (31) respectively. The probabilities of the two events can be written as

$$\mathbb{P}(F_I^{(1)}) = \mathbb{P}(d(A, X) < R, d(X, Y) < R, d(B, Y) < R), \tag{33}$$

and

$$\mathbb{P}(F_I^{(2)}) = \mathbb{P}(d(A, Y) < R, d(X, Y) < R, d(B, X) < R). \tag{34}$$

Let us consider (33) firstly, noting that

$$\mathbb{P}(d(A, X) < R) = F_L(R). \tag{35}$$

Similarly, the probability of $d(B, Y) < R$ is

$$\mathbb{P}(d(B, Y) < R) = \mathbb{P}(d(B, X) < R)$$
$$= 1 - \mathbb{P}(d(B, X) < R) = 1 - F_L(R). \tag{36}$$

As mentioned above, the locations of the nodes X and Y are independent to each other. The joint probability of the event $\{d(A, X) < R, d(B, Y) < R\}$ can be given by

$$\mathbb{P}(d(A, X) < R, d(B, Y) < R)$$
$$= \mathbb{P}(d(A, X) < R)\mathbb{P}(d(B, Y) < R)$$
$$= F_L(R)(1 - F_L(R)). \tag{37}$$

It is obvious that $d(X, Y) < R$ is not independent of events $d(A, X) < R$ and $d(B, Y) < R$. Therefore, we have to consider the conditional probability of $d(X, Y) < R$ given $d(A, X) < R$ and $d(B, Y) < R$, i.e., $\mathbb{P}(d(X, Y) < R|d(A, X) < R, d(B, Y) < R)$. Firstly, we have

$$\mathbb{P}(d(A, X) < l_1|d(A, X) < R)$$
$$= \frac{\mathbb{P}(d(A, X) < l_1, d(A, X) < R)}{\mathbb{P}(d(A, X) < R)}$$
$$= \begin{cases} \frac{F_L(l_1)}{F_L(R)}, & 0 < l_1 < R \\ 1, & l_1 > R \\ 0, & \text{otherwise.} \end{cases} \tag{38}$$

It is known that the cumulative density function can be given by

$$F_X(x) = \mathbb{P}(X < x), \tag{39}$$

and its corresponding probability density function $f_X(x)$ can be written as

$$f_X(x) = \frac{\partial}{\partial x}F_X(x) = \frac{\partial}{\partial x}\mathbb{P}(X < x). \tag{40}$$

Here, we substituting X and x to $d(A, X)$ and l_1 respectively, we can get

$$f_{d(A,X)}(l_1) = \frac{\partial}{\partial l_1}F_{d(A,X)}(l_1) = \frac{\partial}{\partial l_1}\mathbb{P}(d(A, X) < l_1). \tag{41}$$

Adding the condition $d(A, X) < R$, we can write the conditional probability density function

$$\begin{aligned} &f_{(d(A,X)|d(A,X)<R)}(l_1) \\ &= \frac{\partial}{\partial l_1}\mathbb{P}(d(A, X) < l_1|d(A, X) < R) \\ &= \begin{cases} \frac{f_L(l_1)}{F_L(R)}, & 0 < l_1 < R, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{42}$$

Similarly, we have

$$\begin{aligned} &\mathbb{P}(d(A, Y) < l_2|d(B, Y) < R) \\ &= \begin{cases} \frac{F_L(l_2)}{F_L(2R)-F_L(R)}, & R < l_2 < 2R, \\ 1, & l_2 > 2R, \\ 0, & \text{otherwise,} \end{cases} \end{aligned} \tag{43}$$

and

$$\begin{aligned} &f_{(d(A,Y)|d(B,Y)<R)}(l_2) \\ &= \begin{cases} \frac{f_L(l_2)}{F_L(2R)-F_L(R)}, & R < l_2 < 2R, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{44}$$

Noting that the distributions of X and Y are independent,

$$\begin{aligned} &\mathbb{P}(d(A, X) < l_1, d(A, Y) < l_2|d(A, X) < R, \\ &d(B, Y) < R) \\ &= \mathbb{P}(d(A, X) < l_1|d(A, X) < R) \times \\ &\mathbb{P}(d(A, Y) < l_2|d(B, Y) < R). \end{aligned} \tag{45}$$

