

Research Article

R-MAC: Risk-Aware Dynamic MAC Protocol for Vehicular Cooperative Collision Avoidance System

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Received 28 February 2013; Accepted 27 April 2013

Academic Editor: Shukui Zhang

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The key for cooperative collision avoidance (CCA) systems is the real-time and reliable delivery of safety-related messages among vehicles, which include periodical beacons and risk-triggered warning messages. In this paper, we first design a risk-aware dynamic medium-access control (R-MAC) protocol tailored for vehicular CCA applications. In this protocol, each frame is divided into two parts: TDMA segment for transferring beacons and CSMA segment for delivering warning messages. Then, we propose a stochastic model to predict the average total number of potential collisions in a platoon of vehicles, which determines the size of CSMA segment in the R-MAC protocol meticulously. Monte Carlo simulations validate that our model is reliable and practical. The performance of the R-MAC protocol is verified through theoretical analysis and extensive simulations under different traffic scenes. Simulation results show that R-MAC outperforms the traditional IEEE 802.11p protocol in terms of packets delivery rate and transmission delay, as well as the Jain's fairness index of the medium access between beacons and warning messages.

1. Introduction

As a potential technology for intelligent transportation system, vehicular ad hoc network (VANET) has received considerable attention by academic communities and major car manufactures around the world. The Federal Communications Commission (FCC) has allocated a dedicated 75 MHz spectrum for vehicular applications in 1999 [1], and some important projects (e.g., Advanced Driver Assistance Systems (ADASE2) [2], CarTALK2000 [3]) have been launched subsequently. Through wireless vehicle-to-vehicle and vehicle-to-roadside communications, VANET can provide various safety-related services. As a typical representation, cooperative collision avoidance (CCA) systems have greatly evolved in the past years [4, 5], which helps to reduce the probability of vehicular collisions and the corresponding damage significantly. Within a CCA system, when a vehicle in the platoon encounters an obstacle or collision, a warning message will be broadcast backwards to the following vehicles. Upon receiving a warning message, the following drivers will promptly brake instead of reacting to the brake light ahead

immediately in tradition, which saves a lot of time before the following drivers are aware of the accidents in the front [6].

In this paper, we study efficient and fair delivery of different messages in the considered scenario of CCA systems, where many vehicles form a platoon (or a chain) moving along the same road toward the same direction. Within this system, there are mainly two kinds of messages: beacons and warning messages. Beacons are disseminated among vehicles periodically to inform neighbors about their movement states, such as speed, acceleration, and direction. Warning messages are triggered by a specific vehicle which experiences a hazard or collisions and are propagated from the source to following vehicles as far as possible to inform them of the accidental situation. As a result, such messages have a higher priority [7] compared with beacons. One key for a CCA system is the real-time and reliable delivery of warning messages as well as beacons. In traditional CCA applications [4, 5], some simple approaches are employed to deliver messages, which may lead to several problems in an emergent situation. First, message collisions are more likely to occur with the increasing number of vehicles in the platoon due to

a large number of redundant warning messages pertaining to the same emergent event, which results in a serious message-delivery latency and packets loss. Then, the overemphasis on the higher delivery priority of warning messages makes the beacons lose the chance of medium access, especially in the IEEE 802.11p protocol which is based CSMA/CA mechanism. In addition, vehicles will become blind to others without knowledge of their latest movement states, which, in turn, may cause more accidental collisions among the platoon. To overcome these shortcomings, we design a risk-aware dynamic medium access control (R-MAC) protocol tailored for vehicular CCA systems, which makes a good tradeoff between efficient delivery and fairness of messages with different priorities.

To this end, our protocol is based on traditional TDMA mechanism, in which time is divided into periods called frames and each frame can be subdivided into tiny time slots uniformly. However, each frame in R-MAC includes two parts: CSMA segment for sending warning messages and TDMA segment for beacon transmission. In order to ensure the higher transfer priority of warning messages, we allocate slots to CSMA segment prior to TDMA segment in each frame. The number of slots reserved for CSMA segment is determined by the average total number of potential vehicle collisions among the platoon in the next few frames, which can be computed through a stochastic collision prediction model. After allocation for CSMA segment, the left slots fall into the TDMA segment. In this way, both efficiency and fairness of the medium access between the above two kinds of messages can be achieved in R-MAC. In addition, with the rapid spread of 3G and WIFI in recent years, the V2I communications has been feasible. In this paper, the prediction process of average total number of potential collisions operates on a roadside unit (RSU), such as 3G stations, WIFI hot spots.

The main contributions of the paper are listed below.

- (1) Considering the efficiency and fairness of delivering beacons and warning messages on the medium access, we design a risk-aware dynamic (R-MAC) protocol tailored for vehicular CCA systems, which is based on a dynamic TDMA mechanism.
- (2) Since the size of CSMA segment in each frame is determined by the average total number of potential collisions among the platoon in the next few frames, a stochastic collision prediction model is presented, which is based on minimum safety distance and a homogeneous Markov chain.
- (3) Moreover, extensive simulations under various traffic loads show that R-MAC outperforms the traditional IEEE 802.11p protocol in terms of packet delivery rate and transmission delay, as well as the Jain's fairness index of the medium access between beacons and warning messages.

The remainder of this paper is organized as follows. In Section 2, we briefly review the related work on MAC protocols and vehicle collision models in VANET. Section 3 delineates the operation of the R-MAC protocol in detail.

In order to compute the average total number of potential collisions used in R-MAC, the derivation of a stochastic collisions prediction model is introduced in Section 4. The performance of R-MAC is evaluated in different setups in Section 5, which also provides an in-depth analysis of the simulation results. We conclude the paper in Section 6.

2. Related Work

In recent years, various MAC protocols have been proposed to guarantee the real-time and reliable communications in VANET. These protocols are mainly based on two approaches: Carrier Sense Multiple Access (CSMA) and time division multiple access (TDMA). However, most of them cannot be applicable well to the vehicular scenarios with high mobility and fast changing topology.

The TDMA approach operates in a time slotted structure, where time slots are grouped into frames. Due to the collision-free nature of TDMA, it has been widely adopted and become the foundation of several TDMA based protocols [8, 9] in vehicular network. R-ALOHA [10] is the earliest dynamic channel reservation scheme, which enables nodes to reserve a time slot for transmission in a fixed period. RR-ALOHA [11] and ADHOC-MAC [12] are completely distributed TDMA schemes, but both of them are based on the assumption that the network topology stays static. Simulation results show that the throughput reduction of ADHOC MAC protocol can reach up to 30% for an average vehicle speed of 50 km/h [13]. Lam and Kumar designed a DCR protocol with the help of GPS in [14]. However, his work is not suitable for heavy traffic situations. Omar et al. [15] proposed a TDMA-based MAC protocol for reliable broadcast in VANET. This scheme reduces transmission collisions caused by vehicle mobility, but it assumed that there were two transceivers on each vehicle, one used for control channel and the other for service channel.

In CSMA-like random schemes, the prime example is IEEE 802.11 [16], which is a simple, flexible, and contention-based medium access control protocol. In the protocol, when a vehicle wants to transmit messages, it first listens to the desired channel. If the channel is free (not occupied by other vehicles), the vehicle is allowed to transmit. Otherwise, the vehicle has to defer its transmission to the next contention period. Although the approach is simple and flexible, the data delivery delay will increase significantly if the vehicles density is high, especially when an exponential back-off mechanism is employed to resolve the robust contention issues among different vehicles [16]. In order to be delivered timely, warning (emergency) message is assigned a higher priority to contend for the wireless channel with a small contention window size in the IEEE 802.11 p EDCA [17]. Although the small contention window size allows the warning message to be transmitted with a small delay, it introduces the unfairness between warning messages and beacons (with a lower priority than warning message) on the medium access and the delivery delay of beacons is increased greatly. Another limitation for CSMA schemes is that no RTS/CTS exchange is used, which results in a serious hidden terminal problem and

reduces packets delivery rate. Consequently, the effectiveness of CCA applications decreases substantially.

