Delay Analysis and Study of IEEE 802.11p based DSRC Safety Communication in a Highway Environment

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***Abstract*—As a key enabling technology for the next generation inter-vehicle safety communications, The IEEE 802.11p protocol is currently attracting much attention. Many inter-vehicle safety communications have stringent real-time requirements on broadcast messages to ensure drivers have enough reaction time toward emergencies. Most existing studies only focus on the average delay performance of IEEE 802.11p, which only contains very limited information of the real capacity for inter-vehicle communication. In this paper, we propose an analytical model, showing the performance of broadcast under IEEE 802.11p in terms of the mean, deviation and probability distribution of the MAC access delay. Comparison with the NS-2 simulations validates the accuracy of the proposed analytical model. In addition, we show that the exponential distribution is a good approximation to the MAC access delay distribution. Numerical analysis indicates that the QoS support in IEEE 802.11p can provide relatively good performance guarantee for higher priority messages while fails to meet the real-time requirements of the lower priority messages.**

I. Introduction

Communication-based safety technology is considered as a more efficient approach than the traditional active safety technology in terms of detection range, field of view and cost. As a vital part of Intelligent Transportation System (IT-S) Program conducted by USDOT, vehicle-to-vehicle (V2V) communication can provide many safety-related applications such as cooperative forward collision warning, emergency electronic brake lights, lane change assistance, blind spot warning, intersection movement assist and hazardous location notification, etc [1]. The IEEE 802.11p protocol is now approved to better support V2V communications. Statistics show that V2V systems can deal with 79% potential vehicle crashes which can significantly improve road safety [2]. This kind of applications has the additional demand on low latency and direct transmission. Once an emergency situation occurs, it's necessary to inform all surrounding vehicles with safety messages in time. Therefore, most V2V safety applications commonly adopt the broadcast mode for real-time data transmission [3].

One of the most important points in a real-time wireless communication is the MAC protocol, hence, the new standard IEEE 802.11p for VANET is currently attracting much attention. For V2V safety applications, a safety-related message needs to be delivered before the deadline. Thus, it's important to get the MAC access delay of 802.11p to analyze if the standard protocol meets the requirements of real-time wireless communications. The MAC access delay, namely the MAC service time, is the time interval from the time instant when a packet becomes the head of the MAC queue to the time instant that either the packet is successfully transmitted or dropped. So far, many researchers have studied the performance of IEEE 802.11p. Most of them only consider the mean MAC access delay in VANET environment [4]–[6], however, the mean value cannot reflect the practical situation of VANET. Even if the mean delay is less than the deadline, large latency may still take place because of the stochasticity of the IEEE 802.11p MAC scheme. Therefore, the distribution of the MAC access delay has been more practical for designers to understand the characteristic of the IEEE 802.11p MAC protocol. Meanwhile, the distribution of the MAC access delay can be used for further analysis of the queuing delay. [7] and [8] established theoretical models and obtained the MAC access delay distribution of WLANs by constructing probability generating function (PGF) and probability mass function respectively. But these models only take a single type of message into account. [9] and [10] proposed analytical models for the IEEE 802.11e EDCA to evaluate the performance of multi-traffics with different QoS supports. However, these models are conducted under saturated conditions which are not suitable for the V2V safety communication. Moreover, all above models [7]–[10] are based on the unicast mode that cannot be used in the broadcast mode. Until recently, there have been some works that studied the MAC delay distribution of IEEE 802.11p safety messages broadcast via simulation [11]–[13], but they didn't obtain explicit expressions.

In this paper, we aim at constructing a complete analytical model to evaluate the capacity of the standard IEEE 802.11p when applied to V2V safety applications. We establish two Markov Chains for different priority ACs to analyze the delay distribution in the broadcast mode. Moreover, our model can cover both the non-saturated and saturated conditions. Simulation results show that our analytical model for the mean, deviation and probability distribution is very accurate. In addition, we observe that the MAC access delay distribution is close to a shifting exponential distribution. Numerical analysis indicates that 802.11p with QoS support can provide relatively

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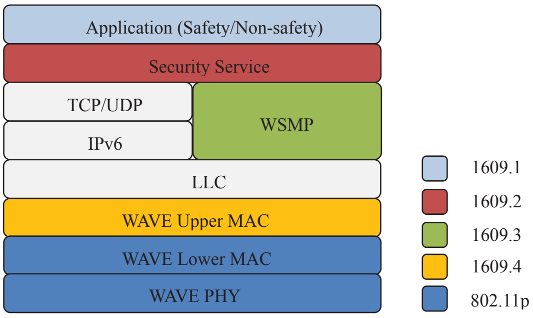


Fig. 1: WAVE protocol stack

good performance for the higher priority messages while fails to guarantee the real-time demand of the lower priority messages.

The rest of this paper is organized as follows. Section II gives a brief overview of IEEE 802.11p protocol and V2V safety communication in a highway environment. Section III presents the analytical model and derives the mean, deviation and probability distribution of the MAC access delay from a certain tagged node's view. Section IV validates our model via NS-2 simulations. Section V analyzes the numerical results. Finally, Section VI draws the conclusion.

II. IEEE 802.11p for Vehicular Communication

A. An Overview of IEEE 802.11p Protocol

IEEE drafts the Wireless Access in Vehicular Environments (WAVE) protocol to better support vehicular communication. The WAVE protocol stack is shown in Figure 1. It's composed of IEEE 802.11p and a standard family IEEE 1609.

