# AODMAC: An Adaptive and On-Demand TDMA-Based MAC for Vehicular Ad Hoc Networks

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**Abstract.** To solve the high transmission collisions and channel resource wastage problems in unbalanced traffic conditions of VANETs, an adaptive and on-demand TDMA-based MAC (AODMAC) protocol is proposed. A dynamic frame is partitioned into equal slot sets according to the lane numbers, and each lane has its own disjoint time slot set for vehicles to access. The key operation of AODMAC is that it can adaptively adjust the size of slot set according to the different traffic density in each lane. Due to each lane can acquire its slot set on-demand, AODMAC can be efficient in both balanced and unbalanced traffic load scenarios. Before a vehicle can acquire a time slot, it should judge the traffic load of its lane. If the density has exceeded a threshold, the node should augment its slot set size from the other lane. Simulation results show that the proposed protocol outperforms VeMAC and MoMAC in terms of the transmission collision rate and channel utilization, especially in high traffic load and unbalanced conditions.

**Keywords:** VANETs · Adaptive MAC · On-demand · TDMA-based · Distributed

## 1 Introduction

Vehicular ad hoc networks (VANETs) is a special kind of mobile ad hoc networks (MANETs) which consist of a set of vehicles equipped with on-board units (OBU) and road-side units (RSUs), through V2V or V2R communications to realize a broad range of safety and non-safety applications [1]. Because of the special characteristics of VANETs, such as high mobility of the node, frequent change of topologies and different quality of service (QoS) requirements of different applications, to design an efficient and fair medium access control (MAC) protocol is a critical and challenging issue. However, we note that some characteristics can help us to develop MAC protocols, such as the sufficient power supply and the limited degrees of freedom in the nodes' movement constraint to the road topology.

Various MAC protocols have been proposed for VANETs. Literature [2] surveys the existing MAC protocols. In particular, the IEEE 802.11p [3] is the standard for Wireless

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Access in Vehicular Environment (WAVE). WAVE is operation mode which is used by IEEE 802.11p devices to operate in the dedicated short range communication (DSRC) band which is firstly coined by FCC. However, the IEEE 802.11p employs CSMA/CA-based distributed coordinated function (DCF) mechanism, which is a contention-based protocol. It performs well in the low traffic density as CSMA/CA can cover the topology changing in a sparse scenario. However, the access delay will grow to a significant level in the dense traffic condition. Moreover, the absence of RTS/CTS scheme in broadcast mode for efficient requirements will aggravate the hidden terminal problem, i.e., a collision occurs at a common neighbor node when other two senders cannot hear each other.

For the delay-bounded requirement in safety-related applications and throughput requirement in non-safety-related applications, time division multiple access (TDMA) based MACs have demonstrated their efficiency in VANETs. These protocols fall into three categories: centralized [4], cluster-based [5, 6] and fully distributed [7–12].

A fully distributed protocol is easy to deploy and its operational principle is relatively simple. Therefore, many distributed TDMA MAC protocols have been proposed. The ADHOC MAC proposed in [7] is a typical one. It operates in a frame-slot structure. By letting each vehicle reports its status within its transmission range in frame information (FI) periodically, ADHOC can support a reliable broadcast service without the hidden terminal problem. Moreover, in ADHOC, each node is guaranteed to access the medium at least once in a frame, which is suitable for the applications with delay-bounded. However, some limitations make ADHOC MAC inefficient. Firstly, due to node mobility, merging collisions may occur frequently. Secondly, ADHOC MAC is a single channel protocol that is not suitable for the seven DSRC channels.

Taking the problems encountered in ADHOC into consideration, Omar et al. proposed VeMAC in [8, 9]. VeMAC is a multichannel protocol with two transceivers and its main idea is to divide the frame into disjoint slot sets and then map these two sets to the vehicles on the opposite direction of road. Accordingly, (adaptive TDMA slot assignment) ATSA MAC in [10] further considers the unbalanced traffic load in opposite direction and it makes an adaptive classification of time slots, dynamically changes the frame length and adjusts the ratio of left slots and right slots according to the density of nodes. The results show that the ATSA can reduce the slot collisions, achieve the minimal time delay and maximum channel utilization compared with the ADHOC and VeMAC protocol. Similarly, A-VeMAC in [11] is based on VeMAC protocol, unlike VeMAC, which equally partitions each frame, the frame partitioning with A-VeMAC is not equal. Instead, it can adaptively vary with the vehicle traffic conditions in opposite directions. However, both VeMAC and ATSA protocols cannot solve the possible merging collision problem that the vehicles with different speeds in the same direction move together. A mobility-aware TDMA MAC (MoMAC) [12] is proposed 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. However, two main limitations still exist in MoMAC. One is that under unbalance traffic load in different lanes, the slot sets assign scheme in MoMAC will cause slot wastage in sparse lanes and severe collisions in dense lanes. The other one is that MoMAC is a single channel protocol which cannot effectively use the seven channels. To solve the problems discussed before, it is necessary to design a multichannel MAC suitable for an unbalanced scenario, which motivates us to design this MAC protocol.

