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ASTSMAC: Application Suitable Time-Slot Sharing MAC Protocol for Vehicular Ad Hoc Networks

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ABSTRACT Vehicles and roadside units can be connected by a vehicular ad hoc network (VANET), which is an important component of future intelligent transport systems that can support various safety and non-safety related services. The network topology changes rapidly in VANET due to the high mobility of vehicles, making it difficult to design a reliable and efficient medium access control (MAC) protocol. Many MAC protocols based on time-division multiple access (TDMA) have been proposed for VANET to optimize network performance, but few of them consider the different requirements of nodes. Nodes may have diverse requirements for spectrum access, and one node may have a diversified strategy for transmitting messages over time, as its motion and network topology change rapidly. The application layer should dynamically adjust the package generation frequency as needed to reduce unnecessary spectrum access. In this paper, we propose a novel application suitable time slot sharing MAC protocol (ASTSMAC) for the broadcasting of the basic safety messages (BSMs) that can adapt to different transmission cycle requirements in the application layer program. In our scheme, one slot can be shared by more than one node, even if they are in each other's communication range. Simulation results show that ASTSMAC can provide significantly higher packet delivery ratio and lower collision rate. Further, the network can accommodate more nodes when the traffic-density is high.

INDEX TERMS Vehicular ad hoc Network (VANET), medium access control (MAC), time-division multiple access (TDMA), time slot sharing.

I. INTRODUCTION

With the rapid development of the automobile industry and continuous improvement of road infrastructure, the road network has become intertwined and complicated, and the number of vehicles running on roads has increased dramatically. The rapid increase of vehicles creates many problems, such as air pollution, traffic accidents, and traffic congestion. The intelligent transport system (ITS) and intelligent connected vehicles (ICVs) represent the future direction of the vehicle industry, as they can make transportation safer, cleaner, and more comfortable. Vehicular ad hoc networks (VANETs) enable transmission of information between ITS-stations (such as vehicles and roadside units), and support various services and applications, which is a key technology of the ITS.

One of the most important goals of VANETs is to provide sufficient quality of service for real-time safety-related applications considering one-hop wireless broadcast [1] and multi-hop wireless broadcast [2] technologies. Nodes share common wireless channels with the same radio frequencies; thus, inappropriate use of a channel may lead to transmission collisions or a waste of bandwidth. Hence, channel sharing is a key issue when seeking to provide a high quality of service [3]. Various MAC protocols have been proposed with the goal of guaranteeing efficiency and fair spectrum sharing among nodes. The most famous is the IEEE 802.11p [4] standard, which is one of the most prominent contention-based MAC protocols. However, hidden terminals have a detrimental impact on the contention-based MAC protocols [5], which also suffer from unbounded transmission delays [6]

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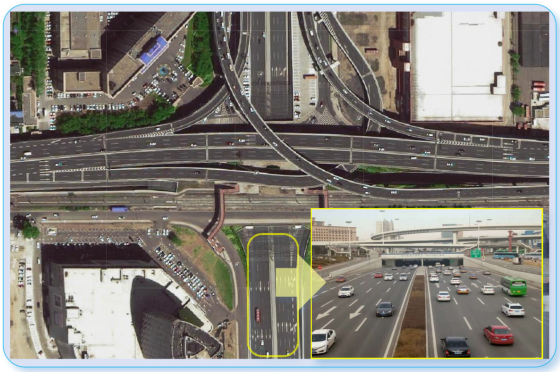

FIGURE 1. Satellite image of an intersection near Jilin university.

and heavy collisions [7], especially when the traffic-density is high. Meanwhile, higher saturation collision probabilities occur for broadcast services than unicast services as there is no binary exponential back-off in the broadcast scheme [8]. Various TDMA-based protocols have been proposed to overcome the shortcomings of contention-based MAC protocols.

TDMA-based protocols divide time into frames, where each frame contains several time slots and only one node is allowed to access the spectrum in a certain slot within a certain range. This provides higher throughput with lower collision ratios compared to contention-based MAC protocols in high traffic-density situations. However, slot resources will be insufficient, and the transmission collision rate will still be high in scenarios where the number of vehicles in a certain range is larger than the number of slots. The current urban road traffic network is intertwined and complicated. Fig. 1 shows a satellite image of an intersection near Jilin University. Consider only the widest 10 lanes in the road; there will be 100 cars within 200 meters when the average distance between vehicles is 20 meters. The number of vehicles will be huge during peak congestion, especially when all roads are considered. Time slots will be insufficient in such situation.

Some protocols focus on adjusting the frame length according to the traffic-density. The length of the frame will be increased when the traffic density is high, then, more slots can be used. These protocols are more flexible and adaptable to density changes. However, nodes have the same priority in these protocols, which means different channel resource requirements cannot be satisfied. In fact, compared with private cars, a police car may need to send basic safety information more frequently, because it may change lanes at any time or even run a red light while on duty. Meanwhile, for nodes who are private cars, they may also have different frequent broadcasting requirements related to their application layer. Adjusting the frame length can accommodate density changes, but each node occupies the same channel resource; hence, the MAC protocol does not satisfy the diversified demand for channel access by different nodes. Information such as the type of vehicle, which was defined in the application-layer, should be considered when adjusting the transmission rate.

