MoMAC: Mobility-Aware and Collision-Avoidance MAC for Safety Applications in VANETs

Feng Lyu, *Member, IEEE*, Hongzi Zhu, *Member, IEEE*, Haibo Zhou, *Senior Member, IEEE*, Liping Qian, *Senior Member, IEEE*, Wenchao Xu, Minglu Li, *Senior Member, IEEE*, and Xuemin Shen, *Fellow, IEEE*

***Abstract*—Time-division multiple access (TDMA) based medium access control (MAC) protocol provides a promising solution to well support delay-sensitive safety applications in vehicular ad hoc networks, since a time-slotted access scheme ensures the transmission within the ultra-low delays. However, due to the varying vehicle mobility, existing TDMA-based MAC protocols may result in collisions of slot assignment when multiple sets of vehicles move together. To avoid slot-assignment collisions, in this paper, we propose a mobility-aware TDMA MAC, named as MoMAC, which can assign every vehicle a time slot according to the underlying road topology and lane distribution on roads with the consideration of vehicles' mobilities. In MoMAC, different lanes on the same road segment and different road segments at intersections are associated with disjoint time slot sets. In addition, each vehicle broadcasts safety messages together with the time slot occupying information of neighboring vehicles; by updating time slot occupying information of two-hop neighbors (obtained indirectly from one-hop neighbors), vehicles can detect time slot collisions and access a vacant time slot in a fully distributed way. We demonstrate the efficiency of MoMAC through theoretical analysis and extensive simulations; compared with state-of-the-art TDMA MACs, the transmission collisions can be reduced by 59.2%, and the rate of safety message transmissions/receptions can be greatly enhanced.**

***Index Terms*—Vehicular ad hoc networks, medium access control, TDMA, slot assignment, mobility.**

I. Introduction

Driving safety has been the top priority in intelligent transportation systems (ITS), since there is a large number of traffic accidents every year, which not only endanger people's life but also cause great economic losses. Transmitting warning messages about dangerous traffic conditions among vehicles through vehicular ad hoc networks (VANETs) has emerged as a promising solution to enhance driving safety [1], [2]. In VANETs, most of the high-priority safety-related messages are broadcast in either the vehicle-to-vehicle (V2V) mode or the vehicle-to-road-side-unit (V2R) mode. Specifically, in the V2V communication mode, every vehicle needs to periodically broadcast their status information including position, velocity, heading direction, acceleration and turn signal status, to all neighbors within one-hop. With such timely updated information, the application layer can support services such as pre-crash sensing, blind spot warning, emergency electronic brake alert, and cooperative forward collision avoidance [3]. On the other hand, in the V2R communication mode, every road-side unit (RSU) periodically broadcasts information such as the traffic signal status, road surface type, weather conditions, speed limits and the current traffic condition, to all nearby vehicles, whereby, services such as traffic management, transportation efficiency and user infotainment services [4] can be provided. All these applications rely on broadcast communication, and thus we need to carefully design Medium Access Control (MAC) protocols to support reliable one-hop broadcast, i.e., with medium access delay guarantee and transmission collision avoidance.

In the literature, various MAC protocols have been proposed for broadcast communication in VANETs, which can be categorized into the contention-based and contention-free MACs [5]–[8]. In general, contention-based MACs such as IEEE 802.11p are efficient when the number of contending vehicles is small. However, the access delay will grow to significant level when the number of users involving the back off procedure is large; therefore the efficiency of the MAC protocol degrades, especially in dense traffic conditions [9], [10]. In addition, the RTS/CTS scheme is disabled in broadcast mode for fast response, which will aggravate the hidden terminal problem. Intuitively, it is challenging to design an efficient MAC for reliable broadcast services under realistic VANETs. First, to support high-priority driving safety applications, safety messages need to be periodically broadcasted with a high frequency, i.e., normally 10 HZ (every 100 msec) [3], which poses great pressures on medium resource management and medium access delay guarantee. Second, due to the variable network topology, diverse spatial densities of vehicles and the hidden/exposed node problems, the MAC should work with a strong scalability, i.e., seamlessly adapting to dynamic communicating environments [11]. Third, the lack of infrastructures in VANETs makes it hard to achieve fine-grained coordinations without global information. To these ends, TDMA-based MACs have demonstrated their efficacy in

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F. Lyu, H. Zhu, and M. Li are with the Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: fenglv@sjtu.edu.cn; hongzi@cs.sjtu.edu.cn; li-ml@cs.sjtu.edu.cn).

H. Zhou is with the School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China (e-mail: haibozhou@nju.edu.cn).

W. Xu and X. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: w74xu@uwaterloo.ca; sshen@uwaterloo.ca).

L. Qian is with the College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China (e-mail: lpqian@zjut.edu.cn).

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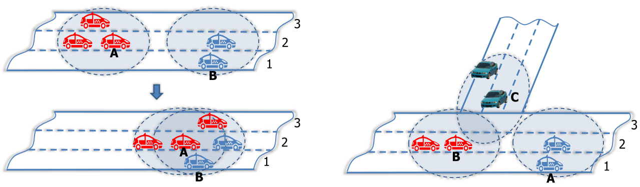


(a) with different lane speed limits (b) at road intersections

Fig. 1. Mobility causes merging collisions with prior TDMA-based MACs.

VANETs [5]–[7], since a predefined time-slot-usage is suitable for periodical broadcasting in a distributed way. In TDMA-based MACs, time is partitioned into frames, each of which has a constant number of equal-length time slots. Time slots are synchronized among vehicles and each vehicle is granted to access the channel at least once in each frame by occupying a time slot.

In existing TDMA-based MACs, if every vehicle is perfectly assigned with a unique time slot then the stringent delay requirement of the safety message delivery can be guaranteed since no transmission collision would happen. However, as vehicles change mobility constantly in real-world driving scenarios, the performance of existing TDMA-based MAC protocols will degrade dramatically due to the collision of slot assignment when multiple sets of vehicles move together, which is called *merging collision*. Fig. 1 shows how merging collisions occur due to the vehicle mobility when adopting existing TDMA-based MACs. Specifically, in Fig. 1(a), vehicles are moving in lanes with different speed limits towards the same direction. At the initial stage, the vehicle set A and vehicle set B are separate from each other and vehicles in each set occupy a unique time slot for data transmission. As vehicles in set A move faster and catch up with vehicles in set B, the two sets overlap, making it possible that vehicles in set A and B use the same time slots and thus causes collisions. Fig. 1(b) shows how merging collisions happen at an intersection. When a previously independent vehicle set C approaches the intersection, it overlaps with the vehicle set B and thus merging collisions happen. To make things worse, if the vehicle set C stops at the intersection due to a red light, it will continuously collide with all sets traversing in front of it. Another significant side effect of red traffic lights is that they make vehicles slow down until completely stop, which means that incoming vehicle sets on the blocked road join the merging sets at the intersection, leading to more severe merging collisions. Contradictorily, it is intersections that have the greatest need for reliable data communication to guarantee driving safety. Therefore, it is important to take into account those identified merging collisions when designs TDMA MAC protocols for VANETs.

Unlike other types of mobile users, the mobility of a vehicle is quasi-predictable, as the movement is constrained by road layout and the traffic regulations, e.g., road signs, traffic lights, etc. It has potential to taking advantage of such predictability of the vehicle mobility to reduce the merging collisions [12]–[15]. We have the following two important observations from the real-world vehicular conditions: 1) vehicles may converge and diverge from time to time due to their distinct velocities and routes; 2) the design of the road topology and lane layout can statistically reflect the actual mobility demands of vehicles. Specifically, vehicles in the same lane share relatively similar mobility; if the vehicle wants to speed up or slow down, it will first choose to change a lane, and vehicles moving in the fast lane will always catch up with vehicles in the slow lane. Likewise, vehicles will eventually move together at the intersection due to the road topology limit. Inspired by this, we propose *MoMAC*, an innovative mobility-aware TDMA MAC protocol, which can assign time slots elegantly according to the underlying road topology and lane distribution on roads. In MoMAC, different lanes on the same road segment and different road segments at intersections are associated with *disjoint slot sets*, i.e., assigning vehicles that are bound to merge, with disjoint time slot sets. The beauty of this design is that each vehicle can easily obtain the collision-avoidance slot assignment as long as the vehicle has a lane-level digital map and knows its current information of belonging to which road and which lane, which can be easily obtained by all the navigation systems [16]–[18]. To achieve common agreement about the usage of slots among neighboring vehicles, we propose a fully *distributed* slot assignment scheme, in which each vehicle selects a free slot according to the received slot-occupying information from neighboring vehicles. Specifically, in addition to application data, each vehicle also broadcasts the information with IDs of its one-hop neighboring vehicles and slot indexes used by them. In doing so, transmission collisions can be detected by verifying the consistence of neighboring messages and all vehicles can keep tracking the link state changes in the moving. We analyze the performance of MoMAC theoretically in terms of average collisions, packet overhead and medium access delay. In addition, we conduct extensive simulations considering various road topologies and traffic conditions and the results demonstrate the efficiency of MoMAC by checking the metrics of collision rate and safety message transmission/reception rate. Compared with state-of-the-art TDMA MACs, i.e., ADHOC MAC [5] and VeMAC [6], the transmission collisions can be reduced by 59.2%. The main contributions of this paper are summarized as follows.

