PTMAC: A Prediction-Based TDMA MAC Protocol for Reducing Packet Collisions in VANET

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***Abstract*—With the rapid development of wireless communications, vehicular ad hoc networks (VANETs) have recently attracted great attention. Although IEEE 802.11p has been approved as the standard medium access control (MAC) protocol for vehicle-to-vehicle communications, its contention-based nature and inability to handle hidden-terminal problems may incur high packet collision probability under high-traffic-density situations. To overcome the shortcoming of IEEE 802.11p, time-division multiple-access (TDMA)-based protocols are proposed. However, packet collisions can still occur due to contention or multiple vehicles using the same slot while approaching each other, i.e., encounter collisions, particularly in two-way traffic roads. Some proposed remedying the encounter collisions for two-way traffic by partitioning a frame into two sets: one for the traffic in each direction. However, these proposed protocols are harder to adapt to the uneven traffic loads on both directions and cannot solve the problem of four-way intersections. In this paper, we propose a new TDMA protocol called prediction-based TDMA MAC (PTMAC) based on a novel way of predicting encounter collisions and effectively reducing the number of collisions. To the best of our knowledge, PTMAC is the first protocol that is designed for both two-way traffic and four-way intersections. It has shown that, based on this predictability, the encounter collisions can be greatly reduced in both two-way traffic and four-way intersections, regardless of the traffic loads on different road segments.**

***Index Terms*—Medium access control (MAC), packet collision prediction, time-division multiple access (TDMA), vehicular ad hoc network (VANET).**

I. Introduction

With the development of wireless communications, vehicular ad hoc networks (VANETs) have recently attracted increasing attention. As a special type of mobile ad hoc networks, VANETs provide communications among vehicles and between vehicles and infrastructures via roadside units (RSUs). In North America, The U.S. Federal Communications Commission has allocated 75 MHz of spectrum in the 5.9-GHz band for dedicated short-range communications (DSRC) to be used by intelligent transportation systems. Different from other ad-hoc networks, VANETs have the unique characteristics of high node mobility, dynamic topology changes, and strict delay constraints. These issues must be considered in developing medium access control (MAC) protocols for VANETs to support both safety- and nonsafety-related applications.

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Although the carrier sense multiple access/collision avoidance (CSMA/CA)-based IEEE 802.11p [1] has been approved as the standard MAC protocol, it has the problem of high collision probability if the traffic density is high, particularly for packet broadcasting [2]–[5]. Broadcasting plays an important role on propagating safety-related messages, such as vehicle accident warning and road condition alerting. In addition to the event-driven messages, wireless access in vehicular environments (WAVE) [6] also develops additional layer protocol, including the basic safety messages (BSMs) and WAVE Basic Service Advertisements (WSAs) [7], [8]. The BSM contains critical vehicle's status information, such as its location and speed. To support most of the applications and make sure that the potential dangers can be detected on time, every vehicle is required to broadcast and exchange BSMs periodically, i.e., at least once in every 100 ms [9]. WSAs are also needed to be periodically broadcast by RSUs or vehicles to mostly support nonsafety services.

Based on the IEEE 802.11p MAC protocol, if the channel is sensed as idle, a vehicle starts the transmission directly. Otherwise, it needs to randomly pick up a backoff value from the contention window (CW) and start a countdown procedure. Transmission will begin when the backoff value reaches 0. If multiple vehicles within a two-hop communication range (two times communication range) try to access the channel simultaneously, a collision will happen and none of the packets can be received successfully. In this case, vehicles have to recompete for the channel to resend the packets. An exponential backoff scheme that extends the CW size for decreasing the possibility of contention collision is applied for unicast retransmission. However, as a contention-based scheme, CSMA/CA has the drawback of potentially unbounded channel access delay [10]. If a vehicle has multiple packets, it has to contend for multiple times. Furthermore, 802.11p is vulnerable to the hidden-terminal problem since it cannot use the request-to-send/clear-to-send mechanism for packet broadcasting [3]. In this case, the packet collision cannot even be detected right away. No exponential backoff scheme can be used for broadcasting, and the probability of packet collision is potentially high [2].

To overcome the shortcomings of IEEE 802.11p, time-division multiple-access (TDMA)-based MAC protocols have been proposed to facilitate efficient transmission in VANETs

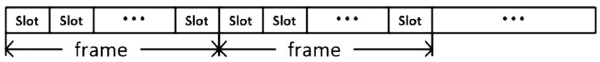

Fig. 1. Time frame and slot in TDMA.

[11], [12]. There are two types of TDMA-based MAC protocols: distributed TDMA and centralized TDMA. Each node manages its time slot by itself in distributed TDMA, whereas all the time slots are allocated by a central node in a centralized TDMA [13]–[16]. The work in [16] took advantage of RSUs to collect vehicle information and make a schedule decision based on the channel quality, speed, and access control. However, this scheme requires a large number of RSUs and is only suitable for urban area. In [13]–[15], cluster heads are used as the central nodes, and vehicles are partitioned into several clusters. However, the cluster-based scheme faces the challenges of cluster forming, cluster head selection, and cluster changing. Therefore, considering the high mobility nature of vehicles, we focus on distributed-TDMA-based MAC protocols that provide a more flexible way for slot management.

The most basic distributed-TDMA-based protocol has been proposed in [11] and [12] using a time-slotted structure. The time is partitioned into repeated frames, and each frame is composed of a fixed number of slots, as shown in Fig. 1. Each vehicle selects a specific time slot to transmit data. If successful, it keeps on using the same slot at subsequent frames until a collision occurs, or the slot is no longer needed. Since every vehicle is required to broadcast the slot information about all its one-hop neighbors, a vehicle is able to know which slot is still available. Therefore, the possibility of transmission collision is reduced, and each node is guaranteed to access the channel at least once in each frame if the reservation is successfully made. There is no need for each individual packet to compete for the channel.

Considering a real traffic environment, a few distributed TDMA MAC protocols have been proposed for a two-way traffic scenario [17], [18]. There are two types of collisions. The first type is contention collision, which happens between newly joining vehicles who are trying to reserve the same available slot within a two-hop communication range. The newly joining vehicles are those that have not reserved a slot and intend to transmit packets. Another type of collision is encounter collision, which happens between vehicles that are currently occupying the same time slot. They are originally out of the two-hop range but approach and encounter each other later. Although some slot partition methods, such as even–odd [17], are proposed for eliminating the encounter collisions between vehicles running at opposite directions, the slot utilization becomes low when the traffic density is high in one direction while low in another. Moreover, they cannot eliminate the encounter collisions among vehicles from the same direction. Furthermore, none of the previously proposed MAC protocols work well at the four-way intersections.

Based on the report by the U.S. Department of Transportation (USDOT) [19], vehicle information, such as speed, position, and moving direction, is required and should be broadcast by every vehicle periodically to support the safety-related applications in VANETs. Therefore, we make an important observation that most of the encounter collisions can be predicted and potentially avoided based on such vehicle information. We design a new prediction-based TDMA MAC protocol (PTMAC) to reduce the possibility of encounter collisions. To the best of our knowledge, PTMAC is the first protocol that is designed for both two-way traffic and four-way intersections. Our main contributions in this paper can be summarized as follows.

- Designing a new prediction-based TDMA MAC protocol (PTMAC) for decreasing the probability of encounter collisions while maintaining high-slot utilization and with very small additional overheads. Most of the encounter collisions can be predicted and, potentially, eliminated before they really happen. The prediction is based on the vehicle information that is already provided to support safety-related applications.
- Our newly designed PTMAC protocol is demonstrated to be suitable for both two-way traffic scenario and four-way intersections in an urban area. Unbalanced traffic densities will not degrade the performance of PTMAC.
- Through measuring and comparing our PTMAC protocol with ADHOC MAC [12] and even–odd TDMA MAC [17], we show that PTMAC has better performance with fewer collisions and higher delivery rate for both two-way and four-way intersection scenarios.

The remainder of this paper is organized as follows. Section II provides an overview of the related work. We introduce our proposed PTMAC protocol under two-way scenarios in Section III and extend it for four-way intersections in Section IV. Performance analysis of ADHOC MAC, even–odd MAC, and PTMAC is provided in Section V. In Section VI, we evaluate the performance of our PTMAC protocol and compare it with other TDMA-based MAC protocols, and Section VII gives a conclusion of this paper.

II. Related Work

In addition to the TDMA-based MAC protocol, space-division multiple-access (SDMA)-based schemes are also considered [20]–[22]. The basic idea of SDMA is to divide the road into separated cells, and each cell has its own assigned time slot. However, the network utilization is potentially low when the traffic is sparse. It is a waste of bandwidth to assign slots to the cells with no vehicle. The fairness may also become a problem for different traffic densities on different cells. Therefore, we focus on the TDMA-based protocol in this paper.

Detailed comparisons between CSMA/CA- and TDMA-based MAC protocols in VANETs have been provided in some previous works [23]–[25]. They have shown that TDMA performs more reliably and robustly when compared with IEEE 802.11p. The ADHOC MAC proposed in [12] is a basic TDMA-based protocol. It was designed for ad hoc networks to provide efficient and reliable data delivery service. It grouped a set of time slots into a frame and defined a concept of frame information (FI) that contains the time slot status. Each vehicle is responsible for broadcasting its FI to inform others about the occupied slots by its one-hop neighbors and itself. In this way, every vehicle can get all its neighbors' slot information within a two-hop range. A new joining vehicle needs to listen to the channel for a frame and then selects an available time slot to transmit data at the next frame. If other nearby vehicles receive the transmitted data, they will add this new slot information into their FI messages to indicate the success of the slot contention. In this way, the new joining vehicle is able to learn whether its slot contention is successful through the broadcast FI messages from its neighbor vehicles. Once a vehicle gets a slot successfully, it keeps on using the same slot at subsequent frames until a collision happens, or it no longer needs the slot. However, this slot reservation scheme cannot handle the encounter collisions.