In this paper, we propose a novel application-suitable time slot sharing MAC protocol (ASTSMAC), which mainly focus on the broadcasting of the BSMs. In contrast to the usual method of transmitting one packet per frame even if no application data needs to be sent. Nodes can transmit using different frequencies, and more than one node can share the same slot, even they are in each other's communication range. This can satisfy the communication needs of more vehicles with fewer time slots, thus reducing the number of invalid message transmissions and increasing the effective data transmission rate of the network. We also propose a cross-layer rate adjustment algorithm, in which the transmission rate is calculated using information in the application layer. Our contributions are summarized as follows:

1. We present an application suitable time-slot sharing MAC protocol that allows more than one node to share the same time slot, even if they are in each other's communication range. Compared with traditional protocols, networks using ASTSMAC can accommodate more nodes for data communication.
2. Nodes only access the spectrum during their transmitting period, meaning fewer channel resources will be needed for one node, and more nodes can be accommodated in the network by adopting a short transmission frequency in high-density network. Unnecessary bandwidth waste can be reduced and the spectrum utilization rate can be greatly improved with ASTSMAC.
3. A density-aware, weight-related frequency adjustment algorithm (DAFA) is presented, which allows nodes to adjust frequency dynamically, based on our proposed ASTSMAC. The performance of DAFA with ASTSMAC is measured and compared with the traditional TDMA MAC protocol. The results show that our ASTSMAC provides better performance with fewer collisions and higher delivery rate.

The rest of this paper is organized as follows. Related research is described in Section II. The network model is presented in Section III and the ASTSMAC protocol is presented in Section IV. The DAFAA algorithm is presented in Section V. Numerical analysis for evaluate the performance of our ASTSMAC is presented in Section VI, and the paper is concluded in Section VII.

II. RELATED RESEARCH

Various MAC protocols have been proposed for VANETs, the most famous of which is the IEEE 802.11p [4] standard, which is a typical contention-based MAC protocol. IEEE 802.11p is easy to deploy, and variable package sizes are supported without enforcing strict synchronization between nodes. IEEE 802.11p networks perform well when the traffic-density is low, but perform poorly when it is high. Rate control [9]–[14] was used as a congestion control mechanism for IEEE 802.11p to avoid beacon loss. Meanwhile, many TDMA-based MAC protocols have been proposed to overcome the shortcomings of contention-based protocols. These protocols can be classified as fully distributed [15]–[20], cluster-based [21]–[24], and centralized [25]–[28]. These protocols are committed to enabling nodes to acquire time slots more efficiently and minimize slot conflicts. Although TDMA-based MAC protocols perform better than contention-based protocols when the density is high, they provide no advantages when it is low. Meanwhile, the collision rate will be high when short length frames are used in a high-density network, resulting in unnecessarily long wait times when the frame length is long in a low-density network. Many prior studies used a frame adjustment method to improve the performance of the TDMA-based protocol.

Liu *et al.* [29] proposed an adaptive ad-hoc (A-ADHOC) mac protocol for VANETs that implements a robust mechanism for supporting the adaptive frame length. A quantitative analysis of the success probability for contending nodes showed that an adaptive frame length is quite necessary. The A-ADHOC protocol was subsequently proposed, in which the frame length dynamically doubled or reduced by half depending on the nodes number and predefined upper and lower thresholds. Frame length can be adjusted only when all nodes accept a change in the frame length. The range of frame lengths was restricted to [8, 16, 32, 64, 128, 256], and these values can be optimized through real-life application.

Yang *et al.* [30] designed an adaptive TDMA slot assignment protocol (ATSA) for VANETs where the frame length could be dynamically doubled or shortened. Each node determines its frame length based on the number of neighboring nodes, but only one slot can be used by this node. Each frame is partitioned into left and right sets of time slots. A node map slot allocation information for neighbors during its two hops into a binary tree. Nodes on the left or right subsides of the binary tree belong to left or right time slots, respectively. Each node dynamically changes its frame length depending on the density of nodes in ATST. The frame length can be shortened to improve channel utilization when the density is low and doubled to ensure that each node can be assigned to a slot when node density is high.

Roadside units (RSUs) are used to schedule time slot assignments and adjust frame length in centralized TDMA-based protocols. Guo *et al*. [31] propose an adaptive collision-free MAC (ACFM) protocol that used RSU to dynamically schedule slot assignments for all vehicles iteratively. A slot assignment cycle can be dynamically adjusted based on the number of vehicles in a subset. A slot assignment cycle will decrease when the number of unassigned slots is large. In contrast, a slot assignment cycle will increase when many vehicles are in a subnet. Cao and Lee [32] proposed a novel adaptive time division multiple access-based mac (VAT-MAC) protocol in which the RSU adjusts the time length in each frame individually. In VAT-MAC, the number of nodes located within the RSU coverage at the end of a frame is estimated; the number of nodes that will enter or leave the RSU coverage can be predicted. The RSU can estimate the number of nodes in its coverage during the subsequent frame. Finally, frame length can be adjusted based this estimate.

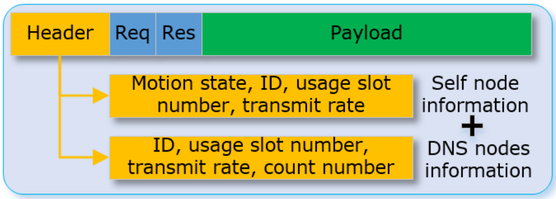

FIGURE 2. Format of transmitted packets.

Adjusting the frame length is one way to optimize TDMA-based protocols, but frame length coordination between nodes requires extra overhead for fully distributed TDMA protocols. Meanwhile, two nodes may require different frame length even when they are in each other's communication ranges, as the density of vehicles around them may be diverse. Forcing them to use the same frame length is clearly not the optimal solution. Regarding centralized TDMA protocols, RSU plays a key role for coordinating slot assignments, meaning these protocols are unsuitable for networks without RSUs. Another point to consider is that different nodes may have diverse spectrum access requirements as their motion, surrounding environment, and application layer definitions are different. Adjusting the frame length cannot satisfy the diverse spectrum requirements of different nodes.

