Research Article

Real-Time Performance Evaluation of IEEE 802.11p EDCA Mechanism for IoV in a Highway Environment

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Received 15 May 2020; Revised 11 July 2020; Accepted 27 July 2020; Published 28 August 2020

Academic Editor: Di Zhang

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With the development of 5G, the Internet of Vehicles (IoV) evolves to be an important component of the Internet of Things (IoT), where vehicles and public infrastructure communicate with each other through an IEEE 802.11p EDCA mechanism to support four access categories (ACs) to access a channel. Due to the mobility of the vehicles, the network topology is time-varying and thus incurs a dynamic network performance. There are many works on the stationary performance of 802.11p EDCA and some on real-time performance, but existing work does not consider real-time performance under extreme highway scenarios. In this paper, we consider four ACs defined in the 802.11p EDCA mechanism to evaluate the limit of real-time network performance in an extreme highway scenario, i.e., all vehicles keep the minimum safety distance between each other. The performance of the model has been demonstrated through simulations. It is found that some ACs can meet real-time requirements while others cannot in the extreme scenario.

1. Introduction

Nowadays, IoT networks are deployed to collect various information from surrounding systems through the real-time interaction with environment [1]. As one kind of IoT, Internet of Vehicles (IoV) enables vehicles and infrastructures to exchange data through the vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications [2]. With the aid of the emerging 5G technologies, IoV will develop rapidly [3, 4]. There are many researches on 5G in the industry and academia [5]; 5G can be utilized to facilitate low latency, high reliability, and higher quality communication of IoV [6, 7]. It is promising to overcome some bottlenecks and thus significantly improve the network performance of IoV [8].

With the development of IoV, effectiveness and safety have become the key factors considered by an intelligent transportation system (ITS) [9]. In the network, each mobile vehicle is considered a node with a variety of secure/nonsecure applications. IEEE 802.11p is a physical layer and medium access control (MAC) layer standard and has been widely used in wireless access in vehicular environments (WAVE) [10]. It adopts an enhanced distributed channel access (EDCA) mechanism to access a channel. The IEEE 802.11p EDCA mechanism defines four ACs to provision services of different priorities through setting different parameters [11].

One of the characteristics of the IoV is dynamic topology changes. For example, when vehicles are moving on the highway, the movement of the vehicles and the drivers’ decision will cause the network topology to change (not always in a stationary state). Some analytical models have been put forward in existing performance modeling studies of the 802.11p EDCA mechanism in IoV [12–14], In [12], Han et al. constructed models to analyze the stationary performance of the 802.11p EDCA mechanism. In [13], Zheng and Wu considered the factors including saturated condition (vehicles always have data to transmit) and nonsaturated
condition (vehicle do not always have data to transmit), standard parameters, backoff counter, internal collision, and computational complexity to analyze the performance of the IEEE 802.11p EDCA mechanism in the stationary state. In [14], Yao et al. used the probability generating function (PGF) approach to capture the nonstationary performance of IoV.

As far as we know, most existing works only studied the stationary performance of the 802.11p EDCA mechanism, but the vehicular network is in a high-speed environment, and thus the number of vehicles in the carrier sensing range of each vehicle is changing all the time, which cause the performance of the 802.11p EDCA mechanism to be changed in real time. Therefore, the traditional analysis methods were not suitable for the real situations. In [15], Xu et al. constructed models to study the time-varying behaviour of the 802.11p EDCA mechanism in a two-way highway scenario, but this work only considers two ACs, which does not consist of the definition of the 802.11p EDCA mechanism. According to the regulations in [16], the vehicles driving on the highway should follow the 4-second rule, i.e., the time interval between two contiguous vehicles on a common lane passing through a fixed reference object beside the highway should be larger in four seconds. Thus, there is a minimum safety distance between contiguous vehicles. To the best of our knowledge, there is no work analyzing the limit of the real-time performance of the 802.11p EDCA mechanism in the extreme highway scenario, i.e., all vehicles keep the minimum safety distance between each other, which motivates us to conduct this work. In this paper, we consider four ACs and conduct models to analyze the limit of the real-time performance of the 802.11p EDCA mechanism in IoV. Note that it is challenging to build a model in complex road conditions and to calculate the performance of the 802.11p EDCA mechanism considering four ACs.