Given $d(A, X) < R$ and $d(B, Y) < R$, the joint conditional probability density function can be written as

$$\begin{aligned} &f_{(d(A,X),d(A,Y)|d(A,X)<R,d(B,Y)<R)}(l_1, l_2) \\ &= f_{(d(A,X)|d(A,X)<R)}(l_1)f_{(d(A,Y)|d(B,Y)<R)}(l_2) \\ &= \frac{f_L(l_1)f_L(l_2)}{F_L(R)[F_L(2R) - F_L(R)]}. \end{aligned} \tag{46}$$

Since

$$d(X, Y) = d(A, Y) - d(A, X), \tag{47}$$

the conditional probability can be written as

$$\begin{aligned} &\mathbb{P}(d(X, Y) < R|d(A, X) < R, d(B, Y) < R) \\ &= \int_R^{2R}\int_{l_2-R}^{R} f_{d(A,X),d(A,Y)|d(A,X)<R,d(B,Y)<R}(l_1, l_2)dl_1dl_2 \\ &= \frac{F_L(2R) - F_L(R)}{1 - F_L(R)} - \frac{1}{F_L(R)[1 - F_L(R)]}\int_R^{2R} f_L(l_2)F_L(l_2 - R)dl_2. \end{aligned} \tag{48}$$

Then, (33) can be rewritten as

$$\begin{aligned} \mathbb{P}(F_I^{(1)}) &= \mathbb{P}(d(A, X) < R, d(X, Y) < R, d(B, Y) < R) \\ &= \mathbb{P}(d(A, X) < R) \cdot \mathbb{P}(d(B, Y) < R)\cdot \\ &\mathbb{P}(d(X, Y) < R|d(A, X) < R, d(B, Y) < R) \\ &= F_L(R) \cdot (F_L(2R) - F_L(R)) - \\ &\int_R^{2R} f_L(l)F_L(l - R)dl. \end{aligned} \tag{49}$$

It can be observed from (34),

$$\begin{aligned} \mathbb{P}(F_I^{(2)}) &= \mathbb{P}(d(A, Y) < R, d(X, Y) < R, d(B, X) < R) \\ &= \mathbb{P}(d(A, Y) < R) \cdot \mathbb{P}(d(B, X) < R)\cdot \\ &\mathbb{P}(d(X, Y) < R|d(A, Y) < R, d(B, X) < R), \end{aligned} \tag{50}$$

we can conclude that the probabilities of events $F_I^{(1)}$ and $F_I^{(2)}$ are equal to each other. Here, we use i to denote number of vehicles between A and B, then, given $i = 2$, the conditional probability of there existing intermediate nodes is

$$\begin{aligned} \mathbb{P}(F_I|i = 2) &= \mathbb{P}(F_I^{(1)}) + \mathbb{P}(F_I^{(2)}) \\ &= 2F_L(R) \cdot (F_L(2R) - F_L(R)) - \\ &= 2\int_R^{2R} f_L(l)F_L(l - R)dl. \end{aligned} \tag{51}$$

To be generalize, we analyze the probability of intermediate nodes exists if there are i vehicles between A and B. We can select a pair of vehicles out of i vehicles, and check whether the selected pair satisfies the conditions that are described in (30) and (31). There are C_2^i different ways, where $C_n^m = \frac{m!}{n!(m-n)!}$. The event of the absence of intermediate nodes occurs if all of the pairs do not satisfy the conditions. Thus, we have

$$\mathbb{P}(F_I|i) = \begin{cases} 1 - (1 - \mathbb{P}(F_I|i = 2))^{C_2^i}, & i \geq 2, \\ 0, & \text{otherwise.} \end{cases} \tag{52}$$

The number of vehicles between A and B can be modeled as geometric Poisson distribution [28]. That is, given the average vehicular density Λ, the probability of finding k vehicles in area S is given by

$$u_k = e^{\Lambda S}\frac{(\Lambda S)^k}{k!}, k = 1, 2, \dots \tag{53}$$

Thus, the probability of the existence of intermediate nodes is

$$\mathbb{P}(F_I) = \sum_{k=2}^{+\infty} u_k\mathbb{P}(F_I|i = k). \tag{54}$$

Substituting (54) into (26), we can obtain the portion of unavoidable merge collisions. The relationship between merge collision probabilities of VeMAC and that of VIMAC can be expressed as

$$p_m^I = \frac{\mathbb{P}(F_I)}{2}p_m^V, \tag{55}$$

where the expression of the merge collision probability of VeMAC can be found in (24).

