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Adaptive TDMA slot assignment protocol for vehicular ad-hoc networks

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Abstract

This paper proposes a novel adaptive time division multiple access (TDMA) slot assignment protocol (ATSA) for vehicular ad-hoc networks. ATSA divides different sets of time slots according to vehicles moving in opposite directions. When a node accesses the networks, it choices a frame length and competes a slot based on its direction and location to communication with the other nodes. Based on the binary tree algorithm, the frame length is dynamically doubled or shortened, and the ratio of two slot sets is adjusted to decrease the probability of transmission collisions. The theoretical analysis proves ATSA protocol can reduce the time delay at least 20% than the media access control protocol for vehicular ad-hoc networks (VeMAC) and 30% than the ad-hoc. The simulation experiment shows that ATSA has a good scalability and the collisions would be reduced about 50% than VeMAC, channel utilization is significantly improved than several existing protocols.

Keywords media access control (MAC) protocol, TDMA, slot assignment, adaptive frame length, binary tree

1 Introduction

Vehicular ad-hoc networks (VANETs) is a distributed, self-organizing communication network built up by moving vehicles, which contains both inter-vehicle (V-2-V) communications among vehicles and vehicle-to-roadside units (V-2-R) communications between vehicles and roadside units (RSUs) which is utilized for a broad range of safety and non-safety applications [1]. As the wide application prospects and high research value, it has attracted a lot of attention [2].

Because of the special characteristics of VANETs, such as the high dynamic network topology and diverse quality of service (QoS) requirements of potential applications, higher demand for delay for security applications, not only does the MAC protocol need to consider the common problems which contains hidden/exposed terminal problem, resource allocation fairness problem in traditional ad-hoc networks, but it also should meet some new requirements [3]: 1) supports high vehicle mobility; 2) ensures real-time communication and reliability; 3) has a good scalability; 4) has a higher channel utilization; 5) supports a fully distributed or semi-distributed networking; 6) provides a fair opportunity of communication for each user; 7) provides efficient and timely broadcast mechanism.

Since in 1999, the U.S. Federal communications commission (FCC) allocated a block of wireless spectrum in the 5.850~5.925 GHz band for dedicated short range communications (DSRC) applications which contains seven 10 MHz channels: six service channels and one control channel to be exclusively used by V2V and V2R communications (FCC (1999) FCC allocates spectrum in 5.9 GHz range for intelligent transportation systems uses, http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/1999/nret9006.html), intended to enhance the safety and efficiency of highway system [4], a large body of literature for MAC protocols for VANET have been proposed based either on IEEE 802.11 or on channelization such as TDMA. The IEEE draft standard

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802.11p [5], included in the wireless access in vehicular environment (WAVE) protocol stack, is the only standard for MAC in V2V communications. Since IEEE 802.11p uses the basic mechanism of the distributed coordination function (DCF) that was originally designed for low mobility networks, it does not operate efficiently for a high mobility communication scenario in VANETs, such as it suffers from Orphan frames and hidden terminal problem [6].

ADHOC is based on reliable reservation additive link on-line Hawaii protocol (RR-ALOHA) to achieve dynamic allocation slots [7]. ADHOC inherently avoids the hidden terminal problem and alleviates the exposed terminal problem at a small cost of packet overhead by careful refinement. Moreover, in ADHOC MAC, each node is guaranteed to access the channel at least once in each frame, and the information of speed, location, and emergency safety can be broadcast in the frame information (FI) information. ADHOC MAC is suitable for non delay-tolerant applications in VANETs. But with the increase of node density, the nodes competition is more intense, the success rate of the nodes access the channel is decreasing and the delay will also increases correspondingly.

In order to improve the success rate of assignment slot and reduce the delay, Ref. [8] based on the ADHOC protocol proposed a new multichannel MAC called VeMAC. It assigns time slots according to the direction of vehicular. VeMAC takes full advantage of the characteristics of the multi-channel in the VANETs, and combines distributed with centralized way for assignment time slots, making nodes acquire time slots on the control channel much faster.