In this paper, we propose an adaptive and on-demand TDMA-based MAC (AODMAC) protocol for VANETs. A dynamic frame is partitioned into equal sets according to the lane numbers, and each lane has its own disjoint time slot sets for vehicles to access. The key operation of AODMAC is that it can adaptively adjust the size of the slot set according to the different traffic density in each lane. Due to each lane can acquire slot sets on-demand, AODMAC can be efficient in both balanced and unbalanced traffic density scenarios. Before a vehicle can acquire a time slot, it should judge the traffic load of its lane. If the density has exceeded the threshold, the node should augment its slot size from the other lane. Once the adjustment is completed, it will determine a set of slots that are available for the vehicle to reserve and randomly select one for reservation.

The remainder of this paper is organized as follows. Section 2 describes the proposed AODMAC protocol. Section 3 evaluates the performance of AODMAC. Section 4 concludes this paper.

## 2 AODMAC Protocol

In this section, we will demonstrate the proposed AODMAC protocol.

### 2.1 Preliminaries

In TDMA-based MAC protocols, access time is divided into consecutive frames consisting of a constant number of fixed duration time slots. The number of time slots per frame on control channel (CCH) is denoted by $N$. Every node (i.e. vehicle) is equipped with a global positioning system (GPS) receiver and thus can accurately determine its position and direction as well as its lane with the help of lane-level digital map. On the one hand, each node must acquire a time slot before transmission and can use it in all subsequent frames until a collision occurs or the node releases it. On the other hand, if a node gets a slot, it must transmit a packet during its time slot even if the node has no data to send. The reason is that the information in the header called frame information (FI) is necessary for other nodes to make decisions such as which time slot they can access on CCH and if the node should adjust the available slot set as discusses later.

In TDMA-based MAC protocols, all the neighboring vehicles in the communication range of a vehicle constitute the one-hop set (OHS) of the vehicle. In addition, the two-hop set (THS) of a vehicle refers to all the vehicles that can reach it in two hops at most. Figure 1 illustrates the notion of the OHS and THS.

There are two kinds of transmission collisions in the existing MAC protocols, i.e., *access collision* and *merging collision*. The access collision refers to two nodes in the same THS simultaneously access the same time slot; while the merging collision happens when the vehicles that occupy the same time slot in the different THS move to the same THS due to mobility or node activation. In VANETs, merging collisions can occur among vehicles in opposite directions as well as among vehicles in the same direction

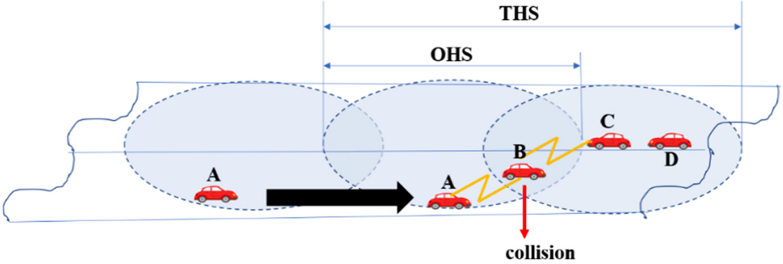

**Fig. 1.** Notion of OHS, THS and merging collision.

but different lanes due to acceleration or deceleration. For example, in Fig. 1, if vehicle A and C use the same slot and A moves to the THS of C, the collisions will happen at B.

These transmission collisions discussed above can be detected based on the FI that received from all the neighboring nodes in the OHS during the previous $N$ time slots. Specifically, for node A, whenever it gets a new time slot or transmits a packet, it should passively listen to the channel for $N$ successive time slots (not necessarily in the same frame), if the FI received from all its OHS (i.e. $y \in N_{CCH}(A)$)[1] indicate that $A \in N_{CCH}(y)$ [12], it means that there are no other vehicle occupies the same time slot in the THS; otherwise, the node may encounter a collision and all the collided nodes should release the slot and access a new one.