We set PTMAC as the other baseline scheme since PTMAC is the only one existing TDMA-based MAC that utilize vehicular information. Note that the merge collision probabilities of our proposed scheme is equal to PTMAC due to the prediction process is the same as PTMAC, i.e., the merge collision probability of PTMAC p_m^T can be expressed as

$$p_m^T = \frac{p_m^V}{2}\sum_{k=2}^{+\infty} u_k\mathbb{P}(F_I|i = k) \tag{56}$$

4.2. Access collision probability

In this subsection, we develop another 1D-CTMC for evaluating the access collision probabilities of the three protocols (one

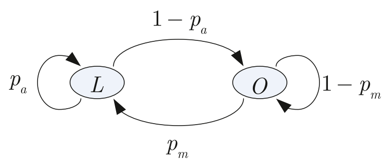


Fig. 6. Markov Chain for each node.

proposed scheme and two baseline scheme). It is difficult to analyze the access collision probability of the proposed VIMAC protocol directly. Fortunately, we can analyze the access collision probability of VeMAC, and then, obtain the probability of PTMAC with the help of the relationship between them. At last, we can get the mathematical expression of the access collision probability of VIMAC from that of PTMAC. It is worth noting that, the relationship between the access collision probability of VIMAC and that of VeMAC is implicit, we have to get the access collision probability of VIMAC from that of PTMAC rather than that of VeMAC. In order to analyze the access collision probabilities, a 1D-CTMC analytical model is proposed firstly, the model describes the behaviors of losing and reserving slots of vehicular nodes.

4.2.1. 1D-CTMC analytical model

As mentioned above, the change of number of vehicles in a two hop set can be modeled as 1D-CTMC. We say the state of a vehicle is O if tagged vehicle occupies a slot, otherwise, the state is L. The state transfer is depicted in Fig. 6. We use π_O and π_L to denote the stationary probabilities of the states O and L, respectively. Then, we have the following formulas

$$\begin{cases} p_a\pi_L + p_m\pi_O = \pi_L, \\ (1-p_a)\pi_L + (1-p_m)\pi_O = \pi_O, \\ \pi_L + \pi_O = 1. \end{cases} \tag{57}$$

Yielding the stationary probabilities

$$\begin{cases} \pi_L = \frac{p_m}{1-p_a+p_m}, \\ \pi_O = \frac{1-p_a}{1-p_a+p_m}. \end{cases} \tag{58}$$

Here, we use the 1D-CTMC that is described in Fig. 6 to analyze the merge and collision probabilities for our proposed approach and baseline protocols.

4.2.2. Access collision probability of VeMAC

We use p_a^V to denote the access collision probability of VeMAC. Given n_T vehicles in tagged two hop set, the number of competitors is

$$v = \left\lceil \frac{n_T \cdot p_m^V}{1-p_a^V+p_m^V} \right\rceil, \tag{59}$$

where the operator $\lceil n \rceil$ represents getting the smallest integer that is no less than n. We denote the number of slots within a frame as M, the number of idle slots can be expressed as

$$u = \left\lceil M - \frac{n_T(1-p_a^V)}{1-p_a^V+p_m^V} \right\rceil. \tag{60}$$

Therefore, the access probability of VeMAC can be expressed as

$$p_a^V = 1 - \frac{(u-1)^{v-1}}{u^v} \tag{61}$$

4.2.3. Access collision probability of PTMAC

Similarly, we have the access collision probability of PTMAC,

$$p_a^T = 1 - \frac{(u_T-1)^{v_T-1}}{u_T^{v_T}}, \tag{62}$$

where

$$v_T = \left\lceil \frac{n_T(1-\beta)p_m^V}{1-p_a^T+(1-\beta)p_m^V} \right\rceil \tag{63}$$

and

$$u_T = \left\lceil M - \frac{n_T(1-p_a^T)}{1-p_a^T+(1-\beta)p_m^V} \right\rceil \tag{64}$$

It is worth noting that $p_a^T < p_a^V$ since $v_T < v$, which means that PTMAC reduces access collision probability indirectly since fewer merge collisions leads to a lower number of competitors.