III. SYSTEM MODEL

We consider a fully distributed VANET with a set of vehicles. Each node is equipped with a transceiver (that operates in half-duplex mode), and a global positioning system (GPS) receiver that can be used to calculate its position, velocity, direction, and acceleration. Synchronization among nodes is achieved using the 1PPS signal provided by the GPS receiver. All channels are symmetric, in the sense that node x is in the communication range of node y if and only if node y is in the communication range of node x [15].

Each transmitted packet contains a header, request migration slot number (req), response to the slot migration (res), and payload, as shown in Figure 2. The motion information (e.g., location, velocity, and direction), ID, usage slot number, and transmission cycle for each node belong to the one-hop neighbor set and are placed in the header of a packet. Regarding vehicles known to node x after parsing received messages, the following sets are defined according to the topological structure of these nodes:

- Direct neighbor set of node x (DNS_x): The set of nodes within the transmission range of node x.
- Indirect neighbor set of node x (INS_x): The set of nodes who are direct neighbors of nodes who belonging DNS_x but are outside of x's transmission range.
- Relative neighbor set of node x (RNS_x): The union of sets DNS_x and INS_x.

If node y belongs to DNS_x, then x knows the motion, ID, usage slot number, and transmission cycle of y and DNS_y by parsing packets received from y. Regarding nodes that belong

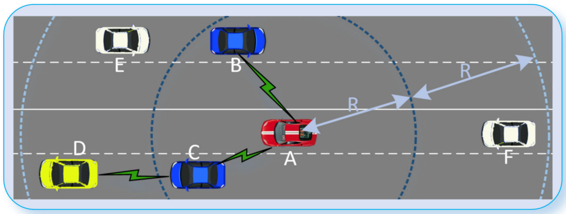

FIGURE 3. Relations between neighboring nodes and node A.

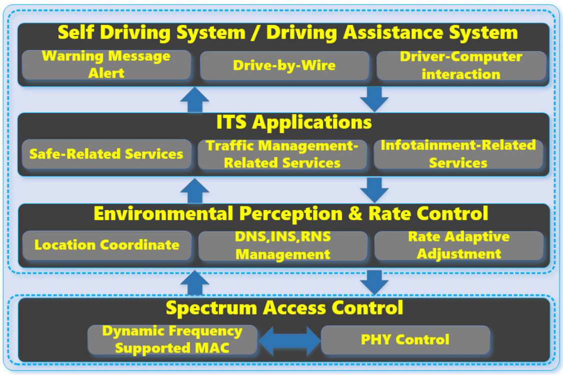

FIGURE 4. Schematic layered illustration of the rate control system.

to INS_x, x only knows their IDs and slots usage information, but x does not know their motion information.

As Fig. 3 shows, assume that node A has received packets sent by nodes B and C, node C has received packets sent by D. Node B has not received packets sent by E as node E has not acquired an available slot after entering the communication range of B. Then, DNS_A is $\{B, C\}$, INS_A is $\{D\}$, and RNS_A is $\{B, C, D\}$. Because nodes E and F are not one-hop neighbors of node A and information of them cannot be delivered to A as no efficient relay nodes exist, E and F do not belong to RNS_A.

Fig. 4 shows a schematic illustration of the layered architecture in our system, which does not necessarily correspond to the actual standard. The onboard unit (OBU) can be seen as a sensor for a self-driving system or driver assistance system, and the ITS applications play an important role in system interaction. The ITS applications require an environmental perception layer that coordinates location and maintains DNS, INS, and RNS by parsing received messages. This layer is also responsible for rate control. A vehicle's status and application definitions are all related to its transmission rate, and all this information is available in this layer. We know that the transmission rate can be easily adjusted in CSMA-based protocols as nodes can access the channel at any time, so long as the channel is idle. However, for usual TDMA-based protocols, nodes can access the channel only in the required time slots in order to lower the transmission collision rate, which makes it difficult to adjust the transmission rate. Thus, more work should be done to realize a dynamic rate supported TDMA-based MAC for VANETs.

IV. ASTSMAC PROTOCOL

We have made an important observation: one node will always use the acquired time slot unless a collision occurs in the usual TDMA-based VANET protocols. This is designed to lower the transmission collision rate. Meanwhile, each node must transmit a packet, even if it has no data to send during its time slot, resulting in considerable waste of network resources. Meanwhile, the environment around a vehicle changes rapidly as it moves at high speed. We consider that a low packet broadcasting cycle is required when the traffic-density is low (to provide near real-time context awareness), whereas a high broadcasting cycle is required when the traffic density is high, which allows the network to accommodate more nodes. Thus, the application layer program should dynamically adjust the packet generation rate, while the MAC layer must support the diverse rate requirement. As a novel TDMA-based protocol, ASTSMAC takes advantage of slot sharing. In ASTSMAC, each time frame is partitioned into time slots with fixed length, where each slot can be used by multiple nodes.

A. DNS,INS AND RNS MAINTENANCE

In usual TDMA-based protocols, one node can determine information from neighboring nodes by listening to S slots, where S is the frame length. Nodes transmit data only in the corresponding time frame in ASTSMAC, which means information on neighboring nodes cannot be collected by only listening to one frame length. It is necessary to combine the last transmission time and transmission cycle from each node to complete maintenance of DNS, INS, and RNS.

When node x receives a packet transmitted from node y, the latest transmission time is updated as the received time, and y's transmission cycle T_y can be known by parsing the header of the received packet. Node x adds y to DNS_x if y does not belong to DNS_x, and a count value θ_{x_y} will be set for y with an initial value T_y. In the following T_y frames starting from the time of receipt, θ_{x_y} will decrease by one at the end of each frame. θ_{x_y} will be reset if x receive a new packet transmitted by y before θ_{x_y} decreases to zero. If no packet is received once θ_{x_y} reaches zero, y will be removed from DNS_x. For nodes belonging to DNS_x, the motion, usage slot number, transmission cycle, and count value information for x are known.