### 2.2 Design Overview

In accordance with MoMAC [12], disjoint slot sets map to the different lanes for vehicles to access. We denote the lane number $l$ as follows. From the center lane to the margin, in the right direction, the number increases from 1; while on the left direction, the number decreases from $-1$. And a vehicle is assumed to move in a left (right) direction if it is moving from north/south to west (east). An example is illustrated as in Fig. 2.

Unlike MoMAC, the partitioning of each frame is not fixed. Instead, it can adaptively adjust according to the different traffic density in each lane. Due to each lane can acquire slot set on-demand, AODMAC can achieve efficiency in both balanced and unbalanced traffic density scenarios. Enhance the MoMAC, for the service channel, AODMAC employs the same access mechanism used in VeMAC.

### 2.3 Frame Structure

The initial frame structure in AODMAC is illustrated in Fig. 3, but it can be dynamically adjusted according to the traffic density in the lane when a vehicle needs to reserve a slot. Denote $L$ as the number of lanes on a specific road, and each frame consists of $N$ time slots, which are partitioned into $L$ disjoint sets: $N_l(x), l = \pm 1, \pm 2, \ldots$, vehicles are allowed for reservation in set $N_l(x)$ when they are moving in the lane $l$. $|N_l(x)|$ denotes the size of the slot set that lane $l$ maps to, and at the first beginning, $|N_l(x)| = \frac{N}{L}, l = \pm 1, \pm 2, \ldots$.

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[1] $N_{CCH}(A)$ denotes the set of IDs of vehicle A's one-hop neighbors, which are updated by whether A has received packets directly on the channel during the previous $N$ slots.

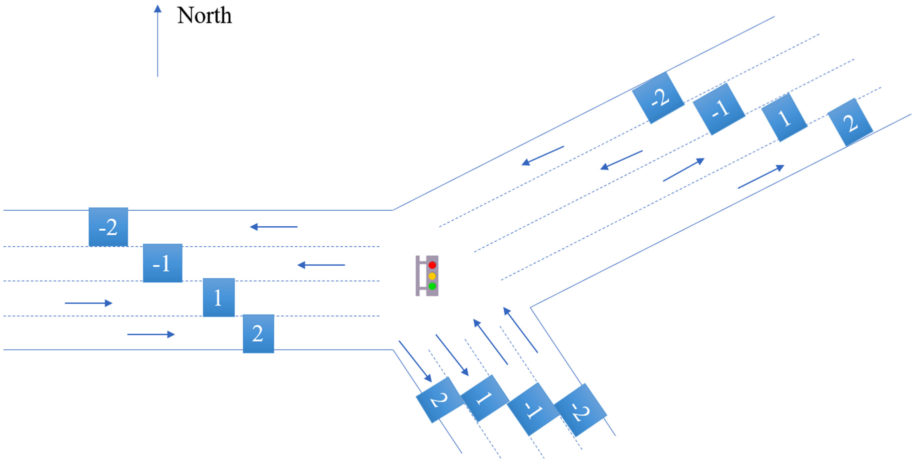


**Fig. 2.** An example of road topology and lane number.

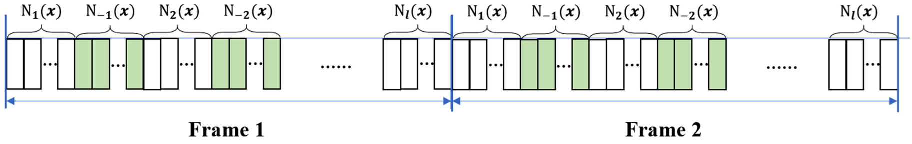


**Fig. 3.** Frame structure in AODMAC.

To facilitate time slot assignment in a distributed way, each vehicle needs to 1) maintain a THS-table including the information of its neighboring vehicles in one-hop and two-hops ranges as well as 2) maintain the frame information (FI). The structure of FI used in AODMAC is shown in Fig. 4 and the THS-table format is shown in Fig. 5. Note that $ID = 0$ and/or $Lane = 0$ means the slot is idle in a THS range. Specifically, for a vehicle, it generates/update its FI and THS-table on the basis of the information received from the previous $N$ time slots and the process is as follows:

- Vehicle $x$ will record its current ID, lane number and slot index into the FI's first three fields;
- According to the FI received from previous $N$ time slots, the vehicle can record each FI's first three fields into the SI, and $SI_k$, $k \in [0, N-1]$ denotes the occupancy status of slot $k$ including ID and lane number;
- Simultaneously, according to the FI received from previous $N$ time slots, vehicle $x$ can record each FI's SI field into THS-table, which denotes the two-hop range slot status.