4.2.4. Access collision probability of VIMAC

Seeing to the condition that is described in Fig. 2, although the nodes A and B encounter merge collisions due to the absence of intermediate nodes, with the help of the old neighbor, i.e., the node W, the node B can occupy the previous slot without incurring access collisions. Therefore, in the process, the node B encountered a merge collision and no access collision. Practical, any node becomes the node B with the probability of 1/2 when it encounter an unavoidable merge collision. Otherwise, the probability of the node becoming A is 1/2. Therefore, the proposed scheme can eliminate half of the access collisions. Hence, the access collision probability of VIMAC is

$$p_a^I = \frac{1}{2} \cdot \left\lceil 1 - \frac{(u_I-1)^{v_I-1}}{u_I^{v_I}} \right\rceil. \tag{65}$$

It is clear that

$$p_a^V > p_a^T > p_a^I. \tag{66}$$

5. Simulation and discussion

5.1. Simulation setup

In this section, we describe the simulation platform and the parameter configurations firstly. Then, simulation results and the discussion are given. We use SUMO and MATLAB to verify our scheme and make compare the performance of with other similar approaches. The baseline TDMA-based MAC protocols are VeMAC and PTMAC, where VeMAC is the typical and practical TDMA-based VANET that do not utilize vehicular information, PTMAC is the only one protocol that reduce merge collisions through making use of vehicular information. We use SUMO to generate a highway scenario and the movement of all of the vehicles in the scenario. We develop simulation program in MATLAB to simulate the protocols and collect results.

The simulation parameters are summarized in Table 1. The number of vehicles in the scenario keeps constant. The vehicle that exits the scenario from one side enters the scenario at the other side. Velocities are changing all the time based on the distance between the vehicles and the former ones. However, velocities could not exceed 200kmph no matter what the traffic condition is.

The reliable issues for TDMA-based VANETs are merge collisions and access collisions. Where the former one occurs when two nodes that are out of each other's two hop range become two hop reachable. In this situation, more slots in a frame leads to a lower merge collision probability. Therefore, frame length is a factor and can influence the merge collision probability. The next issue of reliability is access collision. The behavior of nodes

Table 1
Simulation parameter.

Parameter	Value
Road length	4000 m
Max velocity	200 kmph
Number of lanes (each direction)	4
Lane width	5 m
Traffic density (number of vehicles per direction)	600
Communication range	150 m
Simulation time	600 s
No. of packets in a CAM message	4
Update frequency of CAMs	1000 slots
Mean arrival rate of DENMs	1/220

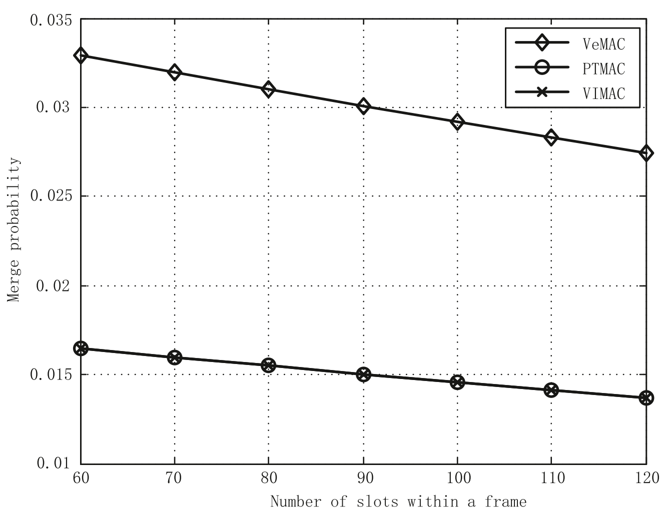


Fig. 7. Merge collision probabilities for various protocols.

competing a slot can be viewed as through balls into boxes with equal probabilities. Collision probability depend on the number of balls and the number of boxes, i.e., number of competitors and number of idle slots in TDMA-based VANETs. The number of idle slots changes as the frame length. Therefore, the frame length is not only a factor to merge collision but also a factor to access collision. In this section, we examine the performance with different frame length.

