2021 20th International Conference on Ubiquitous Computing and Communications (IUCC/CIT/DSCI/SmartCNS)

Performance Analysis of the IEEE 802.11p EDCA for Vehicular Networks in Imperfect Channels

Ning Wang, Jia Hu
Department of Computer Science
College of Engineering, Mathematics and Physical Sciences
University of Exeter
Exeter, UK
E-mail:{nw354, j.hu}@exeter.ac.uk

***Abstract*—The IEEE 802.11p protocol was designed to support effective inter-vehicle communications for Intelligent Transportation Systems (ITS). The Medium Access Control (MAC) sub-layer in IEEE 802.11p employs Enhanced Distributed Channel Access (EDCA) mechanism in order to support differentiated Quality-of-Service (QoS) by introducing four Access Categories (ACs). Performance evaluation of 802.11p EDCA has attracted many research interests. However, most of the existing works assume perfect wireless channels that are error-free. In this paper, we propose a new analytical model based on a 3-D Markov chain and Queuing analysis to evaluate the IEEE 802.11p EDCA under imperfect channels with both saturated and unsaturated traffic. All influential factors of the 802.11p EDCA are considered, including the backoff counter freezing, AIFS defers, the internal collision, and finite MAC buffer sizes. The effectiveness and accuracy of the developed model have been validated through extensive ns-3 simulation experiments.**

***Index Terms*—IEEE 802.11p, Performance Modelling, Quality of Service, Inter-Vehicle Communications.**

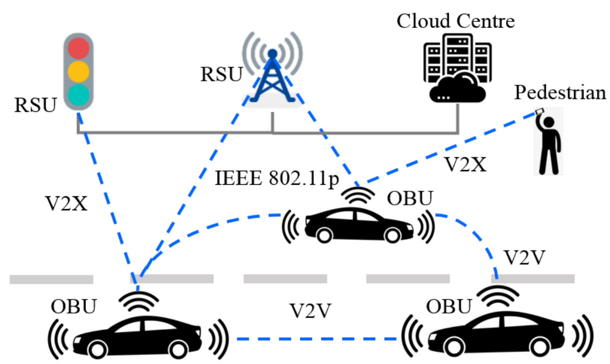

Fig. 1. V2X Communications via IEEE 802.11p

I. Introduction

Inter-Vehicle Communications (IVC) play a crucial role in future Intelligent Transportation Systems (ITS) [1]. IVC provides not only Vehicle to Vehicle (V2V) but also Vehicle to Everything (V2X) wireless network connections to exchange safety, traffic management and infotainment information for automobiles in Smart Cities [2]. As Fig.1 shows, the equipment in a typical IVC topology is composed of Road-Side Units (RSUs) and On-Board Units (OBUs). The RSUs are motionless physical devices installed along the roadside with a wired connection to the Internet, while OBUs are vehicles moving on the road [3]. RSUs and OBUs are communicating safety or non-safety messages through applications of IVC. However, the myriad applications demand various Quality of Services (QoS). In order to support differentiated QoS [4], IEEE 802.11p has been designed for the rapid increasing applications in IVC. Similar to IEEE 802.11e, IEEE 802.11p employ the Enhanced Distributed Channel Access (EDCA) mechanism in its Medium Access Control (MAC) protocol [5]. Applications with different QoS requirements are assigned to one of four Access Categories (ACs). The QoS of each AC is differentiated by specific EDCA parameters, including the Contention Window (CW) and Arbitrary Inter-frame Space (AIFS). Thus, the probability that an AC wins the channel's contention is dependent on the deferring and backoff time decided by the value of the AIFS and CW. Nevertheless, IEEE 802.11p disables the Transmission Opportunity (TXOP) limit and utilize different EDCA parameters due to the unique environment of IVC [6]. Furthermore, different from the traditional wireless network, the dynamic topology of IVC are connected by vehicles moving at high speeds. Therefore, it worsened the channel fading by the Doppler spread on Orthogonal Frequency Division Multiplex (OFDM) [7]. As a result, the channel error rate is higher and significantly impact the performance of IEEE 802.11p. With the specific characteristics described above of IEEE 802.11p, a complete, reliable and effective analytical model of the IEEE 802.11p EDCA mechanism for vehicular networks is required.