As for slot assignment protocol researches, Yong [9] proposed the unifying slot assignment protocol-multiple access (USAP-MA) to improve the channel utilization. In USAP-MA, the frame length can change according to network density. In order to improve the channel utilization, A-ADHOC protocol was proposed in Ref. [10]. It implements a robust mechanism supporting the adaptive frame length and focuses on the conditions of changing the frame length. Compared to the MAC protocol which has a fixed frame, the adaptive frame length can improve the channel utilization, however, with the increasing channel utilization, success rate of a node compete for a slot is reducing, A-ADHOC can also not solve the problem of merging collision in the VANETs [7].

ATSA is based on VeMAC protocol, the main motivations of our work can be concluded as follows: The adaptive frame length can sustain favorable success probability for nodes by maintaining a stable ratio of frame length and nodes density. Our goal is to enable the frame length and the ratio of left slots and right slots adapt to node density, to reduce the convergence time and enhance the runtime performance, to reduce competition collision and improve channel utilization.

The remainder of this paper is organized as follows. In Sect. 2 we introduce the VeMAC protocol and analysis the defect of it in the VANET. In Sect. 3, the system model is introduced. We show the detailed description of ATSA in Sect. 4. The theory analyses and simulation results are given in Sect. 5. Finally, Conclusions and the future work are given in Sect. 6.

2 The VeMAC protocol

2.1 Introduction VeMAC protocol

VeMAC protocol implements a TDMA mechanism that is able to provide prompt access and reliable channels for VANETs traffic message delivery. It under consideration consists of a set of RSUs and a set of vehicles moving in opposite directions on two-way vehicle traffic roads. Each frame is partitioned into three sets of time slots: L, R, and F.

On the control channel, it is full distributed based on ADHOC MAC. To obtain the slot assignment information in the contention area, every node collects FI transmitted by its neighbors. On the service channel, the assignment of time slots to nodes is performed by the providers in a centralized way.

A set-up phase is presented in Fig. 1 where the FI of every node is given; the different colors represent different time slots sets: L, R and F. If node 2 will access to channel, first, it collects neighbor information and randomly selects an available time slot of L. If it contends for slot j when this very slot j comes, it will broadcast FI packets containing the contending message in the slot j. Then it will experience a frame anxious waiting. If all FI received by node 2 in this period contain 'slot j is busy by node 2', then this contending is successful and slot j will belong to node 2 until it releases it; otherwise, node 2 needs to contend in next frame. If after a certain number of frames, say after τ frames (determine the parameter τ is a key issue) the node 2 cannot acquire a time slot and it can compete the time slot set which belong to R or F.

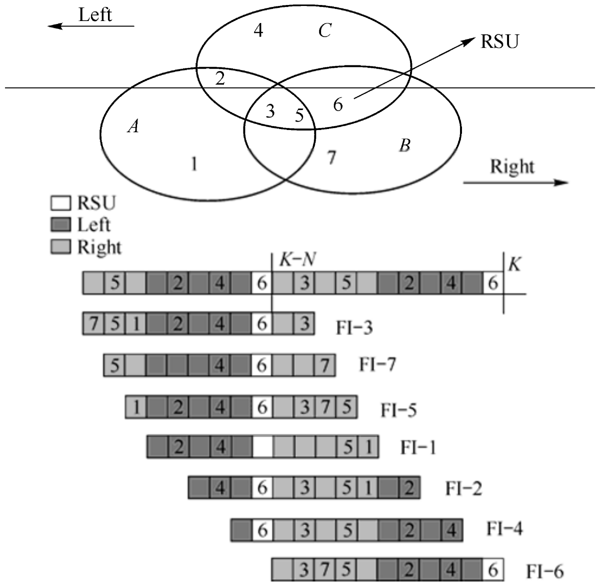

Fig. 1 VeMAC protocol node slot allocation

2.2 Problems

Problem 1 Two types of collision in time slots can happen: (1) Access collision among nodes trying to acquire time slots which will lead to competition failure, as shown in Fig. 2. (2) Merging collision among nodes already acquiring time slots. When two or more nodes within two hops of each other use the same available time slot, merging collision will happen. As shown in Fig. 3, the node A and D occupy the same slot when they located two-hops away and when they move into two hop range, there will be a merging collision. In VANETs, merging collision is likely to occur among vehicles moving in opposite directions or between a vehicle and a stationary RSU. With the node density increasing, collision is more frequent. It directly leads to large delay and becomes a serious problem for emergency security applications in VANETs.