5.2. Results and discussion

Merge collision probabilities of the proposed protocol and the baseline protocols are shown in Fig. 7. Through comparing the data, we can observe that all of the merge collision probabilities for the three protocols decrease slightly as the frame length. However, the decrement is too small when it is compared with the gap between probabilities of different protocols. The results in Fig. 7 show the advantages of PTMAC and VIMAC since the merge collision probabilities of both of the protocols are half of the value of VeMAC.

Fig. 8 provides the comparison of access collision probabilities of the three protocols. In the simulation, access collision probabilities are calculated through number of access collisions divided by number of retransmissions. In other words, access collision probabilities are conditional probabilities that given the nodes lost their slots already. Thus, the numerical value of access collision probabilities are much larger than that of merge collision probabilities. In the case that the frame length is only 60 slots, access probabilities of all of the protocols are more than 0.5. From the figure, we can observe that PTMAC cannot reduce access collision probability when the idle slots are not sufficient. As the

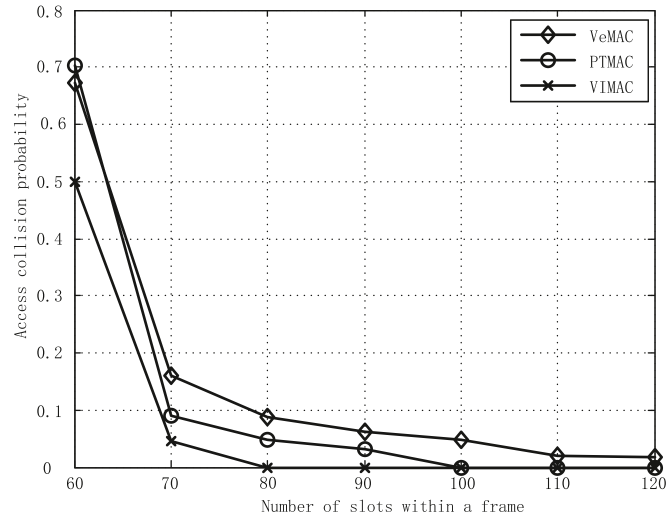


Fig. 8. Access collision probabilities for various protocols.