With the above information, vehicle $x$ can transmit the updated FI when the corresponding slot coming and decide the whole slot status in two-hops range which can be used for slot adjustment or collision detection. Therefore, for a certain node, the following sets are defined and will be used in the next section:

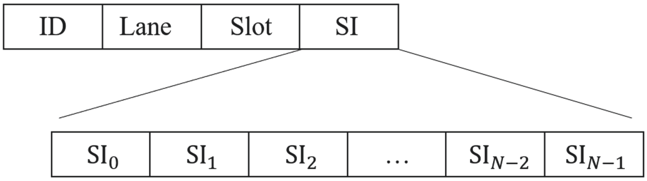
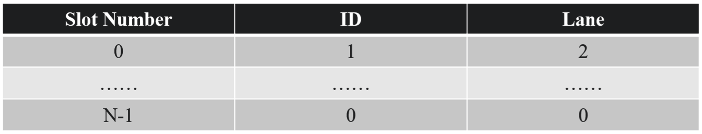


**Fig. 4.** Structure of FI in AODMAC.



| Slot Number | ID | Lane |
|---|---|---|
| 0 | 1 | 2 |
| …… | …… | …… |
| N-1 | 0 | 0 |

**Fig. 5.** THS-table format.

- $V_l(x)$: a set of one-hop and two-hop neighboring vehicles of vehicle $x$ associated with the lane $l$.
- $T(x)$: a set of time slots that reserved by one-hop and two-hop range neighboring vehicles of vehicle $x$.

### 2.4 On-Demand and Adaptive Slot Sets Adjustment Scheme

In AODMAC, slot set size can be adaptively adjusted according to the traffic load in a specific lane. We define $D_l(x), l = \pm 1, \pm 2, \ldots$ as the traffic density in lane $l$ which is calculated by vehicle $x$, and it can be derived as follows:

$$D_l(x) = \begin{cases} L, \frac{|V_l(x)|}{|N_l(x)|} < U_{min} \\ M, U_{min} \leq \frac{|V_l(x)|}{|N_l(x)|} \leq U_{max} \\ H, \frac{|V_l(x)|}{|N_l(x)|} > U_{max} \end{cases}, \tag{1}$$

where $L, M$ and $H$ denote the low, medium and high traffic density, respectively; $U_{min}$ and $U_{max}$ are the thresholds to classify the traffic load and the value are design parameters.

We define two kinds of vehicles in AODMAC, i.e., *reserved vehicle* and *non-reserved vehicle*. A reserved vehicle denotes that the vehicle has acquired a slot no matter from the initial slot set or the augmented slot set; A non-reserved vehicle denotes that the vehicle has not occupied a slot. Accordingly, the slot sets adjustment scheme can be divided into two cases:

**For a Non-reserved Vehicle.** As the flow chart shown in Fig. 6. Before a vehicle $x$ in lane $\lambda, \lambda \in l$ can acquire a slot, it will first estimate $D_l(x), l = \pm 1, \pm 2, \ldots$ based on Eq. (1). If $D_\lambda(x) = L$ or $D_\lambda(x) = M$, then the size of $N_\lambda(x)$ needs not to be adjusted, and the vehicle will try to acquire a slot in $A'_\lambda(x)$, where

$$A'_\lambda(x) = \overline{T_\lambda(x)} \cap N_\lambda(x). \tag{2}$$

However, if $D_{\lambda}(x) = H$, it denotes the density of the lane λ is over the threshold, and hence the size of $N_{\lambda}(x)$ should be augmented. Then, vehicle $x$ compares the $D_l(x)$, $l = \pm 1, \pm 2, \ldots$ to find if $D_l(x) = L$ exists; if true, vehicle $x$ will give preference to select the nearest slot sets to augment, the reason is that we assume the closer the lane, the similar the movement of vehicles, which means the less probability of merging collisions will occur; if false, vehicle $x$ will continue to find if $D_l(x) = M$ exists, similarly, vehicle $x$ will give preference to select the nearest slot sets to augment. After adjusting the slot set, vehicle $x$ can randomly access in set $A''_{\lambda}(x)$ derived as follows:

$$N'_{\lambda}(x) = N_{\lambda}(x) \cup A'_{\mu}(x), \tag{3}$$

$$A''_{\lambda}(x) = \overline{T_{\lambda}(x)} \cap N'_{\lambda}(x), \tag{4}$$

where $A'_{\mu}(x)$ which can be derived from Eq. (2) denotes that vehicle $x$ finally decides to augment from the slot set $\mu$.