There have been several studies on the performance modelling of IEEE 802.11p EDCA. For example, [5] developed a model to analyze the performance under saturated traffic conditions. It introduced contention zones caused by the difference between the AIFS values. However, it ignored the backoff freezing mechanism, and saturated traffic conditions are also the limitation. By contrast, [9] designed an analytical model which is able to work under both saturated and non-saturated conditions. Nevertheless, it did not consider all four AC queues. Similarly, [10] presented a model which considered only two AC queues. Moreover, [8] constructed a 3-D discrete-time Markov chain model that considered the

978-1-6654-6667-7/21/$31.00 ©2021 IEEE
DOI 10.1109/IUCC-CIT-DSCI-SmartCNS55181.2021.00089

CW, AIFS and TXOP as a combination. However, it was designed for 802.11e, which is not suitable for 802.11p. As an essential improvement, [11] 's analytical model combines two discrete-time Markov chains to calculate the throughput and delay for four ACs with the influence of backoff counter freezing in 802.11p. [12] proposed another similar analytical model with updated parameters of the 802.11p protocol. However, both models based on a 2-D Markov chain with another separate 1-D Markov chain, which was unable to combine the CW backoff and AIFSN deferring procedure and increased the complexity. [13] considered the potential influence of the TXOP in 802.11p. Nonetheless, the TXOP is currently disabled in the 802.11p protocol due to the high-speed vehicular ad-hoc network environment. None of the above works considered the wireless channel errors in 802.11p.

Only a few works have discussed the impact of channel error in the IEEE 802.11p modelling. For instance, [14] analyzed the performance of 802.11p under an error-prone channel condition. Meanwhile, [15] proposed an adaptive Multi-Channel assignment and coordination scheme for IEEE 802.11p with the influence of channel errors. However, neither of them considered four AC queues. By contrast, [16] presents an analytical model that calculates channel errors' impact on the throughput, end-to-end delays, and packets loss rates for four ACs. Nevertheless, the asynchronous AIFSN defer of the four ACs are not considered, which is different from the 802.11p protocol.

To fill this gap, in this paper, we propose a complete and accurate analytical model for IEEE 802.11p in IVC environments under imperfect channels. The major contributions include:

- A new analytical model based on 3-D Markov Chain and Queuing analysis is presented to analyze the performance of the EDCA mechanism in IEEE 802.11p under imperfect channels. All influential factors, including backoff counter freezing, AIFS deferring and internal collisions of IEEE 802.11p EDCA, are taken into account.
- The proposed model considers finite MAC buffer sizes, the unsaturated and saturated load traffic. The simulation results validate the accuracy of the proposed model, in terms of throughput under various channel conditions.

The remainder of this paper is organized as follows. First, the EDCA mechanism in IEEE 802.11p is introduced in Section II. Second, the analytical model of the EDCA mechanism in IEEE 802.11p is presented in Section III. After that, the validation of the accuracy of the proposed model is presented in Section IV. Finally, we draw a conclusion in Section V.

II. The EDCA mechanism in IEEE 802.11p

In the IEEE 802.11p standard, the Enhanced Distributed Channel Access (EDCA) is employed in order to support prioritized QoS services. Four ACs with priorities high to low are defined in the IEEE 802.11p standard: Voice - AC_VO, Video - AC_VI, Best Effort - AC_BE, and Background - AC_BK. Each AC works on an independent transmission queue which is all installed in each station. The differentiated QoS is achieved by assigning a unique set of distinct channel access parameters, including CW and AIFS. Generally, a larger value of CW or AIFS means less probability to win the contention to access the channel and longer time of delays.

The EDCA uses carrier sense multiple access with collision avoidance (CSMA/CA) mechanism to reduce the collisions caused by multiple nodes intended to transmit frames simultaneously. It means that a station must sense the status of the channel before a transmission attempt. Therefore, transmission can only start when the channel is sensed idle and keeps for an AIFS. An AIFS is defined by:

$$AIFS_{[AC]} = SIFS + AIFSN_{[AC]} * aSlotTime \qquad (1)$$

Where $AIFSN_{[AC]}$ stands for the number of time slots in $AIFS_{[AC]}$ and $aSlotTime$ is the duration of a time slot.

Otherwise, this transmission attempt defers a random backoff counter, which follows a uniform distribution within the range of $[0, CW_{AC}]$. In the beginning, the value of CW_{AC} is equal to CW_{min}. After experiencing a transmission failure due to a collision or a packet error, it doubles until it reaches CW_{max}. If the transmission succeeds or it reaches the retry limit, the value of CW_{AC} is reset to CW_{min}. During the backoff procedure, the station keeps sensing the channel status. Once the channel is idle for a time slot, the backoff counter decreases one. Otherwise, the backoff counter freezes until the channel is sensed idle continuously for an AIFS. When the backoff counter becomes zero, the AC attempts to transmit the packets. However, if it happens with multiple ACs simultaneously in one station, an internal collision occurs, and the frame from the AC with the highest priority is chosen to be transmitted.