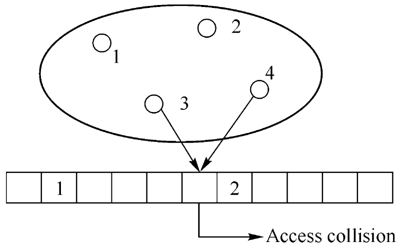

Fig. 2 Access collision

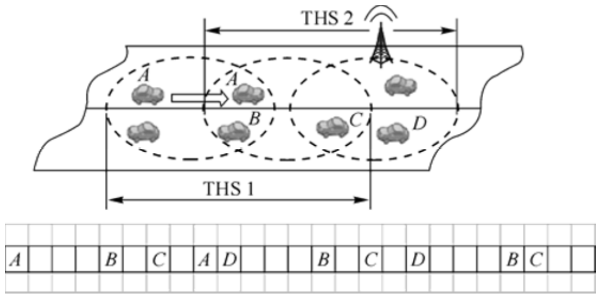

Fig. 3 Merging collision

Problem 2 Scalability issues of MAC, existing distributed real-time MAC protocol such as the VeMAC, as the number of time slot is fixed of each frame, the number of nodes it can accommodate maximum is fixed also. The channel utilization is very low when the node sparse, if the number of nodes exceed this maximum number of slots in the run-time of the MAC protocol, according to the pigeonhole principle, there will be nodes that would not be able to access the channel. It is similar to the blind area when radar is scanning and some of the vehicles can not communicate with the surrounding nodes, then the security applications in the VANETs may cause security incidents. Therefore, the distributed real-time MAC protocol in the VANETs must have a certain degree of scalability.

3 System model

In ATSA, each node can use a different frame length based on the number of the surrounding neighbor nodes, but it can only own one slot of their time frame. Time frame length can be expanded and contracted by the two integer power. Each frame is partitioned into two sets of time slots: L, R, as the Fig. 4 shown.

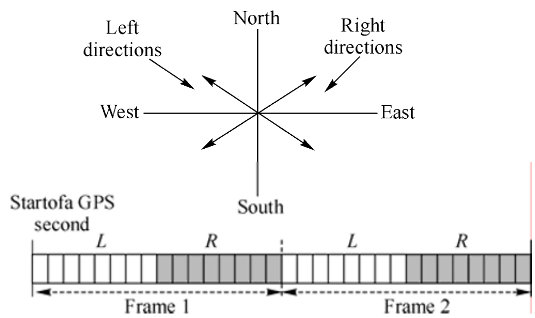

Fig. 4 Partitioning of each frame into L, R

For node x, following six sets are defined:

1) $N_{(x)}$: The set of two-hops neighbors of node x, from/to which node x can receive/transmit FI information.

2) $N_{L(x)}$: The set two-hop neighbors of node x with the left direction.

3) $N_{R(x)}$: The set two-hop neighbors of node x with the right direction.

4) $S_{(x)}$: The frame length of the node x, namely the number of time slots of each frame of node x.

5) $S_{L(x)}$: The number of time slots which belong to L in one frame of node x.

6) $S_{R(x)}$: The number of time slots which belong to R in one frame of node x.

7) $U_{\max}, U_{\min}$: The maximum threshold and minimum threshold, which is a ratio between node density and frame length.

There are following 3 rules in ATSA must be complied with:

Rule 1 The available slot is have not been used by two-hop neighbors.

Rule 2 In order to avoid the access conflict, within two-hop nodes can not use the same slot.

Rule 3 The frame length of two adjacent networks can be equal or double only.

4 The ATSA protocol

4.1 Slots management based on binary tree

For a node, slot allocation information of neighbors in its two hops can be mapping into a binary tree. The nodes set on left subtree can be regarded as the set of slots L, while the nodes set on right subtree seen as the set of slots R.