IEEE 802.11p extends the IEEE 802.11 standard for a high-speed vehicular environment based on dedicated short-range communication (DSRC) spectrum. It covers the data link layer and the physical layer of the WAVE stack, while IEEE 1609 has been developed to define the upper layers. The MAC layer adopts Enhanced Distributed Channel Access (EDCA) for Quality of Service (QoS) support inheriting from IEEE 802.11e, while the physical layer uses an Orthogonal Frequency Division Multiplex (OFDM) modulation scheme to multiplex data which is similar to the IEEE 802.11a standard (with the transmission rates from 3 to 27 Mb/s which is half of the bandwidth in the IEEE 802.11a). IEEE 802.11p provides multi-channel control mechanism to operate seven 10-MHz wide channels defined in DSRC spectrum. One is the control channel (CCH) for common safety communications only and the remaining six are known as the Service Channel (SCH) for other non-safety applications.

B. EDCA Differentiation Parameters and Backoff Procedure

EDCA is designed to enhance the Distributed Coordination Function (DCF) to provide QoS support. It allows four access categories (ACs) with different priorities in a station. Each AC behaves as an enhanced DCF with an independent MAC queue entity that can be differentiated by channel access parameters including Contention Window (CW), Arbitration Inter-Frame Space (AIFS) and Transmission Opportunity (TXOP). The specific definitions of the 802.11p EDCA are shown in Table I, where AC3 corresponds to the lowest priority and AC0 corresponds to the highest priority.

TABLE I: 802.11p EDCA Access Parameters for CCH

AC	CWmin	CWmax	AIFSN	TXOP Limit
3	aCWmin	aCWmax	9	0
2	aCWmin	aCWmax	6	0
1	(aCWmin+1)/2-1	aCWmin	3	0
0	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2	0

Let the $W_{i,j}$ denote the maximum CW size of ACi in the j-backoff stage after the j^{th} unsuccessful transmission, thus, $W_{i,0} = CW_{i,\min} + 1$. Let M_i be the maximum times that the CW of ACi can be doubled, hence,

$$M_i = log_2 \frac{CW_{i,\max} + 1}{CW_{i,\min} + 1}. \tag{1}$$

Then we have

$$W_{i,j} = \begin{cases} 2^j W_{i,0}, j \le M_i \\ 2^{M_i} W_{i,0}, M_i < j \le L_i \end{cases}, \tag{2}$$

where L_i is the retry limit of the ACi backoff. Without loss of generality, we define L_i as L in this paper. One important difference between the DCF and the EDCA is the defer time when the channel is sensed idle. The DCF allows a node to transmit packets when the channel keeps idle for a constant Distributed Inter-Frame Space (DIFS) while the EDCA defines different time intervals called AIFS for the priority-based QoS support. The Arbitration Inter-Frame Space Number (AIFSN) is used to determine the AIFS according to

$$AIFS[i] = SIFS + AIFSN[i] \times \sigma, \tag{3}$$

where AIFSN[i]$\geq$2 corresponds to the DIFS of 802.11 and σ denotes the slot time. In this paper, we define A_i as the AIFS differentiation

$$A_i = AIFSN[i] - AIFSN[0]. \tag{4}$$

The TXOP limit allows the consecutive transmissions of several packets when an AC entity occupies the channel. However, TXOP has not been defined by IEEE 802.11p yet.

The operation of the EDCA backoff procedure is described in [14] shown in Figure 2. The frames from the higher layer arrive at the MAC layer with different priorities, and then enter different queues. The backoff instances in a node can be considered as being independent of each other without virtual collisions. For each AC, if the channel is idle for a period time equal to an AIFS, it transmits. Otherwise, if the channel is sensed busy, the AC will persist to monitor the channel until the idle duration up to the AIFS. At this point, the AC generates a random interval according to its CW value

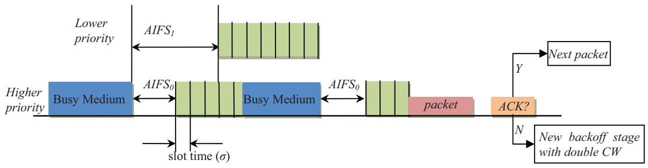


Fig. 2: EDCA backoff procedure

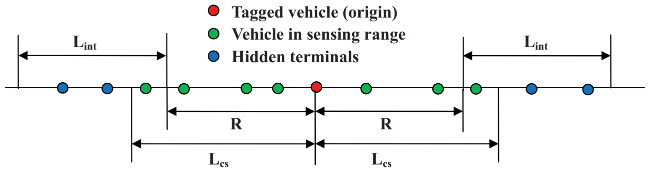


Fig. 3: One-dimensional VANET model

and starts a backoff procedure. The backoff counter decreases again only when then channel keeps idle for an AIFS time. The destination node sends back an ACK frame to the source node as soon as it receives the delivery, and the source node may transmit a next frame or go to an idle state. If the source node does not receive the ACK within a predefined ACK Timeout, another backoff procedure with doubled CW is invoked for transmission failure caused by external collisions. After each unsuccessful transmission, the CW will be doubled until it reaches CW_{max} or the retransmission number is up to the retry limit. In this paper, we are only interested in the delay of packets that are successfully received at the MAC layer.

However, different backoff instances in a station cannot access the channel completely independently because of internal virtual collisions. We will discuss this issue in detail in next Section.