If all the $D_l(x) = H$, vehicle $x$ will not augment its set and acquire a slot in its initial set, and this case will give detailed solutions in our future work, i.e., to adjust the frame time to get a trade-off between the transmission delay and reliability.

**For a Reserved Vehicle.** When the slot of vehicle $x$ coming, before it can transmit a packet, vehicle $x$ should judge if the current using slot $k$ belongs to its initial slot set. If not, it should calculate the $D_{\lambda}(x)$ (assume that vehicle is moving in the lane λ) to judge if $D_{\lambda}(x) = L$, if true, it means that the density of lane λ has turned from high to low, thus, to relieve the possible collisions, vehicle $x$ should release the current slot and acquire

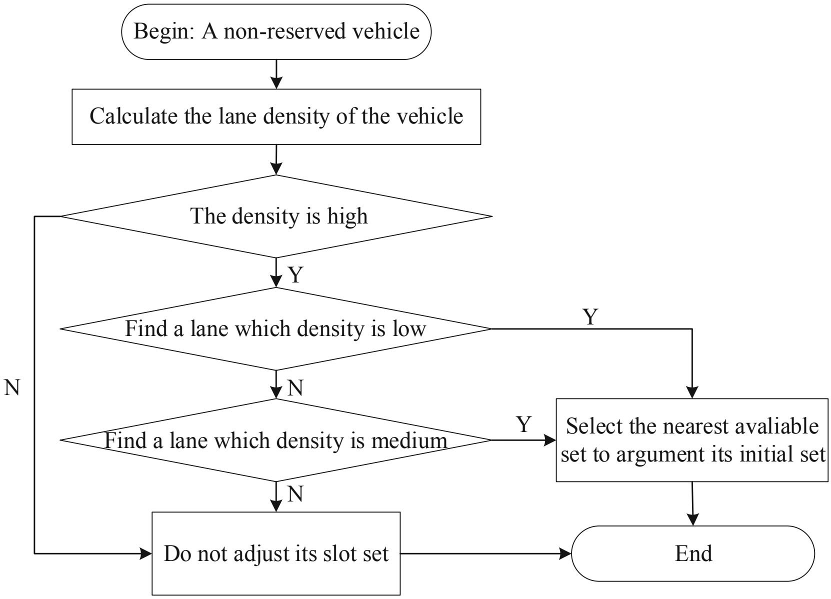


**Fig. 6.** Available slot set adjustment process of a non-reserved vehicle.

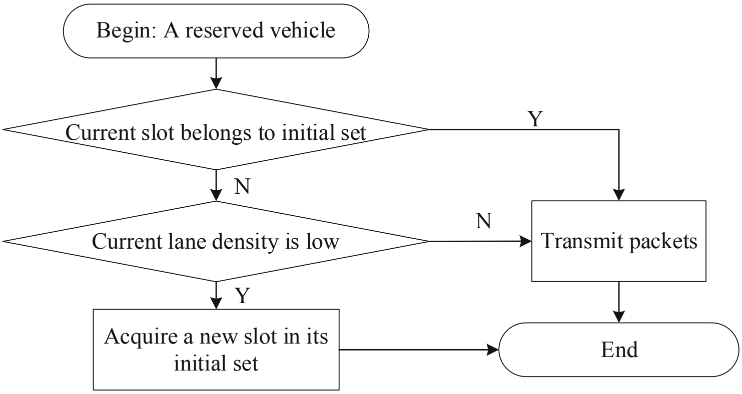
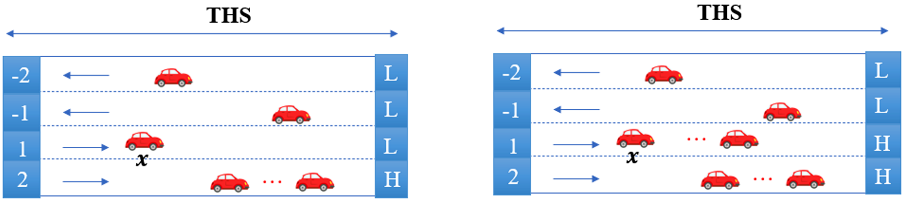