On a binary tree, the root node lies in the 0 layer, nodes in the (L+1)-layer are generated by the nodes in L-layer. If a node number is c_i (a binary number), then the number of its left child is $0c_i$ and the right one is $1c_i$. There are 2^L nodes in L-layer of a binary tree, each leaf node map to a slot; the number of nodes on each layer corresponds to the frame length (it means the number of nodes on a layer is equal to the slot number in the corresponding time frame). Consequently, the slot allocation can be regarded as the node distribution in the binary tree. As shown in Fig. 5. The rule 2 map to the binary tree is that when a time slot in the binary tree has assigned to node x, all its parent points and left sub-nodes can not be reallocated to other node within two-hop neighbors of node x.

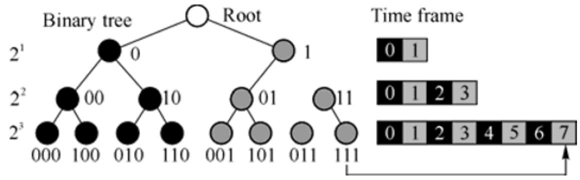

Fig. 5 Relationship of binary tree and the time slots

On the other hand, the structure of the binary tree can be adapted to the dynamic adjustment of the time frame length. If L-layer node i needs to make the time frame length double, the original slot will be expanded into two slots, in which one slot number keeps unchangeable, another slot number is the sum of the original slot number and time frame length. Similarly, in the binary tree, each L-layer node is extended into two child nodes, in which the number of the left child node is unchanged: $c_i = 0c_i$, the right child node number is the sum of nodes number in L-layer and the original node number: $1c_i = 2^L + c_i$. In the (L+1)-layer, we can find that the slot c_i and slot $2^L + c_i$ is still used by node i. Owing to the ingenious corresponding relation, it is convenient for us to use binary tree theory to manage the slot with different time frame length. Expanding time frame length is shown in Fig. 6.

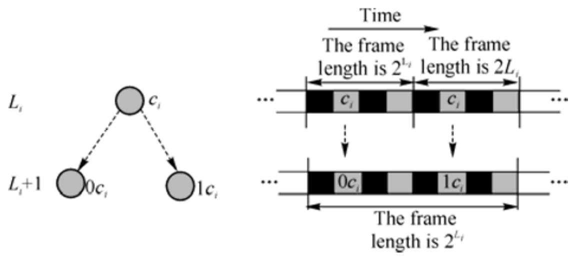

Fig. 6 Double time slots

4.2 Changing frame length

Node x can change their frame length according to node density in ATSA, we shorten the frame length to improve the channel utilization when the node density is low, double the frame length to ensure that each node can be assigned to a slot when the node density is high. When a node $x \in N_{L(x)}$ needs to access network, it first listens for a period of time to collect two-hop neighbors information for building a time slot binary tree and then choices the longest frame which used by neighbors as own frame length. Then it according to the location determines an effective slot $i \in A_x$, $A_x \in S_{L(x)}$ to competition. If the nearest node from the node x is y which occupied the slot j, then the number of slot i is nearest from the number of slot *j*.

Node *x* keeps updating the information of the time slot binary tree and judge whether the ratio between node and slot exceeds the threshold $U_{\max}$ or below the threshold $U_{\min}$. If it meets the Eq. (1), Node *x* broadcasts the message about changing frame length and assignment slot in the FI, if all the one hop neighbors are not opposite and then it double or shorten the frame length of itself. We give an example as follow, assume a linear networks topology as shown in Fig. 7.

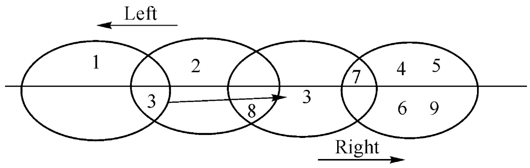

Fig. 7 A linear networks topology

At first, the frame length of node 3 is 8, it establish binary tree and map the slot that have been used by two-hop neighbors to a four-layer binary tree. As the node 3 moving, $N_{(x)}$ is increasing and it meets $N_{(x)}/S_{(x)} \geqslant U_{\max}$, it needs to double the frame length. The algorithm flowchart of Changing frame length is illustrated in Fig. 8, double the frame based on binary tree as shown in Fig. 9.