- We identify two common mobility scenarios which would result in massive merging collisions; however, existing TDMA-based MACs do not consider and handle them well.
- We design a mobility-aware TDMA MAC, named as MoMAC, to enhance the reliability of safety message exchange for safety applications. In MoMAC, the medium resource is assigned according to the underlying road topology and lane distribution on roads. With MoMAC, time-slot-collisions caused by vehicles' relative movements on multi-lane roads and merging together at intersections, can be relieved.
- We evaluate the average number of collisions theoretically for existing TDMA-based MACs and MoMAC to demonstrate the efficiency of the MoMAC design. In addition, the packet overhead and medium access delay are analyzed to verify the feasibility of MoMAC.

The remainder of this paper is organized as follows. Section II presents the related work. We describe the system model in Section III. Section IV elaborates on MoMAC design. Performance analysis is carried out in Section V. We conduct extensive simulations to evaluate the performance of MoMAC in Section VI. Finally, we conclude this paper and suggest future work in Section VII.

II. Related Works

There have been adequate studies on TDMA MACs for VANETs. A survey about TDMA-based MACs is present in the work [19], in which, Hadded *et al.* first discussed the characteristics of VANETs and the special real time requirements of safety applications, then identified the reasons for using the TDMA-based MAC paradigm in VANETs and provided an overview of proposed TDMA-based MACs; in addition, the characteristics, benefits and limitations of these MACs were discussed and compared.

Centralized TDMA MACs are proposed in studies [20]–[22], in which, time slots are assigned by a central controller. For instance, in the work [20], Zhang *et al.* used a RSU as a centralized controller to collect the channel state information and the individual information; then the controller can calculate the respective scheduling weight factors, based on which it can make scheduling decisions. However, the method requires a large number of RSUs which limits the scale of the network. Other works [21], [22], chose cluster heads as central controllers; vehicles were partitioned into several clusters and each cluster chose a head as a controller. However, the method is not practical in VANETs due to the highly dynamic features of VANETs, where it is challenging for clusters forming and cluster heads selection as vehicle topologies change over the time. As a result, many studies focus on distributed TDMA MAC designs, in which, each vehicle manages the time slot by itself. The main challenge in distributed TDMA MACs is how to coordinate among vehicles to use time resource efficiently without global network knowledge. The ADHOC MAC protocol was proposed in the work [5], where a wireless communication channel was set to a slotted/framed structure and coordinated with the well-known Reservation ALOHA (R-ALOHA) protocol [23]. Each node not only transmits its application data but also reports the status of time slots used by its neighbors; by collecting such information, collisions can be detected. Lyu *et al.* designed a slot-sharing TDMA MAC, referred to as SS-MAC [7], to make multiple vehicles (with distinct beacon rates) share a time slot by negotiation in real time, which can help save time slot resources when the vehicle density is high. However, those researches do not consider the moving characteristics of vehicles, which may degrade the performance in real-driving scenarios. Taking the transmission collisions caused by vehicular movements in opposite directions into consideration, Omar *et al.* proposed VeMAC [6] protocol for reliable broadcast in VANETs; VeMAC assigned disjoint sets of time slots to vehicles moving in opposite directions to reduce transmission collisions. ATSA (Adaptive TDMA Slot Assignment) MAC [24] tried to enhance VeMAC protocol when the densities of vehicles moving in opposite directions are not equal, in which, the frame length was dynamically doubled or shortened based on the binary tree algorithm. In both two MACs, the authors just considered the stable moving situations, where the speed, moving direction and distance among vehicles are constant; this kind of setup is not convincing in practical VANETs. In the work [25], Jiang *et al.* proposed PTMAC, a prediction-based TDMA MAC to reduce packet collisions in VANETs. In PTMAC, two-way traffic and four-way intersections were considered; by collecting speed, position, and moving direction information from neighbors, PTMAC predicted the possibility of encountering collisions and tried to decrease the potential collisions. However, PTMAC has to find intermediate vehicles to do potential collision detection and potential collision elimination, causing extra coordinating overhead and delay; moreover, the method needs intermediate vehicles for coordinating, which limits the usage when no intermediate vehicle exists in the environment.

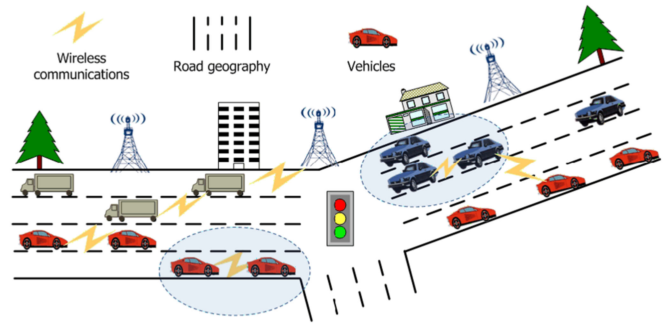


Fig. 2. Illustration of the system model.

III. System Model

Our system model includes three main parts, i.e., wireless communication unit, road geography unit, and vehicles, as shown in Fig. 2.

Wireless communication: All entities in the network communicate via Dedicated Short Range Communications (DSRC), which contains one Control Channel (CCH) and multiple Service Channels (SCHs) with two optional bandwidths of 10 MHz and 20 MHz [26], [27]. The CCH is essential and used to transmit high-priority short messages (such as periodic or event driven safety messages) and control information (such as negotiation of SCHs usage among vehicles), while SCHs are used for user applications. In this paper, we focus on the design of an efficient and reliable MAC protocol for the CCH, which is the cornerstone for safety applications and multi-channel operations. To control the medium access on the CCH, time is partitioned into frames consisting of a given number S of fixed duration time slots and each second contains an integer number of frames. To access the medium, a node has to gain a vacant time slot in a frame before it can transmit messages. In addition, the channel is considered to be symmetric which has been evaluated by analyzing collected real-world DSRC communication data in the work [28]. Thus, a node x is in the communication range of node y if and only if node y is in the communication range of node x.

Road geography: We consider real-world road scenarios involving highways and urban surface roads. We refer to a *road segment* as the road segment in one direction partitioned by two adjacent intersections. Road segments can have multiple lanes with different speed limits and are interconnected by intersections with traffic lights. We allow vehicles to have distinct acceleration and deceleration performance and to take actions such as overtaking or changing lanes whenever necessary.

Vehicles: Vehicles in the network have at least one DSRC radio operating on the CCH and they have identical communication capability and the same communication range R. For driving safety, each vehicle has to broadcast its status information every 100 ms according to the requirement of safety applications [3]. Each vehicle is equipped with a GPS receiver that provides time reference and location information. For specific, the 1 pulse per second (PPS) signal provided by GPS receivers is used as a global time reference to synchronize vehicles. The rising edge of this 1PPS is aligned with the start of every GPS second with accuracy within 100 ns even for low-end GPS receivers [6]. Hence, at any instant, each node can determine the index of the current slot within a frame. In addition, each vehicle has a lane-level digital map of the area of interest. Through GPS, each vehicle can obtain the information of which road and which lane it belongs to, matured in all the navigation systems [16]–[18]. Unlike previous position-guided MAC protocols which rely on the accurate location information of vehicles, MoMAC adopts the underlying road topology and lane distribution on roads into medium resource allocation. It is practical as the road topology and lane distribution are constant and easily obtained. Furthermore, a vehicle just needs to know which road and which lane it belongs to, which are classification problems rather than a absolute positioning problem. As classifying a GPS location to a specific lane and road segment can tolerate localization errors ranging from meters to hundreds meters, the inaccurate localization and temporary GPS shortage have slight impact on the performance of the scheme.[1]

To facilitate time slot assignment in a distributed way, a vehicle x needs to maintain the information of its neighboring vehicles in one-hop and two-hop ranges and the information lists are as follows:

- $N_{cch}(x)$: the set of IDs of its one-hop neighbors, which are updated by whether the node x has received packets directly on the channel during the previous S slots. In addition, the node x needs to broadcast this information with application data in each transmission.
- $N^2_{cch}(x)$: the set of IDs of its two-hop neighbors, indirectly obtained from the packets transmitted by its one-hop neighbors, i.e., $N^2_{cch}(x) = N_{cch}(x) \bigcup \{N_{cch}(y), \forall y \in N_{cch}(x)\}$.
- $U(x)$: the set of time slots that have been used by vehicles in the set of $N^2_{cch}(x)$.
- $G(x)$: the set of time slots pre-defined by MoMAC according to the current position of x, which is the possible set of time slots that x can choose from. $G(x)$ would be updated when x changes its mobility such as changing a lane, approaching or leaving an intersection (elaborated in the next section).
- $A(x)$: the available set of time slots that x currently can choose to use in the next frame. It is obtained based on the sets of $U(x)$ and $G(x)$, i.e., $A(x) = G(x) - U(x)$.