**Fig. 7.** Slot adjustment process of a reserved vehicle.



(a) (b)

**Fig. 8.** An Example of the slot set adjustment scheme.

a new slot in its initial set, i.e., $A'_\lambda(x)$. Note that this process chooses a threshold of $L$ rather than $M$ for the reason to prevent the frequent transformation causing an unstable structure. The flow chart of the process illustrated above is shown in Fig. 7.

To make the analysis more specific, an example of road topology and vehicles is shown in Fig. 8. If a non-reserved vehicle $x$ needs to acquire a time slot, it should first calculate $D_l(x), l = \pm 1, \pm 2$. Due to vehicle $x$ is in lane 1, if the result of $D_1(x)$ is $L$ or $M$, as shown in Fig. 8 (a), it will randomly choose a slot in set $A'_1(x) = \overline{T_1(x)} \cap N_1(x)$. However, if $D_1(x) = H$ as shown in Fig. 8 (b), vehicle $x$ will select the nearest slot set $A'_{-1}(x)$ to argument. After the adjustment, its slot set can be expressed as $N'_1(x) = N_1(x) \cup A'_{-1}(x)$, and its available slot set can be derived as $A''_1(x) = \overline{T_1(x)} \cap N'_1(x)$. Vehicle $x$ will then randomly choose a time slot in $A''_1(x)$ to transmit FI.

## 3 Performance Evaluation

In this section, we conduct extensive simulations to evaluate the efficiency of AODMAC by comparing it with the proposed VeMAC [9] and MoMAC [12] protocols. Moreover, in VeMAC protocol, we choose the split-up parameter $\tau = 5$.

### 3.1 Simulation Environment

We conduct network simulations through OMNeT ++ 4.6 [13] and Simulation of Urban Mobility (SUMO) [14]. We consider three different traffic loads [9] in the highway scenario measured by the parameter

$$\eta = M \times \frac{2R}{L} \times \frac{1}{N}, \tag{5}$$

which is called THS occupancy, the parameter denotes the ratio of the number of slots required by a THS to the total number of slots available for a THS. In Eq. (5), $M$ indicates the total number of vehicles on the road, $R$ is the communication range, $L$ is the length of the highway segment and $N$ is the number of slots in a frame. Based on the THS occupancy, we denote high ($\eta = 0.85$), medium ($\eta = 0.5$) and low ($\eta = 0.2$) to mimic different traffic load in the highway, in each traffic load, we also consider two cases, i.e., balanced condition and unbalanced condition, thus by combining them, we get six different traffic conditions. Specifically, in the balanced condition, vehicles select any lane with the same probability, while in unbalanced condition, some lanes may exceed the capacity and others may be redundant.

In the simulation experiment, to mimic the real traffic environment, we consider a bidirectional 8-lane highway and each of the four lanes in one direction is given a speed limit of 60 km/h, 80 km/h, 100 km/h, 120 km/h, respectively. Moreover, vehicles also have different performance parameters, e.g., maximum velocity, acceleration and deceleration. Other simulation parameters are listed in Table 1.

**Table 1.** Simulation parameters

| Parameter | Value |
|---|---|
| Highway length ($L$) | 1 km |
| Lane width | 3.2 m |
| Slot duration | 1 ms |
| Slots/frame ($N$) | 100 |
| Transmission range ($R$) | 300 m |
| Traffic conditions | High-Balanced/Unbalanced,<br>Medium-Balanced/Unbalanced,<br>Low-Balanced/Unbalanced |
| $U_{min}$ | 0.4 |
| $U_{max}$ | 0.9 |
| Simulation time | 120 s |

### 3.2 Performance Metrics

1. *Rate of transmission collisions.* Refers to the average number of transmission collisions per frame per THS.