However, to the best of our knowledge, little effort has been devoted to design risk-aware MAC protocol by exploiting reliable and practical vehicle collision models. Detailed models of vehicle motion and collision dynamics were given in [18, 19], but they are completely based on deterministic equations for the occurrence of collisions, whereas in fact, randomness is always present introduced by high mobility and driver behavior. In [20], the authors explored the necessary conditions for chain collisions. However, it is assumed that all the vehicles have the same initial speeds and intervehicle distance. A more recent work [21] derived a stochastic model for the number of accidents in the platoon of vehicles equipped with a warning messages communication system. Nevertheless, all the parameters in the model were described by random variables, which cannot give a reliable collision prediction for the real-time traffic scenario. Thus, based on the analysis method in [21], we derive a more reliable and practical stochastic collision prediction model, which takes full advantage of the beacons and warning messages.

In this paper, by combing vehicle collisions model with TDMA-based mechanism, we design a risk-aware and dynamic MAC protocol for the considered CCA application. Besides the reliable and real-time delivery of messages, the fairness between beacons and warning messages on the wireless medium access are also achieved.

3. Details of Risk-Aware Dynamic MAC Protocol

This section mainly presents the detailed description of the dynamic and risk-aware MAC protocol, including the considered traffic scenario, specification of frame structure, and slots allocation algorithm for CSMA and TDMA segments. The number of slots in the CSMA segment is determined by the average total number of potential collisions among the platoon and the corresponding computing method based on a stochastic collision prediction model is given in Section 4.

3.1. The Traffic Scenario. Prior to the detailed description of the proposed protocol, it is essential to give an overview of the considered traffic scenario in which our R-MAC operates. As shown in Figure 1, each RSU and all vehicles under its coverage form a vehicular Ad hoc subnet, which is similar to the model proposed in our previous work [22]. For sake of simplicity, we only consider a platoon of vehicles on highway, which travel along the same road towards the similar direction. However, with vehicles moving on roads at high speeds, the number of vehicles N and the corresponding vehicle density ρ_r in a particular subnet are always varying. In this paper, the vehicle density ρ_r is defined as the average number of vehicles per meter, which can be computed by

$$\rho_r = \frac{N}{R}, \quad (1)$$

where R refers to the coverage range of an RSU. As surrounding conditions of an RSU might affect its practical wireless

transmission range, an RSU updates its current transmission range t_r in the following manner [16]:

$$t_r = T_{\max} \cdot (1 - \varepsilon), \quad 0 < \varepsilon \leq 1, \quad (2)$$

where T_{\max} and ε indicate the maximum wireless transmission range of an RSU and the wireless channel fading conditions at the current position, respectively. If there are many high-rise buildings or the weather is rainy, ε is set as a larger value, vice versa. GPS and sensors deployed on an RSU are used to obtain terrain and meteorological information so that the parameter ε can be appropriately estimated. For simplicity of illustration, R is set as $2t_r$ approximately. In addition, we assume that every RSU can dynamically compute the corresponding vehicle density in its coverage by communications between the vehicles and RSU in a subnet.

3.2. R-MAC Frame Structure. Now, we give the detailed specification of frame in R-MAC, which is a dynamic TDMA protocol. In R-MAC, we divide the time into periods called frames and then each of them is subdivided into tiny time slots uniformly. Every frame is divided into RSU segment and vehicle segment (see Figure 2). The RSU segment is reserved for RSU to disseminate control message and the latter is used for vehicles to transmit beacons and warning messages. In our protocol, the RSU segment always begins from the head of a frame and its size is a constant denoted by α , which means that the length of the vehicle segment is also determined. Based on the different priorities between beacons and warning messages, the vehicle segment is divided into two parts: CSMA segment which is responsible for transmitting warning message in emergency situations and TDMA segment which is in charge of delivering beacons. Without any loss of generality, we introduce β and γ to indicate the corresponding size of CSMA and TDMA segment, respectively.

Based on the above description, we define three sets S_0 , S_1 , and S_2 as (3), which refer to the slots falling into the RSU, CSMA, and TDMA segments, respectively:

$$\begin{aligned} S_0 &= \{R_i \mid 1 \leq i \leq \alpha\}, \\ S_1 &= \{C_i \mid 1 \leq i \leq \beta\}, \\ S_2 &= \{T_i \mid 1 \leq i \leq \gamma\}, \\ S_0 \cup S_1 \cup S_2 &= Q, \\ S_i \cap S_j &= \emptyset, \quad \forall i, j \in \{0, 1, 2\}, i \neq j. \end{aligned} \quad (3)$$

Q means the set of all slots in a whole frame. As illustrated in Figure 2, R_i indicates the yellow slots in RSU segment, C_i refers to the blue slots reserved for CSMA segment, and the white slots allocated to TDMA segment are denoted by T_i . It is worth noting that the corresponding slots of CSMA and TDMA segments are dynamic, which are determined by an RSU according to the real-time collisions situation in the platoon frame by frame. In order to describe the division of a frame into the above three sets intuitively, we introduce ‘‘slot

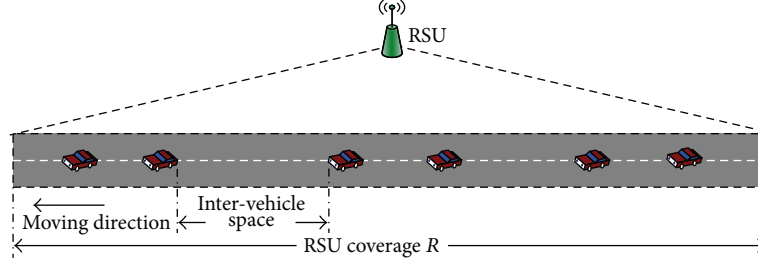


FIGURE 1: Traffic scenario under consideration.

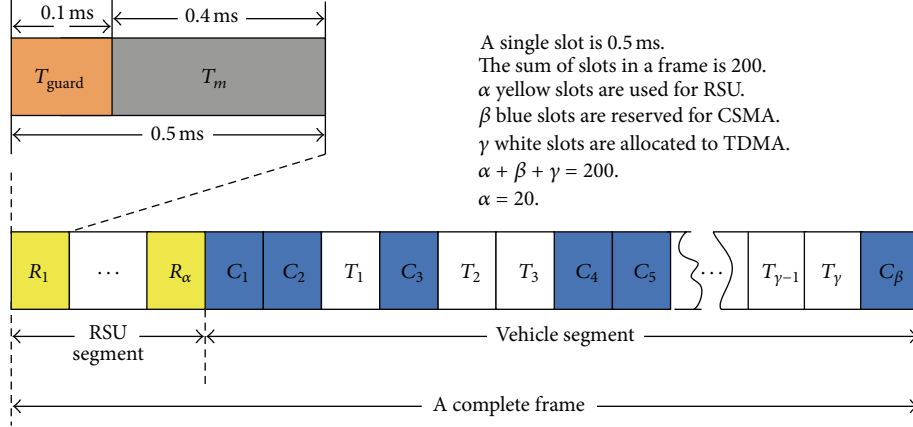


FIGURE 2: R-MAC frame structure.

assignment map” denoted by a vector state, which marks a slot s as the following rules:

$$\text{State}[s \cdot \text{id}] = \begin{cases} 0, & \text{if } s \in S_0, \\ -1, & \text{if } s \in S_1, \\ \text{ID}, & \text{if } s \in S_2, \end{cases} \quad (4)$$

where ID indicates the id of a particular vehicle, which is a positive integer between 1 and N . With the control messages of an RSU, the slot assignment map is broadcast to vehicles every frame.