III. Analytical model

A. Modelling of the backoff procedure

In this section, we present a 3-D discrete-time Markov chain to analyze the EDCA mechanism in IEEE 802.11p. This 3-D Markov chain demonstrates the procedure of the CW backoff and AIFS deferring schemes. The AC_BK AC_BE, AC_VI, AC_VO are denoted by subscripts $AC_v, (v = 0, 1, 2, 3)$, respectively. We consider some assumptions in our work. First, the collision probability, p_v, is irrelevant from the number of retries. Second, we assume the packet arrival traffic for each AC_v follows a Poisson Process with the rate λ_v. Third, for simplicity, the impact of channel fading and modulation is modelled by Bit Error Rates (BER). It means that each bit of a packet shares the same error rate. In addition, the MAC headers, PHY headers and Acknowledgement (ACK) packet are error-free. Therefore, the probability of receiving an erroneous packet is:

$$p_e = 1 - (1 - BER^L) \qquad (2)$$

Where L stands for the frame payload length.

With the assumptions above, we construct the 3-D discrete-time Markov chain. Let s(t) represent the stochastic process

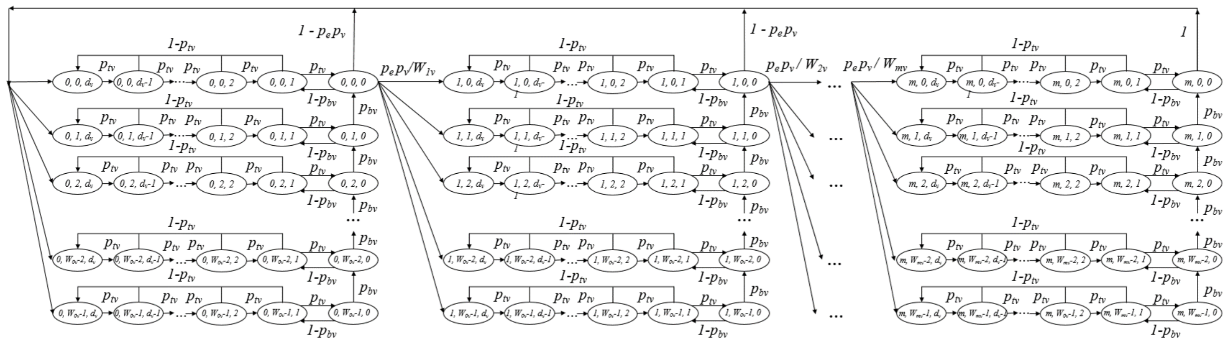

Fig. 2. 3-D Markov chain.

of the backoff stage, b(t) denotes the stochastic process of the backoff counter for a given AC, and c(t) stands for the stochastic process of the AIFS backoff counter from the AIFS of current AC to minimum AIFS. Then, we model these three stochastic processes s(t), b(t), c(t) as a 3-D discrete-time Markov chain which illustrating in Fig. 2.

The state transition probabilities of this 3-D Markov chain are demonstrating as follows:

$$\begin{cases} P_{\{i,j,0|i,j+1,0\}} = p_{bv} \ , \ i \in [0,m] \ , \ j \in [1, W_{iv}-1] \\ P_{\{i,j,d_v|i,j,0\}} = 1 - p_{bv} \ , \ i \in [0,m] \ , \ j \in [1, W_{iv}-1] \\ P_{\{i,j,0|i,j,1\}} = p_{tv} \ , \ i \in [0,m] \ , \ j \in [0, W_{iv}-1] \\ P_{\{i,j,k|i,j,k+1\}} = p_{tv} \ , \ k \in [0, d_v - 1] \\ P_{\{i,j,d_v|i,j,k\}} = 1 - p_{tv} \ , \ k \in [0, d_v] \\ P_{\{i,j,d_v|i-1,0,0\}} = \frac{p_v p_e}{W_{iv}} \ , \ i \in [1,m] \ , \ j \in [0, W_{iv}-1] \\ P_{\{0,j,d_v|i,0,0\}} = \frac{(1-p_v p_e)}{W_{iv}} \ , \ i \in [0,m-1] \ , \ j \in [0, W_{iv}-1] \\ P_{\{0,j,d_v|m,0,0\}} = \frac{1}{W_{0v}} \ , \ j \in [0, W_{iv}-1] \end{cases} \tag{3}$$