C. V2V Safety Communication in a Highway Environment

V2V communications for safety is the dynamic wireless exchange of data between nearby vehicles that offers the opportunity for significant safety improvements. Safety applications usually demand one vehicle interacts with other vehicles nearby directly. Considering the dynamic topology and low delay constraint, single-hop broadcast on CCH is seen as an effective approach to inform neighboring vehicles with safety messages. In VANET, there are two main types of broadcast messages for safety applications. One is emergent safety messages (or event-driven messages) which are sent when detecting dangers or abnormal situations. This type of messages is closely related to the specific safety applications. The other one is routine safety messages (or time-triggered messages). This type of messages basically contains vehicle's location, velocity, direction and other detail attributions like vehicle size, vehicle length and acceleration control, etc. Due to highly dynamic network topology, routine safety messages have to be sent with high frequency (2Hz $\sim$ 10Hz) to ensure up-to-date information. An example of these two types messages is Decentralized Environment Notification Messages (DENM) and Cooperative Awareness Messages (CAM) defined by ETSI. Commonly, emergent safety messages are generated occasionally but need a fast and guaranteed transmission. Therefore, this type of messages has a higher priority than routine messages.

In this paper, we leverage a one-dimensional VANET model of a typical highway scenario like the Figure 3 shows. From the statistic analysis of empirical data, [15] proves that an exponential distribution is a good fit for highway vehicle traffic in terms of inter-vehicle distance. That means the vehicles are dispersed in a line following Poisson point process with intensity β, namely, the traffic density (in vehicles per meter).

The transmission range (denoted by R) is defined as the distance of successfully sending/receiving one packet. It depends on the transmission power and channel fading. The carrier sensing range (denoted by L_{cs}) is defined as the distance of detecting a signal and it is the key parameter in the CSMA/CA scheme. The interference range (denoted by L_{int}) is larger than the transmission range and less than the carrier sensing range, because the signal not reaching the receiving threshold may still have impacts on the normal receiving. With density β, we can derive the average number of vehicles in different areas respectively.

$$\begin{cases} N_{tr} = 2\beta R \\ N_{cs} = 2\beta R \\ N_{ht} = 2\beta(R + L_{int} - L_{cs}) \end{cases} . \quad (5)$$

III. Analytical Model

A. Scenario description

We assume the following scenarios for the IEEE 802.11p broadcast on the CCH.

- We only consider two types of messages in a vehicle which are set priorities with AC0 (emergent safety messages) and AC1 (routine safety messages) respectively.
- The safety-critical messages are usually very short so that they can be encapsulated in a single packet. We assume the average packet size $E[P]$ is the same for all ACs.
- The routine safety message is generated periodically with rate λ_0. Like some previous studies on safety communication in VANET [16]–[18], we assume the packet arrival rate λ_1 (in terms of packets per second) for emergent safety message is satisfied Poisson process.
- We neglect the mobility of vehicles since nodes remain almost stationary within a message transmission time. According to the results of article [19], the vehicles with the speed of 120 mi/h only move around 0.053m during a period of a packet transmission, hence the estimated link breaking probability is 0.0052.

B. Virtual Collision Model

Within one node, each MAC queue of ACi behaves like a virtual station. If two or more ACs of a station try to access the channel in the same time slot, the virtual collision occurs. In this case, the frame with the highest priority will be transmitted and the lower priority frames enter another backoff stage with doubled CWs immediately. If the number

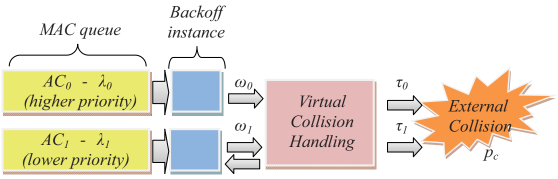
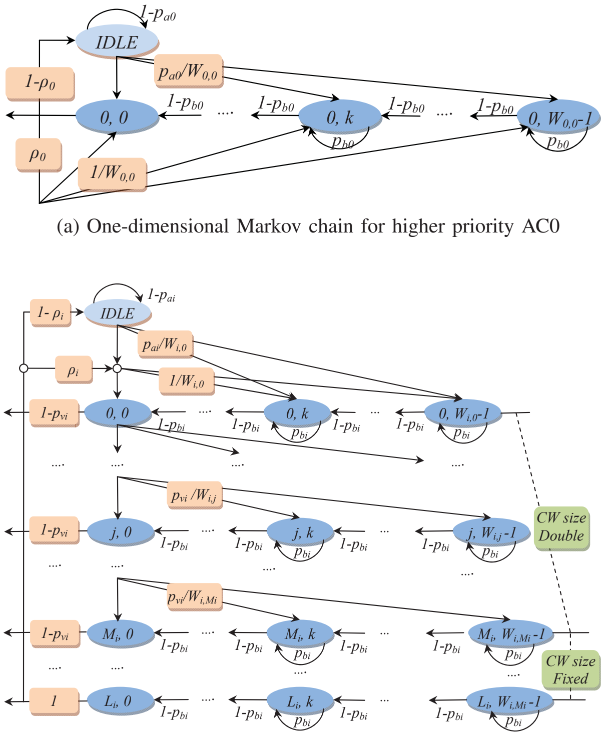


Fig. 4: Virtual collision



(a) One-dimensional Markov chain for higher priority AC0

(b) Two-dimensional Markov chain for lower priority AC1

Fig. 5: Markov chain model for backoff instance

of failed retransmissions reaches the retry limit, the packet will be discarded. Figure 4 gives an overview of a node with the virtual collision handling.