Information on the vehicle ID, usage slot number, transmission cycle, and count value for each node belonging to DNS_y will be packed in the header of each packet transmitted by node y. Let ID_{y_i} denotes the i'th vehicle ID packed in the packet. Node x will compare each vehicle id ID_{y_i} with DNS_x and INS_x after receiving the packets sent by y; if ID_{y_i} does not belong to DNS_x and INS_x, then x adds ID_{y_i} to INS_x and a count value will be set with an initial value $max\{\theta_{x_y}, \theta_{y_i}\}$, where θ_{y_i} is the count value of node ID_{y_i} in the header part of the packet. If ID_{y_i} is already in INS_x, then θ_{y_i} will be updated. Similarly, the count value for each node in INS_x decrease by one at the end of each frame. One node will be removed from INS_x if the count value for the node decreases to zero. For nodes belong to INS_x, the usage slot number, transmission cycle, and count value information is known for x. RNS_x is

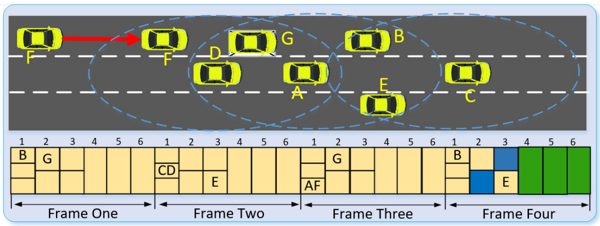

FIGURE 5. Illustration of slot acquisition.

the union of DNS_x and INS_x, which is updated with changes in DNS_x and INS_x.

B. ACQUIRING A TIME SLOT

Node x needs to acquire a new slot in two cases: when x is just powered on and when a transmission collision happens. Slot usage information from neighboring nodes is required for x to determine the set of slots that can be used. In the case when a transmission collision occurs, the information on neighboring nodes is already known from RNS_x. In the case when x is just powered on, RNS_x must first be populated with information from all neighboring nodes, which means x should listen to the channel for a few frames before acquiring a slot.

Fig. 5 shows a simple illustration of slot acquisition in a situation when a collision happens. Each time frame contains six time slots; nodes A, B, C, D, and F transmit every three frames and all use the first slot. Assuming the value of current frame number is f_c, and $f = [(f_c - 1) \mod 3] + 1$, node B transmits a packet when $f = 1$, nodes C and D transmit packets when $f = 2$, nodes A and F transmit packets when $f = 0$. Nodes G and E transmit every two frames, node G sends data using the second slot of each even frame, and E sends data using the third slot of each odd frame. More than one node can transmit using the same slot number in the same frame when their distances are long enough to guarantee no transmission collision. More than one node who are *RNS* neighbors to each other can use the same slot number in different frames when their transmission cycles allow them to send data alternately rather than simultaneously.

Nodes A and F can both use the first slot in the same frame when their distances are large. As the vehicles move, node F runs into node D's transmission range, and a transmission collision occurs as nodes A and F are both in D's transmission range and they transmit simultaneously. Node D cannot parse messages sent by A correctly because A and F transmit simultaneously. As a result, information on A and F will not be packed in the header portion when D sends packages. Node A will release the used slot and try to reacquire a new slot when it determines there is a node D who belongs to DNS_A, but packets sent by D have no information of A; the same is true for node F.

We can see that the DNS_A, INS_A, and RNS_A are $\{B, D, E, G\}$, $\{C\}$, and $\{B, C, D, E, G\}$. When A reacquires a new slot, slot usage information should by counted first. As shown in the fourth frame in Fig. 5, time slots marked green and blue are free time slots, where the last three slots are fully idle slots, the second slot is available in even frames, and the third slot can be used in odd frames. When a node attempts to acquire a new slot, a fully idle slot will be the first choice, unless no idle time slots are left. Nodes occupying slots that have not been fully used tend to merge together, and there will be more idle slots available after nodes merge. In Fig. 5, node A will randomly choose one fully idle slot from the last three slots in the fourth frame.

C. SLOT MIGRATION PROGRESS

Fully idle time slots should be reserved for nodes that cannot share slots with other nodes, e.g., newly entered nodes that transmit one packet per frame, or whose transmission cycle is incompatible with other nodes. Nodes that already acquired useful slots tend to merge together to optimize slot utilization if the number of idle slots is smaller than a threshold value. The principle of the merger process is as follows: nodes whose used slots have a lower utilization release their used slot and transfer to slots with higher utilization. In the process of merging slots, it is necessary to prevent multiple nodes from transferring to the same slot simultaneously; hence, slot migration requires an authentication process.

For a node x who transmits one packet every T_x frames, the usage rate of the node to the slot is:

$$\mathbb{U}_{N_x} = \frac{1}{T_x} \tag{1}$$

If there are n nodes who use the same slot s and these nodes are all belong to each other's *RNS*, then the usage rate of slot s is:

$$\mathbb{U}_{S_s} = \sum_{i=1}^{n} U_{N_i} \tag{2}$$

For node x, slot utilization can be calculated using slot usage information for nodes that belong to RNS_x. Each slot who has a usage rate that is not smaller than the usage rate of the slot which x used can be a candidate for x to transfer into if the following requirements are satisfied.

For a certain slot s with a set of users $U = \{u_1, u_2, \ldots, u_m\}$, the compatibility of node x with slot s is:

$$\mathbb{C}_{xs} = \sum_{i=1}^{m} [(T_x \mod T_{u_i}) \times (T_{u_i} \mod T_x)] \tag{3}$$

T_x denotes the transmission cycle of node x, and T_{u_i} denotes the transmission cycle of node u_i, which is one user of slot s. When C_{xs} does not equal zero, a transmission collision will happen if node x chooses to use this slot. Even if $\mathbb{C}_{xs} = 0$, x must still inspect whether the unused time frames of the slot can satisfy the requirement of x. In Fig. 6, nodes A and B both transmit one packet in every four frames, while node x transmits in every two frames. For both situations a and b, $\mathbb{C}_{xs} = 0$, and a slot can be used in situation b for node x, but it cannot be used in situation a.