The rest of this paper is organized as follows. In Section 2, a review of related work is presented. In Section 3, we describe the scenario and model IEEE 802.11p EDCA mechanism. The analytical model is provided in Section 4. In Section 5, numerical results are provided for performance evaluation and comparison. Finally, Section 6 concludes the paper.

2. Related Work

In this section, we first review the existing works for the performance analysis of the 802.11 distributed coordination function (DCF) mechanism, which is the basis of the 802.11p EDCA mechanism; next, we review the related works on the performance analysis of the 802.11p EDCA mechanism; and finally, the works about the real-time performance analysis of the 802.11p EDCA mechanism is reviewed.

There are lots of existing modeling approaches to analyze the performance of the 802.11 DCF mechanism. In [17], Bianchi proposed a simple two-dimensional Markov chain model under the assumption of an ideal channel and finite number terminals to describe the binary exponential backoff algorithm and computed the saturated throughput performance based on the proposed model. In [18], Ni et al. proposed an analytical model to calculate the throughput under saturated conditions in both congested and error-prone channels. In [19], Malone et al. took the 802.11 DCF mechanism-based network and bursty data traffic into account to derive a carrier sense multiple access/collision avoidance (CSMA/CA) model in a nonsaturated environment and validated the accuracy of the derived model through simulation. Some works analyzed the broadcast performance of the DCF mechanism in IoV. In [20], Vinel et al. proposed an analytical D/M/1 queue model to calculate the message reception probability and mean packet delay in the 802.11 DCF mechanism-based vehicular networks. In [21], Ma et al. proposed a 1-D Markov chain model to analyze the broadcast performance of the 802.11a DCF mechanism and evaluate the packet reception rate (PRR) and packet delay (PD) of V2V safety-related broadcast services.

In addition to those works, there are some studies about the analysis of the 802.11p EDCA mechanism. In [12], Han et al. proposed a three-dimensional Markov chain analytical model to analyze the 802.11p EDCA mechanism under a saturated network condition. The proposed model is validated through simulations and is justified to be suitable for both basic access and the request to send/clear to send (RTS/CST) access mode, but it does not consider backoff freezing. In [22], Gallardo et al. proposed a Markovian model to analyze the performance of the 802.11p EDCA mechanism over the control channel (CCH) under both saturated and nonsaturated conditions. The model is composed by three Markov chains, and each chain describes the backoff procedure of an AC. It can be used to compute the throughput, frame error rate, and delay of the AC. In [23], Kaabi et al. only considered one AC and proposed an analytical model to investigate the performance of the IEEE 802.11p EDCA mechanism for safety messages in IoV, but they did not analyze the delay. In [13], Zheng and Wu considered the factors including saturated and nonsaturated condition, standard parameters, backoff counter, internal collision, and computational complexity and developed two Markov chains to analyze the performance of the IEEE 802.11p EDCA mechanism; the simulation experiments are conducted to verify the effectiveness of the derived performance models. However, these works focus on the stationary performance analysis of the 802.11p EDCA mechanism, which is not realistic in the dynamic IoV.

As described above, researches on stationary performance are mature. There are few works study on the real-time performance analysis of the IEEE 802.11p EDCA mechanism. In [24], Bilstrup et al. analyzed the channel delay of the 802.11p EDCA mechanism through simulations and compared with a self-organizing time division multiple address (TDMA). It is proven that TDMA is more suitable for the time-sensitive application in IoV. In [14], Xu et al. proposed a fluid-flow performance model to analyze the real-time performance of the 802.11p EDCA mechanism. The proposed model is computationally efficient, generalized and accurate to calculate the real-time performance of PD and packet delivery ratio (PDR). However, none of them considered four ACs to analyze the limit of the real-time...
performance of 802.11p EDCA in the extreme highway scenario, which is the motivation of this work.