We use internal/external transmission probability to describe the virtual collision [20]. As shown in Figure 4, let ϖ_i denote the internal transmission probability that the backoff instance of ACi attempts to send a packet in a time slot and p_{vi} denote the virtual collision probability of ACi. Then we have

$$\begin{cases} p_{v0} = 0 \\ p_{v1} = \varpi_0 \end{cases} . \tag{6}$$

The external transmission probability τ_i observed by other nodes outside of the station can be calculated as

$$\begin{cases} \tau_0 = \varpi_0 \\ \tau_1 = \varpi_1(1 - p_{v1}) = \varpi_1(1 - \varpi_0) \end{cases} . \tag{7}$$

The total transmission probability of a station is given as

$$\tau = \tau_0 + \tau_1. \tag{8}$$

The external collision probability p_c can be evaluated as

$$\begin{aligned} p_c &= 1 - \sum_{k=0}^{\infty} (1-\tau)^{N_{cs}-1} \frac{(N_{cs}-1)^k}{k!} e^{-(N_{cs}-1)} \\ &\times \left[\sum_{k=0}^{\infty} (1-\tau)^{N_{ht}} \frac{N_{ht}^k}{k!} e^{-N_{ht}} \right]^{T_{vuln}/\sigma} \\ &= 1 - e^{-(N_{cs}-1)\tau} e^{-N_{ht}\tau T_{vuln}/\sigma} \end{aligned} , \tag{9}$$

where T_{vuln} is the hidden terminal vulnerable period [21], which is twice the packet transmission time if all packets have the same size. The average transmission time is given as

$$T_{tr} = \frac{PHY_H}{R_b} + \frac{MAC_H + E[P]}{R_d} + \delta, \tag{10}$$

where PHY_H and MAC_H is the header length of physical and MAC layer. R_b and R_d are the basic rate and data rate respectively. δ denotes propagation delay.

C. Markov Chain Model for IEEE 802.11p Broadcast

Since there is no ACK frame in broadcast mechanism, the source node cannot detect the external collision. This indicates that only virtual collision affects the backoff procedure. Because the highest priority AC0 is free from virtual collision, its backoff procedure is simplified as a one-dimensional Markov Chain with constant contention window size $W_{0,0}$ shown in Figure 5a. Other lower priority ACs may suffer from internal collisions, which can trigger a new backoff stage with doubled CW, so that should be modeled as a two-dimensional Markov Chain given in Figure 5b.

Let $s_i(t)$ and $b_i(t)$ represent the backoff stage and the backoff counter of ACi at time t. Hence, a state of Markov Chain can be expressed as $\{s_i(t), b_i(t)\}$, and the backoff instance state of AC0 can be simplified as $\{b(t)\}$ for $s_0(t) \equiv 0$. Specially, we define IDLE state as {-1} and {0,-1} in two Markov Chains respectively.

Before solving the Markov Chain, some probabilities here need to be explained and calculated.

p_{ai} : is the packet arrival probability of ACi. As the packet of the routine safety message (AC0) is periodically generated and the packet arrival rate of the emergent safety message (AC1) follows Poisson distribution, the probability that it has packets arrival at each MAC queue in a slot time can be calculated by

$$\begin{cases} p_{a0} = \lambda_0 \sigma \\ p_{a1} = \sum\limits_{k=1}^{\infty} \frac{(\lambda_1\sigma)^k}{k!} e^{-\lambda_1\sigma} = 1 - e^{-\lambda_1\sigma} \end{cases} . \tag{11}$$

ρ_i : represents the probability that there is at least one packet waiting in the queue of AC[i]. In other words, it's the utilization of the server for the MAC queue of ACi defined as

$$\rho_i = \frac{\lambda_i}{\mu_i}, i = 0, 1, \tag{12}$$

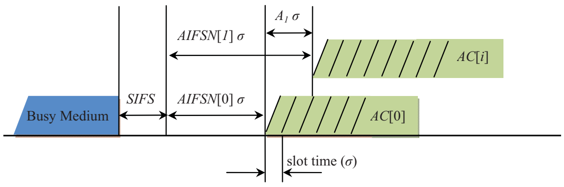


Fig. 6: AIFS differentiation of ACs

where μ_i is the average service rate of the queue (in packets per second). Note that, if ρ_i = 0 is satisfied, it's the extreme non-saturated case that there is no packet preparing to send. On the other hand, when ρ_i is equal to 1, the IDLE state will be eliminated from the Markov Chain. So, our model covers extreme non-saturated, intermediate non-saturated and saturated conditions by changing ρ_i from 0 to 1. As an important role played in our model, the estimation of ρ_i will be elaborated later.

p_{bi} : is the backoff blocking probability. For a given backoff instance of ACi in a node, p_{bi} is equal to the probability that the node senses other nodes occupy the channel or there is transmission attempted by other ACs in the node. As shown in Figure 6, it's obviously that the lower priority ACs are deferred for a longer time than higher ones since the bigger AIFSN, thus, the backoff blocking probability is calculated by

$$\begin{array}{l} p_{bi} = 1 - \left[P(k) \prod\limits_{\substack{j=0 \\ j \neq i}}^{1} (1 - \varpi_j) \right]^{A_i+1}, i = 0, 1 \\ P(k) = \sum\limits_{k=0}^{\infty} (1-\tau)^{N_{cs}-1} \frac{(N_{cs}-1)^k}{k!} e^{-(N_{cs}-1)} \end{array} . \quad (13)$$

The stationary distributions of two chains are defined as

$$\begin{cases} b_{0,k} = \lim\limits_{t\to\infty} P\{b(t) = k\} \, k \in (0, W_{0,0} - 1) \\ b_{1,j,k} = \lim\limits_{t\to\infty} P\{s_1(t) = j, b_1(t) = k\} {}_{k\in(0,W_{1,j,0}-1)}^{j\in(0,L)} \end{cases} . \quad (14)$$

As the fact that the sum of the stationary probabilities of all states in the Markov Chain equals to one, the limiting probability of state $b_{0,0}$ and $b_{1,0,0}$ is obtained as (15).