Let T_{max} denote the maximum transmission cycle value of nodes belong to set $U \bigcup \{x\}$. The set of already-used

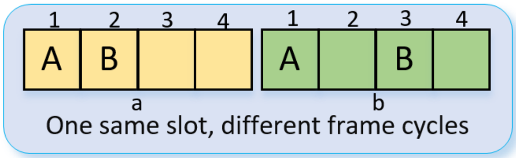

FIGURE 6. Illustration of slot chosen.

frames is:

$$\mathbb{F}_U = \bigcup_{i\in U}\{ \bigcup_{j=1}^{T_{max}/T_{u_i}} [(j-1)*T_{u_i}+\theta_{x_{u_i}}]\} \tag{4}$$

If node x chooses to use slot s and transmit in the ith frame where $i < T_x$, the set of used frames for x is:

$$\mathbb{F}_i = \bigcup_{j=1}^{T_{max}/T_x} [(j-1)*T_x+i] \tag{5}$$

If $F_U \bigcap F_i = \emptyset$, node x can use slot s and transmit packets in the $(i+n*T_x)$'th frames. Let

$$\mathbb{I}_{Ui} = \begin{cases} i, & \text{if } \mathbb{F}_U \bigcap \mathbb{F}_{i_s} = \emptyset \\ \emptyset, & \text{if } \mathbb{F}_U \bigcap \mathbb{F}_{i_s} \neq \emptyset \end{cases} \tag{6}$$

The set of useful frames can be defined as:

$$\mathbb{S}_{Ux} = \bigcup_{i=1}^{T_x} \mathbb{I}_{Ui} \tag{7}$$

Node x cannot use slot s if $\mathbb{S}_{Ux} = \emptyset$; otherwise, x can choose one number i belonging to F_x and request to use slot s with transmission frames $(i+n*T_x)$. In summary, node x who has acquired a slot s_1 can use slot s_2 iff

$$\begin{cases} \mathbb{U}_{S_{s_1}} \leq \mathbb{U}_{S_{s_2}} \\ \mathbb{U}_{N_x} + \mathbb{U}_{S_{s_2}} \leq 1 \\ \mathbb{C}_{xs_2} = 0 \\ \mathbb{S}_{Ux} \neq \emptyset \end{cases} \tag{8}$$

The number of slots s_2 and desired transmit frame number i will be packed in the *Req* field of the packet when node x requires slot s_2, and neighboring nodes within the transmission range of x will receive the slot requirement information. For each node belonging to DNS_x when x sends the request message, it is necessary to judge whether x can be allowed to use slot s_2, and the judgment (*ack* or *nak*) should be packed in the *Res* field of the next packet. When more than one node acquires the same time slot with the same transmit frame number, only the first slot can receive an *ack* response. Node x will release slot s_1 and transfer to using slot s_2 if no *nak* is received after information on nodes belonging to DNS_x is updated.

D. RATE ADJUSTMENT

If no other nodes share the slot used by node x, x can easily adjust its transmission cycle by simply modifying the transmission cycle value packed in the header portion of the packets and the transmission cycle itself simultaneously. If there are other nodes sharing the same slot with x, x should first determine whether the used slot can support the adjusted transmission cycle.

Assuming node x accesses slot s and transmits one packet in every T_{old} frames wants to adjust its transmission cycle and transmit one packet in every T_{new} frames, the set of nodes belonging to RNS_x who use slot s except x is $U = \{u_1, u_2, \ldots, u_n\}$. The slot usage rate of x is $1/T_{new}$ after adjusting the transmission cycle, and the sum of slot usage rate of nodes belong to U is $\sum_{i=1}^{n} \mathbb{U}_{N_i}$.

If x transmits a packet in every T_{new} frames, the compatibility value for node x with slot s is $\sum_{i=1}^{n}[(T_{u_i} \bmod T_{new}) \times (T_{new} \bmod T_{u_i})]$. If node x wants to use slot s after adjusting the transmission cycle the compatibility restriction must be satisfied, sufficient slot capacity is required, and useful frames set cannot be empty:

$$\begin{cases} \frac{1}{T_{new}} + \sum_{i=1}^{n} \mathbb{U}_{N_i} \leq 1 \\ \sum_{i=1}^{n}[(T_{u_i} \bmod T_{new}) \times (T_{new} \bmod T_{u_i})] = 0 \\ \mathbb{S}_{Ux} \neq \emptyset \end{cases} \tag{9}$$

Node x can simply modify the transmission cycle value packed in the header portion and adjust the transmission cycle to T_{new} if Eq. 9 is satisfied. Otherwise, node x cannot use slot s when adjusting its transmission cycle to T_{new}, which means x needs to release the used slot s and request other useful time slots.

E. COLLISION DETECTION

Because no RTS/CTS exchange is used, and no acknowledgment is transmitted from any recipients when broadcasting a packet, an IEEE 802.11p network suffers a collision problem, especially when traffic-density is high. TDMA-based protocols can effectively mitigate collision problems, as nodes transmit using acquired slots. However, collisions still occur when two or more nodes access the same time slot when they are within each other's transmission range, or when they are all one-hop neighbors of one same node. These collisions may occur when nodes acquire new slots, or if the time when nodes that have successfully acquired the same slot run closer due to node mobility.