Based on the slotted structure that has been proposed in [12], some improved TDMA-based MAC protocols have been developed for VANETs [26]–[28]. An adaptive distributed MAC named A-ADHOC was proposed in [26]. Since the fixed-size frames may waste slots and introduce unnecessary delay under a sparse traffic condition, A-ADHOC dynamically adjusts the length of a frame based on the real-time traffic density. In [26], it was shown that A-ADHOC can enhance the performance with less transmission delay. A self-configuring protocol called VeSOMAC was proposed in [27]. Unlike other schemes that select a time slot randomly, the work in [27] paid more attention to the ordering of time slots. The time slots are ordered in the same sequence as the vehicles appear on the road to reduce the packets forwarding delay. In [28], a cooperative protocol named CAH-MAC based on ADHOC MAC was developed. The scheme allows the neighbors who detected a transmission failure to retransmit the packet using an unreserved slot. However, it ignored the fact that new joining vehicles may also contend for the same unreserved slot. Thus, more contention collisions are introduced. These proposed protocols only considered one-way traffic and did not focus on reducing the number of transmission collisions.

A few MAC protocols have been designed for two-way traffic using slot partition [17], [18]. A MAC protocol based on even–odd partition was proposed in [17]. They regulated that vehicles heading right can only contend for even slots while vehicles running left can only contend for odd slots. In this way, encounter collisions caused by vehicles from the opposite directions can be completely avoided. However, the slot utilization is low when the traffic density is high in one direction while low in another direction. Another TDMA-based MAC protocol called VeMAC was proposed in [18]. Each frame is partitioned into three sets of slots: L, R, and F. The F set is related to the RSUs, whereas the L and R sets are associated with the vehicles moving in left and right, respectively. Unlike the MAC protocol in [17], this slot partition is not strict, i.e., if a vehicle cannot reserve a slot successfully in a period of time, it is allowed to contend for a slot that originally assigned to the opposite direction. Although such a compromise can somewhat increase the slot utilization, its random slot borrowing scheme increases the probability of encounter collisions among vehicles at opposite directions. The more slots borrowed from the opposite direction, the more likely an encounter collision will happen. If the number of borrowed slots is large, the partition scheme become meaningless, and it can no longer efficiently eliminate the encounter collisions. In addition, before a vehicle is allowed to contend for a slot that is assigned to the other direction, it may already experience several contention collisions.

Although the TDMA-based MAC protocols proposed in [17] and [18] using the slot partition method can reduce the number of encounter collisions, they potentially incur low slot utilization and more contention collisions for the direction with heavier traffic density. They also cannot avoid the encounter collisions among vehicles heading the same direction. Furthermore, the traffic pattern at four-way intersections is much more complicated than two-way traffic, and protocols that were proposed previously no longer work. Therefore, we design a novel prediction-based MAC protocol to solve these problems.

III. PTMAC Protocol for Two-Way Traffic

We have made an important observation that most of the encounter collisions can be predicted and potentially avoided based on vehicles' moving patterns and traffic condition. Therefore, instead of using the slot partition method, we propose a novel MAC protocol that takes advantage of prediction to remove potential collisions. Our PTMAC protocol is described under a two-way traffic scenario here, and it will be extended to four-way intersections later. For both two-way and four-way scenarios, there are three steps that need to be processed in the PTMAC protocol: potential collision detection, potential collision prediction, and potential collision elimination. A potential collision needs to be detected first based on the slot information. Then, we can predict whether this potential collision will really happen in the future based on the real-time traffic condition and vehicles information. Finally, we reschedule the slots to eliminate this potential collision. Detailed descriptions of these three steps will be provided later. Notice that the collisions we mentioned here mean encounter collisions, so as the following collisions mentioned in this paper, unless we point out that it is a contention collision. Recall that in a TDMA-based protocol, each vehicle will first contend for an empty slot in a frame. It will continuously use this slot if it successfully transmitted the first time. A contention collision happens if multiple vehicles within a two-hop communication range contend for the same slot. An encounter collision is caused by two vehicles approaching each other while using the same slot in a frame.

A. Assumptions

First, some assumptions are made based on the basic TDMA MAC protocol that has been proposed in VANETs.

1) Every vehicle broadcasts a message at every frame, which includes its own location, speed, and moving direction. Such vehicle information is required by most of the safety-related applications. This message also contains the FI about all the occupied slots by it and its one-hop neighbors.
2) Every vehicle keeps the slot information about its one-hop and two-hop neighbors, which are shared by its one-hop neighbors.
3) Each newly joining vehicle that has not obtained a slot and wants to get a slot needs to listen to the channel for

one frame. Then, they can randomly choose an available slot at the next frame for transmission.

4) Each vehicle is equipped with a GPS device that provides the information about its own location, moving direction, and speed. Road information, such as road length, is also available. Such information can be obtained from RSU broadcasting.

The assumptions about the slot information follow the ADHOC MAC proposed in [12]. ADHOC MAC does not need additional information other than the FI and works well for one-way traffic. PTMAC needs more vehicle information for predicting the potential encounter collisions. Fortunately, information, such as vehicle speed, location, and moving direction, are generally required by most of the applications for safety purposes. To support most of the safety-related applications, USDOT considers two types of safety messages as helpful for dissemination: event-driven messages and periodic messages [19]. The event-driven messages are sent when a dangerous condition is detected. Meanwhile, the periodic messages are broadcast by every vehicle periodically. It usually contains the vehicle status information, such as speed, position, and moving direction. Since each vehicle is aware of its neighbor vehicles, unsafe situations can be avoided. This type of packets is required to be broadcast frequently enough in order to provide the most updated information. The Vehicle Safety Communications Consortium (VSCC) suggests that the periodic messages should be broadcast at a frequency of at least ten messages per second. Example applications identified by VSCC include traffic signal violation warning, curve speed warning, emergency electronic brake lights, precrash warning, cooperative forward collision warning, left turn assistant, lane-change warning, and stop sign movement assistant [9]. The packet size basically ranges from 200 to 500 B [29].

For potential collision detection, vehicle information is unnecessary, and the detection can be completed only by slot information. Therefore, there is typically no additional overhead for potential collision detection in PTMAC. On the other hand, vehicle information, such as speed, position, and moving direction, will be helpful for potential collision prediction. Once a potential collision is detected, such vehicle information will be requested and used for potential collision prediction. In this case, very small overhead is introduced for collision prediction in PTMAC since only the potentially colliding vehicle's information will be transmitted upon the detected collision and request. More details will be discussed in the following.

B. Potential Collision Detection

We start from the first step of our PTMAC protocol: how to detect a potential encounter collision. Typically, two vehicles within their communication range (i.e., one-hop distance) using the same slot will cause a transmission collision. However, in a broadcast environment, a collision will happen if these two vehicles are within two times of their transmission range (i.e., two-hop distance) since a vehicle in between these two will not receive either broadcasting sent by these two vehicles. To detect a potential collision before it actually happens, we intend to identify any two vehicles using the same slot that are out of the two-hop communication range from each other. That is, a vehicle needs to know the slot usage information of other vehicles that are beyond the two-hop distance.

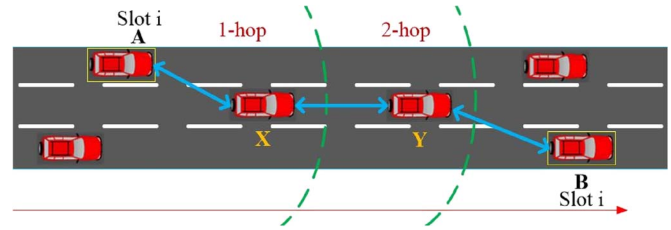

Fig. 2. Potential collision detection for the same direction.

The most naive solution is to require each vehicle to broadcast the information of its two-hop neighbors in addition to its one-hop neighbors. The major drawback of this approach is that significant overheads will be introduced with longer packet length. Therefore, to avoid such additional overheads, we use "intermediate vehicles" to detect the potential collisions between vehicles currently out of the two-hop range. Since each vehicle is able to obtain the information of its two-hop neighbors from its one-hop neighbors, the intermediate vehicles are able to get knowledge of its two-hop neighbors ahead and two-hop neighbors behind. In this way, these intermediate vehicles can detect potential collisions between vehicles out of the two-hop range but within the three- or four-hop range who are reserving the same slot. This is the most essential observation for our proposed protocol.

The process of potential collision detection can be described as: Based on the message containing the FI received from other vehicles (one-hop neighbors), every vehicle needs to check whether any two of its one-hop or two-hop neighbors are occupying the same time slot. Every vehicle learns the information of its two-hop neighbors from its one-hop neighbors. Therefore, a potential collision can be detected between two vehicles at most four hops away. Since each vehicle tries to avoid reserving the same slot with other vehicles within a two-hop range, a potential collision can only be detected before it happens between two vehicles that are three hops or four hops away. However, since two vehicles with four-hop potential collision are still far away from each other and will be safe for a time, we only need to concern the potential collisions detection for vehicles that are between two to three hops distance. For example, Figs. 2 and 3 show the potential collisions that are detected among vehicles at the same direction and opposite directions, respectively. In both cases, vehicles A and B are currently out of the two-hop range but are within the three-hop range. They are occupying the same slots i, but they cannot find this potential collision by themselves. Instead, the intermediate vehicles X and Y have the slot information about both A and B; therefore, they are able to detect this potential collision between A and B.