The internal transmission probability can be expressed by

$$\begin{cases} \omega_0 = b_{0,0} = \left[\dfrac{(W_{0,0}+1)}{2(1-p_{b0})} + \dfrac{1-\rho_0}{p_{a0}} \right]^{-1} \\ \omega_1 = \sum\limits_{j=0}^{L} b_{1,j,0} = \dfrac{1-p_{v1}^{L+1}}{1-p_{v1}} b_{1,0,0} \end{cases} . \quad (16)$$

D. MAC Access Delay Analysis

The MAC access delay, namely the MAC service time, is the time interval from the time instant when a packet becomes the head of the MAC queue to the time instant that either the packet is successfully transmitted or dropped. The MAC delay of ACi is a non-negative random variable of which the distribution can be seen as a discrete time sequence $ts_{i,k}$ with probability $q_{i,k}$ when the time is slotted by a very small unit ($q_{i,k}$ is the steady state probability that the delay equals to $ts_{i,k}$ times slottime). Hence, the probability generating function (PGF) of the access delay (Ts_i) is given by

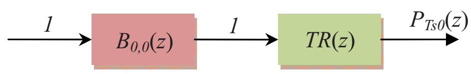
$$P_{Ts_i}(z) = \sum_{k=0}^{\infty} q_{i,k} z^{ts_{i,k}}. \quad (17)$$

We can use the transfer-function approach to evaluate the PGF because the whole process can be seen as a Z-transform domain linear system shown in Figure 7. The access delay is composed of the backoff time and the transmission time. The backoff time is a random variable according to the backoff blocking probability while the transmission time is deterministic. Since packet size is assumed same for all ACs, the transmission time of one packet is a constant, thus, the PGF of transmission time (T_{tr}) is expressed as

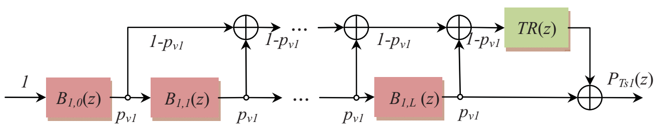
$$TR(z) = z^{T_{tr}}. \quad (18)$$

In the EDCA backoff procedure, the backoff counter of ACi decreases one slot time (σ) when the channel is sensed idle, while it is frozen for a time period of $T_{tr} + AIFS[i]$ once a successful transmission is detected. Considering the backoff blocking probability mentioned above, the PGF of the average time that backoff counter decreases by one of ACi is given as

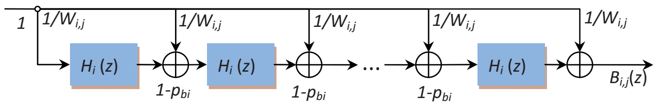
$$H_i(z) = (1 - p_{bi}) z^{\sigma} + p_{bi} z^{T_{tr}+AIFS[i]}, i = 0, 1. \quad (19)$$



(a) System block diagram for packet processing of AC0



(b) System block diagram for packet processing of AC1



(c) System block diagram for backoff instance of ACi (i=0,1)

Fig. 7: Z-transform linear system

From Figure 7, we can obtain the transfer functions, i.e. the PGF $B_{i,j}(z)$ and $P_{Tsi}(z)$ through mason formula.

$$\begin{cases} B_{0,0}(z) = \frac{1}{W_{0,0}} \sum\limits_{k=0}^{W_{0,0}-1} [H_0(z)]^k \\ B_{1,j}(z) = \begin{cases} \frac{1}{W_{1,j}} \sum\limits_{k=0}^{W_{1,j}-1} [H_1(z)]^k, j \in (1, M_1) \\ \frac{1}{W_{1,M_1}} \sum\limits_{k=0}^{W_{1,M_1}-1} [H_1(z)]^k, j \in (M_1, L) \end{cases} \end{cases} . \quad (20)$$

$$\begin{cases} b_{0,0} = \left[\dfrac{(W_{0,0}+1)}{2(1-p_{b0})} + \dfrac{1-\rho_0}{p_{a0}} \right]^{-1} \\ b_{1,0,0} = \left[\dfrac{1-p_{v1}^{L+1}}{1-p_{v1}} + \dfrac{W_{1,0}-1}{2(1-p_{b1})} + \dfrac{W_{1,0}p_{v1}[1-(2p_{v1})^{M_1}]}{(1-p_{b1})(1-2p_{v1})} + \dfrac{2^{M_1-1}W_{1,0}p_{v1}^{M_1+1}(1-p_{v1}^{L-M_1})}{(1-p_{b1})(1-p_{v1})} + \dfrac{1-\rho_1}{p_{a1}} \right]^{-1} \end{cases}. \quad (15)$$

$$\begin{cases} P_{Ts0}(z) = TR(z)B_0(z) = \frac{TR(z)}{W_{0,0}} \sum\limits_{k=0}^{W_{0,0}-1} [H_0(z)]^k \\ P_{Ts1}(z) = (1-p_{v1})TR(z) \sum\limits_{n=0}^{L} \left[p_{v1}^n \prod\limits_{j=0}^{n} B_{1,j}(z) \right] \\ \qquad + p_{v1}^{L+1} \prod\limits_{j=0}^{L} B_{1,j}(z) \end{cases}. \quad (21)$$

The mean of the MAC access delay can be calculated by

$$T_{Si} = \frac{1}{\mu_i} = \frac{dP_{Tsi}(z)}{dz}|_{z=1} = P_{Tsi}{}'(1), i = 0, 1. \quad (22)$$

And the deviation of the MAC access delay is given as

$$D_{Si} = P_{Tsi}{}''(1) + P_{Tsi}{}'(1) - \left[P_{Tsi}{}'(1)\right]^2, i = 0, 1. \quad (23)$$

We can derive ρ_i by iterative method elaborated below.