Where p_v is the collision probability of the Head-of-Queue (HoQ) frame of the AC_v, p_{bv} stands for the probability of the channel is sensed idle for a time slot after the AIFS period of the AC_v. p_{tv} denotes the probability the channel is sensed idle for a time slot within the AIFS period of the AC_v. m is the retry limit. And d_v denotes the difference of the AIFS value of the current AC between the minimal value of AIFSN. Hence, $d_v = AIFS_v - AIFS_{min}$. W_{iv} represents the current CW value after i times failed transmission. According to the IEEE 802.11p protocol [6], the W_{iv} can be calculated as follow:

$$W_{iv} = \begin{cases} CW_{min}+1 \ , \ i = 0 \\ 2^i W_{0v} \ , \ i \in [1, m') \\ CW_{max}+1 \ , \ i \in [m', m] \end{cases} \tag{4}$$

Where m' is the maximum backoff stage for the AC_v, and m is the retry limit.

Hence, let $b_{i,j,k}$ stands for the stationary distribution of the 3-D Markov chain above. The $b_{i,j,k}$ satisfies the following normalization condition with $i \in [0,m], j \in [0, W_{iv}-1], k \in [0, d_v]$:

$$1 = \sum_{i=0}^{m} \sum_{j=0}^{W_{iv}-1} b_{i,j,0} + \sum_{i=0}^{m} \sum_{j=0}^{W_{iv}-1} \sum_{k=1}^{d_v} b_{i,j,k} \tag{5}$$

Now, we can derive the expression of the initial state $b_{0,0,0}$ by solving this 3-D Markov process:

$$b_{0,0,0} = \left\{ \frac{(1-p_{tv}^{d_v})}{(1-p_{tv})p_{tv}^{d_v}} [(1-p_{bv}) \sum_{i=0}^{m} \frac{W_{iv}-1}{2p_{bv}} (p_v p_e)^i + \sum_{i=0}^{m} \frac{(p_v p_e)^i}{W_{iv}}] + \sum_{i=0}^{m} \frac{W_{iv}-1}{2p_{bv}} (p_v p_e)^i + \frac{1-(p_v p_e)^{m+1}}{1-p_v p_e} \right\}^{-1} \tag{6}$$

let τ_v' denotes the transmission probability of AC$_v$ when there are at least one frame is waiting in the queue. Then, τ_v' can be derived as follow:

$$\tau_v' = \sum_{i=0}^{m} b_{i,0,0} = b_{0,0,0} \sum_{i=0}^{m} (p_v p_e)^i = \frac{1-(p_v p_e)^{m+1}}{1-p_v p_e} b_{0,0,0} \tag{7}$$

Therefore, the transmission probability of AC_v under the unsaturated traffic condition, τ_v, can be derived as follow:

$$\tau_v = \tau_v'(1 - p_{0v}) \tag{8}$$

Where p_{0v} denotes the probability of the transmission queue is empty, which will be derived in the section of queuing model.

The collision probability of AC_v, p_v, can be calculated as follow:

$$p_v = 1 - \prod_{a=0}^{A} (1-\tau_a)^{n-1} \prod_{a>v}^{A} (1-\tau_a) \tag{9}$$

Where A is the number of the AC queues, and n is the number of vehicles.

If the channel is sensed idle for a time slot during the AIFS period of the AC$_v$, it means that all of other ACs with higher priority are not transmitting in the current time slot. Hence, let p_{bv} to be this probability, and p_{tv} can be calculated as follow:

$$p_{tv} = \prod_{A>v} (1-\tau_x)^n \tag{10}$$

If the channel is sensed idle for a time slot after the AIFS period of the AC$_v$, it means that all of other ACs are not transmitting in the current time slot. Hence, let p_{bv} represent this probability, and p_{bv} can be calculated as follow:

$$p_{bv} = (1-\tau_v)^{n-1} \prod_{a \neq v} (1-\tau_a)^n \tag{11}$$

B. Analysis of the service time

In this section, we analyze the mean service time of each frame. Transmission time and channel access time combine the service time. The transmission time means the time duration of transmitting the frame. Its value has two possibilities: the packet is delivered, or the transmission failed due to an internal collision. Hence, let T_v^{tr} represent for the first case, and T_v^{col} for the second. We have:

$$\begin{cases} T_v^{tr} = AIFS_v + T_{header} + T_{SIFS} + T_{ACK} + T_L \\ T_v^{col} = AIFS_v + T_{header} + T_{SIFS} + T_{ACK} \end{cases} \tag{12}$$

Where T_{header}, T_{ACK} and T_L represent the time duration of transmitting the header, ACK and payload, respectively, and the T_{SIFS} and $AIFS_v$ denote for the time duration of SIFS and AIFS deferring of AC_v.