Then, we define the time duration parameters according to the US standards within IEEE. The update frequency is $f_p = 10$ Hz. Therefore, the total frame size is 100 ms. The slot time is given by

$$T_{\text{slot}} = \frac{P}{M} + T_{\text{guard}}, \quad (5)$$

where the packet size of message in VANET is $P = 300$ bytes, the data transmission rate is 6 Mbits/s, and the guard time T_{guard} is 100 μs between two adjacent slots [23]. So a single slot reserved for a vehicle is 0.5 ms and the total number φ of available slots in each frame can be given as

$$\alpha + \beta + \gamma = \varphi = 200. \quad (6)$$

In the following, we give more detailed specifications for RSU and vehicle segments, separately.

3.2.1. Specification of RSU Segment. As shown in Figure 2, the number of slots reserved for an RSU is fixed and the size of set S_0 is 20. Moreover, twenty consecutive slots at the beginning of a frame are allocated to an RSU, and the total time T_{rsu} reaches up to 10 ms. According to slot assignment map, we set the variable $\text{State}[i] = 0$, $1 \leq i \leq 20$. Similar to (5), the maximum packet size of an RSU control message can be given by

$$S_{\text{control}} = \frac{1}{8} (T_{\text{rsu}} - \alpha \cdot T_{\text{guard}}) \cdot M, \quad (7)$$

where α is the size of the set S_0 . Obviously, the size of an RSU control packet S_{control} can reach up to 6 Mbytes which are enough to transmit the control message for a whole frame [23]. In our R-MAC, the control message mainly consists of the slot allocation map in every frame.

3.2.2. Specification of Vehicle Segment. In contrast to the RSU segment, the vehicle segment of a frame is further divided into CSMA segment and TDMA segment. For the TDMA segment, a vehicle with a chosen slot will send beacon which contains safety-related information to vehicles around it and the corresponding RSU. However, for the CSMA slots, only delivery of warning (emergency) messages is allowed to contend the medium access in CSMA mode. When a vehicle desires to send a warning message, it first listens to the channel and waits for the CSMA slots. If the medium is idle, the vehicle is allowed to transmit. If the medium is busy, the vehicle will defer its transmission to the next

CSMA slot, which is different from the exponential back-off mechanism executed in IEEE 802.11 MAC protocol [16]. In order to ensure sufficient slots for vehicles to sending warning messages, the size of CSMA segment is set as the average total number of potential collisions among the platoon in the next several frames. In our protocol, TDMA and CSMA segments coexist in each frame dynamically, which helps to achieve the delivery fairness between beacons and warning messages. In the worst case, all the slots of a frame are allocated for CSMA segment to transmit the massive amounts of warning messages and no slots are left for beacons, in which our protocol operates as a traditional CSMA-based MAC protocol just like IEEE 802.11p. Indeed, once the case above appears, the traffic accident must be disastrous and the whole network has to be flooded by massive of emergency messages. However, the probability of this case is little and both of beacons and warning messages have corresponding slots reserved to be transmitted for most case.

3.3. Slot Allocation Algorithm for CSMA and TDMA (SACT).

In this section, we describe how to allocate slots for CSMA and TDMA segments. The whole slot allocation algorithm abbreviated as SACT includes three steps: slot allocation for CSMA, slot reservation for TDMA and slot allocation map broadcast. In consideration of the higher priority of delivering warning messages triggered by vehicle collisions, we allocate slots to CSMA segment prior to TDMA segment. For ease of description, we assume that each slot in a frame will be labeled with a number from 1 for the first slot to φ for the last one consecutively, which is called the id of each slot.

3.3.1. Slot Allocation for CSMA. The slot set of CAMS segment S_1 is determined by the following two steps. (i) The RSU analyzes the risk of collision and computes the average total number of potential collision NUM_{acc} among the vehicles under its coverage. The detailed computation for NUM_{acc} will be given in Section 4, which is another important contribution of this paper. (ii) The RSU selects NUM_{acc} appropriate slots from the vehicle segment for delivering warning messages in the mode of CSM A, whose ids are between $\alpha + 1$ and φ . Obviously, there are $\binom{NUM_{acc}}{\varphi - \alpha}$ selections for the set S_1 . Since the generation of warning messages is random absolutely, it is hard to make the optimal selection for S_1 . For simplicity, we assure that the ids of NUM_{acc} slots are uniformly distributed between $\alpha + 1$ and φ . Once NUM_{acc} available slots are determined, all of them are marked as occupied by CSMA segment and pushed into the set S_1 . Moreover, the slots are denoted by C_i , where the value of i is from 1 to α consecutively. According (4), we set the variable $State[C_i \cdot id] = -1$, $1 \leq i \leq \beta$. So the slot allocation map of CSMA segment is finished here.

3.3.2. Slot Allocation for TDMA. Once the slot set S_1 has been determined, the left slots in vehicle segment will be used for TDMA, all of which fall into the corresponding slot set S_2 uniquely. For ease of description, the size of set S_2 is denoted by γ . T_i indicates the slots in the set S_2 , where $1 \leq i \leq \gamma$. Then, a RSU allocates a particular slot T_i to a vehicle in its coverage,

SACT Algorithm:

Begin: $S_1 = S_2 = \emptyset$

Step 1: Slot Allocation for CSMA

Compute the average total number NUM_{acc} of potential collisions among the vehicles platoon by Algorithm 2;
 Select NUM_{acc} integers from $[\gamma + 1, \varphi]$ uniformly.
 Push the slots whose id equals to the above selected NUM_{acc} integers into set S_1 , denoted by $C_1, C_2, \dots, C_\alpha$,
 $\alpha = NUM_{acc}$;
 For $i = 1$ to α
 $State[C_i \cdot id] = -1$

Step 2: Slot Reservation for TDMA

$S_2 = Q - S_0 - S_1, \bar{S}_2 = \emptyset$,
 For each vehicle in the coverage of a RSU
 If the RSU received a beacon in the last three Frame
 Then select a slot s from set S_2 randomly,
 remove s from S_2 and add it to \bar{S}_2 ,
 $State[s \cdot id] = vehicle.ID$;
 Else remove the vehicle from the vehicle list under its coverage;

Step 3: Broadcasting the slot allocation map

The RSU broadcast the vector $State[i]$, $1 \leq i \leq \varphi$ to all the vehicles

ALGORITHM 1: Formal description of the SACT Algorithm.

as the following steps. (i) If there are beacons received from a vehicle in the last frame, the RSU will select a available slot s randomly from set S_2 for the vehicle and attach the vehicle ID to it, namely, $State[s \cdot id] = vehicle \cdot ID$, which marks s as occupied by a particular vehicle. Moreover, once T_i has been occupied by a vehicle, it will be removed from S_2 to the set \bar{S}_2 . Obviously, the sizes of the two sets meet the following equation:

$$|S_2| + |\bar{S}_2| = \gamma. \quad (8)$$

(ii) In a case of an anomaly, in which a vehicle fails to send its beacons in the last consecutive three frames, the RSU will believe the vehicle has moved out of its coverage and no slots will be allocated to it in the next frame. According to these rules, RSU is able to complete the corresponding slot allocation map of TDMA segment.

In fact, the slot allocation procedure, including CSMA segment selection and TDMA slot allocation, is conducted on a particular RSU. Then, the RSU broadcasts the final slot allocation map to all vehicles moving under its coverage. Based on the above description, the integrated SACT algorithm is formally described in Algorithm 1.

4. Computation of the Size of CSMA Segment

As described in the SACT algorithm in Section 3, the corresponding size of CSMA segment in a frame is determined by the average total number of potential collisions NUM_{acc} among the platoon in the following several frames, which is the focus of R-MAC. Therefore, in this section, we give a novel computation method of total average number of

potential accidents among the platoon (CMAA) as follows. First, a stochastic collision prediction model is introduced to compute the parameter NUM_{acc} in the platoon, and then the probability of collision between adjacent vehicles is derived, which is an input parameter in the prediction model. Moreover, extensive Monte Carlo simulations are conducted to verify the performance of the stochastic model in the end.

4.1. Stochastic Collision Prediction Model. Prior to a detailed description of the envisioned stochastic collision prediction model, we point out a number of assumptions regarding the considered traffic scenario in this paper, which are listed as follows.