Step 1: Initialize ρ_i according to the network condition;

Step 2: Solve the multivariate nonlinear equations which is composed of (6), (7), (13) and (16) with 8 variables p_{vi}, p_{bi}, ϖ_i and τ_i (i=0, 1);

Step 3: Calculate the average MAC access delay Ts_i according to equations (18) $\sim$ (22);

Step 4: $\rho_i = \min(\lambda_i Ts_i, 1)$, if all $\rho_i \leq \varepsilon$ are satisfied, where ε is a predefined error bound, the iteration is completed. Otherwise, go to Step 2 with new ρ_i.

Finally, we can derive the probability density function (PDF) of the MAC access delay according to the properties of PGF.

$$p_k(t_{si}) = P\{t_{si} = k\} = \frac{P_{Tsi}^{(k)}(0)}{k!}, i = 0, 1. \quad (24)$$

IV. Model Validation

In this section, we compare the theoretical values of our model for the mean, standard deviation, and PDF of the MAC access delay with NS-2 simulation results. [12] indicated that packet size of 100 bytes is just long enough to broadcast basic status of vehicles, but for security consideration, the length should be much longer. In this paper, the packet size $E[P]$ is set to be 500 bytes. Each vehicle has two active ACs with packet arrival rates of 2pkts/s (AC0) and 10pkts/s (AC1) respectively. Since the transmission range of IEEE 802.11p is up to 1000m at data rate of 3Mbps and less than 200m at data rate of 27Mbps, we choose a moderate value 500m as the transmission range R at rate 6Mbps in simulation. Table II presents the traffic parameters of a typical highway scenario and the network parameters of the IEEE 802.11p MAC layer.

TABLE II: Traffic and network parameter settings

Parameter	Value	Parameter	Value
Highway length	2200m	PHY header	48bits
Density	0.01∼0.1 vhls/m	MAC header	112bits
Average distance	100m∼10m	Date rate	3Mbps
Transmission range	500m	Basic rate	1Mbps
Carrier sensing range	700m	Slot time	13μs
Interference range	600m	SIFS	32μs
Retry limit	4	Propagation delay	2μs

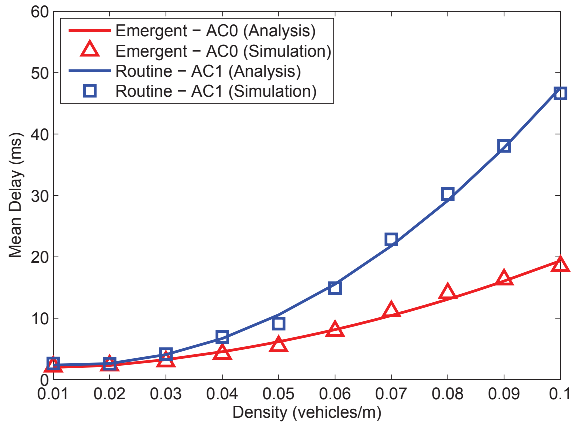


Fig. 8: Mean of the MAC access delay

Figure 8 and 9 show the mean access delay and standard deviation (by taking square root of equation (23)) of the IEEE 802.11p MAC layer with varied traffic density respectively. Meanwhile, min and max delay observed from simulations are listed in Table III. From Figures 8 and 9, there is a good agreement between analytical values and simulation results. We can observe that both the higher and the lower priority ACs have the very low average access delay. However, the standard deviation curve of AC1 grows rapidly with the traffic density increasing. This indicates that the maximum delay deviates from average delay largely so that the mean value cannot reflect the real network condition at heavy traffic density. From the table III, we can see that the maximum delay of AC1 is over 300ms at the traffic density of 0.1 vhls/m.

Figure 10 shows the probability distribution of the MAC

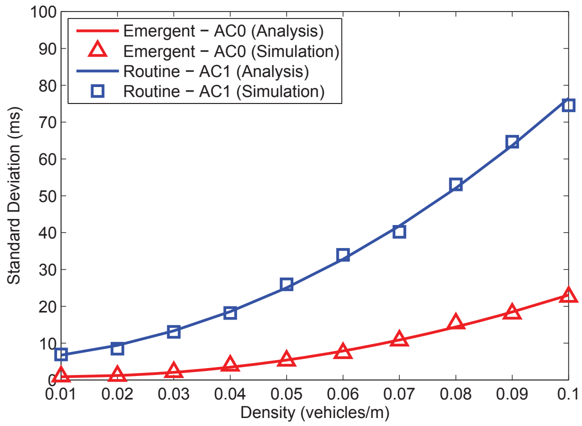


Fig. 9: Standard deviation of the MAC access delay

TABLE III: Min/Max MAC access delay

Density (vhls/m)	Min Delay (ms) AC_0/AC_1	Max Delay (ms) AC_0/AC_1
0.01	1.5373/1.5638	3.9954/6.4080
0.02	1.5377/1.5634	5.3343/16.5296
0.03	1.5371/1.5633	8.6794/32.4688
0.04	1.5376/1.5642	11.4207/56.8845
0.05	1.5373/1.5638	25.1149/84.8991
0.06	1.5371/1.5632	45.4646/124.9323
0.07	1.5372/1.5635	62.9478/176.2043
0.08	1.5371/1.5635	75.3410/211.8008
0.09	1.5370/1.5639	86.0945/268.5323
0.10	1.5371/1.5641	98.7202/325.5742

access delay with varied traffic density. Observe that all the analytical results match the simulation results very well, especially, our model has a close tail distribution with simulation.