Notice that, if the traffic density is very low, an intermediate vehicle may not exist between the two vehicles with a potential collision. For example, in Fig. 3, at least two intermediate vehicles X and Y are needed to inform each other the slot information of A and B. If there is only one or no intermediate

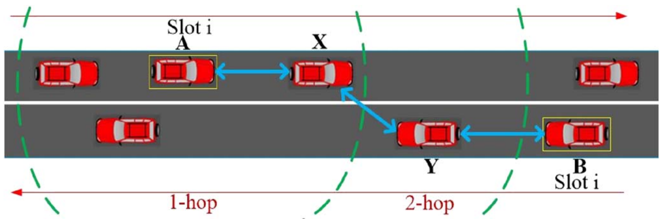

Fig. 3. Potential collision detection for opposite direction.

vehicle, the potential collision cannot be detected. In this case, the PTMAC protocol performs similar to ADHOC MAC. Vehicles that get encounter collision will recontend for an available slot to transmit the packet. Meanwhile, the packet collision will not become a problem in such sparse traffic condition.

C. Potential Collision Prediction

When an intermediate vehicle detects a potential collision between two other vehicles, e.g., vehicles A and B, it needs to predict whether A and B will "encounter" each other, and the potential collision will really happen. In this paper, the "encounter" means that two vehicles come into two-hop communication range of each other. The predictions that can be done based on the vehicle information include the locations, speeds, and moving directions of these two potentially colliding vehicles (in term of transmission). Since every vehicle periodically broadcasts its vehicle information to meet the requirement of safety-related applications, the intermediate vehicle has the vehicles information of one of the potentially colliding vehicles, which is its one-hop neighbor. However, it has no knowledge about the other potentially colliding vehicle, which is its two-hop neighbor.

To obtain the vehicle information of the potentially colliding vehicle in two-hop distance, the intermediate vehicle needs to add a request to its broadcast message. Other intermediate vehicles that require the same information do not need to send duplicate requests. The vehicle (must also be an intermediate vehicle) that hears such request and is a one-hop neighbor of the requested, potentially colliding vehicle and will add the requested vehicle information into its broadcast message. Similarly, other vehicles, which receive the same request and find the required information that has already been broadcast, can ignore this request. Once the requested vehicle information is received, the intermediate vehicle will begin the potential collision prediction. For example, in Fig. 3, the intermediate vehicles X and Y have the slot information about both A and B. Thus, they can detect the potential collision between A and B. However, X only knows the vehicle information about A and needs Y to pass B's information to finish the prediction. For a three-hop potential collision (two vehicles are between the two- and three-time communication range), assuming the communication range is 300 m and the vehicle speed is 30 m/s (67 mi/h), even if the two potentially colliding vehicles are running toward each other, it will take 5 s (50 frames) before these two vehicles encounter each other. Therefore, there is plenty of time for an intermediate vehicle to request for and get the needed vehicle information.

A potential collision that is predicted to happen is considered "active." We classify the potential encounter collisions into two types: potential collisions among vehicles running at the same direction and among vehicles driving at the opposite directions. Different methods will be used for these two types of potential collisions to predict if they are active or not.

1) Same Direction Potential Collision Prediction: For vehicles running along the same direction, they are likely to catch up with each other if the one behind has much faster speed. The distance between two vehicles may shorten to or be less than the two-hop communication range ($2R$) in a short time from now due to their speed difference. Assuming vehicle A locates behind B and they are occupying the same slot, this potential collision is regarded as active if the distance between them can be reduced to $2R$ in a short duration of times, where R is the communication range of a vehicle. This is shown in the following:

$$\begin{cases}(V_a - V_b) \times T \geq D - 2R, \quad (\text{if } V_b < V_a)\\ T = \min\left\{K, \frac{L_b}{V_b}\right\}\end{cases} \tag{1}$$

where V_a and V_b are the speeds of vehicles A and B, respectively. L_b is the length of the road that B has not finished, and D is the current distance between A and B. T stands for a short duration time, which is used to check whether vehicles A and B can run into a two-hop range of each other within this short duration T. It is unnecessary for a potentially colliding vehicle to change its slot too early. If two potentially colliding vehicles will not encounter each other within time T, the potential collision can be removed later. K represents a short period of time that enables a potentially colliding vehicle to change its slot with high success probability. It is still possible that a potentially colliding vehicle can safely switch its slot to a new slot, but it gets into a potential collision with another three-hop neighbor. If we set a larger K, the potentially colliding vehicle will have multiple chances to switch its slot and a higher probability of removing the collision can be achieved. On the other hand, if we set K to be too large, the original slot for the potentially colliding vehicle will be open for competition, and other vehicles may take over this slot. In this case, a new potential collision may appear right away, and the whole process needs to be done again. Therefore, a smaller K can save resource and slot utilization. T equals to either K or the time before B leaves the road, depending on whichever is smaller. Since T is a really short period of time (e.g., less than 1 s), we regarded V_a and V_b as constant within T, and their variability is less important. If A is faster than B and (1) is satisfied, this potential collision is considered active and has to be eliminated. Otherwise, if V_a is not larger than V_b or (1) is not satisfied, this potential collision is currently harmless.

2) Opposite Direction Potential Collision Prediction: For vehicles running at opposite directions, potential collisions may be detected between vehicles that are running toward each other or farther away from each other. An example is shown in Fig. 4. Vehicles A and B are reserving the same slot and driving toward each other. Thus, the potential collision detected by intermediate vehicle I_1 and I_2 will definitely happen in the future. On the other hand, if intermediate vehicle I_1' and

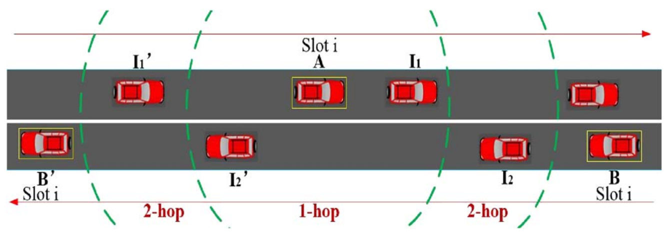

Fig. 4. Potential collision prediction in opposite directions.

I_2' detect a potential collision between vehicles A and B′, this collision can be ignored since A and B′ are running farther away from each other. We set up two conditions for intermediate vehicles to check whether the potentially colliding vehicles are approaching or running farther away from each other.

1) The intermediate vehicle finds that one of the potentially colliding vehicles, which is running at the same direction, locates behind it.
2) Meanwhile, the other potentially colliding vehicle, which is running at the opposite direction, locates ahead of it.

If both conditions are satisfied, the intermediate vehicle knows that the two potentially colliding vehicles are approaching each other. Otherwise, this potential collision can be ignored. Assuming the DSRC communication range is 300 m and vehicle speeds are 30 m/s (67 mi/h) on a highway, for a three-hop potential collision, the time to shorten the distance between two potentially colliding vehicles to a two-hop range is about 5 s. Therefore, there is plenty of time for a potentially colliding vehicle to change its slot since every vehicle needs to broadcast its information at least every 100 ms. Similar to the same direction collision, only if the distance between A and B can be reduced to $2R$ in a short duration of time T, the potential collision is active. This is shown in

$$(V_a + V_b) \times T \geq D - 2R \tag{2}$$

where T equals to the K in (1). When an intermediate vehicle finds that two potentially colliding vehicles are approaching each other and (2) is satisfied, it regards this potential collision as active.

D. Potential Collision Elimination

If an active potential collision is found, we need to prevent this collision from happening in the near future. One of the potentially colliding vehicles needs to give up its current reserved slot and switch to another available slot. Since there may be multiple intermediate vehicles detecting the same potential collision, we need to select one of them to handle this potential collision. Then, the selected intermediate vehicle has the responsibility to decide which one is the "switching vehicle" to release its current reserved time slot. Finally, the switching vehicle needs to switch to another empty slot after receiving a switching notification from the responsible intermediate vehicle. Recall that we focus only on the potential collisions detected between vehicles three hops away.

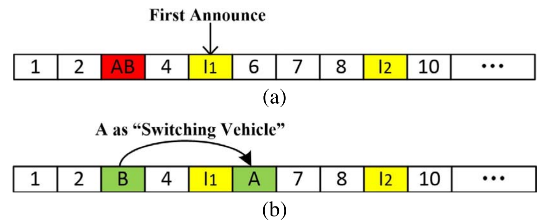

Fig. 5. Potential collision elimination. (a) Before potential collisions elimination. (b) After potential collision elimination.

The basic rule is to select the potentially colliding vehicle that is a one-hop neighbor of the responsible intermediate vehicle as the switching vehicle. There may be more than one intermediate vehicle that can detect the same potential collision. When an intermediate vehicle finds an active potential collision, it first listens to the channel until its own reserved slot comes. If it has not received any notification from others about this active potential collision, it becomes the responsible intermediate vehicle to broadcast a notification about this potential collision. Meanwhile, the potentially colliding vehicle within one hop of this responsible intermediate vehicle is selected as the switching vehicle. In this way, the responsible intermediate vehicle can directly inform the switching vehicle without further forwarding. Notice here that the intermediate vehicles that detect the same potential collision must be in the communication range of each other. Thus, they are able to receive the notification about the potential collision from each other.