- (i) The distance between two neighboring vehicles, named intervehicle space, is a random variable. Moreover, it is an exponentially distributed random variable with parameter λ , which represents the density of vehicles on the road and equals to ρ_r computed by (1).
- (ii) Each vehicle is capable of estimating its motion state accurately, including velocity, regular acceleration.

The first assumption is based on the fact that inter-space calculated by real-time coordinates on map benefit from GPS and GIS is not accurate and reliable, because the positioning precision of GPS hardly meets the need of the considered scenario. In the worse case, a vehicle is evolving into more critical areas; there may be certain undesired problems in the availability of GPS in certain scenarios where GPS signals may not be detected (e.g., such as inside tunnels and underground parking). Moreover, it has been shown that exponential distribution describes well the intervehicles space when traffic densities are small [24]. In addition, it is easy to get accurate velocity and acceleration of a vehicle, via adequately deployed sensor monitoring the motion state of a vehicle in real-time.

The collision scenario considered in our paper is a platoon (or a chain) of N vehicles traveling along the same road toward the same direction. As a vehicle V_a among the vehicle platoon collides with an obstacle or the preceding vehicle on the road, at time $t_0 = 0$, it immediately sends a warning message to the following vehicle V_j , $j \in a + 1, \dots, N$. Upon receiving the warning message, all the following vehicles start to brake at the maximum deceleration. That is, after a time lapse t_{res} . Let us remark here that the time lapse t_{res} is mainly determined by the reception delay of the warning message generated by the communication system and the reaction time of the driver, denoted by T_d and T_r , which will be used again in next section. Each warned driver will decelerate immediately, even if the preceding vehicle has not started to decelerate (see Figure 3). For simplicity, we assume every vehicle has the same maximum deceleration a_{max} .

Within this model, the accidental vehicle V_a , $a \in 1, \dots, N$, may collide with an obstacle and stop suddenly, which only increases the likelihood of a crash for the following vehicles behind the accident spot. Moreover, the final outcome (collision or stop successfully) of a following vehicle depends on the outcome of the preceding vehicles.

Therefore, the collision model is based on the construction of the probability graph depicted in Figure 4, the length of which is $N - a + 1$ [21]. We consider an initial state in which no vehicle has collided. Once the danger of collision has been detected at vehicle V_a , the first vehicle in the following chain V_{a+1} (immediately after the accidental one) may collide or stop successfully. Similarly, for each vehicle behind V_{a+1} , there are two possible cases: collision with its preceding vehicle or successful stop. As a result, at the right-most of the probability graph, there are $N - a + 1$ possible final outcomes which represent the number of collided vehicles between 0 and $N - a$. And $c_{m,n}$ represents the state with m collided vehicles and n successfully stopped vehicles (see Figure 4).

The transition probability between two nodes in the graph is the corresponding collision probability between adjacent vehicles in the chain p_j , $j \in a + 1, \dots, N$ (or the complementary: $1 - p_j$), which will be used in the model. The detailed computation method is described in Section 4.2. Next, we should note that every path in the graph from the left source node $c_{0,0}$ to the right-most nodes leads to a possible outcome involving all the following vehicles behind V_a . The probability of the particular path is determined by all the transition probabilities of nodes which belong to the whole path. Noting that there are multiple paths which may lead to the same final outcome (different paths may end at the same node) referring to a right-most node in the probability graph, the probability of a final outcome is the sum of the resulting probabilities of all possible paths ending at it.

To compute the probabilities of the final outcomes, we can construct a Markov chain whose state diagram is based on the previously discussed probability graph. If the following accidental collisions are caused by the vehicle V_a , there are $(N - a + 1)(N - a + 2)/2$ vertices in the probability graph. And a homogeneous Markov chain can be established with a state set $C = (c_{0,0}, c_{1,0}, c_{0,1}, \dots, c_{N-a,0}, c_{N-a-1,1}, c_{N-a-2,2}, \dots, c_{1,N-a-1}, c_{0,N-a})$, whose size equals to $(N - a + 1)(N - a + 2)/2$. In addition, the transition matrix \mathbf{P} of the corresponding Markov chain is a square matrix of dimension $(N - a + 1)(N - a + 2)/2$. It's worth noting that there are at most two other states to reach each state in the state set C , which ensures the matrix \mathbf{P} is sparse. For ease description, a brief example is illustrated in Figure 5, where only two vehicles V_{N-1} and V_N follow with the leading accidental vehicle V_{N-2} .

Then, we compute the probabilities of paths which start from state node $c_{0,0}$ to each of the $N - a + 1$ final states by computing \mathbf{P}^{N-a} . In fact, the final outcome probabilities are the last $N - a + 1$ entries of the first row of the matrix \mathbf{P}^{N-a} . Let $\sum k$ be the probability sum of all the paths reaching the final outcome states with k collided vehicles in the following vehicles behind V_a , namely, state $c_{k,N-a-k}$. Therefore, $\sum k$ equals to the $((N - a + 1)(N - a + 2)/2) - k$ th entry of the first row in matrix \mathbf{P}^{N-a} , which can be given as follows:

$$\sum k = \mathbf{P}^{N-a} \left[1, \frac{(N - a + 1)(N - a + 2)}{2} - k \right], \quad (9)$$

$$a \in 1, \dots, N.$$

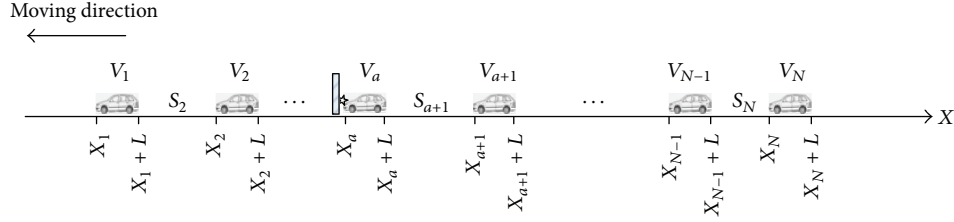


FIGURE 3: Collision model under consideration.

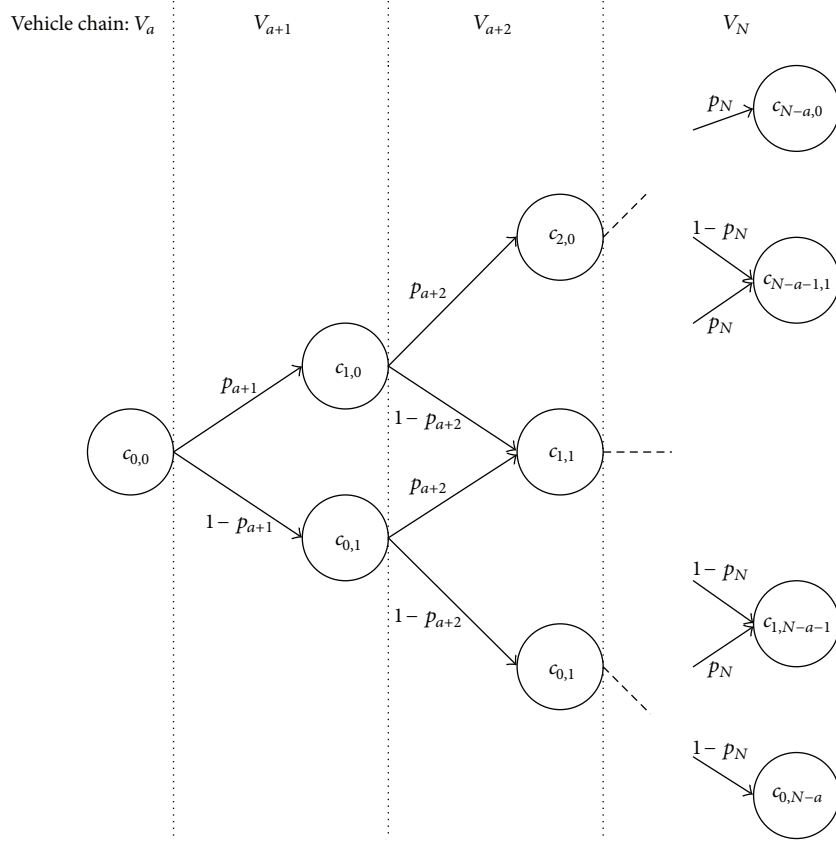


FIGURE 4: Probability graph defined in the collision model.