Transmission collisions should be detected timely so that nodes can change slots to avoid more collisions in-time. Transmission collisions cannot be determined directly as no RTS/CTS exchange is used when considering the broadcasting services. Nodes identify whether transmission collisions occur by determining whether the broadcast packets are lost or not in distributed TDMA-based protocols. In fact, a poor radio channel condition can also cause packets loss. Whether a packet loss comes from a transmission collision or from a poor radio channel condition can be distinguished [33], which is out of scope of this paper.

The main impact of transmission collision is that perception accuracy of neighbor nodes will be reduced as

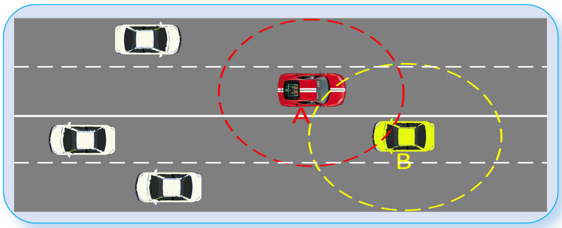

FIGURE 7. Illustration of newly joined neighbor nodes.

safety-related messages packed in the payload portion cannot be received successfully. Meanwhile, information used to maintain DNS, INS, and RNS packed in the header portion of the packet is also lost, which lower the accuracy of these sets. A node must reacquire a new slot once a transmission collision is detected to avoid more transmission failures. However, unnecessarily releasing of time slots should be prevented.

Each time node x receives a packet, collision detection should be performed except for payload data parsing, and except for DNS_x, INS_x, RNS_x updating, and slot migration judgment. Assuming node x receives a packet sent by node y, the IDs of nodes belonging to DNS_y can be found in the header of the packet. If x belongs to DNS_y, then y received the last packet sent by x and no transmit collision happens at node y. Two conditions may result in a case where x does not belong to DNS_y. The first is that nodes x and y are new neighbors to each other and y transmits packets first after the time they run into each other's transmission range. The other case is that there are other nodes that are one-hop neighbors of y and use the same slot as x, which results in a collision. Obviously, node x should release the used slot and acquire a new slot in the second case, but it should continue to use the slot in the first case.

An illustration of the second case is shown in Fig. IV-E, where nodes A and B run into each other's transmit range. Obviously, $\{A \notin DNS_B \wedge B \notin DNS_A\}$ when their distance is larger than R. As a result, no matter who transmits the first packet after the time their distance is equal to R, the header portion will not contain the information of the other node. This kind of situation should be identified to prevent unnecessary release of a time slot.

To identify whether one node is a new neighbor to node A when A receives a packet from that node, the set of DNS_A should be remembered the last time A sends a packet. A set DNS_TS_A is defined to remember DNS_A at the time when the last packet is sent by A, and DNS_TS_A updates each time A sends a packet. When node A receives a packet sent by node B and information on A is not packed in the header field of the packet, A should check whether B belongs to DNS_TS_A. If B does not belong to DNS_TS_A, then A has never received packets sent by B before the time A sends the last packet. Therefore, node B is a new neighbor to A, and node A can continue to use the usage time slot. If node B belongs to DNS_TS_A, A and B are already neighbors to each other when A sent the last packet, thus no information regarding A is packed in the header field of the packet, i.e., a transmit collision occurs and A should release the used slot and reacquire a new slot.

V. DENSITY AWARE FREQUENCY ADJUSTMENT

In this section, we study the transmission frequency adjustment problem and develop a distributed cycle control algorithm.

When considering rate adjustment, many factors should be considered, and there are many ways to adjust the transmission rate of vehicles. We present a density aware frequency adjustment algorithm (DAFA) here. Vehicles decrease their transmission rates when traffic-density is high, and increase their transmission rates when it is low. A vehicle can transmit one packet every T_x frames, where $T_x \in \{1, 2, 4, 8\}$.

Node x continues to monitor the usage rate of channel U_{C_x}:

$$U_{C_x} = \frac{\sum_{i \in RNS_x} U_{N_i} + U_{N_x}}{L} \tag{10}$$

where L denotes the number of time slots in one frame. The average transmission rate $r_{x_{ave}}$ for x can be calculated with the following equation:

$$T_{x_{ave}} = \frac{T_x + \sum_{i \in RNS_x} T_i}{(|RNS_x| + 1)} \tag{11}$$

where $|DNS_x|$ denotes the number of nodes belong to DNS_x. Because there are collision nodes, new nodes and rate-adjusted nodes who need to acquire a new time slot will increase the usage rate of the channel. Therefore, U_{C_x} should be less than a threshold value U_{up}. Meanwhile, a threshold value U_{down} is defined to ensure that the channel can be fully utilized

To support a density aware rate adjustment method, we propose a new heuristic algorithm called DAFA. The DAFA algorithm monitors the channel usage rate and slot usage information of nodes that belong to the set RNS. If $U_{C_x} > U_{up}$ and $T_x \leq T_{x_{ave}}$, node x will double its transmission cycle. The transmission cycle of node x will be halved if $U_{C_x} < U_{down}$ and $T_x \geq T_{x_{ave}}$. It will halve the transmission cycle if $U_{C_x} > U_{up}$ and $T_x \leq T_{x_{ave}}$. Rate adjustment for nodes is shown in Algorithm 1.

VI. PERFORMANCE EVALUATION

A series of simulations based on a highway scenario for evaluating the proposed protocol are presented in this section. We evaluate the performance of the protocols using MATLAB. Each node broadcast one BSM per frame using the acquired slot. The duration of one frame lasts 0.1s, which contains 100 time slots. We measure the performances of the protocols using different traffic densities. Number of vehicles running on the road are set from 400 to 800, with the step value equals to 100. At the beginning of the simulation, vehicles are randomly set at different locations on the road. The simulation begins when all the vehicles have acquired time slots.