A one-bit flag will be added into the broadcast FI of the responsible intermediate to indicate that a slot has an active potential collision. Assuming slot i is currently occupied by the switching vehicle A, the responsible intermediate vehicle will broadcast its FI with an active flag on slot i. Therefore, when vehicle A receives the FI from the intermediate vehicle, it finds its slot will conflict with another vehicle and can conclude that it has to change its slot. Other intermediate vehicles found the same active potential collision could just broadcast their FIs without adding an active flag on the same slot. After the switching vehicle changes to a new slot, it will update its FI and transmit using its new slot. Vehicles that received such updated FI from A will update their FI. We can also allow a switching vehicle to use its original slot one more time to preannounce which slot it will switch to. This way, other vehicles that received such messages can avoid selecting the same slot. The contention collisions among multiple switching vehicles from different potential collisions and newly joining vehicles can be prevented.

We take Fig. 4 as an example, and the original slot arrangement is shown as Fig. 5(a). Vehicles A and B are occupying the same slot 3. This potential collision will be detected by both the intermediate vehicles I_1 and I_2. Since I_1 has not received a notification about the detected potential collision, it will become the responsible intermediate vehicle who needs to broadcast a notification about this potential collision. As I_1's one-hop neighbor, vehicle A will be selected as the "switching vehicle". Meanwhile, since the slot of vehicle I_2 is behind the slot of I_1, I_2 is able to hear the switch notification from I_1 and does not need to broadcast a duplicate notification. As shown in Fig. 5(b), when vehicle A receives the notification, it will randomly switch to another available slot. After A switches to a new slot, all its neighbors will update their FI about A. Therefore, the potential collision between vehicles A and B can be eliminated before it happens.

IV. PTMAC Protocol for Four-Way Traffic

A. More Assumptions and Traffic Model

After explaining our PTMAC under two-way traffic scenario, we extend it to a four-way intersection scenario. Vehicles can drive at four possible directions: north, south, west, and east. We consider a traffic light model in which the intersection has a traffic light for controlling the traffic from all four directions. Vehicles can go straight, turn right, turn left, or make a U-turn at a four-way intersection. More assumptions in addition to what we mentioned in Section III are made for four-way traffic.

1) Each vehicle periodically broadcasts their turning direction at the coming intersection before passing the intersection. This information can come from the turning left/right signal or from the GPS device base on a predetermined route.
2) The location of an intersection and the phases of its traffic lights are provided by RSU broadcasting.

The PTMAC protocol still processes with the three steps for a four-way intersection scenario. The steps of potential collision detection and potential collision elimination are similar to what we described in the two-way traffic scenario. We will focus on explaining the most different part: potential collision prediction under a four-way scenario. Similar to the two-way scenario, the intermediate will first request for the information about the potentially colliding vehicle that is two hops away and then begin the prediction. We further separate the potential collision prediction into two parts: road segment prediction and intersection prediction. The road segment prediction concerns the collisions between vehicles running on the same road segment, either heading in the same direction or the opposite directions. The intersection prediction pays attention to the potential collisions among vehicles driving on different road segments while approaching to or leaving the intersection. Since the road segment prediction is the same as what we have explained in a two-way traffic scenario, we concentrate on describing the intersection prediction that is used to check whether two vehicles are currently out of the two-hop range and reserving the same slot will encounter each other.

B. Potential Collision Prediction at an Intersection

We take an example of a four-way intersection scenario as shown in Fig. 6 to explain our PTMAC protocol. Vehicles A and B are occupying the same slot i and are currently three hops away from each other. After the intermediate vehicles X and Y

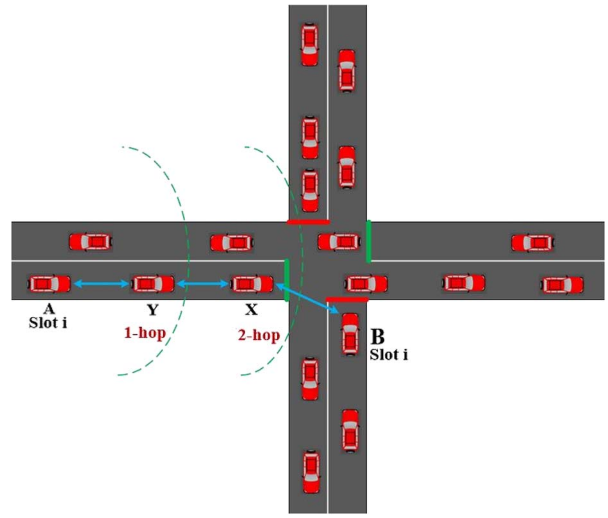

Fig. 6. Potential collision in a four-way intersection.

detected this potential collision, they need to predict whether this collision is active or not. We consider the potential collision prediction in three possible cases based on the current locations of two potentially colliding vehicles A and B. The first case is that both A and B have passed the intersection. The second case is that one of them has passed the intersection, whereas the other one has not. The third case is that none of them has passed the intersection.

In the first case, both A and B have already passed the intersection and are driving away from the intersection. If A and B have turned to different directions, they are running farther away from each other, and no collision will happen. If A and B have turned to the same direction, the prediction problem becomes the road segment prediction. The second possible case is that A has already passed the intersection, but B has not. B will turn to the same or different direction as A's. If B did not encounter A before it passes the intersection and turns to the same direction as A, the problem will become road segment prediction again. On the other hand, if B did not encounter A before it passes the intersection and turns to a different direction as A, their distance will become larger, and they have no more chances to encounter each other. Thus, we only need to check whether the potential collision is active before B passes the intersection.

We also consider the third case in which neither A nor B has passed the intersection. The distance between these two vehicles will be shortened before one of them passes the intersection. Assuming A passes the intersection first, if A turns to the opposite direction of B's current driving direction of the same road segment, then the problem becomes road segment prediction. If A turns to other directions, then the problem becomes similar to the second case. Thus, for this case, we only need to check whether the potential collision is active before A or B passes the intersection. We summarize all the cases in Table I.

To check whether two vehicles can encounter each other before passing the intersection, we first need to compute when they will pass the intersection. Based on a travel-time estimation model proposed in [31], we develop an improved model

TABLE I
INTERSECTION COLLISION PREDICTION WITH DIFFERENT POSITIONS OF VEHICLES A AND B

A passed	B passed	Action of Intermediate Vehicle
√	√	N/A
√	×	Check if potential collision is active before B passes the intersection
×	×	Check if potential collision is active before one of A and B passes the intersection

to estimate the travel time that a vehicle needs before it passes the intersection. We provide more accurate estimations with the help of VANET communication and real-time information. The total travel time T_t from a vehicle's current position to the intersection is separated into two components: signal delay time T_s and cruise time T_c. Vehicles' behaviors are complicated when they approaching the intersection, and they are greatly influenced by the traffic lights, particularly when they need to wait for a red signal. In this paper, we use the simplified Webster formula, which is the widely used model to estimate the signal delay. It is computed based on the traffic light phases, traffic volume (vehicles per second), and degree of saturation. The degree of saturation is the traffic-volume-to-capacity ratio. The capacity is the maximum rate at which vehicles can pass through a point in a period of time. Both the capacity and the traffic volume can be estimated by either an individual vehicle or from RSU broadcasting. Knowing the current locations and speeds of all its two-hop neighbors, an intermediate vehicle can compute the number of vehicles passing a point in a period of time and then get the traffic volume. This information is also widely used in many traffic control applications, such as intelligent traffic light [32]. Each vehicle also receives the red and green light phases information at an intersection from RSU broadcasting. Therefore, the signal delay can be calculated by the intermediate vehicle.

On the other hand, we modify the model in [31] by computing the cruise time based on real-time traffic information from vehicles periodically broadcasting information instead of using loop detector. The cruise time will be the time cost from a vehicle's current location to the end of the queue at an intersection. Since every vehicle has its two-hop neighbor's location and speed information, one simple way to estimate the queue length is counting the number of vehicles whose speeds are 0. Therefore, an intermediate vehicle is also able to compute the cruise time of two potentially colliding vehicles. The way we compute cruise time is more accurate than that in [31], since they considered the cruise time is from a vehicle's current location to a fix point (loop detector) regardless of the current queue length.

We set T_a and T_b as the total travel times needed for A and B to pass the intersection, respectively. L_a and L_b stand for the current distance from A and B to the intersection, respectively. V_a and V_b are the speeds of vehicles A and B. We regard V_a and V_b as constant in a short period of time. $T_{\rm ac}$ and $T_{\rm bc}$ are the cruise times of vehicles A and B, whereas $T_{\rm aq}$ and $T_{\rm bq}$ are the waiting times of vehicles A and B, respectively. If they do not need to wait for the signal, the cruise time will be exactly the total travel time. For the second case that A already passed the intersection, if $V_a < V_b$, then we directly check whether (3) or (4) shown in the following is satisfied:

$$\begin{cases} \sqrt{(L_a + V_a \times T)^2 + (L_b - V_b \times T)^2} \le 2R \\ (L_a + L_b) + (V_a - V_b) \times T \le 2R \\ T = \min\{K, T_{\rm bc}\} \end{cases} \tag{3}$$

$$\begin{cases} X = L_a + V_a \times T_b \\ Y = \sqrt{(L_a + V_a \times T_{\rm bc})^2 + (L_b - V_b \times T_{\rm bc})^2} \\ Y' = (L_a + L_b) + (V_a - V_b) \times T_{\rm bc} \\ \min\{X, Y(Y')\} \le 2R. \end{cases} \tag{4}$$

K is the short duration of time that we set for the switching vehicle to change its slot. If $K < T_b$, (3) is used. If $K \ge T_b$, then (4) will be checked. In (3), the first subequation checks two vehicles that are running in different directions and on different road segments. The second subequation is used for two vehicles running in the same direction but on different road segments. Similarly, in (4), Y and Y' are used for two vehicles that are running in different directions and in the same direction on different road segments, respectively. The shortest distance between A and B may appear at two points: when B reaches the waiting queue and when B is passing the intersection. Therefore, we check both points. X in (4) estimates the distance between A and B when B reaches the waiting queue. Y or Y' stands for the distance between A and B when B is passing the intersection. If (3) or (4) can be satisfied, the potential collision is considered active.