3. System Model

In this section, we first describe the extreme highway scenario; then, the 802.11p EDCA mechanism is reviewed briefly.

3.1. Extreme Highway Scenario. In order to find the performance limit of the network, we consider an extreme highway scenario as shown in Figure 1. Specifically, vehicles are driving on a one-way four-lane highway, where vehicles driving on the common lane with the same velocity and the velocities of the vehicles on the different lane are different. The distance between any of the contiguous vehicles on the common lane, i.e., intervehicle distance, is set to the minimum safety distance according to the 4-second rule. Since the minimum safety distance is determined by the velocity of vehicles, the intervehicle distances are different on different lanes. Each vehicle adopts the IEEE 802.11p protocol to exchange data packet through wireless communication. The channel access mechanism of the 802.11p protocol is the EDCA mechanism. Packets arrive at AC\_m (m = 0, 1, 2, 3) of a vehicle according to the Poisson process with arrival rate \( \lambda_m(t) \). In order to investigate the real-time performance of the 802.11p EDCA mechanism for each vehicle in the network, we denote the investigated vehicle as the target vehicle. As shown in Figure 1, the red vehicle is the tagged vehicle, and the blue vehicles are the vehicles within the carrier sensing range of the target vehicle which can successfully send or receive the packet from the tagged vehicle. Meanwhile, the black vehicles are not within the carrier sensing range of the target vehicle and they cannot communicate with the tagged vehicle. Next, we review the 802.11 EDCA mechanism briefly.

3.2. IEEE 802.11p EDCA Mechanism. The IEEE 802.11p EDCA mechanism defines four AC queues to support different priorities of services to access a channel [25], i.e., voice (VO), video (VI), best effort (BE), and background (BK) [26], where each AC queue has a specific parameter configuration, including the minimum backoff window \( CW_{\text{min}} \), maximum backoff window \( CW_{\text{max}} \), arbitration interframe space number AIFSN, and the retransmission limit. When a packet arrives at the AC\_m queue of a vehicle, it will be transmitted when the channel status is idle. If the channel is busy, the vehicle will continue to detect the channel until the channel keeps idle for AIFS\_m, then start a backoff process, where AIFS\_m is calculated as

\[
\text{AIFS}[m] = \text{AIFSN}[m] \times \sigma + \text{SIFS},
\]

where SIFS is the short interframe space and \( \sigma \) is a slot time.

The backoff process is described as follows. The contention window size \( W^0_m \) is first set to \( CW_{\text{min}}^m + 1 \) and a value is randomly selected from \([0, W^0_m]\) as the value of a backoff counter; then, it would be decreased by one after each idle slot [27]. If the channel is busy during the backoff process, the value of the backoff counter will be frozen until the channel becomes idle again [28]. When the backoff counter is decreased to 0, the packet will be transmitted. At this time, the transmission is successful if no AC of other vehicles and no higher priority AC of the vehicle are transmitting. Otherwise, a collision occurs. Specifically, an external collision occurs if at least one AC of other vehicles is transmitting, and an internal collision occurs if at least one other AC of this vehicle is transmitting. In the condition of a collision, the contention window size is doubled, and a new backoff process is initiated to retransmit the packet. The contention window would not be doubled after the number of retransmission reaches \( M_m \). If the number of retransmission reaches the retransmission limit \( M_m + f_m \), the packet would be dropped. The contention window of the AC\_m queue under the number of retransmission \( i \) is given by

\[
W^i_m = \begin{cases} 
CW_{\text{min}}^m + 1, & i = 0, \\
2^i W^0_m, & 1 \leq i \leq M_m, \\
CW_{\text{max}}^m + 1, & M_m \leq i \leq M_m + f_m.
\end{cases}
\]

The access process of 802.11p is shown in Figure 2. Note that if an internal collision occurs, the packet with the highest priority will be transmitted, the contention window of the lower priority will be doubled, and then a backoff process is initiated.
4. Analytical Model

In this section, we elaborate our model to analyze the real-time performance of the 802.11p EDCA mechanism. We first construct a connectivity metric to denote the connection of vehicles in the network, and then, we develop models to derive the real-time performance of the IEEE 802.11p EDCA mechanism including the mean service time and variance for the target vehicle. The notations used in this paper are summarized in Table 1.