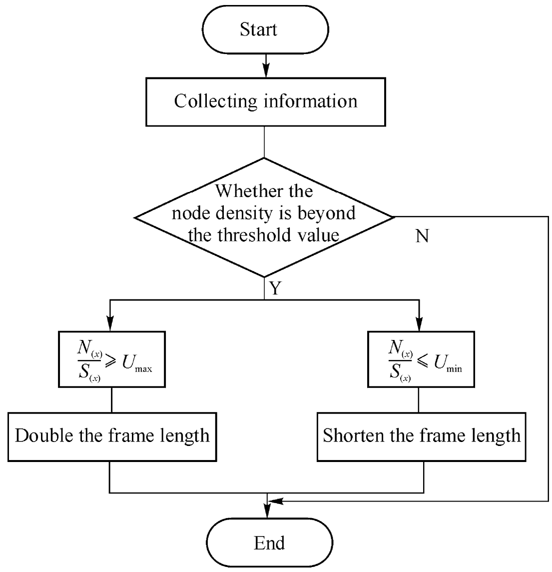

Fig. 8 The algorithm flowchart

The specific method of double slot in the binary tree as follow:

Step 1 Each leaf node of the last layer as a parent expands two children nodes, so it has build a five-layer binary tree and the number of leaf nodes on the fifth layer doubles fourth layer, that is to say the frame length of node 3 has been doubled.

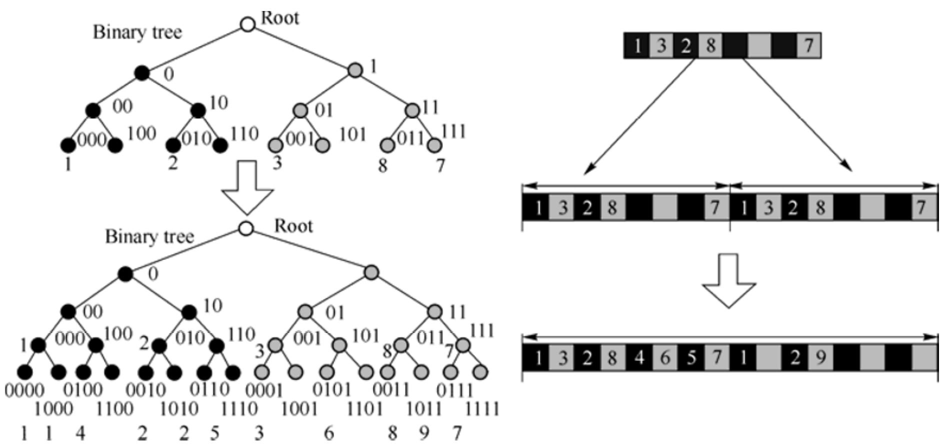

Fig. 9 Changing frame length based on binary tree

Step 2 Mapping the slots that have been used by the two-hop neighbors to the leaf node. If one parent node is in the *i* layer have been used by node *x* whose frame length is 2^i, so the two child nodes of the parent are also used by *x*; if the frame length of node *x* is 2^{i+1}, we set the left child used by node *x* and the right child node as the slot for new node competition. As shown in Fig. 9, the frame length of the node 1 and node 2 is 8, so the two children nodes of the parent nodes which number is 000, 010 also use by node 1 and node 2; the frame length of node 8 is 16, so the left child node which number is 0011 use by node 8 and the right child node which number is 1011 is available slot for new node.

Shorten the frame length is similar to redouble frame length, if the sibling node of the node that has been used node *x* is a available slot, then the node *x* uses it, Otherwise, node *x* uses a new father node witch the children node have not been used and releases the time slot that occupied previously.

The parameter $U_{\max}$ and $U_{\min}$ are referred to as split up parameter, and the choice of the value is critical since it directly affects the channel utilization and the probability of access collision. For example, when $U_{\max} \to 1$ and $U_{\min} \to 0.5$, the channel utilization is maximized since when the density of nodes is enough high, the channel utilization close to 1; but at the same time, the access collision is maximized since the probability is maximized of two or more nodes competition the same slot. On the other extreme, $U_{\max} \to 0.5$ and $U_{\min} \to 0$, the channel utilization is minimized since there are a lot of idle slots; the access collision is minimized since there are more idle slots for competition. How to determine a suitable value for to balance between the channel utilization and access collisions should be further studied.