Then, the average total number of collisions caused by a particular accidental vehicle V_a in the chain is obtained by the weighted sum as (10):

$$N_{\text{acc}} = \sum_{k=1}^{N-a} k \cdot \sum k, \quad a \in 1, \dots, N. \quad (10)$$

In order to facilitate statistics, we assume that each vehicle in the platoon has the same probability $1/N$ to be the accidental vehicle. In other words, for the vehicle V_a , the parameter a is a uniformly distributed variable between 1 and N . Therefore, from the perspective of a RSU in the CCA system as described

in Section 3, the average total potential collisions NUM_{acc} in the whole platoon can be computed by (11) as follows:

$$\text{NUM}_{\text{acc}} = \frac{1}{N} \sum_{a=1}^N \sum_{k=1}^{N-a} k \cdot \sum k, \quad a = 1, 2, 3, \dots, N. \quad (11)$$

4.2. Computation of the Adjacent Vehicles Collision Probability. In this section, we come to the problem of computing the collision probabilities p_j , $j \in a + 1, \dots, N$ for adjacent vehicles, which is an important variable used in our stochastic collision prediction model. To the end and for ease of description, we first explore the movement features of vehicles especially when braking, and then a novel method based on minimum safety distance (MSD) is introduced, which takes into full

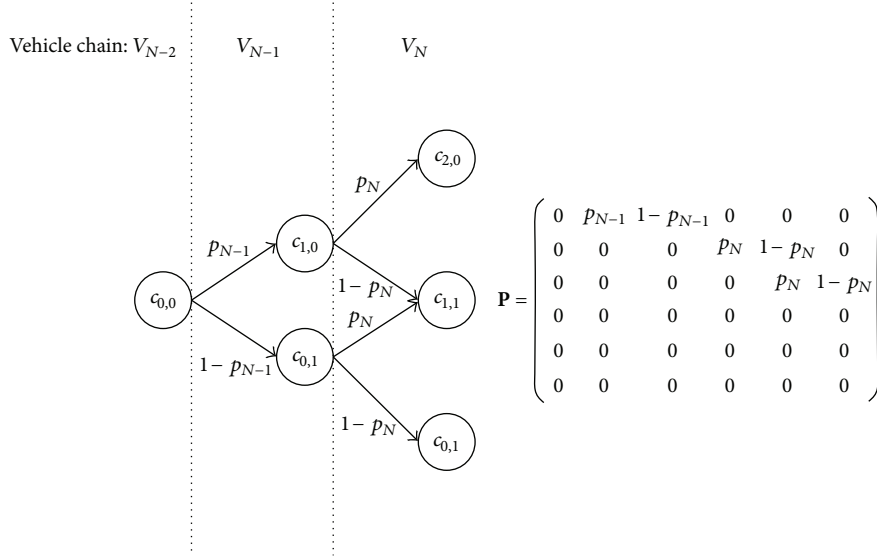


FIGURE 5: Probability graph and corresponding transition matrix for scenario where the collision is caused by vehicle V_{N-2} .

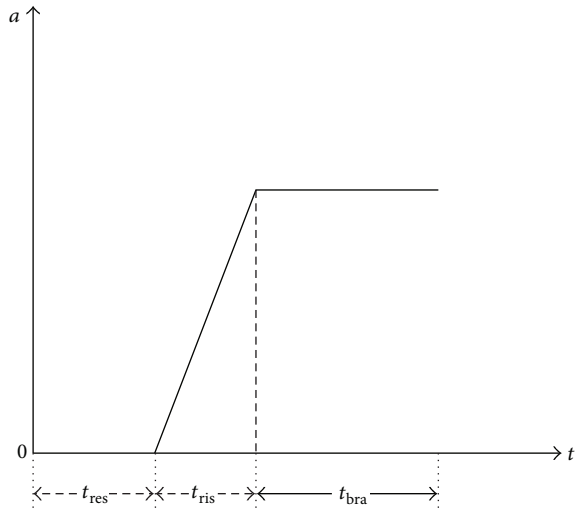


FIGURE 6: A complete vehicle braking process.

account of different movement states of adjacent vehicles, to compute collision probabilities p_j .

Based on the analysis of the vehicular moving procedure for vehicle in [20, 25], a complete braking procedure is divided into three different stages where acceleration a of a vehicle varies along with time as shown in Figure 6. As mentioned above in the collision prediction model, we still let V_a denote the accidental vehicle which encounters an obstacle and stops suddenly in the platoon. t_{res} indicates the braking response time from the instant V_a sends warning messages to the instant when the following drivers are aware of the collision ahead. In fact, it is mainly determined by the reception delay of the emergency message generated by the communication system and the reaction time of the driver, denoted by T_d and T_r , respectively. To consider a worse communication system and without loss of generality, we

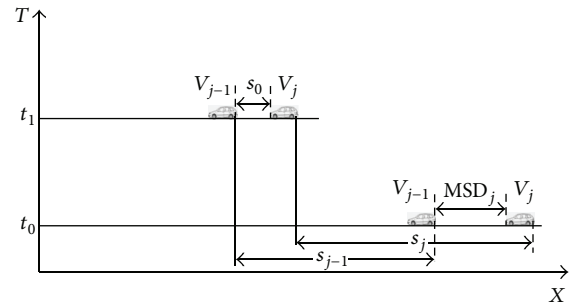


FIGURE 7: MSD model for vehicles V_j and V_{j-1} .

set T_d as 0.1 ms, which is the maximum delay for warning messages that vehicular communication standards specify [26]. Generally, the average reaction time of drivers is set as $T_r = 0.9$ s [6]. As shown in Figure 6, the value of deceleration speed is still rising during the process t_{ris} , which is about 0.1-0.2 s and is overlooked for easy of calculation. During the period of t_{bra} , a vehicle keep its maximum deceleration a_{max} until collision with the preceding vehicle occurs or stops successfully. Here, for simplicity, we assume that all the following vehicles behind the accidental vehicle V_a has the same braking response time $t_{res} = T_d + T_r = 0.1 + 0.9 = 1$ s, which is the sum of reception delay of warning messages T_d and the reaction time of drivers T_r . During the period of t_{res} , we assume that a particular vehicle V_j still keeps its original movement state. After t_{res} , its speed will linearly decrease due to the braking operation with the maximum deceleration speed. Then, $v_{0,j}$ and a_j denote the initial velocity and acceleration of a vehicle V_j during the period of t_{res} , respectively. From [4], the movement state during time $(0, t_{res})$ can be expressed as

$$v_j(t) = v_{0,j} + a_j \cdot t, \quad t < t_{res}. \quad (12)$$

After the period t_{res} , the vehicle speed is linearly decreasing with the maximum deceleration a_{max} as following:

$$v_j(t) = v_{0,j} + a_j \cdot t_{\text{res}} - a_{\text{max}}(t - t_{\text{res}}), \quad t > t_{\text{res}}. \quad (13)$$

In order to compute the collision probabilities p_j , we introduce a Minimum Safety Distance (MSD) model for the vehicles in a platoon. Based on this model, an RSU can compute the accurate minimum safety distance MSD_j for each vehicle V_j in the platoon according to the current movement state, which mainly includes velocity v_j and acceleration a_j . We let d_j denote the distance between a particular vehicle V_j and its preceding vehicle V_{j-1} in the platoon, which is an exponentially distributed random variable with parameter λ as mentioned in assumption (i). It is obvious that if intervehicle distance d_j is greater than or equals to corresponding minimum safety distance MSD_j , the vehicle V_j can stop successfully without collision with its preceding vehicle V_{j-1} . Otherwise, there will be a collision between vehicle V_j and V_{j-1} . So for any vehicle V_j , $a + 1 \leq j \leq N$, the collision probability p_j will be computed as follows:

$$\begin{aligned} \lambda &= \rho_r = \frac{N}{R}, \\ p_j &= P(d_j < \text{MSD}_j) \\ &= 1 - e^{-\lambda \cdot \text{MSD}_j}, \quad a + 1 \leq j \leq N. \end{aligned} \quad (14)$$

Based on the aforementioned analysis, we give the MSD computation model as Definition 1.