4.1. Connectivity Metric. There are \( N \) vehicles in this scenario, the vehicles are numbered sequentially from lane 4 to lane 1, and on each lane vehicles are numbered from left to right, e.g., the number of the leftmost vehicle on lane 4 is 1 and the number of the rightmost vehicle on lane 1 is \( N \). The coordinate of vehicle \( l \) is denoted as \( (s_{l,1}^l, s_{l,2}^l) \); here, we set that the coordinate of vehicle 1 as \((0,0)\). Each vehicle can acquire the coordination of other vehicles through communications; thus, each vehicle can acquire the matrix of the coordination of \( N \) vehicles at time \( t \), i.e.,

\[
S(t) = \begin{bmatrix}
[s_1^1(t), s_{ord}^1(t)] \\
[s_1^2(t), s_{ord}^2(t)] \\
\vdots \\
[s_N^N(t), s_{ord}^N(t)]
\end{bmatrix}.
\]

If the Euclidean distance of the two vehicles is less than the carrier sensing range, they are considered to be connected with each other, i.e., communicate with each other. Each vehicle can calculate a connectivity metric \( H(t) \) according to \( S(t) \) to denote the connectivity of the vehicles in the network at time \( t \), i.e.,

\[
H(t) = \begin{bmatrix}
h_{1,1}(t) & h_{1,2}(t) & \cdots & h_{1,N}(t) \\
h_{2,1}(t) & h_{2,2}(t) & \cdots & h_{2,N}(t) \\
\vdots & \vdots & \ddots & \vdots \\
h_{N,1}(t) & h_{N,2}(t) & \cdots & h_{N,N}(t)
\end{bmatrix},
\]

where \( h_{k,l}(t) \) denotes whether vehicle \( k \) can connect with vehicle \( l \).

In our scenario, vehicles drive on the same lane with the same velocity and drive on different lanes with different velocities. Since the intervehicle distance is related with the velocity of vehicles, the intervehicle distances of vehicles are the same on the same lane and are different on different lanes. Therefore, the connection of the vehicles in the network is changed in real time due to the different velocities and intervehicle distances on different lanes, thus causing the matrix \( H(t) \) to be time varying. Let vehicle \( k \) be the target vehicle in the network, the number of vehicles in the carrier sensing range of the tagged vehicle \( k \) can be calculated according to \( H(t) \), i.e.,

\[
N_{rr}^k(t) = \sum_{l=1}^{N} h_{k,l}(t). \tag{5}
\]

4.2. Real-Time Mean Service Time and Variance. In this section, we regard access process of the 802.11p EDCA mechanism as the service process and derive the real-time performance of the IEEE 802.11p EDCA mechanism including the mean service time and variance for the target vehicle \( k \). The mean service time and variance can be calculated according to the first and second moments of the probability generating function (PGF) of service time of \( AC_m \) for vehicle \( k \), i.e.,

\[
E_m^k = \left. \frac{dP_{T_s}^k(z)}{dz} \right|_{z=1}, \tag{6}
\]

\[
D_m^k = \left. \left( \frac{d^2 P_{T_s}^k(z)}{dz^2} + \frac{dP_{T_s}^k(z)}{dz} - \left[ \frac{dP_{T_s}^k(z)}{dz} \right]^2 \right) \right|_{z=1}, \tag{7}
\]