4.3 Time slots allocation and radio adjust

Node x keeps updating the information of the time slot and according the information dynamically adjusts the ratio between $S_{L(x)}$ and $S_{R(x)}$. When it from Eq. (2) change to Eq. (3), it needs to adjust the ratio between $S_{L(x)}$ and $S_{R(x)}$, make it to meet the Eq. (4). The node x broadcasts a proposal that redistributes the amount of the left and right slots in the FI, if the neighbor nodes agree to the proposal, the new slot allocation scheme will be adopted by the neighbor nodes that have the same frame length in next time frame. Nodes only competition the slots which correspond to the direction, so it can significantly reduce the probability of happening collision, Fig. 10 illustrates the time slot adjustment base on binary tree.

$$\frac{N_{(x)}}{S_{(x)}} \geqslant U_{\max} \text{ or } \frac{N_{(x)}}{S_{(x)}} \leqslant U_{\min} \tag{1}$$

$$\frac{N_{L(x)}}{N_{R(x)}} \approx 1 \tag{2}$$

$$\left.\begin{array}{l} \dfrac{N_{R(x)}}{S_{R(x)}} > U_{\max} \text{ or } \dfrac{N_{L(x)}}{S_{L(x)}} > U_{\max} \\ \dfrac{N_{(x)}}{S_{(x)}} < U_{\max} \end{array}\right\} \tag{3}$$

$$\left.\begin{array}{l} \dfrac{N_{(x)}}{S(x)} < U_{\max} \\ \dfrac{N_{L(x)}}{S_{L(x)}} < U_{\max}, \dfrac{N_{R(x)}}{S_{R(x)}} < U_{\max} \end{array}\right\} \tag{4}$$

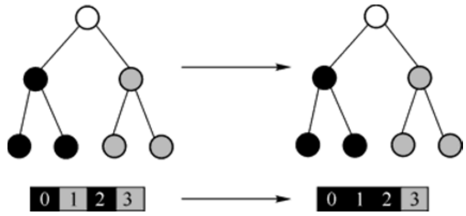

Fig. 10 Adjustment for left-right slot ratio

5 Performance evaluation and simulation

In this section, we first analyze the theoretical performance of ATSA on access delay τ. The access delay is the time period which begins when a node has the accessing channel requirement and ends when the node has a slot on the channel.

To simplify the analysis, the following assumptions are made: all the contestants belong to the same set of two-hop and have the same information of the neighbors, at the end of each frame, each node is aware of all acquired time slots during the frame and all contestants are informed whether their attempts to access a time slot during this frame were successful. Consider K nodes and N time slots of one frame for competition of n frame, each of which needs to acquire a time slot on the channel. If the probability of a node x decides to compete a slot in the frame is P, assuming that each node has the same opportunity to compete every slot. In Eq. (5) S is the probability of node x successfully occupied the slot in the first frame. In order to maximize S, we create a function $f(x)$. When P meets the Eq. (6), $f(x)$ will obtain the maximum as shown in Eq. (7).

$$S = N\frac{P}{N}\left(1-\frac{P}{N}\right)^{K-1}; \quad P \in [0,1] \tag{5}$$

$$\left.\begin{array}{l} f(x) = P\left(1-\dfrac{P}{N}\right)^{K-1} \\ p = \begin{cases} \dfrac{N}{K}; & N < K \\ 1; & N > K \end{cases} \end{array}\right\} \tag{6}$$

$$f(x) = \begin{cases} \left(\dfrac{N}{K}\right)\left(1-\dfrac{1}{K}\right)^{K-1}; & N < K \\ \left(1-\dfrac{I}{N}\right)^{K-1}; & N \geqslant K \end{cases} \tag{7}$$

In ATSA, the probability of successfully take non-collision slots of a special node is given by Eq. (8). We suppose the successful competition probability of a node in the first frame is S_1, slots are divided left and right sets, S_1 is given by Eq. (9), the successfully competing number of nodes u_1 is given by Eq. (10). After the first round of competition, the remaining nodes compete for the remaining time slots according to their current locations. Suppose the rest of the time slot and nodes are equally partitioned into m sets, then in the i frame, the successful probability is given by Eq. (11) and u_i is give by Eq. (12).