Definition 1. Minimum safety distance in our work is defined as the needed minimum distance between two adjacent vehicles to avoid collision based on V2V communications, both of which receive a warning message and start to brake hard at the same time.

For simplicity, we assume that all the vehicles have the same mechanical brake performance with a common maximum deceleration value a_{max} . However, the velocity and regular acceleration of vehicles before the time are different with each other, denoted by v_j and a_j , respectively. Without loss of generality, we select a particular vehicle V_j and its preceding vehicle V_{j-1} to describe the minimum safety distance MSD_j (see Figure 7), both of which receive the same warning messages from the front of the platoon at the same time. t_0 indicates the instant a warning message is triggered by a accidental vehicle V_a in the front of the platoon and sent backwards, while t_1 denotes the instant when collision between V_j and V_{j-1} has been successfully avoided. The displacements of V_j and V_{j-1} are denoted by s_j and s_{j-1} during the period between t_0 and t_1 , respectively. s_0 refers to the permitted minimum distance between V_j and V_{j-1} at t_1 [4], which can be set an appropriate constant according to different safety requirements in CCA systems. Based on the above analysis, the MSD for vehicle V_j is given as follows:

$$\text{MSD}_j = s_j - s_{j-1} + s_0, \quad j = a + 1, \dots, N. \quad (15)$$

According to the different movement states, we further divide the computation of MSD into three cases as follows. In case 1, the vehicle V_j follows the accidental vehicle V_a immediately, where j equals to $a + 1$. Whereas in case 2, j doesn't equal to $a + 1$ and the velocity of V_j is greater than that of V_{j-1} before the time t_{bra} . In contrast to case 2, j doesn't equal to $i + 1$ either while the velocity of V_j is less than or equals to that of V_{j-1} . Here, we continue to adopt the notations as above: let $v_{0,j-1}$ and $v_{0,j}$ indicate the initial speed of V_{j-1} and V_j , while a_{j-1} and a_j denote the corresponding acceleration/deceleration during the period of t_{res} , respectively.

Corollary 2. *If the vehicle V_j follows the accidental vehicle V_a immediately, the MSD for V_j is*

$$\begin{aligned} \text{MSD}_j &= \text{signal}(v_{0,j} + a_j \cdot t_{\text{res}}) \\ &\cdot \left(v_{0,j} \cdot t_{\text{res}} + \frac{1}{2} a_j \cdot t_{\text{res}}^2 + \frac{(v_{0,j} + a_j \cdot t_{\text{res}})^2}{2a_{\text{max}}} \right) \\ &+ \text{signal}(- (v_{0,j} + a_j \cdot t_{\text{res}})) \cdot \frac{v_{0,j}^2}{2a_{i+1}} + s_0, \quad j = a + 1, \end{aligned} \quad (16)$$

where the signal function $\text{signal}(x)$ is defined as follows:

$$\text{signal}(x) = \begin{cases} 0, & \text{if } x < 0, \\ \frac{1}{2}, & \text{if } x = 0, \\ 1, & \text{if } x > 0. \end{cases} \quad (17)$$

Proof. Noting that the accidental vehicle V_a encounters an obstacle and stops immediately, its displacement is overlooked ($s_i = 0$). Obviously, the MSD of V_{a+1} is the displacement s_{i+1} of the vehicle V_{a+1} before it stops successfully without collision with its preceding vehicle V_a . Based on the description of braking procedure, there are two parts generally: the reaction time of braking operation and the linearly decreasing stage. During the period of braking reaction stage, the V_j keeps its initial velocity and acceleration/deceleration speed.

If $v_{0,j} + a_j \cdot t_{\text{res}} > 0$, the distance of V_{a+1} traveling during $(0, t_{\text{res}})$ is:

$$s'_{a+1} = v_{0,j} \cdot t_{\text{res}} + \frac{1}{2} a_j \cdot t_{\text{res}}^2. \quad (18)$$

The displacement of the vehicle V_{a+1} during the period of t_{bra} until it stops safely is

$$s''_{a+1} = \frac{(v_{0,j} + a_j \cdot t_{\text{res}})^2}{2a_{\text{max}}}. \quad (19)$$

So the total displacement s_{a+1} for V_{a+1} is

$$s_{a+1} = s'_{a+1} + s''_{a+1}. \quad (20)$$

Else if $v_{0,j} + a_j \cdot t_{\text{res}} < 0$, it means that vehicle V_{a+1} has stopped regularly before the stage of linearly decreasing stage. Then the total distance for V_{a+1} to stop successfully is

$$s_{a+1} = \frac{v_{0,j}^2}{2a_{a+1}}. \quad (21)$$

In conclusion, with (20), (21) and (15), we obtain (16). \square

Corollary 3. *If the vehicle V_j doesn't follow the accidental vehicle V_a immediately and the velocity of V_j is greater than that of V_{j-1} before linearly decreasing procedure, the MSD for V_j can be given by (22):*

$$MSD_j = \frac{(v_{0,j} + a_j \cdot t_{\text{res}})^2 - (v_{0,j-1} + a_{j-1} \cdot t_{\text{res}})^2}{2a_{\text{max}}} + s_0, \quad j = a + 2, \dots, N. \quad (22)$$

Proof. Based on the assumption that V_j and V_{j-1} have the same maximum braking deceleration a_{max} , the distance between V_j and V_{j-1} becomes smaller and smaller if the velocity of V_j is greater than that of V_{j-1} before linearly decreasing stage. Two vehicles are safe only when both of them have stopped without collision.

Obviously, the displacement for vehicle V_j to stop safely is

$$s_j = \frac{(v_{0,j} + a_j \cdot t_{\text{res}})^2}{2a_{\text{max}}}. \quad (23)$$

Similar to V_j , the displacement s_{j-1} of V_{j-1} is

$$s_{j-1} = \frac{(v_{0,j-1} + a_{j-1} \cdot t_{\text{res}})^2}{2a_{\text{max}}}. \quad (24)$$

So, with (23), (24), and (15), (22) is derived. \square

Corollary 4. *In this situation, the velocity of V_j is less than or equal to that of V_{j-1} before linearly decreasing procedure, the MSD for V_j is expressed as follow:*

$$MSD_j = s_0. \quad (25)$$

Proof. In contrary to case 2, the distance between V_j and its preceding vehicle V_{j-1} is always increasing until both of them have stopped one after another. So in this situation, it's always safe for the two consecutive vehicles. We set the minimum safety distance MSD_j as the initial permitted minimum distance s_0 . \square

4.3. Validation of Stochastic Collision Prediction Model. Based on the above detailed description in Sections 4.1 and 4.2, the integrated computation method of the total average number of potential accidents in the platoon (CMAA) is formally described in Algorithm 2. In order to verify the effectiveness of stochastic collision prediction model, we conduct a Monte

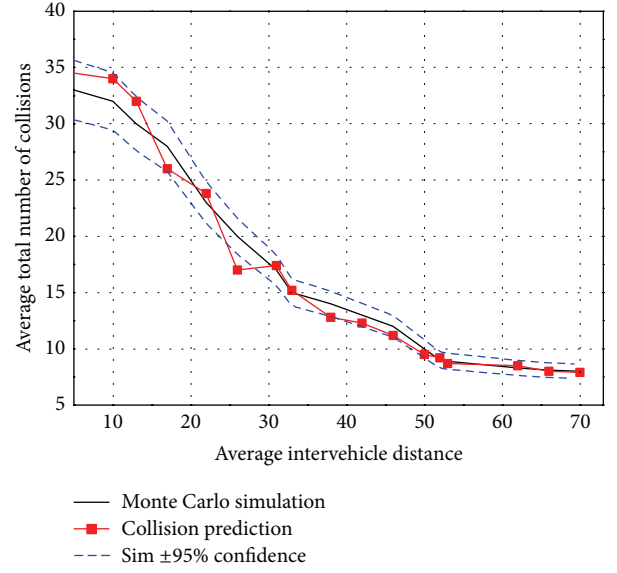


FIGURE 8: Average total number of collisions in the platoon versus average intervehicle distance.