where \( P_{T_s}^k(z) \) is the PGF of service time and is calculated according the Markov chain in [29], which is shown as follows:
where $\text{TR}(z)$ is the PGF of transmission time, $B_{m,i}(z)$ is the PGF of stationary probability of AC, at stage $i$ for vehicle $k$, $H_{m}(z)$ is the PGF of the average duration that the backoff counter of AC, for vehicle $k$ is decremented by one, and $p_{k}^{m}(t)$ is the internal collision probability of AC, for vehicle $k$ at time $t$. According to Equation (8), $p_{k}^{m}(t)$ depends on $\text{TR}(z)$, $B_{m,i}(z)$, $H_{m}(z)$, and $p_{k}^{m}(t)$, which need to be further derived. We first derive $\text{TR}(z)$. Since the duration of a transmission is composed of the propagation delay and the duration occupied by the physical header, MAC header, and packet, the transmission time $T_{tr}$ can be calculated as

$$T_{tr} = \frac{\text{PHY}_{H}}{R_{b}} + \frac{\text{MAC}_{H} + E[P]}{R_{d}} + \delta,$$  \hspace{1cm} (9)

where $\delta$ is the propagation delay, PHY$_{H}$ and MAC$_{H}$ are the size of the physical and MAC header, respectively. Assuming each packet for all ACs has the same size, let $E[P]$ be the packet size. According to Equation (9), the transmission time $T_{tr}$ is a constant; thus, the PGF of transmission time $T_{tr}$ is expressed as

$$\text{TR}(z) = z^{T_{tr}}.$$  \hspace{1cm} (10)

Next, we derive $B_{m,i}(z)$. According to the Markov chain model for backoff instance in [29], $B_{m,i}(z)$ can be calculated as

$$B_{m,i}(z) = \frac{1}{\min (W_{m}, M_{m})} \sum_{i=0}^{\min (W_{m}, M_{m})-1} \left[H_{m}(z)\right]^{i},$$  \hspace{1cm} (11)

where $i \in (0, M_{m} + f_{m})$.

Since the channel may be idle or busy when the backoff counter is decremented by one, $H_{m}(z)$ can be calculated as

$$H_{m}(z) = \left[1 - p_{busy}^{m}(t)\right] z^\alpha + p_{busy}^{m}(t) z^{\text{TR} + \text{AIFS}[m]}.$$  \hspace{1cm} (12)

The probability $p_{busy}^{m}$ is channel busy probability of AC for vehicle $k$ at time $t$, i.e., the probability that at least one AC is transmitting in a time slot, including the probability that the other ACs of the vehicle $k$ is transmitting and the probability that the ACs of another vehicle is transmitting. Considering the priority of different ACs, the channel busy probability of AC can be derived according to the following equation:

$$p_{busy}^{m}(t) = 1 - \left\{ 1 - A(t)^{N_{m}(t)-1} \prod_{j=0}^{3} \left(1 - \alpha_{m}^{j}(t)\right) \right\}^{A_{m}+1}.$$  \hspace{1cm} (13)

The packet will be transmitted when the backoff counter becomes 0; the internal transmission probability for AC can be expressed by $\alpha_{m}$,

$$\alpha_{m}^{k}(t) = \begin{cases} b_{0,0}^{k}(t), \\ \sum_{j=0}^{M_{m} + f_{m}} b_{j,m,0}^{k}(t) = 1 - p_{busy}^{m}(t) \frac{p_{bus}^{m}(t) M_{m} + f_{m} + 1}{1 - p_{bus}^{k}(t)} b_{0,0}^{k}(t), \end{cases}$$  \hspace{1cm} (14)

where the probability of the highest priority AC is the probability of the backoff state 0; the internal transmission probability for other ACs is equal to the sum of all backoff states. According to the transition probability of the Markov chain, the probability can be calculated as