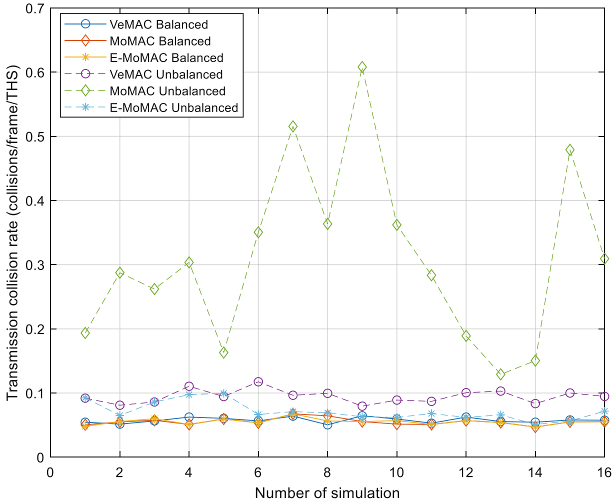
2. *Channel utilization.* The ratio of the average number of time slots reserved by the vehicles to the total number of slots available for a THS.

### 3.3 Simulation Results

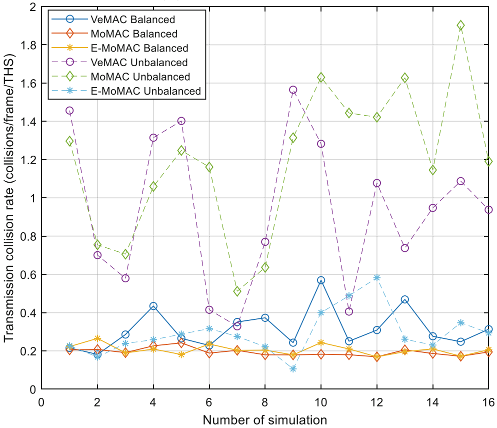
Figure 9 shows the transmission collision rate versus number of simulations in different traffic conditions. Firstly, in both conditions, no matter in balanced or unbalanced conditions, AODMAC protocol can achieve the minimum number of collisions and is more effective especially in high traffic load. Specifically, the mean value of transmission collision rate of AODMAC with unbalanced condition is 0.07, 0.29 and 1.41 in the low, medium and high traffic load, respectively, while the mean value in MoMAC is 0.31, 1.19 and 2.37, in VeMAC, the mean value is 0.09, 0.93 and 5.63. The main reason is that AODMAC can adaptively adjust the slot sets on demand according to the lane density. Secondly, in all three different traffic loads, the curves of unbalanced condition always have more violent fluctuations compared to balanced conditions in VeMAC and MoMAC, while it is more stable in AODMAC. This indicates that although in the same traffic load, different moving status or topology distribution (i.e., different simulation seeds in simulations) will matter a lot in VeMAC and MoMAC. Moreover, the transmission collision rate in MoMAC under unbalanced conditions shows worse performance than other protocols. It is mainly because MoMAC protocol is unable to cope with the surge of traffic load in some certain lanes. Lastly, both in balanced and unbalanced conditions, AODMAC shows similar curves that demonstrates the efficiency and stability of the protocol.

Figure 10 shows the channel utilization versus number of simulations in different traffic conditions. Firstly, in low traffic load, the performance of the three protocols are very close in balanced and unbalanced conditions respectively due to low contention. Secondly, based on the same condition, AODMAC always has a better channel utilization due to its lowest collision rate. Specifically, the mean value of channel utilization of AODMAC with unbalanced condition is 0.31, 0.64 and 0.66 in the low, medium and high traffic load, respectively, while the mean value in MoMAC is 0.30, 0.52 and 0.40, in VeMAC, the mean value is 0.30, 0.61 and 0.60. The main reason is that the adaptive slot sets adjustment in AODMAC is beneficial to take full advantage of the free slot as well as relieve the burden of the busy slot sets. Thirdly, the channel utilization will not monotonically increase with the traffic load due to the collision dramatically increasing when the number of vehicles is closing to slots in a THS. Moreover, when the traffic load is high, the performance of MoMAC will dramatically worse off, the reason is that excessive subdivision results in small size of each slot set and thus incur more collisions.