Carlo simulation and compare the simulation results with that of CMAA algorithm. In the simulation, the initial speed v_i and regular acceleration a_i of vehicles before emergency brake are uniformly distributed variables from $[15, 32]$ m/s and $[4, 8]$ m/s². The maximum deceleration value a_{max} is set as 8 m/s². The above parameters are the same with that listed in Table 1. However, for simplicity, the number of vehicles in the platoon is $N = 40$, $t_{\text{res}} = T_d + T_r = 0.1 + 0.9 = 1$ s and the minimum distance between vehicles $s_0 = 1.3$ m, which has been described in Section 4.2. Without loss of generality, all the Monte Carlo simulations have been performed many times per simulation point. Two dotted lines in Figure 8 denote the 95% confidence intervals of the simulation results. Figure 8 shows that the mean error between the results of our model and the Monte Carlo simulation does not exceed 6%. So the stochastic collision model is correct and reliable.

5. Performance Evaluation

In this section, we describe the simulation results to demonstrate the efficiency of the proposed R-MAC protocol. In our simulation, we implement our R-MAC protocol on the NS-2 simulator and evaluate its performance fairly against the IEEE 802.11p, which is the standardized MAC protocol for VANET. The objective is two-fold: (1) evaluate the fairness of the medium access between beacons and warning message and (2) compare the performance of R-MAC and IEEE 802.11p on the packet loss rate and transmission delay.

5.1. Simulation Settings. The R-MAC protocol is implemented on the network simulator (NS-2.33). In order to conform to the realistic traffic scenario, a $1000 \text{ m} \times 300 \text{ m}$ rectangle road network with a straight 4-lane highway is created, where a 3G station is introduced to act as a RSU. Different

CMAA Algorithm:
Begin: $\text{NUM}_{\text{acc}} = N_{\text{acc}} = 0$
For vehicle V_a $a = 1$ **to** N
Step; 1: Computation of Minimum Safety Distance MSD_j
of V_j
 For $j = a + 1$ **to** N
 If $j = a + 1$
 Then MSD_j is computed through (16)
 Else if $v_{0,j} + a_j \cdot t_{\text{res}} > v_{0,j-1} + a_{j-1} \cdot t_{\text{res}}$
 Then MSD_j is computed through (22)
 Else $\text{MSD}_j = s_0$
 End for
Step; 2: Computation of collision probabilities of p_j
 For $j = a + 1$ **to** N
 $p_j = P(d_j < \text{MSD}_j) = 1 - e^{-\lambda \cdot \text{MSD}_j}$
 End for
Step; 3: Construction of Matrix P
 Compute the matrix \mathbf{P}^{N-a}
 For $k = 1$ **to** $N - a$
 $\sum k = \mathbf{P}^{N-a}[1, ((N - a + 1)(N - a + 2))/2] - k,$
 $N_{\text{acc}} = N_{\text{acc}} + k \cdot \sum k,$
 End for
End for
 $\text{NUM}_{\text{acc}} = N_{\text{acc}}/N$

ALGORITHM 2: Formal description of the CMAA Algorithm.

traffic loads of the road are considered by setting various vehicle numbers. All the traffic scenario and vehicle mobility patters are generated from the VanetMobiSim engine [27]. For each traffic loads, the simulation are conducted ten times to take the average result.

During our simulation, each vehicle broadcasts a beacon packet of 300 bytes every 100 ms. When a vehicle encounters an obstacle or collision with its preceding vehicle, a packet of 300 bytes is sent immediately backwards to simulate a warning message. For simplicity, we assume that a collision will happen when the intervehicle space is less than the permitted minimum distance s_0 , which is set as 1.3 m. The initial velocities and regular accelerations of vehicles are uniformly distributed variables from [15, 32] m/s and [4, 8] m/s², which are selected randomly but constant in a simulation case. Detailed parameters are listed in Table 1.

5.2. Evaluation Metrics. The performance of the R-MAC protocol is evaluated in terms of average packet delivery rate, delay and fairness. The particular evaluation metrics are defined as follows.

5.2.1. Packet Delivery Rate. Packet delivery rate is defined as the rate of the total number of data packets transmitted successfully to the total number of data packets sent from source vehicles to the destination vehicles in the whole simulation.

5.2.2. Delay Metric. In our simulations, we just consider the delay caused in the MAC layer, which is defined as the total

TABLE 1: Parameters used in simulations.

Parameters	Values
Number of lanes	4
Number of vehicles, N	[20, 160]
Bandwidth for channel, M (Mbps)	6
Beacon interval (ms)	100
Speed of vehicles, v_i (m/s)	[15, 32]
Regular acceleration/deceleration, a_i (m/s ²)	[4, 8]
Maximum brake deceleration, a_{max} (m/s ²)	8
Packets size (byte)	300
Delay time in MSD model, t_{res} (s)	1.0
Transmission range of vehicle (m)	180
Simulation time (s)	60
The permitted minimum distance, s_0	1.3

time elapsed since the message's (beacon or warning) generation till it accesses the medium and is sent out successfully by a vehicle. And we count the average delays of beacons and warning messages together.

5.2.3. Fairness of the Medium Access. In order to quantitatively evaluate the fairness of the medium access between beacons and warning messages, we adopt the Jain's fairness index in [28]. Prior to the particular definition of Jain's fairness index in this paper, we first introduce the medium utilization for both beacons and warning messages, denoted by u_b and u_w , respectively. The medium utilization of beacons is defined as the rate of all the slots reserved for beacons to the total number of beacons. And the medium utilization of warning messages u_w is similar to u_b . Without loss of generality, let bs_i denote the number of slots assigned to a vehicle for beacon transmission and bn_i denote the number of all the beacons to be broadcasted in the simulation. So u_b can be expressed as

$$u_b = \frac{\sum_1^N bs_i}{\sum_1^N bn_i}. \quad (26)$$

Similarly, the medium utilization of warning messages u_w can be computed by

$$u_w = \frac{\sum_1^N ws_i}{\sum_1^N wn_i}. \quad (27)$$

Based on the above description, the Jain's fairness index is defined as $(u_b + u_w)^2 / 2 \cdot (u_b^2 + u_w^2)$ [17]. It indicates how well the medium utilizations are distributed between beacons and warning messages. If Jain's fairness index equals to 0.5, it means that the warning messages preempt all the resource of the medium access. While Jain's fairness index is 1, the beacons and warning messages share the medium access fairly.

5.3. Simulation Results. The first set of experiment mainly investigates the performance of R-MAC on the average packets delivery rate, where beacons and warning messages

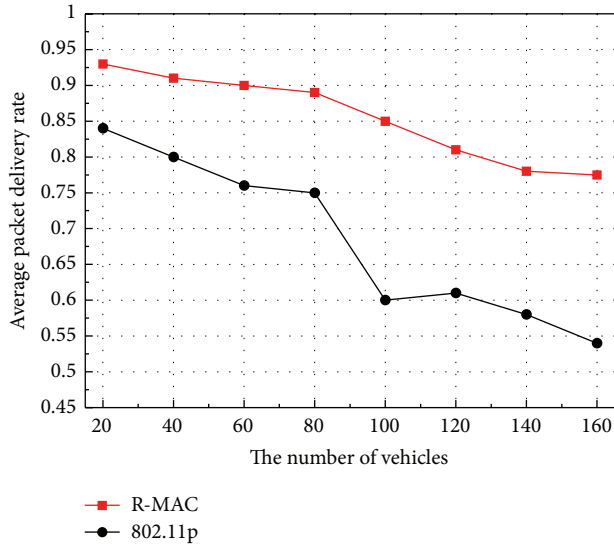


FIGURE 9: The packets delivery versus number of vehicles.

are counted together. We vary the number of vehicles from 20 to 160 with an interval of 20 to simulate various traffic loads. As the number of vehicles increases, more packet collisions will occur, which leads to the decrease of the average packets delivery rate. Figure 9 shows that the average packet delivery of 802.11p experiences an abrupt fall from 75% to 60%. While in our R-MAC protocol, the average packets delivery rate is kept above 85% before the number of vehicles reaches 100. Even in a heavy traffic scenario where the number of vehicles is up to 160, the average packet delivery rate is still around 75%, which guarantees the Qos in safety-related applications greatly.