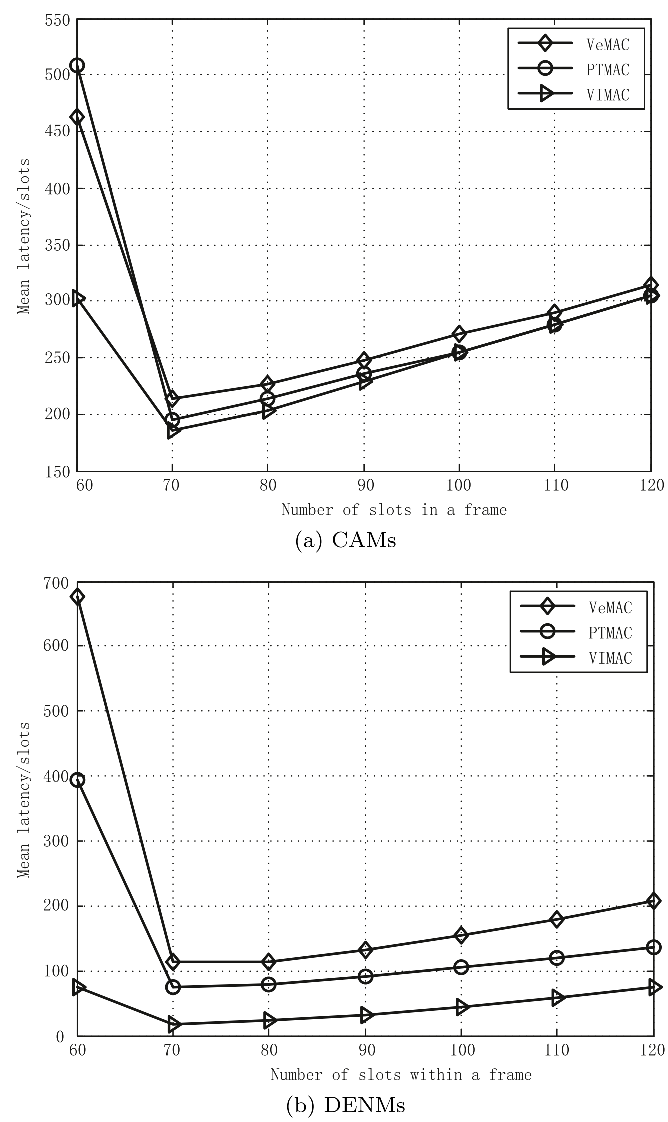


Fig. 9. Mean latencies for different safety related applications.

number of slots within a frame increases, PTMAC outperforms VeMAC in terms of access collision probability since the reduced merge collision probability leads to fewer competitors. Although the number of idle slots is not enough, VIMAC can provide a lower access collision probability. The access collision probability of VIMAC approaches to zero after the frame length is larger than 80 slots.

Fig. 9 provides mean latency performances of CAMs and DENMs as functions of the frame length, respectively. There are two queues in each node for buffering CAMs and DENMs, respectively. The latency of a packet can be divided into two components, queueing latency and service latency. The former one is defined as the interval between a packet entering the queue and becoming the head of the queue. We define the service latency as the interval between the packet becoming the head of the queue and transmitting successfully. As described in [27], CAM messages can by described by batch arrival model since the information in a CAM message is too much to transmit in a single slot. Here, each CAM message is divided into 4 packets and transmitted in 4 different slots which are reserved to the tagged node. The frequency of CAMs cannot be greater than the total latency of a CAM message in order to keep the queue stable. Therefore, we set the update frequency as 1000 slots. The typical requirement of update frequency of CAMs is 10 Hz, therefore, the slot duration should be much shorter than 1 ms, which is defined in the legacy TDMA-based VANETs [22,23]. We use Poisson arrival process to describe DENMs, the arrival rate is set as 1/220 in order to guarantee the stability of the queue.

From the trends of merge collision probabilities and access collision probabilities, it is known that we can enhance the reliability through prolong the frame length. However, the latencies of CAMs and DENMs applications are prolonged if we configure a longer frame length simply. From Fig. 9(a), We can see that all of the protocols get the optimal latency performance when the frame length is 70 slots. In the case of short frame length, collisions occur frequently, a large portion packets are transmitted after successive collisions. After the frame length exceeding 70 slots, the reliability changes insignificantly, frame length is the main factor that influences channel access interval.

6. Conclusion

This paper presented a high reliable TDMA-based MAC protocol that called the VIMAC. The protocol involves various technologies, such as cross-layer and temporal centralized network. There are two processes in the VIMAC, prediction and allocation. In the first process, the MAC layer make use of vehicular information from the upper layer to predict the upcoming merge collision. One of the intermediate node that knows the vehicular information of the two nodes plays a role of centralized node temporally. On the other hand, in the allocation process, the old neighbor that is allowed to broadcast first is the temporal manager. Simulations and analysis are given to show the advantages of the proposed scheme. The future work will be focused on building an analytical model to verify the performance theoretically and design protocols to optimize the performance of different safety related applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported in part by the National Natural Science Foundation of China (NSFC) under Grants 61271169 and 61701086, by the MOST of 2015ZX03002010 and by the Fundamental Research Funds for the Central Universities under Grant ZYGX2016KYQD143.

References

[1] Z. Lv, W. Kong, X. Zhang, D. Jiang, H. Lv, X. Lu, Intelligent security planning for regional distributed energy internet, IEEE Trans. Ind. Inf. (2019) early access.

[2] Z. Lv, B. Hu, H. Lv, Infrastructure monitoring and operation for smart cities based on IoT system, IEEE Trans. Ind. Inf. (2019) early access.

[3] Y. Zang, L. Stibor, B. Walke, H.J. Reumerman, A. Barroso, Towards broadband vehicular ad-hoc networks - the vehicular mesh networks (VMESH) MAC protocol, in: IEEE Wireless Commun. and Netw. Conference, WCNC, 2007 pp. 417–422.