IV. MoMAC Design

A. Preliminaries About TDMA-Based MACs

In TDMA-based MAC protocols, time is partitioned into frames with each consisting of a fixed number of time slots. When using the TDMA-based MAC protocol, vehicles are synchronized via the GPS, and then every vehicle is assigned a slot in a frame before it can transmit messages. Once a vehicle obtains a slot successfully, it can use the same slot in all subsequent frames until a transmission collision is detected. In such protocols, neighboring vehicles within the communication range of a vehicle constitute the *one-hop set* (OHS) of this vehicle. If two OHSs overlap with each other, the union of these two OHSs is referred to as a *two-hop set* (THS), i.e., each node in a THS can reach any other node in the same THS in two hops at most. Fig. 3 illustrates an example where the respective OHSs of vehicle A and vehicle C form one THS with vehicle B standing in between.

[1]In addition, to support future autonomous driving, the usage of HD (high definition) map is necessary, which can easily provide lane-level position information.

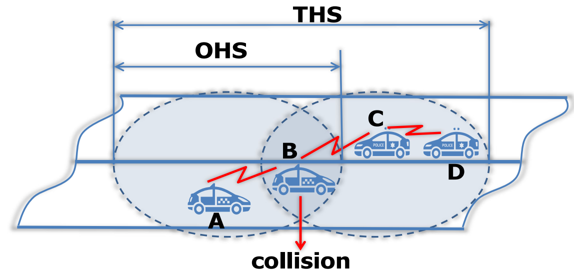


Fig. 3. Illustration of the hidden terminal problem and the THS.

Obviously, vehicles in the same OHS should select different time slots to transmit messages. Moreover, vehicles in the same THS should also choose distinct time slots for communication in order to overcome the hidden terminal problem. The hidden terminal problem can arise in a THS when two vehicles, locating in each of the two OHSs respectively, cannot hear with each other and decide to transmit a message in parallel. For example in Fig. 3, vehicle A wants to transmit a message to vehicle B and at the same time vehicle C wants to transmit a message to vehicle D. As vehicle A is not within the communication range of vehicle C, vehicle C thinks that the channel is free and starts to transmit even though vehicle A has already started the transmission. As a result, there is a collision at vehicle B. To eliminate the hidden terminal problem when there is no RTS/CTS mechanism, each vehicle should collect (passively hear) and broadcast time slot-occupying information of one-hop neighbors, to its OHS so that vehicles in one THS can know all occupied time slots and detect possible collisions. As in the above example, since vehicles A and C transmitted simultaneously and caused the collision at the vehicle B, the IDS of A and C will not be included in $N_{cch}(B)$; if vehicle B broadcasts this information with application data together, vehicle A (and C) could detect the collision since $B \in N_{cch}(A)$ but $A \notin N_{cch}(B)$.

B. Design Overview

In VANETs, vehicles may converge and diverge from time to time due to different velocities and routes. The collisions of slot assignment would arise when vehicles merge together on the move. Therefore, we need to assign disjoint time slots to those vehicles are bound to merge, which is the key operation of MoMAC. Specifically, the time slot assignment in MoMAC has the following three focuses:

1) When vehicles move on a multi-lane road segment, we take advantage of lane information to divide time slot sets.
2) When vehicles are at an intersection, we utilize the topology of the intersection, which converged by directional road segments, to divide time slot sets.
3) When vehicles enter an intersection from a road segment or leave an intersection to a road segment, we splice the upper two schemes together according to the geographical connection.

In the following subsections, we will first elaborate the three focuses in the time slot assignment scheme subsection and then present the time slot access approach for each vehicle.

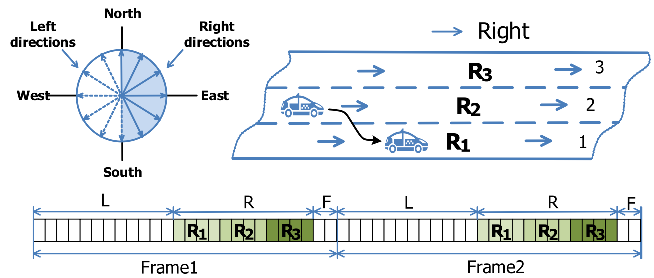


Fig. 4. Frames are divided into three slot sets, i.e., L, R, and F; set R on a 3-lane road in the right direction is further split into 3 subsets, i.e., R_1, R_2, and R_3, with each lane using one corresponding subset.

C. Time Slot Assignment Scheme

We divide complex road network into individual road segments and intersections and assign slots for each of them so as to minimize potential collisions caused by vehicle sets moving together.

On multi-lane road segments: We partition each frame into three sets of time slots, i.e., L, R, and F as shown in Fig. 4. The F set is associated with RSUs, while the L and R sets are associated with road segments in left and right directions, respectively. A road segment is said to be a left (right) road segment if it heads to any direction from north/south to west (east) as shown in Fig. 4.

As vehicles moving in different lanes in the same direction can also cause merging collisions, in MoMAC, sets L and R are further divided into l subsets according the number of lanes l in that direction, i.e., $L_1, L_2, \ldots, L_l$ and $R_1, R_2, \ldots, R_l$. The subset L_i and R_i, $i \in [1, l]$ is assigned to the ith lane in left and right direction respectively, counted from the right direction; the l can be different in left and right direction in the practical. For example in Fig. 4, set R on a 3-lane road segment in the right direction is further split into 3 subsets, i.e., R_1, R_2, and R_3, with each lane using one corresponding subset. Notice that, in practical, the system sometimes may obtain the inaccurate lane information or miss the lane-changing detection, due to the technique problem. However, it has slight effect on MoMAC, as each node holds the frame information of its THS, which can help the node choose a free slot. Moreover, MoMAC can still work like VeMAC in the worst case, when without lane information.

At intersections: To eliminate merging collisions happening at intersections as shown in Fig. 1(b), for an intersection, we assign a separate slot set for each road segment entering the intersection, called an *inbound* road segment. More specifically, given a n-way intersection, a frame is partitioned into $n + 1$ sets of time slots, i.e., ①, ②, $\ldots$, ⓝ, and F. The F set is associated with RSUs, while set ⓚ, $k \in [1, n]$, is assigned to the kth road segment entering the intersection counted anticlockwise from the north direction. In addition, set ⓚ, $k \in [1, n]$, is also assigned to the kth road segment leaving the intersection, called *outbound* road segment, counted anticlockwise from the south direction. Fig. 5 illustrates the slot assignment schemes for different types of intersections. For example, a three-way intersection is shown in Fig. 5(a). Because the road segment in the north-south direction enters the intersection (denoted by a solid arrowed line) and is the first road segment counted anticlockwise from the north, set ① is associated with this road segment. In contrast, the road segment in the opposite direction (i.e., in the south-north direction) leaves the intersection (denoted by a dashed arrowed line) and is the second road segment counted anticlockwise from the south, and therefore set ② is assigned. The same assign scheme applies to other types of intersections such as four-way intersections and five-way intersections, as shown in Fig. 5(b) and 5(c).

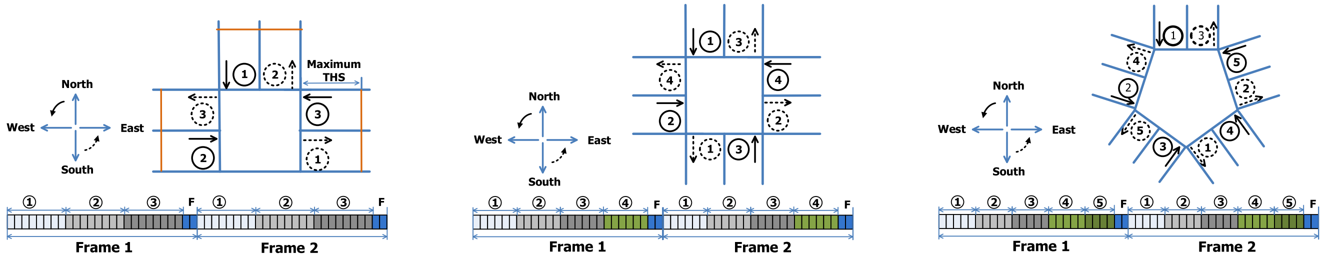
Furthermore, as the density of vehicles at intersections could be very high because of traffic control such as traffic lights and speed limits, we do not further divide set ⓚ, $k \in [1, n]$, according to lanes at intersections in order to fully utilize time slots in set ⓚ. To guarantee that any two neighboring road segments connecting to the same intersection are collision-free, the range of slot sets on each road segment is defined to be the maximum size of a possible THS, which is $2R$, as shown in Fig. 5(a).