A vehicle reenters the road from one end of the highway when it reaches the other end. Then, the number of vehicles on

Algorithm 1 The DAFA Algorithm for Node Transmission Rate Control

$Initialize: U_{sum} = 0, T_{sum} = 0, flag = 0$
if $\forall i \in RNS_x \quad NewDataFlag_i = true$ **then**
  for $i \in RNS_x$ **do**
    $U_{sum} = U_{sum} + U_i$
    $T_{sum} = T_{sum} + T_i$
  end for
  $U_{C_x} = \frac{u_{sum}+U_x}{L}$
  $T_{x_{ave}} = \frac{T_x+T_{sum}}{|RNS_x|+1}$
  if $U_{C_x} > U_{up}$ **and** $T_x \leq T_{x_{ave}}$ **then**
    if $T_x \leq 4$ **then**
      $T_x = T_x \times 2$
    end if
  end if
  if $U_{C_x} < U_{down}$ **and** $T_x \geq T_{x_{ave}}$ **then**
    if $T_x \geq 2$ **then**
      $T_x = T_x/2$
      $v_{mod} = 0$
      for $i \in RNS_x$ **do**
        $v_{mod} = v_{mod} + (T_i\%T_x) \times (T_x\%T_i)$
        if $U_{sum}+\frac{1}{T_x} \geq 1$ **or** $v_{mod} > 0$ **or** $\mathbb{S}_{Ux} = \emptyset$ **then**
          $slot_x = ChooseNewSlot()$
        end if
      end for
    end if
  end if
end if

the highway segment remains constant during the simulation time. Each vehicle moves with a constant speed drawn from a normal distribution which ranges from 60-120 km/h. The wireless channel is assumed ideal, which means each node can successfully receive packets transmitted by other nodes within the transmission range R, unless transmission collisions occur. Table 1 lists the main parameters used unless a change is mentioned explicitly. Three performance metrics are mainly considered,

1) Numbers of broadcast packets Tx_g and Tx_b, where Tx_g denotes the average number of successful transmissions per frame, Tx_b denotes the average number of transmission collisions per frame.
2) Packet delivery rate, calculated by $\frac{R_g}{R_g+R_b}$, where R_g and R_b denote number of packets that have been received successfully and number of packets which are lost because of the transmission collisions.
3) Packet transfer rate, calculated by $\frac{R_g}{Tx}$, where T_x denotes number of packets that have been broadcast.

We first evaluated the performance of the protocols without adjusting the transmission rate of the vehicles. The transmission cycle value of a vehicle was set to 1 or 2. $r_{full} = \frac{t_{full}}{t_{full}+t_{half}}$ was defined, where t_{full} denotes number of vehicles whose

TABLE 1. Simulation parameters.

Parameter	Value
Highway Length	$5Km$
Lanes per Direction	2
Lane Width	$5m$
Number of Lanes (each direction)	4
Transmission Range	$300m$
Speed	$[60km/h, 120km/h]$
Slots per Frame	100
Frame Duration	$0.1s$
Simulation Time	$3min$

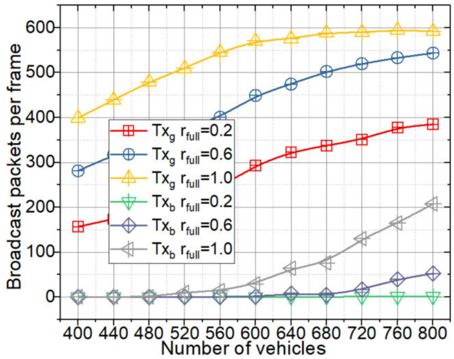

FIGURE 8. The Tx numbers with fixed transmission rate.

transmission cycle equals 1 and t_{half} denotes the number of vehicles whose transmission cycle equals 2.

Fig. 8 shows the numbers of the broadcast packets per frame for all situations. It's obviously that more packets will be broadcast when nodes adopt a higher transmission rate. However, we can see that transmission collisions increase sharply in a dense network when $r_{full} = 0.8$. Excessive wireless channel utilization will lead to an increase in transmission collisions. The perception accuracy of the surrounding nodes will be reduced when the collision rate is high. Meanwhile, accuracy of sets of DNS, INS, and RNS will be lower as nodes reacquire slots frequently, which will further lower the performance of the network. Thus, proper transmission rates should be selected according to the density of the networks, so that more packets can be broadcast successfully without causing high transmission collision rate.

Fig. 9 shows the packet delivery rate. It is obvious that a lower transmission rate results in fewer transmission collisions, leading to a higher packet delivery rate. All the schemes perform well when the traffic density is low. With the increase of vehicles, the packet delivery rate decrease faster when the proportion of nodes with high transmission rate is higher. The reason is that more packets need to be broadcast when higher transmission rate is selected. Then, the channel utilization will be higher, and the channel will be saturated earlier with the increase of the vehicles. In this situation, more packets will be lost due to the increased transmission collisions.

Fig. 10 shows the packet transfer rate. With the increase of vehicles, more nodes are supposed to received the broadcast packets as more one-hop neighbors exist for nodes. However, transmission collisions have a negative impact on the packet

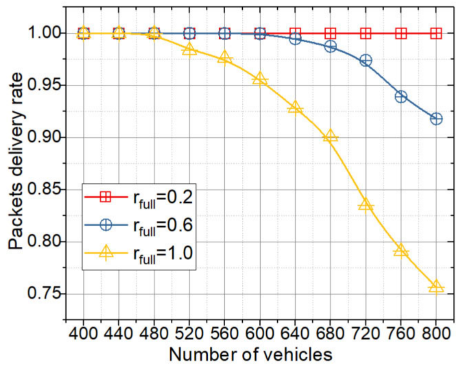

FIGURE 9. The packet delivery rate with fixed transmission rate.