V. Numerical Analysis

A. Distribution Analysis

We notice that the PDF envelope of the MAC access delay is similar to the exponential distribution. In this section, we compare the cumulative distribution function (CDF) of the exponential distribution with the distributions of two samples. One is derived from simulation, and the other is generated with PDF of our analytical model. Since the minimum delay of an AC is not 0, we assume the distribution of the MAC access delay of ACi satisfies a shifting exponential distribution with its minimum delay (denoted by a_i). We first calculate the minimum delay of each AC.

If an ACi detects the channel is idle for AIFS[i] and successfully accesses the channel without any contention, this ACi will get a minimum delay value (noted by a_i in our work). With the given packet size and data rate, we can easily obtain the minimum delay as follows

$$a_i = AIFS[i] + T_{tr}, i = 0, 1. \tag{25}$$

With the parameter settings in Section IV, a_0 and a_1 are 1.5371 ms and 1.5631 ms, respectively. Then, the PDF of the shifting exponential distribution is defined as follows

$$f_i(x) = \begin{cases} \theta_i e^{-\theta_i(x-a_i)}, x \geq a_i \\ 0, x < a_i \end{cases}, i = 0, 1. \tag{26}$$

According to the properties of PDF, we can further derive the mean, deviation and CDF of the MAC access delay

$$E[X_i] = \int_{a_i}^{\infty} x f_i(x)dx = \frac{1}{\theta_i} + a_i, i = 0, 1. \tag{27}$$

$$E[X_i^2] = \int_{a_i}^{\infty} x^2 f_i(x)dx = \frac{2}{\theta_i^2} + \frac{2a_i}{\theta_i} + a_i^2, i = 0, 1. \tag{28}$$

$$D[X_i] = E[X_i^2] - E^2[X_i] = \frac{1}{\theta_i^2}, i = 0, 1. \tag{29}$$

$$F_i(x) = \begin{cases} 1 - e^{-\theta_i(x-a_i)}, x \geq a_i \\ 0, x < a_i \end{cases}, i = 0, 1. \tag{30}$$

Here, we derive the parameter of the shifting exponential distribution by using the maximum likelihood estimate (MLE).

$$\frac{1}{\hat{\theta}_i} = \bar{X}_i - a_i, i = 0, 1, \tag{31}$$

where $\bar{X}_i$ is the mean of samples of the MAC access delay for ACi.

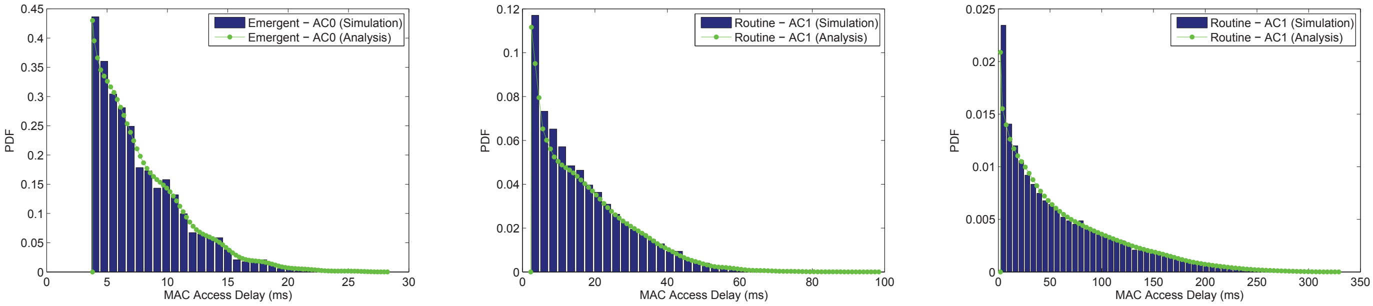
The results of the comparison are shown in Figure 11. From this figure, we can see that the differences among all three curves are very small. It demonstrates that the shifting exponential distribution is a reasonable approximation to the MAC access delay distribution. With this approximation, we can simplify our analytical model of the MAC access delay distribution. For the given highway traffic parameters and predesigned network parameters, we can first calculate the mean access delay and the minimum delay based on our model (equations (22) and (25)). Then, we can estimate the unique parameter θ by using the MLE

$$\hat{\theta}_i = \frac{1}{Ts_i - a_i}, i = 0, 1. \tag{32}$$

B. Performance Analysis

Due to the stochasticity of the IEEE 802.11p protocol, a safety application may not meet the real-time requirement even if the mean delay is less than the delay constraint. Moreover, it's hard to say whether a safety message can be successfully received within a firm deadline. Therefore, we introduce the Deadline Miss Rate (denoted by DMR_i) for each AC_i to evaluate if a safety application satisfies the real-time requirement.

For the given delay constraint D_c, we can derive the DMR_i according to Complementary Cumulative Distribution Function (CCDF) of the approximated exponential distribution.