Then, the expression of the mean duration of a time slot, $\overline{\sigma}_v$, is given as follow:

$$\overline{\sigma}_v = \alpha_v T_v^A + (1-\alpha_v)\sigma + \sum_{a=0}^{A} \beta_a T_a^{tr} + (\alpha_v - \sum_{a=0}^{A} \beta_a) T_v^{col} \tag{13}$$

Where T_v^A is the time spent on the AIFS deferring period of AC_v, and σ is the duration of a physical time slot defined in the 802.11p protocol [6]. Meanwhile, α_v represents the probability that the channel is occupied by another AC_a during AC_v in the CW backoff procedure. Also, β_a denotes the probability that transmission of this AC_a experienced a successful transmission. The value of α_v and β_a are given by:

$$\begin{cases} \alpha_v = 1 - p_{bv} \\ \beta_a = n\tau_a (1-\tau_v)^{(n-2)} \prod_{b \neq v} (1-\tau_b)^{n-1} \prod_{b>x}^{A} (1-\tau_b) \end{cases} \tag{14}$$

Similarly, let $\overline{\alpha}_v$ represent the probability that the channel is occupied by another AC_a during AC_v in the AIFS deferring procedure. And $\overline{\beta}_a$ denotes the probability that transmission of this AC_a experienced a successful transmission. The value of $\overline{\alpha}_v$ and $\overline{\beta}_a$ are given by:

$$\begin{cases} \overline{\alpha}_v = 1 - p_{tv} \\ \overline{\beta}_a = n\tau_a \prod_{b>v} (1-\tau_b)^{(n-1)} \prod_{b>max\{a,v\}}^{A} (1-\tau_b) \end{cases} \tag{15}$$

Then, let T_v^a stands for the time cost for each attempt of AC_v to proceed to the CW backoff procedure while AC_v is in the AIFS deferring procedure. Hence, T_v^a can be calculated as follow:

$$T_v^a = \sum_{a>v}^{A} \overline{\beta}_a T_a^{tr} + (\overline{\beta}_a - \sum_{a>v}^{A} \overline{\beta}_a) T_v^c + \sigma \sum_{x=1}^{d_v - 1} x p_{tv}^x \tag{16}$$

Therefore, from the Markov chain showing in Fig. 2, T_v^A can be derived as follow:

$$T_v^A = \sum_{z=1}^{\infty} p_{tv}^{d_v} (1 - p_{tv}^{d_v})^{z-1} z T_v^a \tag{17}$$

Where z is the number of attempts.

Note that (17) can be solved by the summation of the series formula. Therefore, the mean duration of a time slot can be calculated by (12)-(17).

Turn to the analysis of the mean channel access time. Similar to the transmission time, the channel access time also has two possibilities: the packet is transmitted successfully or discarded due to the retry limit reached. Let $\overline{D}_v^a$ represent for the mean value for the first case, and $\overline{D}_v^b$ for the second. Therefore, the expressions of $\overline{D}_v^a$ is given as follow:

$$\overline{D}_v^a = \left[(1-p_e)T_v^{col} + p_e T_v^{tr}\right] \sum_{i=0}^{m} \frac{i(p_v p_e)^i (1 - p_v p_e)}{1 - (p_v p_e)^{m+1}} + \overline{\sigma}_v \sum_{i=0}^{m} \sum_{j=0}^{i} \frac{(W_{jv} - 1)(p_v p_e)^i (1 - p_v p_e)}{2\left[1 - (p_v p_e)^{m+1}\right]} \tag{18}$$

Similarly, the the expressions of $\overline{D}_v^b$ is given as follow:

$$\overline{D}_v^b = (m+1)\left[(1-p_e)T_v^{col} + p_e T_v^{tr}\right] + \overline{\sigma}_v \sum_{i=0}^{m} \frac{W_{jv} - 1}{2} \tag{19}$$