\begin{align*}
\begin{cases}
    b_{0,0}(t) & = \left\{ \frac{W_{m}^{0} + 1}{2} \left[1 - p_{bus}^{m}(t)\right] + \frac{1 - p_{bus}^{m}(t)}{p_{bus}^{m}(t)} \right\}^{-1}, \\
    b_{j,m,0}(t) & = \left\{ \frac{1 - p_{bus}^{m}(t) M_{m} + f_{m} + 1}{1 - p_{bus}^{m}(t)} + \frac{W_{m}^{0} - 1}{2} \left[1 - p_{bus}^{m}(t)\right] + \frac{p_{bus}^{m}(t) M_{m} + f_{m} + 1}{1 - p_{bus}^{m}(t)} \right\}^{-1}, \\
    b_{0,1}(t) & = \left\{ \frac{M_{m} + f_{m}}{2} \left[1 - p_{bus}^{m}(t)\right] + \frac{1 - p_{bus}^{m}(t)}{p_{bus}^{m}(t)} \right\}^{-1}, \\
    b_{j,m,1}(t) & = \left\{ \frac{1 - p_{bus}^{m}(t) M_{m} + f_{m} + 1}{1 - p_{bus}^{m}(t)} + \frac{W_{m}^{0} - 1}{2} \left[1 - p_{bus}^{m}(t)\right] + \frac{p_{bus}^{m}(t) M_{m} + f_{m} + 1}{1 - p_{bus}^{m}(t)} \right\}^{-1}.
\end{cases}
\end{align*}

(15)
Denote \( p_a^m(t) \) as the packet arrival probability of \( AC_m \) at time \( t \). Due to the packet arrival process of \( AC_m \) is a Poisson process with arrival rate \( \lambda_m(t) \), thus \( p_a^m(t) \) is calculated as

\[
p_a^m(t) = \sum_{i=1}^{\infty} \frac{[\lambda_m(t)]^i}{i!} e^{-\lambda_m(t)} = 1 - e^{-\lambda_m(t)}.
\]  

As mentioned in the system model, an internal collision occurs when there are more than two ACs in a vehicle trans-

mitting at the same time. In this case, the AC with the highest priority is transmitted successfully. Let \( \alpha_k^m(t) \) be the transmission probability and \( p_c^m(t) \) be the internal collision probability of \( AC_m \) for vehicle \( k \) at time \( t \), we have
Since the packet transmission is considered to be successful only when there is no internal collision, and the transmission probability of a vehicle is the sum of four ACs, the transmission probability of a vehicle is calculated as

\[
\begin{align*}
p_{c0}^k(t) &= 0, \\
p_{c1}^k(t) &= \alpha^k_0(t), \\
p_{c2}^k(t) &= 1 - \left(1 - \alpha^k_0(t)\right)\left(1 - \alpha^k_1(t)\right), \\
p_{c3}^k(t) &= 1 - \left(1 - \alpha^k_0(t)\right)\left(1 - \alpha^k_1(t)\right)\left(1 - \alpha^k_2(t)\right).
\end{align*}
\]  

(17)

Since the packet transmission is considered to be successful only when there is no internal collision, and the transmission probability of a vehicle is the sum of four ACs, the transmission probability of a vehicle is calculated as

\[
\tau^k(t) = \alpha^k_0(t)\left(1 - p_{c0}^k(t)\right) + \alpha^k_1(t)\left(1 - p_{c1}^k(t)\right) + \alpha^k_2(t)\left(1 - p_{c2}^k(t)\right) + \alpha^k_3(t)\left(1 - p_{c3}^k(t)\right).
\]  

(18)

By now, we have found all the relationships between \(\rho^k_m\), \(p_{\text{busy}}^k\), \(n_{0,0,0}^k\), \(n_{a,p}^k\), \(n_{c,m}^k\), and \(r^k\) in Equations (13), (14), (15), (16), (17) and (18). Since the number of variables is more than that of the equations, iterative method is used to solve the system, and thus we can further calculate the mean and variance of the service time.