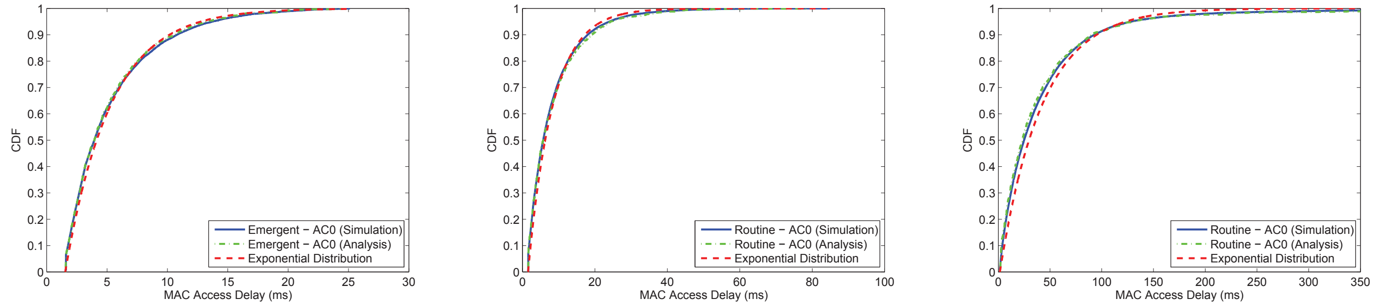


(a) Emergent - AC0 (β = 0.05)

(b) Routine - AC1 (β = 0.05)

(c) Routine - AC1 (β = 0.1)

Fig. 10: PDF of the MAC access delay



(a) Emergent - AC0 (β = 0.05)

(b) Routine - AC1 (β = 0.05)

(c) Routine - AC1 (β = 0.1)

Fig. 11: CDF of the MAC access delay

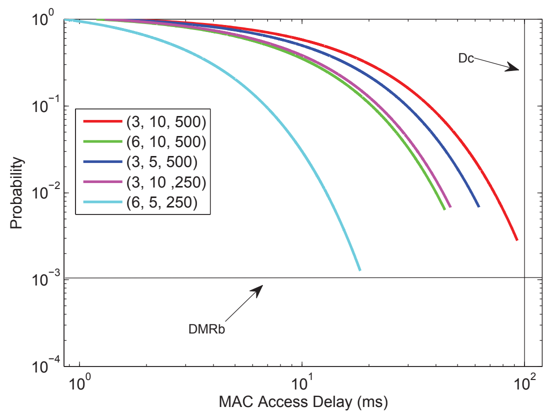
$$DMR_i = \bar{F}_i(D_c) = 1 - F_i(D_c) = e^{-\hat{\theta}(D_c - a_i)}, i = 0, 1. \tag{33}$$

It has reported in [22] that an allowable maximum delay requirement for some commonly used safety applications (such as forward collision warning and intersection collision warning) is 100 ms. In this paper, the Deadline Miss Rate Bound (denoted by DMR_b) is set to be 10^{-3}. It means one out of a thousand packets misses the deadline is tolerable. With these performance targets, we evaluate the impacts of different network parameters on the MAC access delay. Figure 12 shows that the CCDF curves of the MAC access delay. Each curve is parameterized by the triplet (bit rate [Mbps], packet arrival rate [packets per second], packet size [Bytes]). From the figure, we find that the emergent safety messages with the higher priority can always meet the real-time requirement, but the routine safety messages with the lower priority miss the deadline in most cases except for the higher bit rate, the lower packet arrival rate and the smaller packet size. It also indicates that it is possible to ensure the real-time broadcast if we increase the bit rate and decrease the packet arrival rate and the packet size. However, the ranges of these three parameters are more or less under restrictions in practice. For example, the higher bit rate can reduce the delay significantly, but it needs the better channel quality to correctly decode the packet with higher modulation and coding rate. Indeed, the appropriate bit rate in the highway environment is ranging from 3 to 6Mbps. The packet arrival rate and the packet size are more related to the specific application. DMR_i can present an intuitive statistics value to such specific application with real-time requirement of delay constraint D_c. Therefore, it is a good feedback for designers to retune the network parameters.

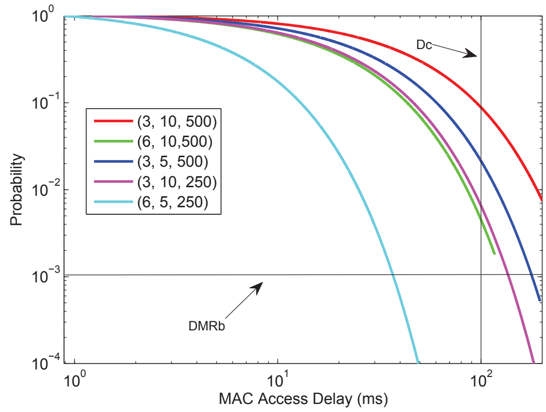
VI. Conclusion

In this paper, we evaluate the performance of the IEEE 802.11p MAC protocol which is applied to V2V safety communications in a typical highway environment. We propose an analytical model for the performance of the IEEE 802.11p safety message broadcast, in terms of the mean, deviation and probability distribution of the MAC access delay. We show that the exponential distribution is a good approximation to the MAC access delay. This can provide us opportunities to simplify the analytical model and conduct further analysis of the queuing delay for the MAC layer.

As a contention-based MAC scheme (CSMA), there is no finite upper bound on the MAC access delay of IEEE 802.11p. Although the conflict-free MAC methods (TDMA, FDMA) can provide deterministic service, the demand of a centralized node contradicts with the general nature of fully distributed and fast-changing vehicular networks. Our analysis indicates



(a) Emergent - AC0 (β = 0.1)



(b) Routine - AC1 (β = 0.1)

Fig. 12: CCDF of the MAC access delay

that the IEEE 802.11p with QoS support can provide relatively good guarantee for higher priority applications, but the lower priority ones may still miss the deadline. With the distribution of the MAC access delay, we can derive the probability DMR that the message delay may exceed the given deadline. This value is useful for designers to adjust network parameters. However, because of the non-determinism of the IEEE 802.11p MAC layer, care should be taken in designing the critical real-time applications for future V2V safety communications.

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