For the third case, assuming $T_b > T_a$, i.e., vehicle A will pass the intersection first, the following will be used to check whether the distance between A and B can reduce to $2R$ or smaller before A passes through the intersection

$$\begin{cases} \sqrt{(L_a - V_a \times T_1)^2 + (L_b - V_b \times T_2)^2\}} \le 2R \\ (L_a - V_a \times T_1) + (L_b - V_b \times T_2) \le 2R \\ T_1 = \min\{K, T_{\rm ac}\} \\ T_2 = \min\{K, T_{\rm bc}\} \end{cases} \tag{5}$$

$$\begin{cases} L_b - V_b \times T \le 2R \\ T = \min\{T_a, T_{\rm bc}\}. \end{cases} \tag{6}$$

If $K < T_a$, then (5) is used, whereas (6) will be checked when $K \ge T_a$. In (5), the first subequation checks two vehicles that are running at different directions and different road segments. The second subequation is used for two vehicles running at the same direction but different road segments. Equation (6) checks the distance between A and B when A is passing the intersection. If (5) or (6) is satisfied, this potential collision is active. Otherwise, we need to check whether the distance between A and B can be reduced to $2R$ or smaller before B passes the intersection using (3) or (4). This becomes the same situation as the second case.

V. PERFORMANCE ANALYSIS

A. *Probability of Contention Collisions*

As a reminder, there are two types of collisions: contention collision and encounter collision. We first investigate the contention collisions probability of the three MAC protocols. N denotes the total number of slots in each frame. N_E and N_R stand for the number of empty slots and reserved slots, respectively. M is defined as the number of new joining vehicles within two-hop communication range. They currently do not occupy slots but are trying to compete for slots. Here, we consider only the case that M is larger than one. Otherwise, no contention collision will happen. For the basic ADHOC MAC protocol, if N_E is greater than 1, the probability that a vehicle among these M competitors can reserve a slot successfully is computed as

$$P_S = \left(1 - \frac{1}{N_E}\right)^{M-1}. \tag{7}$$

If the N_E is less or equal to 1, the contention collision will definitely happen, and no one can make a reservation successfully.

If the number of current empty slots is equal to or larger than the number of competitors, i.e., $N_E \geq M$, then the probability that all these M vehicles can successfully gain a slot is computed as follows:

$$P_{\mathrm{ALLS}} = \frac{\prod_{i=0}^{M-1}(N_E - i)}{N_E^M}. \tag{8}$$

Since PTMAC does not use the slot partition method, the way of computing the contention collision probability for PTMAC is similar to ADHOC MAC.

For even–odd MAC protocol, the total number of available slots is halved for each direction. Assuming the traffic densities are completely balanced for both directions, there will be $N_E/2$ empty slots left for each direction. The contention collision can be analyzed in two cases. In the first case, if there are M number of competing vehicles from the same direction and $N_E/2$ is greater than 1, the probability that one of them can reserve a slot successfully is computed as

$$P_S = \left(1 - \frac{2}{N_E}\right)^{M-1}. \tag{9}$$

Then, if $(N_E/2) \geq M$, the probability that all these M vehicles gain a slot successfully is computed as

$$P_{\mathrm{ALLS}} = \frac{\prod_{i=0}^{M-1}\left(\frac{N_E}{2} - i\right)}{\left(\frac{N_E}{2}\right)^M}. \tag{10}$$

In another case, if there are a total of M competing vehicles within a two-hop communication range, half of them are running to the left, whereas half of them are driving to the right; the probability that one of them can reserve a slot successfully is computed as follows:

$$P'_S = \left(1 - \frac{2}{N_E}\right)^{\frac{M}{2}-1}. \tag{11}$$

If $N_E \geq M$, the probability of all these M vehicles gaining slots successfully in this case will be computed as

$$P'_{\mathrm{ALLS}} = \left(\frac{\prod_{i=0}^{\frac{M}{2}-1}\left(\frac{N_E}{2} - i\right)}{\left(\frac{N_E}{2}\right)^{\frac{M}{2}}}\right)^2. \tag{12}$$

Therefore, we can see that, when using even–odd MAC, more contention collisions are introduced in the first case, whereas smaller contention collision probability is achieved in the second case. However, since more contentions are happening between newly joining vehicles and they are heading the same direction, the first case happens more frequently. The second case is more suitable for the collisions that happen between new joining vehicles and recompeting vehicles or among recompeting vehicles.

For all the three MAC protocols, the contention collisions are not only caused by the newly joining vehicles but also from the vehicles that have suffered encounter collisions and have to recompete for new slots. Therefore, reducing the number of encounter collisions is also helpful for decreasing the number of contention collisions.

B. Probability of Encounter Collisions

An encounter collision is caused by two vehicles that are currently reserving the same slot and out of the two-hop range but will encounter each other in the near future. Assume that there are two newly joining vehicles A and B, and they are trying to reserve their slots. If we know that they will encounter in the future (e.g., driving at opposite directions and approaching each other), the probability that A and B will select the same slot (an encounter collision will happen) is computed as

$$P_{\mathrm{EC}} = \frac{N_E(A \cap B)}{N_E(A) \times N_E(B)}. \tag{13}$$

Notice here that vehicles A and B have different neighbors and slot allocations. $N_E(A)$ and $N_E(B)$ stand for the numbers of empty slots from the view of A and B, respectively. $N_E(A \cap B)$ expresses the number of empty slots from both A and B's views. Notice here that, for even–odd MAC protocol, no encounter collision happens between vehicles running at opposite directions. However, it cannot avoid the encounter collisions from the same direction. Since the number of available slots is halved in even–odd protocol, the probability of the encounter collision from vehicles at the same direction is increased.

C. Probability of Removing Potential Collisions

In our proposed PTMAC protocol, it is likely that a detected potential collision cannot be successfully removed under heavy traffic density. One possible situation is that there is no other empty slot for the switching vehicle to switch to. Another possible situation is that the switching vehicle switches its slot to a new slot, but this new slot incurs a new potential collision with another vehicle. Therefore, under increased traffic density, this vehicle may have to keep changing its slot until it finds a slot without potential conflict with others or the collision really happens. Assuming that vehicle A is detected having a potential collision with vehicle B, the probability that this potential collision can be removed at the next frame is expressed as

$$P_{\mathrm{RM1}} = 1 - \frac{N\left(A(E) \cap A(3)\right)}{N_E(A)}, \quad (N_E(A) > 0). \tag{14}$$

Here, $N_E(A)$ is the number of empty slots, and $A(E)$ expresses the empty slots from A's view. $A(3)$ stands for the three-hop neighbors of A, and they will encounter A within T (short duration). We call those neighbors as three-hop encounter neighbors. Therefore, $N(A(E) \cap A(3))$ expresses the number of slots that are empty from A's point of view and meanwhile are occupied by A's three-hop encounter neighbors.

As long as the potential collision has not really happened, vehicle A still has chance to switch to elsewhere. If A has N_{SW} number of chances to change its slot, the probability that vehicle A can eventually remove the potential collision is computed as

$$P_{\mathrm{RM}} = 1 - \prod_{i=0}^{N_{\mathrm{SW}}} \frac{N\left(A(E) \cap A(3)\right) - i}{N_E(A) - i}, \quad \left(N_E(A) > i\right). \quad (15)$$

Therefore, we can see that, with higher traffic density, a vehicle may need to switch its slot multiple times to avoid the encounter collision. This is also the reason that T should not be too small. Otherwise, A only has one or two chances to switch its slot, which may cause failed collision elimination, particularly under a heavy-traffic-density scenario.

VI. Simulation and Performance Evaluation

Here, we evaluate the performance of our proposed PTMAC protocol. We use Matlab and Simulation of Urban Mobility (SUMO) to construct a simulation environment in which both two-way and four-way traffic scenarios are considered. SUMO is a traffic simulator to generate real-world mobility models, including road map, traffic light information, and vehicle's moving pattern. Vehicles' speeds are adjusted based on the traffic condition and traffic light information when they are approaching an intersection. A mobility trace file that contains the position of each vehicle at any time is generated by SUMO and input to Matlab. Matlab is used for building a VANET communication environment and for implementing the MAC protocols. We compare our PTMAC with ADHOC MAC [12] and even–odd TDMA protocol [17].

The first simulation scenario is a highway with two-way traffic. Vehicles are running at different speeds within different maximum speeds. A vehicle can catch up with and pass over other vehicles if its speed is faster. We measure the performances using different traffic densities. In total, 200, 400, and 600 vehicles are generated for each direction during the simulation time of 600 s. We also investigate the impact of unbalanced traffic densities for different directions on these three MAC protocols. The second simulation scenario is an intersection with four-way traffic. There are three lanes for each direction. The right lane is for vehicles turning right, the middle lane is for vehicles going straight, and the left lane is used for vehicles turning left or making a U-turn. The number of vehicles that has been generated for each direction is varied from 150 to 200 vehicles within a simulation time of 600 s. For both scenarios, the packet size is assumed as 400 B and the data rate is 6 Mb/s.