The second experiment mainly observes the performance of the R-MAC protocol on the average delay of the medium access. Similar with the first experiment, we count the delay of beacons and warning messages together. Figure 10 shows that the average delay of the medium access increases with the increase of the vehicle number. In addition, the delay gap between R-MAC and 802.11p becomes larger and larger (better) with the increase of the vehicle number, which verifies a good performance of average delay in our R-MAC. Nevertheless, as seen from Figure 10, R-MAC and 802.11p reach nearly the same delay performance (reaching up to 115 ms) when the number of vehicles increases to 140. Obviously, neither the R-MAC nor 802.11p protocol can work well in the heavy traffic situations. So, we will study the traffic overload tolerant R-MAC in the future.

In the third set of experiments, we mainly investigate the performance of R-MAC on the medium utilizations between beacons and warning messages. Various traffic loads are configured the same as the first experiment. As seen from Figure 11, when the number of vehicles on the road is small (less than 40), the medium utilizations of warning messages approach 100% in both R-MAC and 802.11p. That is because there are few warning messages generated when the traffic is light, and there are enough slots and chance for them to be transmitted. With the increase of vehicles, particularly

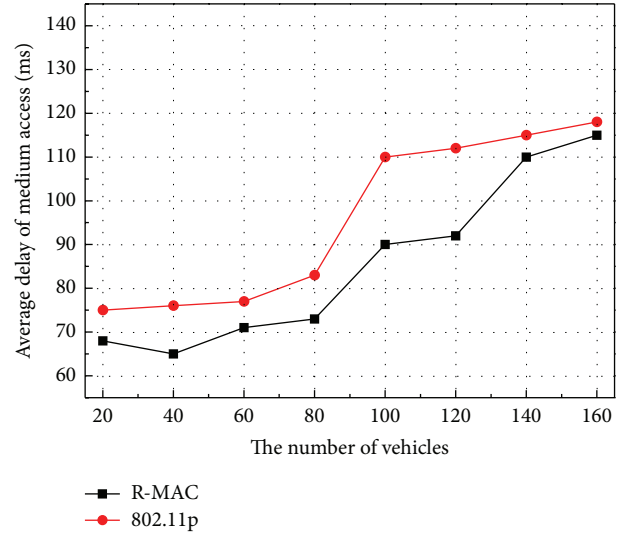


FIGURE 10: Average delay of the medium access versus number of vehicles.

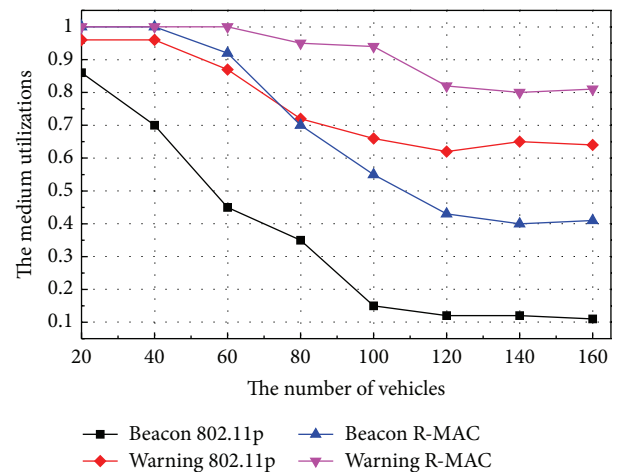


FIGURE 11: The medium utilization versus number of vehicles.

from 60, the medium utilizations of warning messages and beacons decrease dramatically in 802.11p, which is caused by the more and more collisions among messages. However, even in a heavy traffic (number of vehicles more than 140), Figure 11 shows that the medium utilizations of beacons and warning messages are greater than 82% and 40% in our R-MAC, respectively.

In order to demonstrate the fairness of the medium access between beacons and warning messages, the final experiment is conducted with the same settings as the third one. The Jain's fairness index is computed and plotted in Figure 12. As shown in Figure 12, the Jain's fairness index decreases dramatically with the increase of vehicles in 802.11p, which is caused by inherent attribute of contest in CSMA and different priorities of messages. When the number of vehicles reaches up to 140, the Jain's fairness index in 802.11p even drops to 0.65, which almost indicates the worst case. However, the Jain's fairness index in R-MAC always floats between 0.9 and 1.0, which

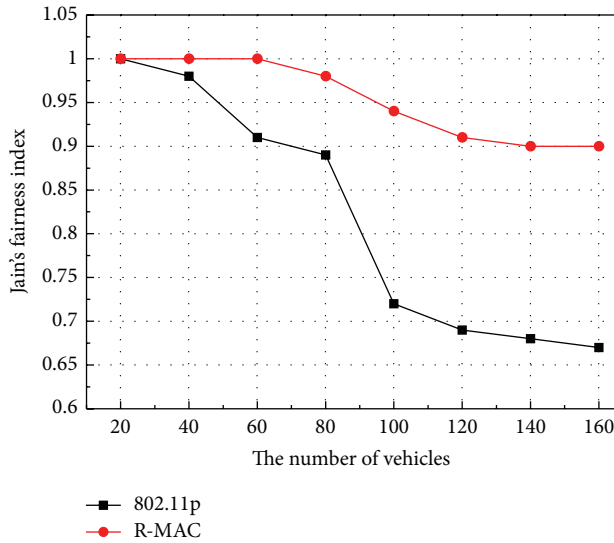


FIGURE 12: Jain's fairness index versus number of vehicles.

means that a good fairness between beacons and warning messages is achieved. Compared with 802.11p, our proposed R-MAC protocol can improve the Jain's fairness index by about 39% even in heavy traffic scenarios.

6. Conclusions

This paper has studied the dynamic MAC protocol problem to satisfy real-time and reliable delivery of messages while achieving the fairness of the medium access between different kinds of messages in cooperative collision avoidance (CCA) systems. We have designed a risk-aware dynamic medium-access control (R-MAC) protocol for this problem. In order to ensure the accuracy of risk-aware in R-MAC, a stochastic prediction model of the average total number of potential collisions in the platoon is presented. Extensive Monte Carlo simulations verify that our model is reliable and practical enough. Efficiency and fairness of R-MAC are verified by simulations against the standardized MAC 802.11p protocol of VANET. The simulation results show that R-MAC can improve the Jain's fairness index by about 39% compared with 802.11p. Even in heavy traffic scenarios, the packet delivery rate is still above 80% in R-MAC and the average delay is reduced significantly, which meets the communication requirements in CCA systems adequately in general scenarios. From the simulations, we have found that the transmission delay is relatively larger in overload traffic scenario. As a future work, we will study the traffic overload tolerant R-MAC protocol for CCA applications.

Acknowledgments

This paper is supported by the National Grand Fundamental Research 973 Program of China under Grant No. 2011CB302905, the National Science Foundation of China under Grant No. 61170058, 61272133 and 61228207, National Science and Technology Major Project under Grant No.

2011ZX03005-004-04 and 2012ZX03005009, Special Project on Industry Technology of Suzhou (No. ZXG201041), and China Postdoctoral Science Foundation under Grant No. 20110490821.

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