$$S=\left(1-\frac{1}{N}\right)^{K-1} \tag{8}$$

$$S_1=\left(1-\frac{2}{N}\right)^{\frac{K}{2}-1} \tag{9}$$

$$u_1=S_1K \tag{10}$$

$$S_i=\left(1-\frac{m}{N-\sum_{l=1}^{i-1}u_l}\right)^{\frac{K-\sum_{l=1}^{i-1}u_l}{m}-1} \tag{11}$$

$$u_i=S_i\left(K-\sum_{l=1}^{i-1}u_l\right) \tag{12}$$

$$K_s=\sum_{l=1}^{i-1}u_l \tag{13}$$

After n frame, the number of the nodes that have owned a slot is K_s. If all nodes have a slot, then the condition, $K_s=K$ is need to meet. We define the successful competition proportion of the node as $P_s=K_s/K$. Fig. 11 shows that P_s for ADHOC which is random competition slots and VeMAC which is direction-based competition slots and ATSA protocol with different values of K and N. The average number of nodes which acquire a time slot within n frames is calculated for different K and N, as shown in Fig. 12.

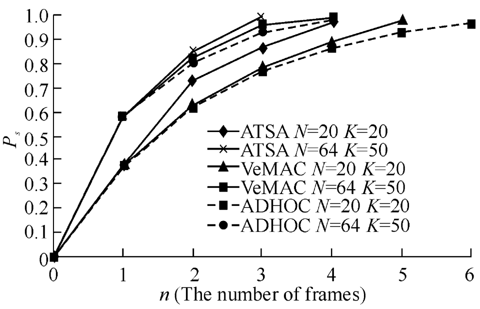

Fig. 11 The proportion all nodes acquire a time slot within n frames

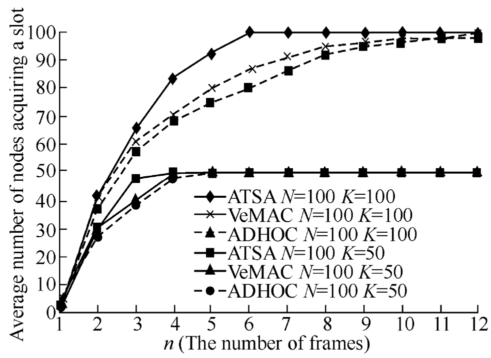

Fig. 12 Average number of nodes acquiring a slot within n frames

If the frame length is t, it is observed that, with a probability around 0.95, all nodes acquire a time slot within three frames ($\tau=3t$) for the case (N= 64; K= 50) in ATSA and four frames ($\tau=4t$) in VeMAC and ADHOC; There are four frames ($\tau=4t$) for the case (N= 20; K= 20) in ATSA and five frames ($\tau=5t$) in VeMAC, six frames($\tau=6t$) in ADHOC. From the data of the time delay, we can come to a conclusion: ATSA protocol can reduce the time delay at least 20% than the VeMAC and 30% than the ADHOC.

In Fig. 12, it is clear that, when $N>K$, nodes acquire a time slot much faster in ATSA than in VeMAC and ADHOC. For example, for (N =100; K = 50), all nodes acquire a time slot within three frames in ATSA, which increases to four frames in VeMAC, and five frames in ATSA. This result indicates that, for the same N and K, when $N>K$ ATSA can decrease the rate of access collision, as compared to VeMAC and ADHOC. When K increases, the gap between the performances of the three protocols increasing, and ATSA performs slightly better when K=N. So the number of the nodes that acquiring a slot is most with one frame in ATSA and it take the least time made all nodes own a slot.

We use pseudorandom generator to generate a serial of random data sequence within a certain range in Matlab, which indicates nodes number in each subnet region. With it, we can calculate self-adaptive frame length efficiency in ATSA protocol under nodes random distribution. We set $U_{max}=4/5$ and $U_{min}=1/4$.