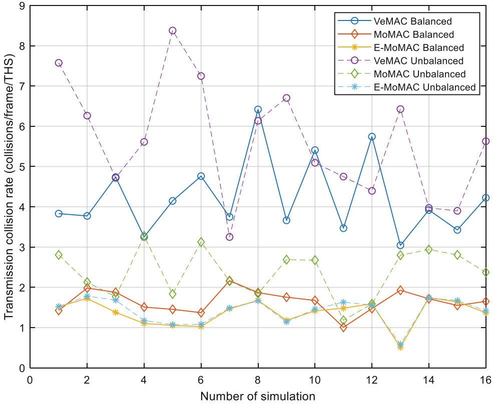
In summary, under balanced traffic conditions, the performance (transmission collision rate and channel utilization) with AODMAC is close to those with VeMAC and MoMAC when the traffic load is low. When the traffic load is high, the performance with AODMAC is better than that with VeMAC and MoMAC. Under unbalanced traffic conditions, the three protocols have close performance when the traffic load is low. With the traffic load increasing, the performance with AODMAC becomes significantly better than those with VeMAC and MoMAC.



(a) Low traffic load

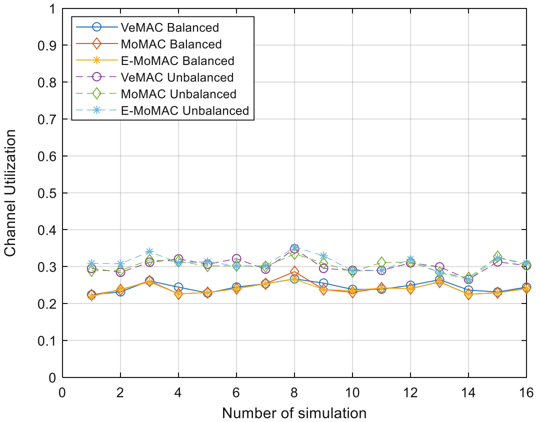


(b) Medium traffic load

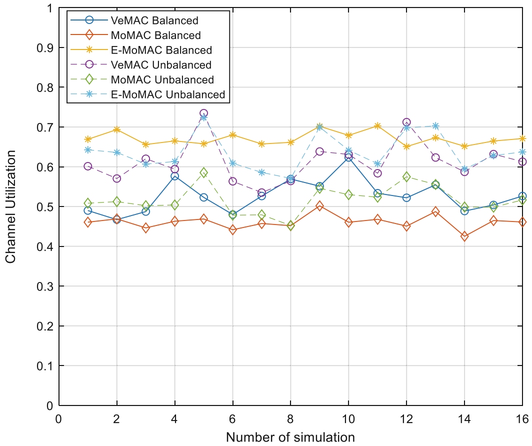


(c) High traffic load

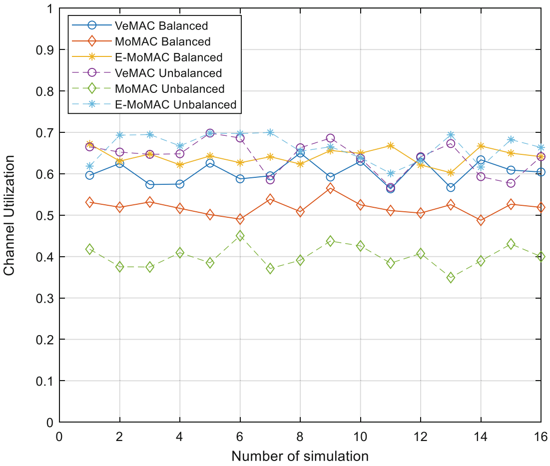
**Fig. 9.** Transmission collision rate versus number of simulations in different traffic conditions.



(a) Low traffic load



(b) Medium traffic load



(c) High traffic load

**Fig. 10.** Channel utilization versus number of simulations in different traffic conditions.

## 4 Conclusions

In this paper, in order to solve the high transmission collisions and channel resource wastage problems in unbalanced traffic conditions of VANETs, we propose an adaptive and on-demand MAC protocol for VANETs, named AODMAC. It is a fully-distributed MAC protocol based on the MoMAC. Its frame is partitioned into equal sets according to the lane numbers, and each lane has its own disjoint time slot sets for vehicles to access. In AODMAC, the partitioning of each frame is not fixed. Instead, it can be adaptively adjusted according to different traffic density in each lane. Due to each lane can acquire its slot set on-demand, AODMAC can solve the slot wastage problem in sparse lanes and the slot shortage problem in dense lanes. Thus, it is efficient in both balanced and unbalanced traffic density scenarios. Simulation results show that the proposed MAC protocol can achieve a better performance than VeMAC and MoMAC in terms of the transmission collision rate and channel utilization, especially in high traffic load and unbalanced condition. The results demonstrate the efficiency and stability of our proposed protocol.

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