To ensure driving safety, the 3-s rule is generally used, which suggests that a vehicle should stay 3 s behind the vehicle in front of it. For a highway scenario, we consider two-way traffic,

TABLE II
Simulation Parameters Setting

Parameter	Highway	Intersection
Highway Road Length	2000m	N/A
Urban Road Length before Traffic Light	N/A	1500m
Vehicle Max Speed	25-32m/s	20-25m/s
Green Light Phase	N/A	42s
Number of Lanes (each direction)	4	3
Traffic Density (number of vehicles per direction)	200, 400, 600	150, 175, 200
Communication Range	300m	300m
Per Frame Length	0.1s	0.1s
Data Rage	6Mbps	6Mbps
Packet Size	400 Bytes	400 Bytes
Simulation Time	600s	600s

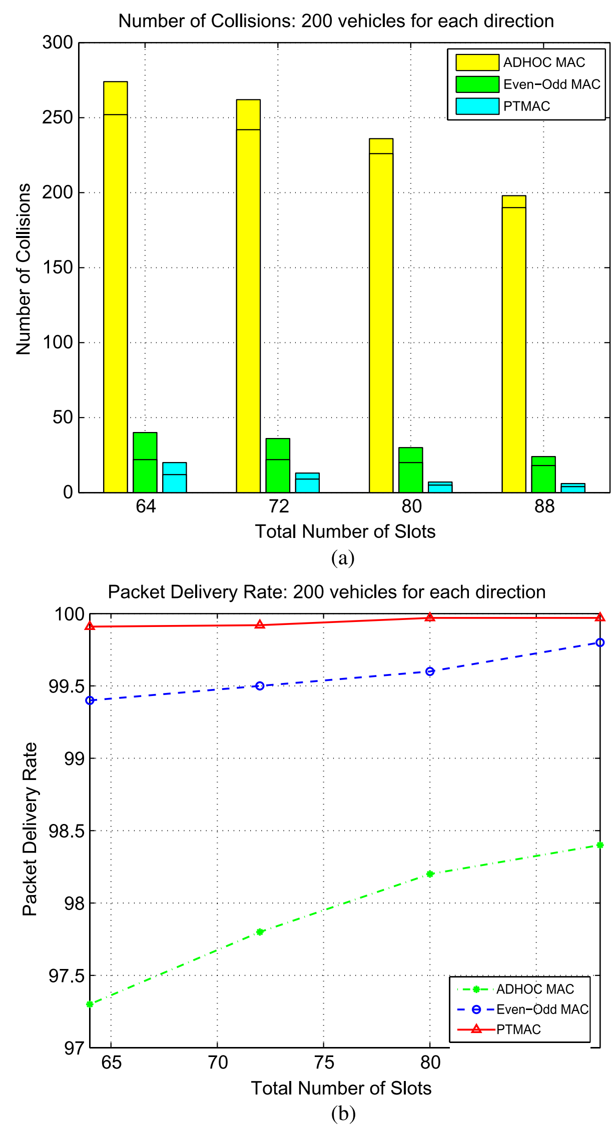

Fig. 7. Performance with 200 vehicles in each direction on the highway. (a) Number of collisions. (b) Packet delivery rate.

and each direction with four lanes. Assuming that the average vehicle speed is 30 m/s (67 mi/h), the distance between the two vehicles should be 90 m. Assuming the average vehicle length is 4 m, one vehicle will have a maximum 48 neighbor vehicles in its communication range (six vehicles for each lane). For the urban area, the average vehicle speed is assumed as 20 m/s (45 mi/h), and the distance between the two vehicles should be

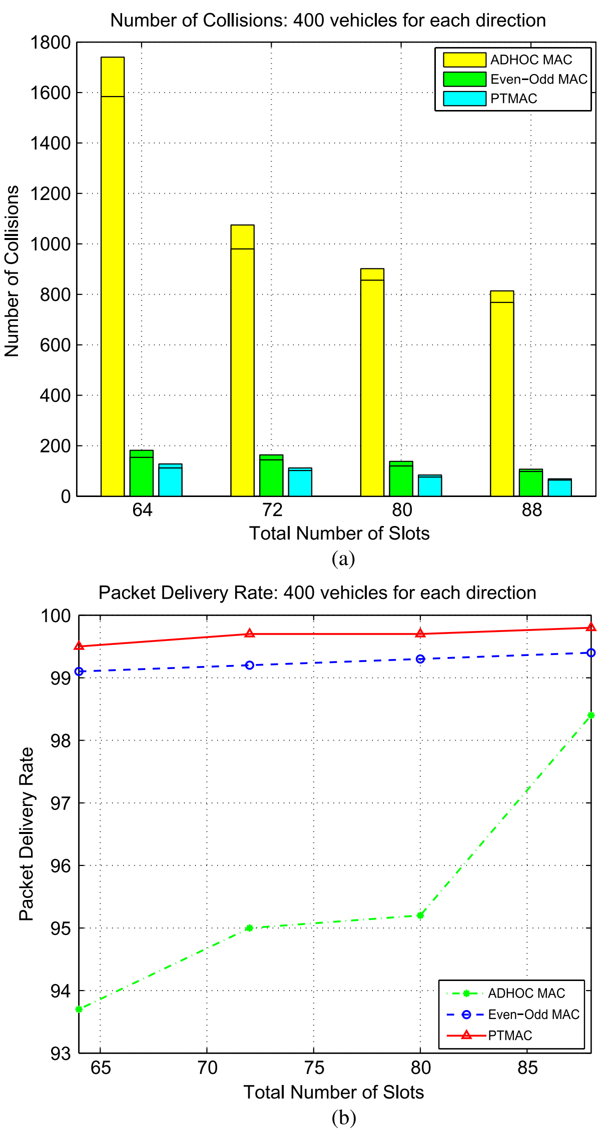

Fig. 8. Performance with 400 vehicles in each direction on the highway. (a) Number of collisions. (b) Packet delivery rate.

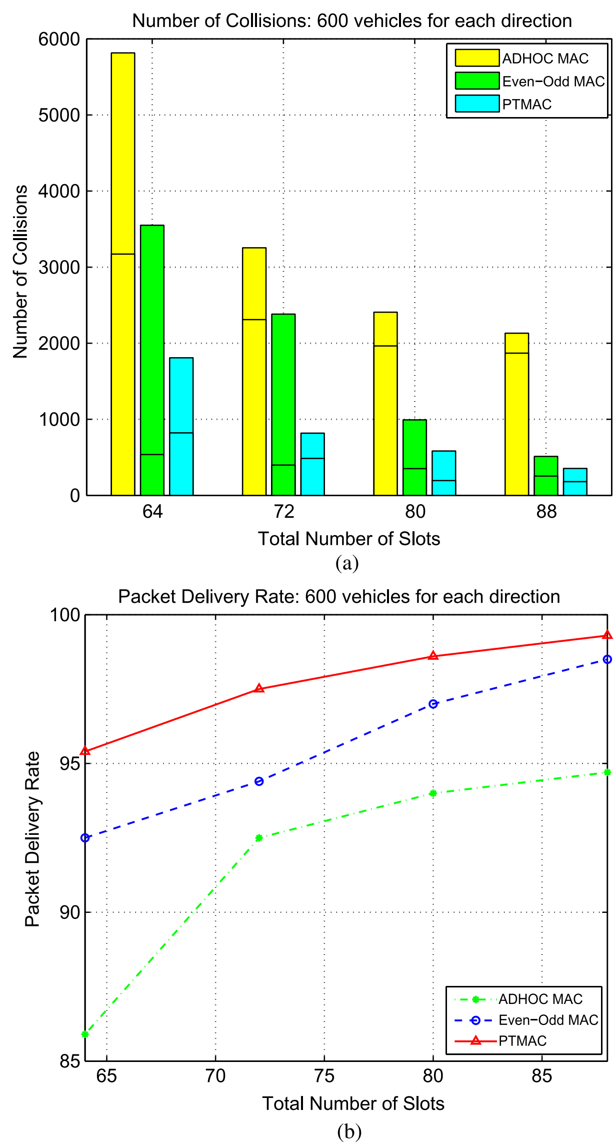

Fig. 9. Performance with 600 vehicles in each direction on the highway. (a) Number of collisions. (b) Packet delivery rate.

60 m. If there are three lanes for each direction, a maximum of 54 vehicles will be in the communication range (nine vehicles for each lane). Considering the aggressive driving and stops at the intersection, we vary the number of slots in a frame from 64 to 88 and investigate its impact on the performance. The detailed simulation parameters are summarized in Table II. To focus on the packet collisions, the simulation runs using an ideal physical channel, i.e., the packet will be successfully transmitted within the communication range, if there is no packet collision.