The numerical analysis result is shown in Fig. 13 (Fig. 14 is one fragment from Fig. 13), the black line in the bottom denotes actual distribution of nodes and the gray dashed line indicates the node's frame length. We can see ATSA protocol can provide a dynamic and adaptive frame length according to the nodes density, which means in sparse area nodes will benefit from considerable response time reduction, and in dense area we can cope with arbitrarily large number of nodes with little additional time overhead. We also have thought about the quickly changing topology. In fact, if a node with different frame length rushes into another network, it can simply free its slot and alter its frame length to the value used by this network, as a new coming node does. So the ATSA has the scalability and can adapt to different network.

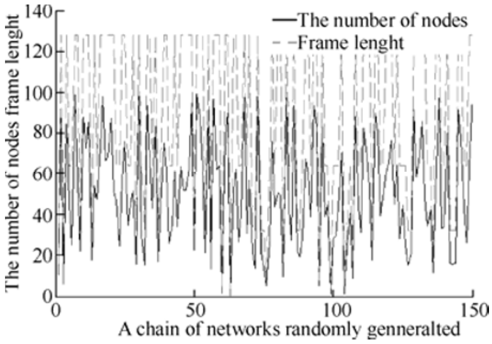

Fig. 13 The relation between the node density and frame length

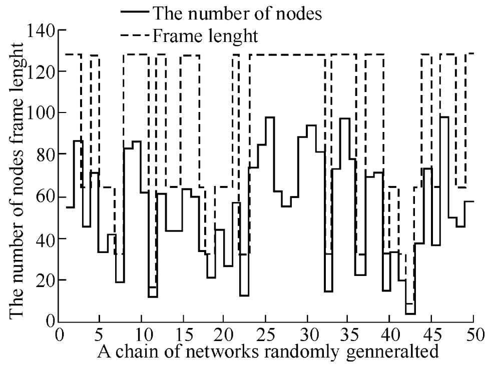

Fig. 14 The change of frame length and node density are enlarged

Fig. 15 shows that the number of the nodes has conflicts in a slot for ADHOC, VeMAC and ATSA protocol in a period of simulation time. We can see the conflict could be reduced about 70% than ADHOC, about 50% than VeMAC through ATSA.

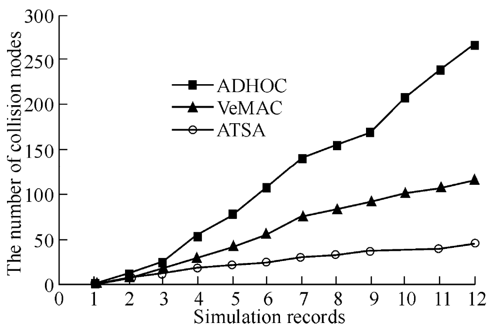

Fig. 15 The number of collision slot

Fig. 16 shown the channel utilization that use ATSA and VeMAC protocol, the average channel utilization is more than 65% in ATSA and it is high than in VeMAC of 35%. So the ATSA has the minimal number of the nodes conflicts and maximum channel utilizations compared to the several existing MAC protocols.

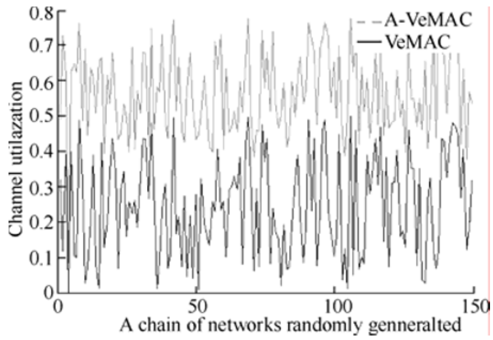

Fig. 16 The channel utilization in VeMAC and ATSA

6 Conclusions and future work

In this paper, we propose an adaptive ATSA for wireless vehicular network base on previous VeMAC MAC protocol. The main contributions of the protocol are adaptive classification of time slots, dynamic changing the frame length and adjusting the ratio of left slots and right slots according to the density of nodes. We achieve the protocol based on binary tree and analyze the performance from theory and simulation. The results show that the ATSA can reduce the slot collision and have the minimal time delay and maximum channel utilization comparing with the ADHOC and VeMAC protocol. In the future, we plan to determine the value of $U_{\max}$ and $U_{\min}$ in order to more reasonable change the frame length. We will evaluate the performance of ATSA via simulations with realistic mobility models. We will also delve into how to assignment slots most quickly by consider more difference factor of node.

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