Splicing road segments with intersections: For any given road segment and the corresponding intersections associated with the road segment, it is straightforward to splice the slot assignment schemes according to the geographical connection between the road segment and the intersections. For example, in Fig. 6, the left-direction road segment is partitioned into three parts and associated with three slot sets, i.e., set ⓘ associated with a range of $2R$ at the very left end of the road segment, set ⓜ associated with a range of $2R$ at the very right end, and set L in between.

On one hand, due to the high density of vehicles at intersections, it is possible that vehicles at intersections would contend for time slots if the number of time slots in set ⓚ, $k \in [1, n]$, is not sufficient. On the other hand, the density of vehicle at the middle of road segments tends to be low. To mitigate the slot shortage issue at intersections, in MoMAC, two extra ranges of $2R$ are added. For example of the left road segment in Fig. 6, if set L and set ⓜ have common subset, a range of $2R$ associated with set $L -$ ⓜ is arranged after set ⓜ. The purpose of this arrangement is to release time slots occupied by vehicles that have already left the intersection so that there are more free time slots available in set ⓜ for vehicles that are still at the intersection. Similarly, a range of $2R$ associated with set $L -$ ⓘis arranged before set ⓘ.

D. Time Slot Access Approach

In the header of each packet transmitted on the control channel, the transmitting node x should include set $N_{cch}(x)$ and the time slot used by each node $y \in N_{cch}(x)$. When a node x needs to acquire a time slot, it firstly listens to the channel for S consecutive time slots (not necessarily in the same frame). At the end of the S slots, the node x can obtain the information of $N^2_{cch}(x)$ and $U(x)$. As the set of $G(x)$ can be achieved based on the belonging to which road and which lane information of the vehicle as described in above subsection, the node x can derive set $A(x) = G(x) - U(x)$ and randomly choose a slot t from set $A(x)$ to use. After the node x transmits at the time slot t, it listens to the next $S - 1$ slots to determine whether the attempt to acquire the slot t is successful. If packets received from all $z \in N_{cch}(x)$ indicate that $x \in N_{cch}(z)$, it means that there is no other node in the two-hop ranges of x attempting to access the same slot t. In this case, node x is successful in acquiring slot t and each node $z \in N_{cch}(x)$ adds x to its $N_{cch}(z)$ and



(a) three-way intersection (b) four-way intersection (c) five-way intersection

Fig. 5. Assigning time slots at intersections.

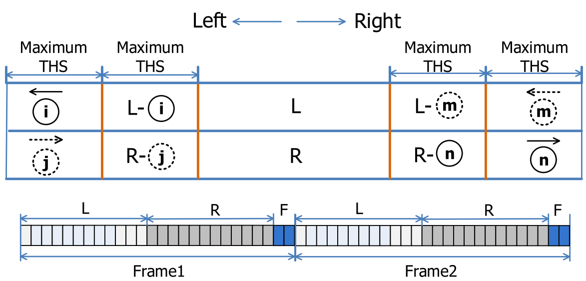


Fig. 6. Splicing road segments with intersections.

updates the corresponding set $U(z)$. Otherwise, there is at least one node within the two-hop range of node x contending with x for slot t, and collisions (called *access collisions*) happen. As a result, all nodes contending for slot t fail and each of them attempts to acquire a new time slot until succeeds. Similarly, at the end of each time slot, a particular node x can actively perform the collision detection by checking a received packet from node $y \in N_{cch}(x)$. If the packet indicates that $x \notin N_{cch}(y)$, the transmission from node x collides at node y with other concurrent transmissions. Once a collision is detected, node x will release its time slot and try to gain a new time slot.

In addition, in MoMAC, a node x needs to actively release its time slot and acquire a new one whenever necessary in order to adapt its real-time road scenarios such as changing a lane and entering or leaving an intersection. As shown in Fig. 4, assume that a vehicle x moves in the second lane of a right-direction road segment and thus the current $G(x)$ is R_2. Later, when vehicle x changes the lane from the second lane to the first lane (e.g., about to make a right turn), its $G(x)$ now also changes to R_1. Based on the latest updated $U(x)$, if there is a free time slot in R_1, it releases the original time slot in R_2 and choose a new time slot in R_1 for transmission; otherwise, it would keep its time slot in R_2 until a free time slot in R_1 is available or a collision with another vehicle in the second lane using the same time slot is detected. In this way, merging collisions caused by mobility changes can be greatly reduced. In MoMAC, although vehicles need to change slot frequently, it will not cause extra overhead cost to the original TDMA schemes. All decisions can be made based on information heard from one-hop neighbors and the local position information.

V. Performance Analysis

In this Section, we first evaluate the average number of collisions for existing TDMA-based MACs and MoMAC to demonstrate the efficiency of MoMAC theoretically. To make the MoMAC design more convincing, we then analyze the packet overhead and the medium access delay in MoMAC.

A. Average Number of Collisions

Existing TDMA-based MACs focus on how vehicles acquire time slots, detect collisions, reapply after collisions and access time slots on an individual time slot set. What MoMAC making difference on is, when time slot sets merge due to the diverse mobility. In this subsection, we theoretically analyze the average number of collisions of existing TDMA-based MACs and MoMAC respectively.

Collisions in existing TDMA-based MACs: In existing TDMA-based MACs, for instance, in Fig. 7(a), there are n ($n \geq 2$) time slot sets, each slot set includes N time slots and K vehicles accessing time slots on it. For safety applications, each vehicle needs to be assigned with a distinct time slot, thus N satisfies $N \geq nK$. When these n time slot sets merge at an intersection or in multi-lanes, hordes of vehicles from different sets may access common time slots, incurring merging collisions. For any specific time slot among N, let p_0 and p_1 be the probability of 0 and 1 vehicle using the time slot, and we have

$$p_0 = \left(\frac{C_{N-1}^K}{C_N^K}\right)^n = \left(1 - \frac{K}{N}\right)^n, \tag{1}$$

$$p_1 = C_n^1 \left(\frac{C_{N-1}^{K-1}}{C_N^K}\right)\left(1 - \frac{C_{N-1}^{K-1}}{C_N^K}\right)^{n-1} = n\frac{K}{N}\left(1 - \frac{K}{N}\right)^{n-1}. \tag{2}$$

The probability that a collision happens at a specific time slot is $(1 - p_0 - p_1)$, meaning that two or more vehicles are accessing the time slot simultaneously. Let $P(i)$ be the probability of i ($i \leq \lfloor \frac{nK}{2} \rfloor$) time slots among N encountering collisions, which satisfies

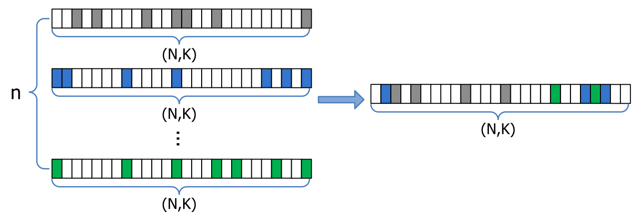
$$P(i) = C_N^i \left(1 - p_0 - p_1\right)^i \left(p_0 + p_1\right)^{N-i}. \tag{3}$$

Let M represent the average number of merging collisions, i.e.,

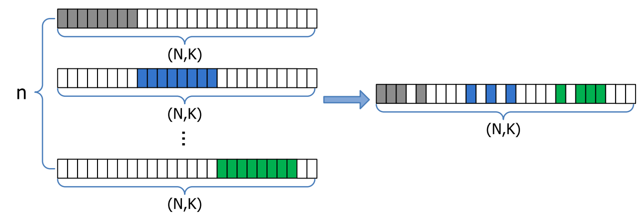
$$M = \sum_{i=1}^{\lfloor \frac{nK}{2} \rfloor} i * P(i). \tag{4}$$

As shown in Fig. 7(a), assume $2 * M$ vehicles meet merging collisions, then these vehicles will try to acquire a new time slot, incurring access collisions.[2] Consider a problem that $2 * x$

[2]For simplification, we just consider collisions which are caused by two vehicles. As three or more vehicles accessing a common slot simultaneously happens rarely, which is also hard to find in our simulation results.



(a) Merging happens in existing MACs. Collision vehicles need to acquire a new time slot.



(b) Merging happens in MoMAC. Vehicles actively release its time slot and acquire a new one when changing the mobility.