[4] W. Wei, M. Wozniak, R. Damas, et al., Algorithm research of known-plaintext attack on double random phase mask based on WSNs, J. Internet Technol. 20 (1) (2019) 39–48.

[5] C. Campolo, A. Molinaro, A. Vinel, Understanding the performance of short-lived control broadcast packets in 802.11p/WAVE vehicular networks, in: IEEE Veh. Netw. Conference, VNC, November 2011, pp. 102–108.

[6] G. Araniti, C. Campolo, M. Condoluci, A. Iera, A. Amolinaro, LTE for vehicular networking: a survey, IEEE Commun. Mag. 51 (5) (2013) 148–157.

[7] METIS, Scenarios Requirements and KPIs for 5G Mobile and Wireless System, D11, 2013.

[8] W. Wei, X. Xia, W. Marcin, et al., Multi-sink distributed power control algorithm for cyber-physical-systems in coal mine tunnels, Comput. Netw. 161 (2019) 210–219.

[9] S. Eichler, Performance evaluation of the IEEE 802.11p WAVE communication standard, in: 66th IEEE Veh. Technol. Conference, VTC'07-Fall, Baltimore, Md, USA, 2007, pp. 2199–2203.

[10] T.V. Nguyen, F. Baccelli, K. Zhu, S. Subramanian, X. Wu, A performance analysis of CSMA based broadcast protocol in VANETs, in: Proc. of IEEE INFOCOM, 2013 pp. 2805–2813.

[11] Q. Wang, S. Leng, H. Fu, Y. Zhang, H. Weerasinghe, An enhanced multi-channel MAC for the IEEE 1609.4 based vehicular Ad Hoc networks, in: Proc. of IEEE Conference on Comput. Commun. Workshops, INFOCOM '10, San Diego, Clif, USA, 2010, pp. 1–2.

[12] V. Nguyen, T.Z. Oo, P. Chuan, C.S. Hong, An efficient time slot acquisition on the hybrid TDMA/CSMA multichannel MAC in VANETs, IEEE Commun. Lett. 20 (5) (2016) 970–973.

[13] I. Chu, P. chen, W. Chen, An IEEE 802.11p based distributed channel assignment scheme considering emergency message dissemination, in: Proc. of IEEE 75th Veh. Technol. Conference, VTC '12, Yokohama, Japan, 2012, pp. 1–5.

[14] R. Mangharam, R. Rajkumar, M. Hamilton, P. Mudalige, F. Bai, Bounded-latency alerts in vehicular networks, in: 2007 Mobile Netw. for Veh. Environments, 2007, pp. 55–60.

[15] Z. Doukha, S. Mussaoui, A sdma-based mechanism for accurate and efficient neighborhood discovery link layer service, IEEE Trans. Veh. Technol. 2 (65) (2015) 603–613.

[16] J. Mo, H.W. So, J. Walrand, Comparison of multichannel MAC protocols, IEEE Trans. Mob. Comput. 7 (1) (2008) 50–65.

[17] A. Ahizoune, A. Hafid, R.B. and Ali, A contention-free broadcast protocol for periodic safety message in vehicular Ad-Hoc networks, in: IEEE 35th Conference on Local Comput. Netw. LCN, 2010, pp. 48–55.

[18] F. Borgonovo, A. Capone, M. Cessana, L. Fratta, RR-ALOHA, A reliable R-ALOHA broadcast channel for Ad-Hoc inter-vehicle communications networks, in: Proc. of Med-Hoc-Net, 2002.

[19] F. Borgonovo, A. Capone, M. Cessana, L. Fratta, ADHOC MAC: New MAC architecture for Ad Hoc networks providing efficient and reliable point-to-point and broadcast services, Wirel. Netw. 10 (4) (2004) 359–366.

[20] Y. Liu, J. Niu, J. Ma, L. Shu, T. Hara, W. Wang, The insights of message delivery delay in VANETs with a birdirectional traffic model, J. Netw. Comput. Appl. 36 (5) (2013) 1287–1294.