A. Two-Way Simulation Results

We first evaluate the performance of these three MAC protocols under two-way traffic with balanced traffic densities. We focus on two metrics: packet delivery rate and total number of collisions. Fig. 7 shows the results of the number of packet collisions and packet delivery rate with 200 vehicles generated for each direction. In Fig. 7(a), every bar is separated into two parts by a black line. The part below the line stands for the number of encounter collisions, whereas the part above the line is the number of contention collisions. From the results, we can see that with the increment of the number of slots, all of the three MAC protocols get better performance since more available slots decreases the collision probability. With 64 slots per frame, PTMAC works better than ADHOC MAC and the even–odd MAC protocol with 92.7% and 50% fewer collisions, respectively. This is because PTMAC not only eliminates the collisions among vehicles from opposite directions but also avoids the collisions from the same direction. The delivery rate of PTMAC also improves by 2.6% and 0.5% compared with that of ADHOC MAC and even–odd MAC protocol, respectively. PTMAC also has fewer contention collisions. The number of contention collisions is affected by the number of encounter collisions since the collided vehicles have to recompete for slots. Therefore, reducing the number of encounter collisions is also helpful for decreasing the number of contention collisions. Since the traffic density is pretty low in this case, the problem of packet collision is not severe.

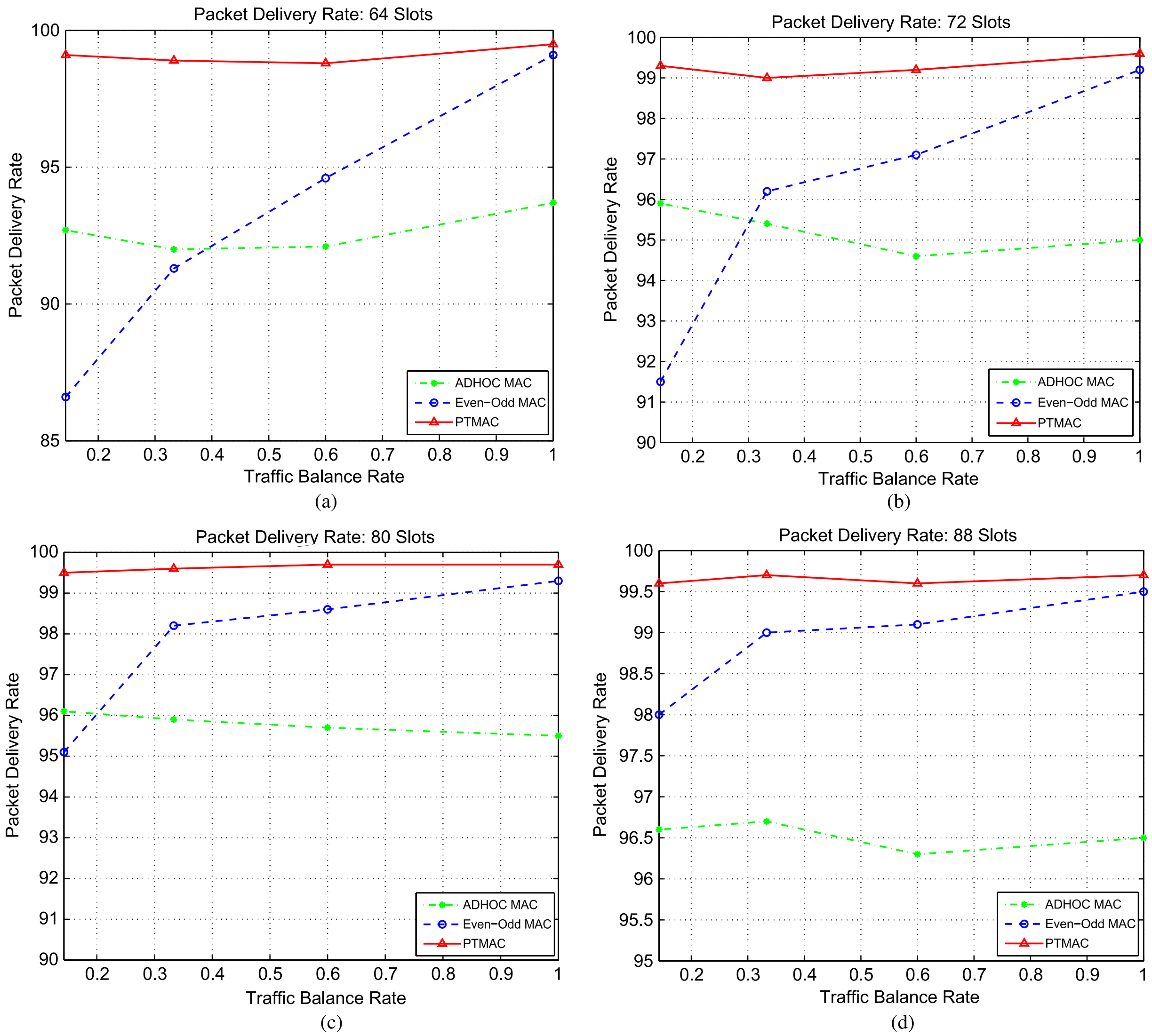

Fig. 10. Packet delivery rate with 800 vehicles and different traffic balance rates (TBRs). (a) 64 slots per frame. (b) 72 slots per frame. (c) 80 slots per frame. (d) 88 slots per frame.

Then, we increase the traffic density by generating 400 vehicles for each direction. The results about the number of collisions and packet delivery rate are shown in Fig. 8. With 64 slots per frame, PTMAC has 90.6% and 29.7% fewer collisions than ADHOC MAC and even–odd MAC protocol, respectively. The packet delivery rate of PTMAC improves by about 5.8% and 0.4% compared with that of the ADHOC MAC and even–odd, respectively. We continue to increase the traffic density to 600 vehicles for each direction, and Fig. 9 shows the results. The number of contention collisions of the even–odd protocol is sharply increased in this case. Basically, the even–odd scheme has no great impact on the number of contention collisions among vehicles driving at different directions, since both the number of available slots and the number of competing vehicles have been halved. However, if a contention happens among vehicles in the same direction (among newly joining vehicles and recompeting vehicles), a higher probability of contention collision may occur since only half of the slots are available. Higher traffic density means more newly joining vehicles are generated, and more encounter collisions happen among vehicles along the same direction. Thus, more contention collisions are introduced for the even–odd scheme. On the other hand, PTMAC has a little bit more encounter collisions than the even–odd MAC protocol with 64 and 72 numbers of slots in a frame. This is because the total number of available slots is not enough. Even if a potential collision has been identified, there is no other available slot to change to. In addition, it is likely that a switching vehicle switches to another slot but collides with another vehicle. However, even with 64 slots per frame under this dense traffic, the proposed PTMAC still has better overall performance with 9.2% and 3.4% higher delivery rate than ADHOC MAC and even–odd protocol, respectively. When we increase the number of slots in a frame to 80 and 88 (i.e., enough number of slots is provided for vehicles to switch to when eliminating the potential collisions), PTMAC has fewer encounter and contention collisions compared with the even–odd scheme.

In addition, we study the influence of unbalanced traffic densities on these three MAC protocols. Here, we define a new parameter called a traffic balance rate (TBR). It is computed as

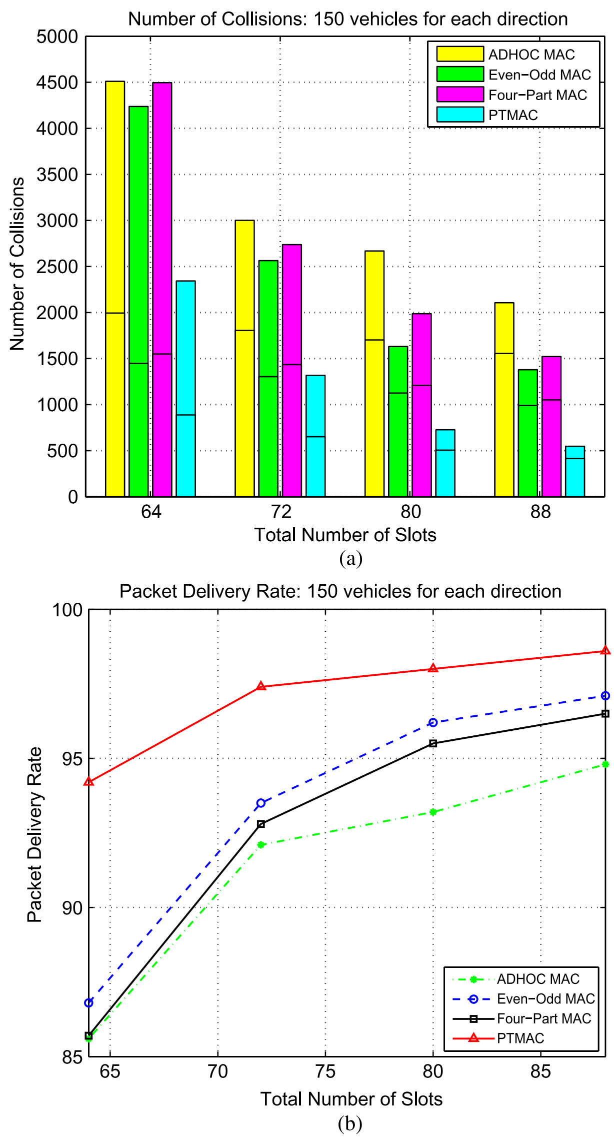

Fig. 11. Performance with 150 vehicles in each direction at the intersection. (a) Number of collisions. (b) Packet delivery rate.