Fig. 7. Merging happens, where n time slot sets, N time slots in a frame and K vehicles accessing time slots. In addition, white blocks denote free time slots while colorful blocks denote occupied time slots.

vehicles simultaneously contend for y $(2x \leq y)$ free time slots. Let p_0 and p_1 be the probability of 0 and 1 vehicle accessing an any specific time slot among y time slots, i.e.,

$$p_0 = \frac{(y-1)^{2x}}{y^{2x}}, \tag{5}$$

$$p_1 = \frac{(y-1)^{2x-1}}{y^{2x}}. \tag{6}$$

Let $P(i)$ be the probability of i $(i \leq x)$ time slots with access collisions, i.e.,

$$P(i) = C_y^i \left(1 - p_0 - p_1\right)^i \left(p_0 + p_1\right)^{y-i}. \tag{7}$$

Then the average number of access collisions A can be calculated as

$$A = \sum_{i=1}^{x} i * P(i). \tag{8}$$

Notice that, these $2 * A$ collision vehicles will try to acquire a new time slot, which may cause new access collisions. The new average number of access collisions can be calculated like the above process until all vehicles occupy an unique time slot and then no collision will happen. Let A_j be the average number of access collisions at the jth frame. In initial stage to calculate A_1, merging collisions M can be x and free time slots y is $(N - nK + 2M)$. Then A_1 can be calculated through Eq. (8). Based on the A_j, to compute A_{j+1}, x is A_j and y is $(N - nK + 2A_j)$. Therefore, total average number of collisions T is

$$T = M + \sum_{j=1} A_j. \tag{9}$$

Collisions in MoMAC: In MoMAC, before time slot sets merging, the time slots will be rescheduled based on the vehicle mobility and road topologies described in Section IV. As shown in Fig. 7(b), before n time slot sets merging, vehicles are scheduled to disjoint time slot subsets. As a result, merging collisions M can be eliminated. However, when vehicles change the mobility such as leaving the intersection, they have to actively release their time slots and acquire a new one, which would cause additional access collisions. For instance, at an intersection, consider the access collisions caused by vehicles leaving the intersection. For each road segment, like the problem described above, the initial x and y is $\frac{(n-1)*K}{2*n}$ and $\frac{N-K}{n}$ respectively,[3] then A_1 can be calculated. Based on A_j, x and y can be expressed as A_j and $(\frac{N-K}{n} - \frac{(n-1)*K}{n} + 2 * A_j)$ for calculating A_{j+1}. Differently, the last average number of access collisions should multiply n, for n road segments existing, and thus we have

$$T = n * \sum_{j=1} A_j. \tag{10}$$

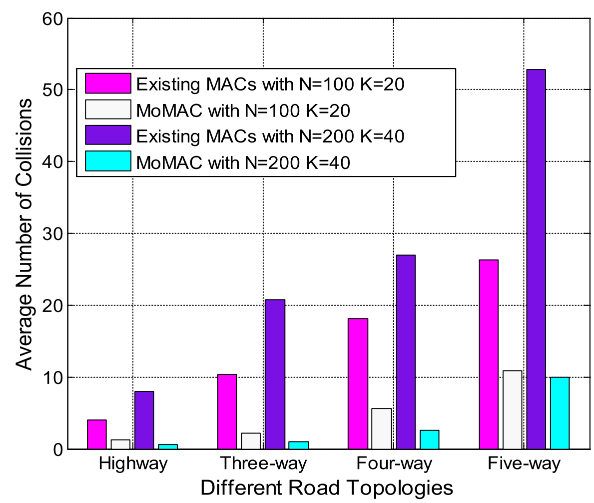


Fig. 8. Theoretical average number of collisions under different road topologies with different configuration of N and K.

Theoretical results: Fig. 8 shows the theoretical results of Eq. (9) and (10) with different configuration of n, N and K. We have the following three main observations. First, with the same N and K, MoMAC always achieve a better performance under all road topologies. For instance, when n, N and K is set to be 5, 200 and 40, respectively, the average number of collisions is 52.77 and 9.99 in existing MACs and MoMAC, respectively, which about 81.1% collisions are reduced by MoMAC. Second, when the road topology becomes complex, the average number of collisions will increase in all MACs. However the increasing range is more obvious in existing MACs, which means that

[3] We assume that, each vehicle enters another new road segment with an equal probability. Thus, for a road segment, $\frac{(n-1)*K}{n}$ vehicles may enter it and contend for unoccupied $\frac{N-K}{n}$ time slots. Notice that, due to the traffic light control, vehicles cannot enter a road segment at the same time. Thus, parameters set here are for conservative calculation.

MoMAC could be more scalable to adapt to different scenarios. Third, when increasing the value of N and K, under all road topologies, the average number of collisions increase in existing MACs while decrease in MoMAC. The reason is that, bigger values of N and K would cause much serious merging collisions, while mitigate the effect of access collisions. However, the merging collision has more negative effects than the access collision, as shown in Eq. (9).

B. Packet Overhead

The main overhead of MoMAC is the needed coordination information for medium access, including the vehicle IDs and the corresponding time slot indexes of neighbors in OHS. Let $V_{\max}$ and $V_{\max}^2$ be the maximum number of vehicles existing in a OHS and THS of one vehicle. The number of $\lceil \log_2 V_{\max}^2 \rceil$ bits are needed to represent the individual ID of vehicles in its THS, where the symbol $\lceil . \rceil$ is ceil function. To identify a specific time slot among S slots, $\lceil \log_2 S \rceil$ bits are necessary. Hence, the total overhead of MoMAC H (in bits) is

$$H = |N_{cch}(x)| \left(\lceil \log_2 V_{\max}^2 \rceil + \lceil \log_2 S \rceil \right). \tag{11}$$

As the maximum OHS area of a vehicle is a circle with the radius R, the $V_{\max}$ on a road can be computed by

$$V_{\max} = \left(\frac{2R}{\text{length}_{\text{vehicle}} + \text{distance}_{\text{safety}}} \right) * L, \tag{12}$$

where the $\text{length}_{\text{vehicle}}$ is the length of a vehicle, normally 3-5 meters for sedans, $\text{distance}_{\text{safety}}$ is the safe following distances and L is the number of lanes on the road. According to the 2 second rules, drivers should drive at least 2 seconds behind the vehicle in front during ideal conditions; given a normally speed 60 km/h in the urban environment, the $\text{distance}_{\text{safety}}$ can be obtained $\text{distance}_{\text{safety}} \approx 35$ m. Let $R = 300$ and $L = 6$ respectively for normal case, then $|N_{cch}(x)| = V_{\max} = (\frac{600}{5+35}) * 6 = 90$. Considering the conservative setting to guarantee each vehicle with a unique time slot in a THS, we set the S and $V_{\max}^2$ to be 200 empirically. The overhead in this case is $H = 90 * 16 = 1440$ bits ≈ 180 bytes. As the size of application data broadcasted by safety applications in VANETs is small, normally 200-500 bytes [29], adding such extra 180 bytes coordination data in broadcast packets is *acceptable* due to the total packet size is far less than the size of MAC layer protocol data unit.

C. Medium Access Delay

To consider the medium access delay of safety applications, we can analyze the following two cases. First, when a vehicle has acquired a time slot and use it in all contiguous frames without collisions called *stable state*, the access delay depends on the number of S and the duration of a time slot. Considering that the total packet size of MoMAC is 380 bytes and DSRC radios adopt a moderate transmission rate 12 Mbps [8], the transmission needs 0.25 ms. After adding a extra 0.05 ms for guard periods and the physical layer overhead, a 0.3 ms time slot duration can be set. A complete frame last $S = 200$ time slot durations, i.e., 60 ms, which means that the vehicle can access the medium once every 60 ms for safety message transmissions. Adding the upper layers delay and the packets queueing delay, it can still satisfy the stringent requirement 100 ms of most high-level safety applications.

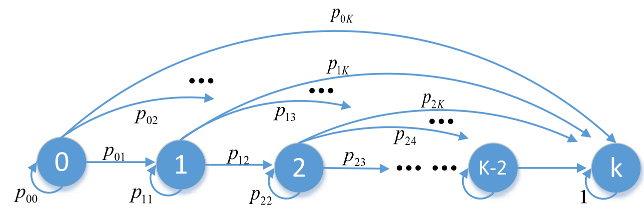


Fig. 9. The transition process of X_n.