1. Assign initial values to four \(\rho^k_m\)
2. Bring \(\rho^k_m\) into Equations (13), (14), (15), (16), (17) and (18) and solve the other 21 variables
3. Combining relations Equations (6), (7), (8), (9), (10), (11) and (12), we obtain the average service time \(E^k_m\) and then calculate \(\rho^k_m = \min\left(\lambda^k_m E^k_m, 1\right)\)
4. Setting an error bound \(\epsilon\), compare the error of the actual \(\rho^k_m\) with \(\epsilon\), if it is less than the error, the iteration is completed, otherwise, go to step (2)
Calculating the mean and variance of service time according to Equations (6) and (7).

5. Results and Discussion

In this section, we evaluate the network performance in the extreme highway scenario with four lanes. The simulation is conducted on MATLAB R2018a. The distance between contiguous vehicles is set to be the minimum distance according to the 4-second rule. As the speed range of the American highway is from 20 m/s to 30 m/s, we set the speeds of the four lanes to be 20 m/s, 23 m/s, 20 m/s, and 30 m/s, respectively. The total length of the highway is 3000 m and the transmission range is 300 m, the values of 802.11p parameters and scenario description are shown in Table 2.

In order to ensure that the target vehicle is always within the scope of the scenario, we take the fifth vehicle in the second lane as the target vehicle. Each vehicle has four ACs to broadcast packets. Since the vehicle speed of each lane is different, the relative position of the vehicle is time varying, thus causing other vehicles to move in/out of the transmission range of the target vehicle. In this case, the number of vehicles in the carrier sensing range of the target vehicle may change in real time.

As shown in Figure 3, at first, the number of vehicles in the transmission range of the target vehicle is 18. About three seconds later, vehicles in the fast lane which were previously out of the range move into the transmission range of the target vehicle, which causes the total number of vehicles increasing immediately. The total number of vehicles keeps for about four seconds; then, vehicles in the slow lane that were previously in the transmission range of the target vehicle move out the transmission range and the number of vehicles decreases immediately. As described above, the number of vehicles is changed due to different vehicle speeds in different lanes and is fluctuated repeatedly according to Equations (3), (4) and (5).
Figures 4 and 5 show the real-time mean and standard deviation of service time, which is the value calculated by Equations (6) and (7). The trend of the mean and standard deviation of service time keeps consistent with the change of the number of vehicles. The number of vehicles will impact the probability of backoff block $p_{\text{busy}}^m$, which will further affect the state probability $b_{m,0,0}^c$, resulting in the change of the mean and standard deviation of service time. Therefore, the mean and standard deviation increase with the number of vehicles increasing. From Figure 4, we can find that the higher priority AC has less average service time delay than low priority AC. Moreover, we can see that as the average delay of $AC_0$, $AC_1$, and $AC_2$ is less than 0.01 s, which is the minimum delay to ensure safety in IoV [7]. Therefore, $AC_0$, $AC_1$, and $AC_2$ can meet the real-time requirements, while $AC_3$ cannot meet the requirements.

6. Conclusion
In this paper, we considered four ACs and proposed models to investigate the limit of the real-time performance of the 802.11p EDCA mechanism in the extreme highway scenario. Specifically, we model the real-time network between vehicles, study the connection between vehicles, calculate the real-time number of vehicles within the carrier sensing range, and then calculate the real-time performance metrics of the 802.11p EDCA mechanism including mean and variance of service time. The simulation result is employed to demonstrate that $AC_0$, $AC_1$, and $AC_2$ are able to meet the real-time requirement in the extreme highway scenario but $AC_3$ cannot. In the future work, we will study the real-time performance modeling of the 802.11p EDCA mechanism in other scenarios.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare no conflicts of interest.

Acknowledgments
This work was supported in part by the National Natural Science Foundation of China under Grant Nos. 61701197 and 61540063, in part by the Yunnan Natural Science Foundation of China under Grant Nos. 2016FD058 and 2018FD055, in part by the 111 Project under Grant No. B12018, and in part by the Jiangsu Laboratory of Lake Environment Remote Sensing Technologies Open Fund under Grant No. JSLERS-2020-001.

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