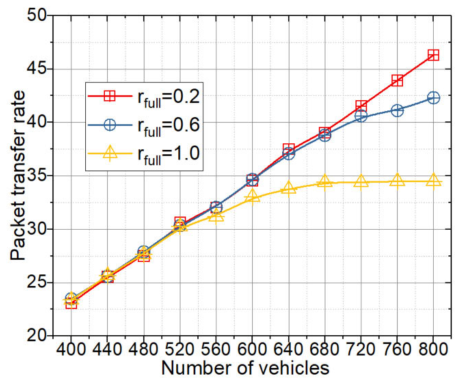

FIGURE 10. The packet transfer rate with fixed transmission rate.

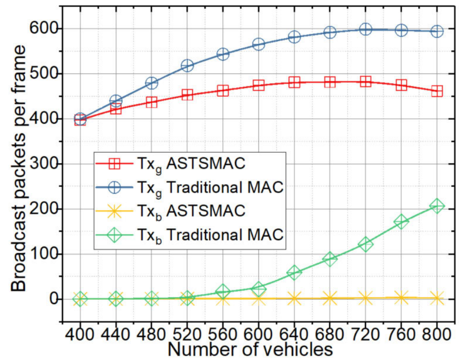

FIGURE 11. The Tx numbers with using the DAFA algorithm.

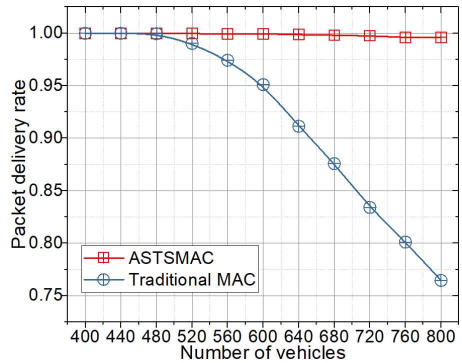

FIGURE 12. The packet delivery rate with using the DAFA algorithm.

transfer rate. As shown in Fig. 10, the growth rate slows down earlier when the proportion of nodes with high transmission rate is higher.

We can see that nodes can adopt different transmission rates using our scheme. Higher transmission rate should be used when the density of the network is low. Higher Tx throughput, packet delivery rate, and packet transfer rate can be achieved in such situation. However, with the increase of the network density, transmission rate should be adjusted properly. Otherwise, more transmission collisions occur. Packet delivery rate will be low as packets may not be received successfully due to the transmission collisions. Meanwhile, packets can not be received by more neighbors successfully even number of one-hop neighbors is increased.

Then, we evaluated the performance of our protocol using the DAFA algorithm. U_{up} and U_{down} were set to 0.9 and 0.8, respectively. The protocol is compared with a traditional MAC scheme, i.e., a vehicle broadcasts one packet each frame using an acquired time slot.

Fig. 11 shows the numbers of the broadcast packets per frame for all the protocols. Because nodes decrease their transmission rate when the traffic density is high, fewer packets are broadcast when using ASTSMAC. Although average number of successful transmissions per frame is larger when using traditional MAC. Transmission collision rate is too high, which is unacceptable. A node x may encounter continuous transmission collisions when receiving packets from another node y, then, x will unable to know the running state of y in time.

Fig. 12 shows the packet delivery rate of the protocols. It is obvious that the delivery rate decreases sharply when using traditional MAC in high-density networks. Nodes broadcast one packet per frame using acquired slots in traditional MAC. When the number of slots acquired by vehicles is large, the ratio of merging collisions increases as the vehicles move. Meanwhile, fewer idle slots can be acquired for collision nodes, resulting in a higher accessing collision rate. The packet delivery rate will be low when the transmission collision rate is high. Because nodes decrease their transmission rate when traffic-density is high in ASTSMAC, the burden of the channel is much smaller; hence, higher delivery rate can be achieved as fewer Tx collisions occur.

Fig. 13 shows the packet transfer rate of the protocols. The packet transfer rate almost stopped increasing when the number of vehicles is larger than 600 in the traditional MAC protocol. ASTSMAC exhibits better performance compared with the traditional MAC protocol, especially when the traffic-density is high. Because nodes adjust their transmission rate dynamically according to the density of the network, the network will not be saturated with the increase of the vehicles. Then, transmission collision rate can be controlled at a lower level. The packet transfer rate increase with the increase of the traffic density.

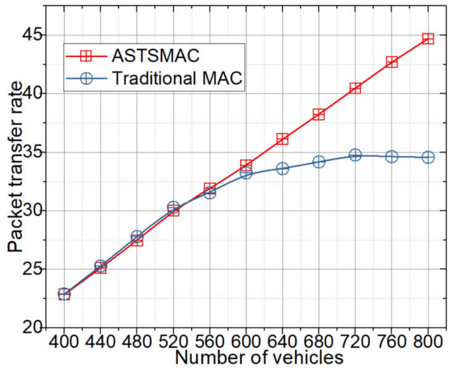

FIGURE 13. The packet transfer rate with using the DAFA algorithm.

VII. CONCLUSION

In this paper, an application suitable time slot sharing MAC protocol, called ASTSMAC, is proposed for VANET. Nodes can access the acquired time slots cyclically; one time slot can be shared by multiple nodes even if they belong to each other's *RNS* set. We present constraints on slot sharing and the operational process of ASTSMAC. There are many principles or methods to guide the adjustment of transmission rate, and we provide a density aware and weight related frequency adjustment algorithm (DAFA), which combines the support for an intelligent transport system. VANET has more knowledge about the vehicles, while the intelligent transport system has a better understanding of the road; therefore, more information should be exchanged between VANET and ITS. Simulation results show that ASTSMAC is flexible and adaptable to changes in traffic-density, providing a much higher throughput and lower collision rate compared with usual TDMA-based protocols.

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