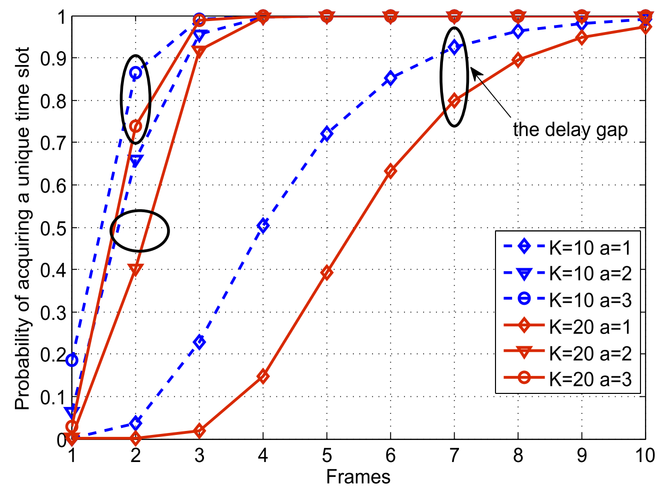


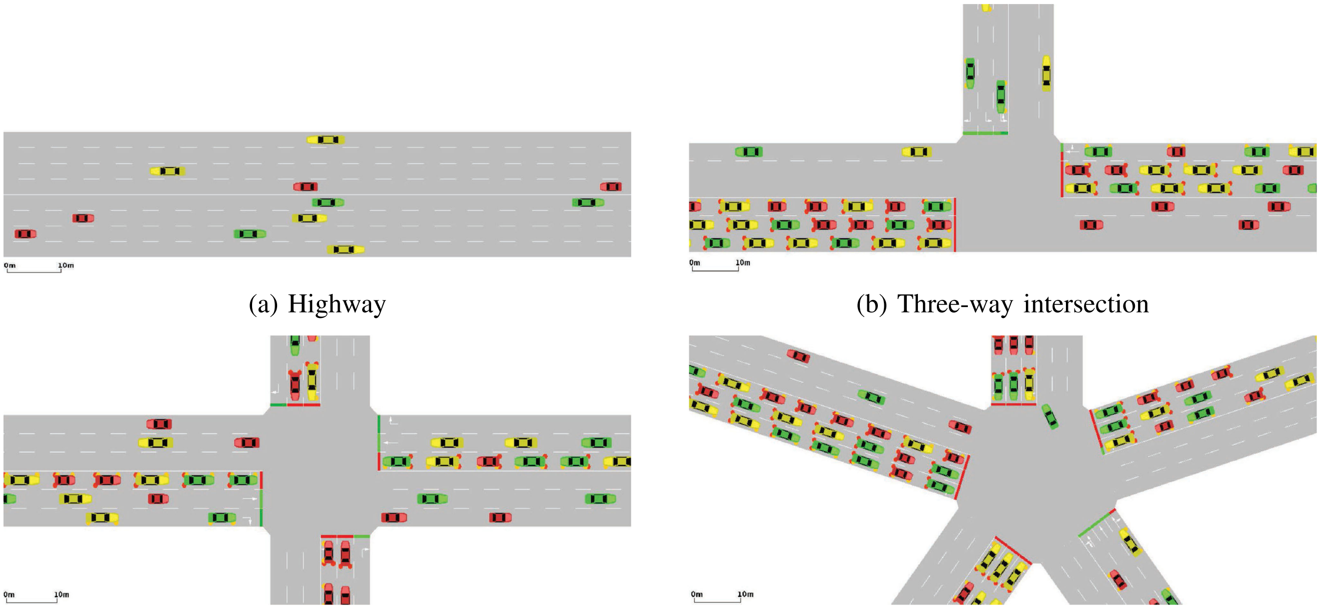
Fig. 10. The access delay under unstable state.

Another case is when a vehicle (newly opened or after colliding with others) tries to access a unique time slot, called *unstable state*. Considering a THS vehicles, there are K vehicles contending F free time slots. For safety applications, each vehicle should be guaranteed an unique time slot; we only consider $F \geq K$. During every frame, each contending vehicle will try to occupy a slot and can detect whether this trying acquisition is successful; if the vehicle successfully acquired a time slot in the frame, then the vehicle will end the contending process and transfer to stable state; otherwise the vehicle has to continue contending a slot in the following frame. Assuming that the K contending vehicles are keeping in the same THS during the contending process, the contending process can be modeled as follows. Let X_n be the number of vehicles that have successfully acquired a unique time slot at the end of nth frame and $X_0 = 0$ be the initial state, X_n then is a stationary discrete-time Markov chain and the transition process is shown in Fig. 9[4] with the following transition probabilities,

$$p_{ij} = \begin{cases} \dfrac{f(j-i, K-i, F-i)}{(F-i)^{K-i}} & 0 \leq i \leq K-2, \\ & i \leq j \leq K; \\ 1 & i = j = K; \\ 0 & i > j \quad \text{or } i = K-1 \\ & \text{or} \quad j = K-1, \end{cases} \tag{13}$$

where the $f(l, u, v)$ is the number of cases that for v available free time slots, l nodes successfully acquire a unique time slot

[4]Note that, the X_n has no possibility to be the value $K-1$, as one vehicle cannot collide only by itself.



(a) Highway (b) Three-way intersection (c) Four-way intersection (d) Five-way intersection

Fig. 11. Snapshots of the simulated scenarios.

among u contending nodes. To compute the value of $f(l,u,v)$, $l \le u \le v$, we can consider the case that there are u balls needed to pack into v boxes; each box can support more than one balls; $f(l,u,v)$ is the number of packing ways satisfying that existing l boxes only contain one ball and the other $v-l$ boxes are either empty or contain more than one balls. Then the $f(l,u,v)$ satisfies

$$f(l,u,v) = \begin{cases} C_u^l A_v^l ((v-l)^{u-l} - \\ \sum_{i=1}^{u-l} f(i, u-l, v-l)) & 0 \le l < u; \\ A_v^l & l = u. \end{cases} \quad (14)$$

Based on this, the one-step transition probability matrix P can be computed. Let P^n be the n-step transition probability matrix, the first row of P^n represent the distribution of X_n, i.e.,

$$p(X_n = i) = P^n_{1,i+1}, i \in [0, K]. \quad (15)$$

The probability that a specific vehicle successfully acquires a unique time slot within n frames is

$$p_{\text{success}} = \Sigma_{i=1}^{K} \frac{C_{K-1}^{i-1}}{C_K^i} p(X_n = i) = \frac{\Sigma_{i=1}^{K} i P^n_{1,i+1}}{K} \quad (16)$$

Fig. 10 shows the numerical results of Eq. (16). For better comparison, we introduce a coefficient a to describe the relationship between contending nodes K and available free time slots F, i.e.,

$$F = aK \quad (17)$$

From Fig. 10, we have the following two guidelines. First, when resource is limited, collisions should be carefully avoided as they can incur severe access delay; for instance, when $K = 10$, to achieve a more than 90% probability of successfully acquiring a unique time slot, 7 frames, 3 frames and 2 frames are required under the set of $a = 1$, $a = 2$ and $a = 3$, respectively. Second, under the same resource conditions, collisions can also affect the access delay; specifically, when $a = 1$, the probability can reach 72% at the 5th frame with the set of $K = 10$, while the probability would only be 39% at the 5th frame with the set of $K = 20$. As safety applications in VANETs have a very low tolerance in terms of messages delivery delay, medium access delay as the main delay should be carefully guaranteed without collisions, which is also the main focus of MoMAC.

VI. Performance Evaluation

In this section, we conduct extensive simulations to evaluate the efficiency of MoMAC, considering various practical road topologies and traffic conditions.

A. Methodology

Simulation setup: We conduct simulations to evaluate the performance of MoMAC by using the Simulation of Urban Mobility (SUMO)[30]. Specifically, we construct two typical VANET scenarios, i.e., highways and urban surface road network. Specifically, in the highway scenario, a bidirectional 8-lane highway of 10 km long is used and each of the four lanes in one direction is given a speed limit of 60 km/h, 80 km/h, 100 km/h and 120 km/h, respectively. On the other hand, in the urban scenario, three different star topologies are used with different types of intersections, i.e., 3-way, 4-way and 5-way, locating at the center and connecting to three, four and five bidirectional 6-lane roads of 4km long, respectively. Additionally, a respective speed limit of 50 km/h, 60 km/h and 70 km/h is set for each of the three lanes in one direction. Plus, traffic lights are set at each inbound road segment at intersections with the duration of green light being 20 s. Note that the reason that we consider star topologies is to gain better control over different traffic conditions, without losing generality. More complex topologies can be easily build with star topologies.

In both scenarios, vehicles have different performance parameters, e.g., maximum velocity (ranging from 80 km/h to 240 km/h), acceleration ability (ranging from 1 m/s^2 to 5 m/s^2),

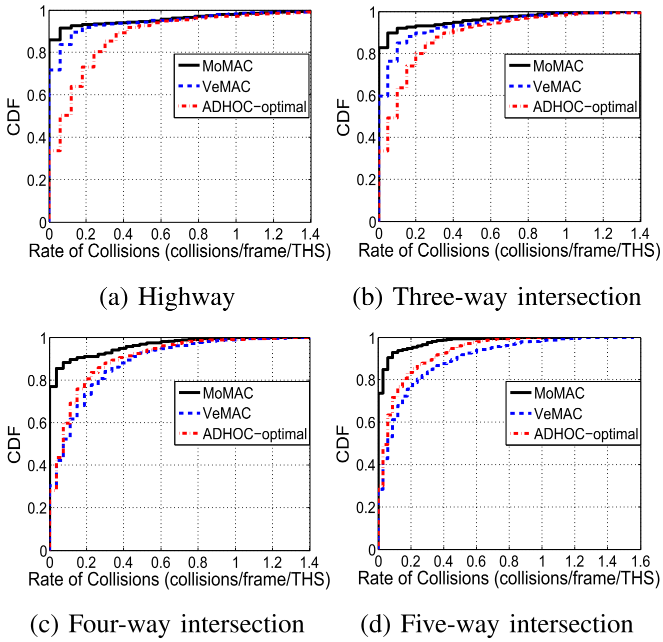


Fig. 12. CDFs of rate of collision in different scenarios under moderate traffic condition.