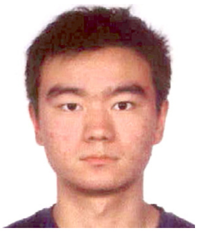
[21] F. Borgonovo, L. Campelli, M. Cessana, L. Fratta, Impact of user mobility on the broadcast service efficiency of the ADHOC MAC protocol, in: IEEE Veh. Technol. Conference, vol. 4, 2005, pp. 2310–2314.

[22] W. Yang, W. Liu, P. Li, L. Sun, TDMA-based control channel access for IEEE 802.11p in VANETs, Int. J. Distributed Sens. Netw. (2014) 1–9.

[23] H.A. Omar, W. Zhuang, L. Li, VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs, IEEE Trans. Mob. Comput. 12 (9) (2013) 1724–1736.

[24] P. Chen, J. Zheng, Y. and Wu, A-VeMAC: An adaptive vehicular MAC protocol for vehicular Ad Hoc networks, in: IEEE ICC, 2017.

[25] X. Jiang, H. David, C. Du, PTMAC: A prediction-based TDMA MAC protocol for reducing packet collisions in VANET, IEEE Trans. Veh. Technol. 65 (11) (2016) 9209–9223.
[26] T. Zhuang, Q. Zhu, Game-based TDMA MAC protocol for vehicular network, J. Commun. Netw. 19 (3) (2017) 209–217.
[27] H.A. Omar, W. Zhuang, L. Li, Delay analysis of VeMAC supporting periodic and event-driven safety messages in VANETs, in: IEEE GLOBECOM, 2013, pp. 4621–4626.
[28] W. Li, X. Ma, J. Wu, K.S. Trivedi, X. Huang, Q. Liu, Analytical model and performance evaluation for vehicle safety services, IEEE Trans. Veh. Technol. 66 (3) (2017) 1926–1939.



Yuanxin Sun received his B.S. degree from University of Electronic Science and Technology of China (UESTC) in 2007, and M. Eng. degree from Chongqing University of Post and Telecommunication in 2011. He worked as an FPGA engineer in NTS-INTL Inc. in Chengdu, China from 2011 to 2014. He is currently a Ph.D. candidate in National Key Lab of Communications Science, University of Electronic Science and Technology of China (UESTC). His current research interests include vehicular communications, TDMA-based MAC layer design and high speed hardware implementation for MAC layer protocols.

Ruoxin Kuai received the B.S. degree in communications engineering from University of electronic science and technology in 2018, where she is currently pursuing the M. Eng. degree with the National Key Lab of Communications Science in University of Electronic Science and Technology of China (UESTC). Her current research interests include, MAC layer design and vehicular communications.

Sa Xiao (M18) received the B.S.E., M.S.E., and Ph.D. degrees from the University of Electronic Science and Technology of China, Chengdu, China, in 2009, 2012, and 2017, respectively, where he is currently a Postdoctoral Researcher with the Center for Intelligent Communications and Networking (CINC). In 2015, he was a Visiting Student with the Department of Electrical and Computer Engineering, Southern Illinois University, Carbondale, IL, USA. He was a Visiting Student with the Division of Electrical and Computer Engineering, Louisiana State University, Baton Rouge, LA, USA, from 2015 to 2017.

His research interests include device-to-device communications, full-duplex communications, heterogeneous networks, and the Internet of Things communications.

Wanbin Tang received B.S. , M. Eng. and Ph.D. degree in Electrical Engineering from University of Electronic Science and Technology of China (UESTC), in 1993, 1998 and 2013, respectively. From August 2006 to August 2007, he worked as a Visiting Scholar in U.C. Berkeley. He is a professor at the National Key Laboratory of Science and Technology on Communications, UESTC. His current research interests include cognitive radio, signal processing in wireless communication.

Xiaoping Li received the B.S. degree in mathematics from Sichuan Normal University in 2006 and the Ph. D degree in information and communication engineering from Xian Jiaotong University in 2016. From 2006–2010, he was an assistant professor in the College of Information Engineering, Tarim University, Alar, China. From December 2103 to January 2015, he was a visiting scholar at the Department of Electrical and Computer Engineering, University of Delaware, Newark. Currently, he is a lecturer at University of Electronic Science and Technology of China.

His main research interests include signal processing theory, computer cryptography and coding theory.