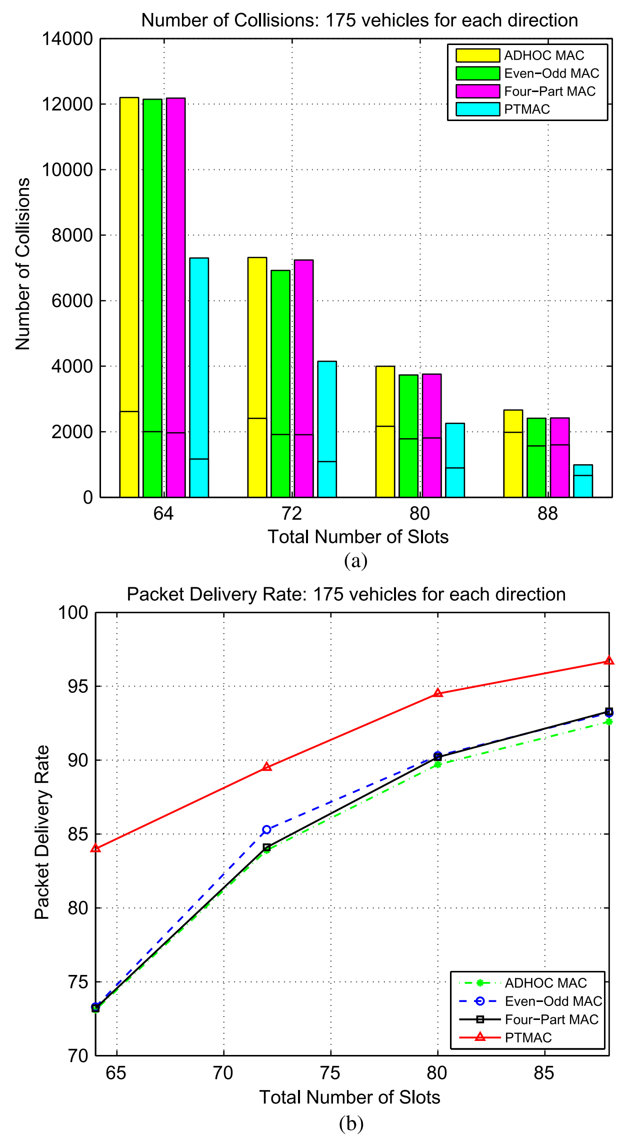

Fig. 12. Performance with 175 vehicles in each direction at the intersection. (a) Number of collisions. (b) Packet delivery rate.

the ratio of the number of vehicles in the direction with sparser traffic to the number of vehicles in the direction with denser traffic. Therefore, TBR equals to 1 when the exact number of vehicles is generated for each direction during the simulation. A small TBR means a scenario with severely unbalanced traffic densities. We fix the total number of vehicles that are generated through the simulation as 800 and measure the packet delivery rates by using different TBRs. Fig. 10(a)–(d) represent the packet delivery rates with 64, 72, 80, and 88 number of slots in a frame, respectively. The performances of ADHOC MAC and PTMAC are not greatly affected and degraded by the unbalanced traffic densities since these two protocols do not use a slot partition method. On the other hand, the even–odd protocol shows its sensitivity to a small TBR with a low packet delivery rate, particularly for smaller numbers of slots in a frame. With 64 slots in a frame, the performance of the even–odd protocol is worse than the ADHOC MAC when TBR is set as 1/7 or 1/3. Thus, vehicles in the direction with heavier density will suffer a high probability of contention collision, even if there are many empty slots left in another direction. With 64 slots and 1/7 TBR, PTMAC has higher delivery rate of 6.4% and 12.5% compared with ADHOC MAC and even–odd protocol, respectively. In addition, for even–odd, if a vehicle finds that all the slots assigned for its direction have been occupied, it will not have a chance to access the channel even if there are still empty slots left for the other direction. It cannot begin the slot contention until someone in its direction release the slots. In this case, the slots of the sparse traffic density side will be wasted, and contentions will be considered failed. These failed contentions are unnecessary and can be fully prevented if the number of available slots can be well adapted. Both PTMAC and ADHOC MAC do not suffer such unnecessary failures since vehicles freely select any available slots for channel contention.

B. Four-Way Simulation Results

We also evaluate the performances of the MAC protocols under the four-way intersection scenario. Similar to the two-way scenario, we measure their performances using different

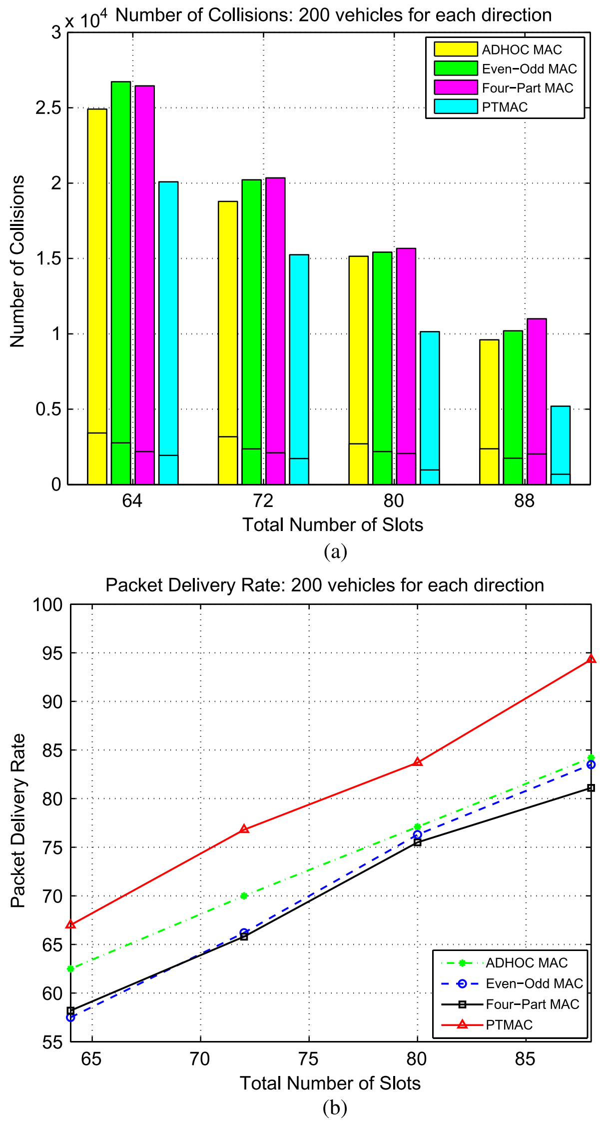

Fig. 13. Performance with 200 vehicles in each direction at the intersection. (a) Number of collisions. (b) Packet delivery rate.

numbers of slots in a frame and traffic densities. Four MAC protocols are compared for the four-way traffic scenario. For the even–odd MAC protocol, we regulate that vehicles moving to the east and north can use only even slots, whereas vehicles heading west and south can reserve only odd slots. Moreover, we measure another MAC protocol called the four-part MAC. In four-part MAC, all the slots in each frame are evenly partitioned into four disjointed parts: one part for each direction. Therefore, there will be no interference between vehicles running to the different directions.

Figs. 11–13 represent the results under different traffic densities. From the simulation results, we can see that PTMAC works the best with the least number of collisions and highest delivery rate. Since ADHOC MAC allows a vehicle to contend for any empty slot without considering the vehicles' mobility nature, it is suitable for only one-way traffic, and its performance is severely affected by the huge number of encounter collisions under such a four-way intersection scenario. Meanwhile, both even–odd and four-part MACs do not have obvious improvements for this four-way intersection scenario. They even perform worse when traffic density becomes heavier. More encounter collisions happen among vehicles at the same direction in this four-way intersection since a vehicle ahead may need to stop and wait for the red signal, so it is easy to be caught up by other vehicles behind. Such collisions cannot be handled by even–odd and four-part MACs. Moreover, even–odd MAC cannot avoid the contention collisions that happen near the intersection between vehicles using the same set of slots (such as vehicles heading north and east that both use the even slots). For the four-part MAC, although no contention collision will happen between vehicles that are originally driving at different directions, vehicles may change their directions at the intersection. Furthermore, the quartered number of available slots not only increases the probability of contention collisions but also causes more encounter collisions between vehicles running in the same direction.

Contrasting with ADHOC MAC, even–odd, and four-part protocols, PTMAC performs better with 48.1%, 44.7%, and 47.9% fewer collisions, respectively, when we set 64 slots in a frame and 150 vehicles for each direction. In the same environment, the packet delivery rate of PTMAC improves by about 8.6%, 7.4%, and 8.5% compared with that of ADHOC MAC, even–odd, and four-part protocols, respectively. When we increase the traffic density to 175 vehicles for each direction, PTMAC has 10.9%, 10.7%, and 10.8% higher delivery rate compared with that of ADHOC MAC, even–odd, and four-part protocols, respectively. For heavier traffic density with 200 vehicles for each direction, the efficiency of PTMAC is weakened with a smaller number of slots in each frame since the number of slots is not enough. However, it still has 5.5%, 10.5%, and 8.8% higher delivery rate than that of ADHOC, even–odd, and four-part protocols, respectively, for 64 slots per frame.

VII. Conclusion

In this paper, we propose the PTMAC protocol to decrease the number of packet collisions, particularly for encounter collisions. Potential collisions among vehicles that are currently out of the two-hop communication range can be detected by intermediate vehicles, predicted, and then eliminated before they really occur. Our simulations show the effectiveness of the proposed protocol. Since no slot partition is used, unbalanced traffic densities will not degrade the performance of PTMAC. Unlike a few existing MAC protocols that work only for one-way or two-way traffic scenarios, PTMAC is also suitable for handling four-way traffic.

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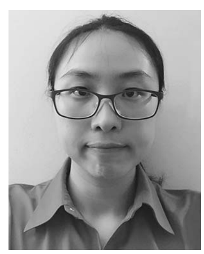

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