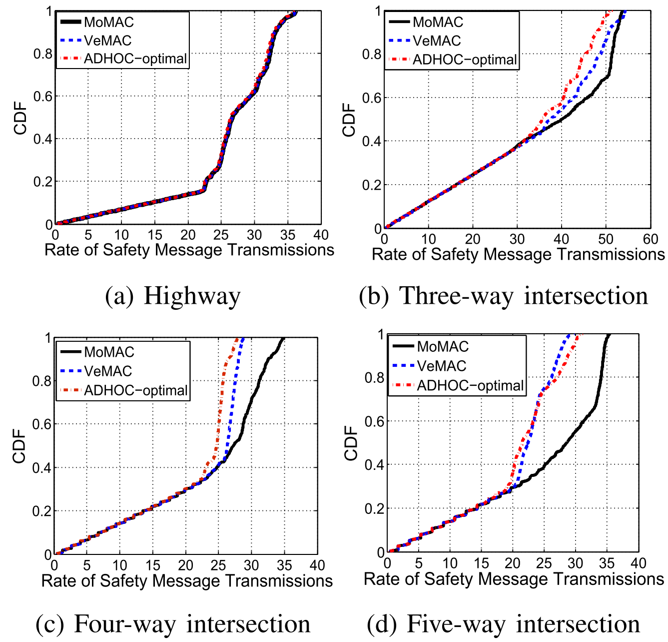


Fig. 13. CDFs of rate of safety message transmissions in different scenarios under moderate traffic condition.

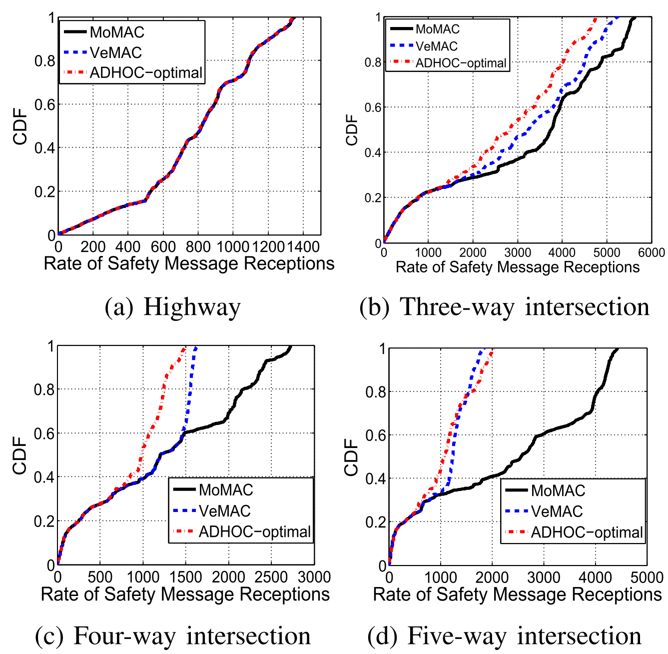


Fig. 14. CDFs of rate of safety message receptions in different scenarios under moderate traffic condition.

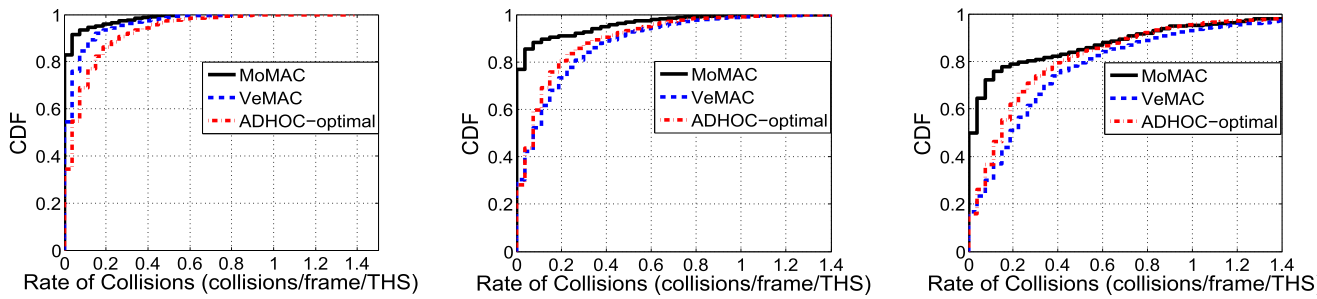
and deceleration ability (ranging from 3 m/s^2 to 10 m/s^2). We configure ten different settings of vehicle parameters according to the main types of vehicles on the market and randomly associate one of them to every vehicle. To mimic different traffic conditions in a day, vehicles are generated at the open end of each road segment with respective rates heavy (10 vehicles/lane/minute), moderate (5 vehicles/lane/minute), and light (3 vehicles/lane/minute). Each vehicle randomly chooses the destination road segment and the lane when enters a road segment, and are driven under the Krauss car-following model and the LC2013 lane-changing model. In addition, driver imperfection parameter is also introduced in simulations to mimic normal driving behaviors of human. Fig. 11 shows the simulated scenarios, including highways, three-way, four-way and five-way intersections; vehicles with different colors are configured with different performance.

In all simulations, the transmission range R is set to be 300 m according to the observation that 802.11p-compatible onboard units can support reliable data transmission within 300 m [27]. As the performance of MAC protocols is studied, we consider all transmissions successful unless slot usage collisions happen. Following the requirement of safety applications [3], the time duration of a frame is set to be 100 ms in light with the rigid time requirement on safety-related applications and the number of time slots in a frame is set to be 200. Each simulation lasts for 1,500 s of simulation time.

Performance metrics: We consider the following metrics to evaluate the performance of MoMAC:

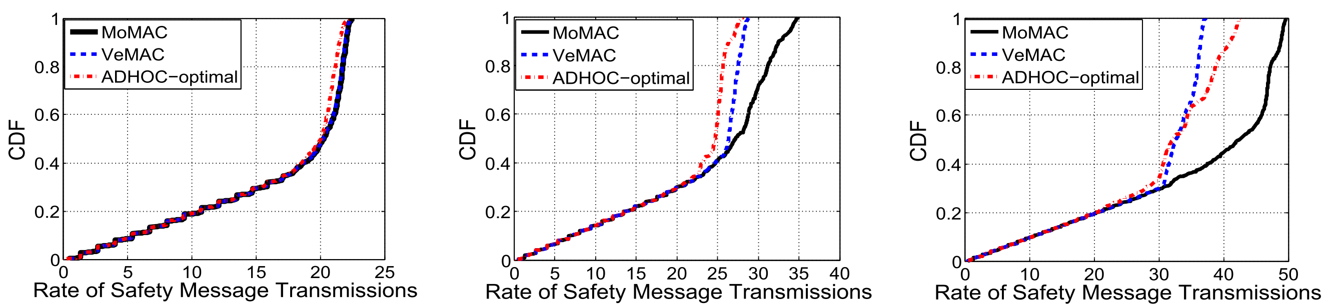
1) *Rate of collisions:* refers to the average number of transmission collisions per frame per THS.[5]
2) *Rate of safety message transmissions:* refers to the average number of successful safety messages transmissions per frame per THS. A successful transmission means when a node broadcast a packet, there is no other concurrent transmissions happening at the same time slot within its THS.
3) *Rate of safety message receptions:* refers to the average number of successfully received packets per frame per THS.

[5]To get the metrics in per THS, the metric is calculated first for the whole simulation area, and then multiplied by $\frac{2R}{L}$ or $\frac{2R}{L} \times \frac{1}{N}$ for the highway and urban scenarios respectively, where $2R$ is a maximum THS length, L is the length of the road segment and N is the number of inbound road segments at an intersection.



(a) Light traffic (b) Moderate traffic (c) Heavy traffic

Fig. 15. CDFs of rate of collisions under different traffic conditions in the four-way intersection scenario.



(a) Light traffic (b) Moderate traffic (c) Heavy traffic

Fig. 16. CDFs of rate of safety message transmissions under different traffic conditions in the four-way intersection scenario.

We compare MoMAC with ADHOC-optimal (i.e., an upgraded version of ADHOC MAC [5]) and VeMAC [6].

B. Impact of Various Road Topologies

We first evaluate how the road topology affects the MoMAC performance. Fig. 12 shows the cumulative distribution functions (CDFs) of rate of collisions in different scenarios with the moderate traffic condition. We have the following two main observations. First, MoMAC can achieve lowest rate of collisions in all scenarios. Second, with the topology becoming complex, the performance of both VeMAC and ADHOC MAC degrade, while the performance of MoMAC remains stable in all scenarios. For instance, the probability of a transmission without being collided achieved by MoMAC is 85.9%, 82.8%, 76.8%, and 73.6% in the highway, three-way intersection, four-way intersection and five-way intersection, respectively, while the probability in VeMAC is 71.7%, 59.8%, 30.4%, and 28.3%; in ADHOC MAC, the values are less than 33.6% in all scenarios. As more road segments combine at the intersection, more vehicle sets will move together incurring hordes of merging collisions. In MoMAC, just a slight increasing of transmission collisions shows its advantages to adapting diverse road topologies.

Fig. 13 shows the CDFs of rate of safety message transmissions in different scenarios. We have the following two main observations. First, MoMAC can achieve supreme rate of safety message transmissions in all scenarios. Second, the CDF gaps between MoMAC and other two MACs increases when the road topology becomes complex. For example, in Fig. 13(a), the CDFs of rate of safety message transmissions under three protocols are tightly closed, whereas in Fig. 13(d), the obvious CDF gaps show up. As the road topology becomes complicated and more vehicles are bound to merge, the transmission collision effects on VeMAC and ADHOC MAC are more serious than the effect on MoMAC. The similar observations are also held for rate of safety message receptions, as shown in Fig. 14. Differently, due to the broadcast scheme, much more benefits are achieved by MoMAC in terms of rate of safety message receptions. For instance, in Fig. 13(d) and 14(d), with the CDF value of 0.5, the gap between MoMAC and other two MACs of rate of safety message transmissions is about 10/frame/THS, while the gap of rate of safety message receptions reaches 1200/frame/THS. This means that more than 1200 safety message receptions can be achieved every 100 ms by vehicles in a THS when adopts MoMAC.

C. Impact of Dynamic Traffic Conditions

We further investigate the impact of traffic conditions on MoMAC performance. Fig. 15 shows the CDFs of rate of collisions under different traffic conditions in the four-way intersection scenario. We have the following two main observations. First, MoMAC can achieve the minimum number of collisions in all traffic conditions. Second, with heavier traffics, the performance degrades in all three MACs. However, when meeting the heaviest traffics as shown in Fig. 15(c), MoMAC still effectively works with a probability of 49.9% without collisions, whereas the probability is about 16.6% and 15.6% in VeMAC and ADHOC MAC, respectively. The results demonstrate that MoMAC can work reliably under all traffic conditions while VeMAC and ADHOC MAC have poor performance when meeting heavy traffics. Fig. 16 shows the CDFs of rate of safety message transmissions under three different traffic conditions in the four-way intersection scenario. We have the following two main observations. First, MoMAC achieves a higher rate of safety message transmissions in all traffic conditions. Second, the CDF gaps between MoMAC and other two MACs become more obvious when the traffic condition becomes heavier, which indicates that the heavy traffic has slighter effects on MoMAC compared with other two MACs. Results of rate of safety message receptions are omitted due to the similar observations and space limitations.

VII. Conclusions and Future Work

In this paper, we have proposed a mobility-aware TDMA MAC protocol for VANETs, named as MoMAC, to reduce transmission collisions in the moving. We have first identified two common mobility scenarios that would incur massive transmission collisions in vehicular environments. A simple yet effective slot assignment scheme is then proposed which fully utilizes the underlying road topology and lane layout, to reply the potential demands of vehicular mobility. To eliminate the hidden terminal problem, MoMAC adopts a fully distributed slot access and collision detection scheme. Theoretical analysis and extensive simulation results demonstrate the efficiency of MoMAC. Our future work is to utilize RSUs to act as coordinators, which can calculate the current traffic condition, make an optimal slot assignment for uneven traffic, and broadcast to vehicles in vicinity. MoMAC can fit in this solution very well as RSUs can listen to all broadcasted messages and do statistics about the traffic condition on each road segment and then use their time slots to broadcast out the up-to-date slot assignment scheme. We leave this as one interesting direction to further enhance the performance of MoMAC in the future.

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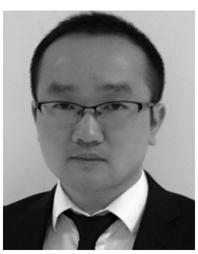
Feng Lyu (M'18) received the B.S. degree in software engineering from Central South University, Changsha, China, in 2013 and the Ph.D. degree from Shanghai Jiao Tong University, Shanghai, China, in 2018. His research interests include vehicular ad hoc networks, cloud/edge computing, and big data driven application design.

Hongzi Zhu (M'10) received the M.Eng. and B.S. from Jilin University, Changchun, China, in 2001 and 2004, respectively, and the Ph.D. degree from Shanghai Jiao Tong University, Changchun, China, in 2009. He was a Postdoctoral Fellow with the University of Waterloo and the Hong Kong University of Science and Technology in 2009 and 2010, respectively. He is currently an Associate Professor with the Department of Computer Science and Engineering, Shanghai Jiao Tong University. His research interests include wireless networks, mobile sensing and mobile computing, and vehicular ad hoc networks. He was the recipient of the Best Paper Award from IEEE Globecom 2016. He is a member of IEEE Computer Society and IEEE Communications Society.



Haibo Zhou (M'14–SM'18) received the Ph.D. degree in information and communication engineering from Shanghai Jiao Tong University, Shanghai, China, in 2014. From 2014 to 2017, he was a Postdoctoral Fellow with the Broadband Communications Research Group, ECE Department, University of Waterloo. He is currently an Associate Professor with the School of Electronic Science and Engineering, Nanjing University, Nanjing, China. His research interests include resource management and protocol design in cognitive radio networks and vehicular networks.

Liping Qian (S'08–M'10–SM'16) received the Ph.D. degree in information engineering from the Chinese University of Hong Hong, Hong Kong, in 2010. During 2010–2011, she was a Postdoctoral Research Associate with the Chinese University of Hong Kong, Hong Kong. Since 2011, she has been with the College of Information Engineering, Zhejiang University of Technology, Hangzhou, China, where she is currently a Full Professor. From 2016 to 2017, she was a Visiting Scholar with the Broadband Communications Research Group, ECE Department, University of Waterloo. Her research interests include wireless communication and networking, resource management in wireless networks, massive IoTs, mobile edge computing, emerging multiple access techniques, and machine learning oriented towards wireless communications. She was a co-recipient of the IEEE Marconi Prize Paper Award in Wireless Communications in 2011, and the Best Paper Award from IEEE ICC 2016, and the Best Paper Award from IEEE Communication Society GCCTC 2017. She is currently on the Editorial Board of IET Communications.

Wenchao Xu received the B.E. and M.E. degrees from Zhejiang University, Hangzhou, China, in 2008 and 2011, respectively. He is currently working toward the Ph.D. degree at the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. In 2011, he was with Alcatel Lucent Shanghai Bell Co. Ltd., where he was a Software Engineer for telecom virtualization. His research interests include wireless communications with emphasis on resource allocation, network modeling, and mobile data offloading.

Minglu Li (M'08–SM'10) received the Ph.D. degree in computer software from Shanghai Jiao Tong University, Shanghai, China, in 1996. He is currently a Full Professor and the Vice Dean of the School of Electronics Information and Electrical Engineering, the Director of Network Computing Center, Shanghai Jiao Tong University. His research interests include grid computing, services computing, and sensor networks.

Xuemin (Sherman) Shen (M'97–SM'02–F'09) received the B.Sc. degree from Dalian Maritime University, Dalian, China, in 1982 and the M.Sc. and Ph.D. degrees in 1987 and 1990, respectively, from Rutgers University, NJ, USA, all in electrical engineering. He is currently a University Professor and the Associate Chair of graduate studies with the Department of Electrical and Computer Engineering, University of Waterloo, ON, Canada. His research interests include resource management, wireless network security, social networks, smart grid, and vehicular ad hoc and sensor networks. He was the Technical Program Committee Chair/Co-Chair for IEEE Globecom'16, Infocom'14, IEEE VTC'10 Fall, and Globecom'07, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08, the General Co-Chair for ACM Mobihoc'15, Chinacom'07 and the Chair for IEEE Communications Society Technical Committee on Wireless Communications. He was the Editor-in-Chief for the IEEE INTERNET OF THINGS JOURNAL, IEEE NETWORK, *Peer-to-Peer Networking and Application*, and *IET Communications*; a Founding Area Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, COMPUTER NETWORKS, AND ACM/WIRELESS NETWORKS, etc.; and the Guest Editor for the IEEE JSAC, IEEE WIRELESS COMMUNICATIONS, and IEEE COMMUNICATIONS MAGAZINE, etc. He was the recipient of the Excellent Graduate Supervision Award in 2006, and the Premiers Research Excellence Award in 2003 from the Province of Ontario, Canada. He is a Registered Professional Engineer in the State of Ontario, Canada, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, a Royal Society of Canada Fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology Society and Communications Society.