Finally, the mean service time can be calculated by summing up the transmission time and the mean channel access time. Hence, let D_v^s denotes the mean service time of a frame is transmitted successfully, and D_v^f stands for the mean service time of a frame is discarded due to the retry limit reached. Therefore, D_v^s and D_v^f can be calculated as follow:

$$\begin{cases} D_v^s = \overline{D}_v^a + T_v^{tr} \\ D_v^f = \overline{D}_v^b \end{cases} \tag{20}$$

C. Queuing analysis and throughput calculation

In this section, we discuss the calculation of the throughput based on the queuing model. Since the traffic of packet arriving follows Poisson Distribution, the queue of AC_v can be modelled as an $M/G/1/k$ queuing system, where k is equal to the MAC buffer size and the arrival rate is equal to λ_v. Similar to the mean service time, the mean service rate μ_v is composed of two components: the service rate of the packet is transmitted successfully, μ_{sv}; and the service rate of the packet is discarded due to the retry limit reached, μ_{fv}. From (20), μ_{sv} and μ_{fv} are given as follow:

$$\begin{cases} \mu_{sv} = \frac{1}{D_v^s} \\ \mu_{fv} = \frac{1}{D_v^f} \end{cases} \tag{21}$$

Therefore, μ_v can be calculated as follow:

$$\mu_v = \mu_{fv}(p_v p_e)^{m+1} + \mu_{sv}[1 - (p_v p_e)^{m+1}] \tag{22}$$

Therefore, the probability that no frame is waiting in the queue, p_{0v}, and the probability that a frame is discarded due to the finite buffer being full, p_{kv}, can be calculated easily by the queuing system theories.

Note that from (1) to (22), all variables can be expressed by τ_v and p_v with constants. Furthermore, the relationships between τ_v and p_v are shown in (8) and (9). Thus, the value of τ_v and p_v can be solved by a numerical method. Finally, the throughput of AC_v, S_v, can be calculated as follow:

$$S_v = \lambda_v L(1 - p_{kv})[1 - (p_v p_e)^{m+1}] \tag{23}$$

Where L is the size of the payload.

IV. Model validation

In this section, the effectiveness and precision of our analytical model are verified by a series of simulation results. The simulation experiments are designed with the simulation tool ns-3 (ns-3 3.30). We consider an urban environment with 10 OBUs (vehicles) running in a 300m × 300m rectangular grid map. Each vehicle is moving around with a constant velocity 10 m/s following the Random Way Point model. One RSU is at the centre of this map. All vehicles install four AC queues and transmit packets to the RSU. The transmission power is set strong enough to cover all of the map. The packet arrival rates of four ACs are equal and follow a Poisson Process with a mean value λ_v. Other parameters follow the definition in the IEEE 802.11p protocol [6] and showing in Table I.

TABLE I
SYSTEM PARAMETERS

Modulation	OFDM	Vehicles	10
Frame payload	500Bytes	PHY header	192bits
MAC header	224bits	ACK	304bits
Slot time	13μs	Retry limit	7
SIFS	32μs	Buffer size	50 frames
Data rate	6Mbit/s	$AIFS_{(0,1,2,3)}$	9,6,3,2
$CW_{min(0,1,2,3)}$	15,15,7,3	$CW_{max(0,1,2,3)}$	1023,1023,15,7

Fig. 3 demonstrates the results of the throughput versus the offered loads per AC under a perfect channel condition. It is clear that the results of the proposed analytical model closely match the results obtained from the simulation experiments. In addition, due to the dramatic changes of the throughput during the transition period, the differences between the results of the proposed analytical model and the results of simulation experiments are noteworthy.

Fig. 4 demonstrates the results of the throughput versus the offered loads per AC under an error-prone channel with $BER = 10^{-5}$. Similarly, the proposed analytical model results are also very close to the results obtained from the simulation experiments. Moreover, errors in the transition period of each AC are also showing a similar tendency.

Fig. 5 demonstrates the results of the throughput versus the offered loads per AC via under error-prone channel with $BER = 10^{-4}$. In this case, the channel error significantly decreased the throughput. Again, the proposed analytical model precisely predicts the throughput of this case.

Fig. 6 shows the impact of bit errors on the throughput. In this case, the packet arrival rate is set to 1Mbps. We can see that while the growth of BER, the throughput drops sharply. It means that an imperfect channel with channel fading and modulation errors can result in significant influences on the

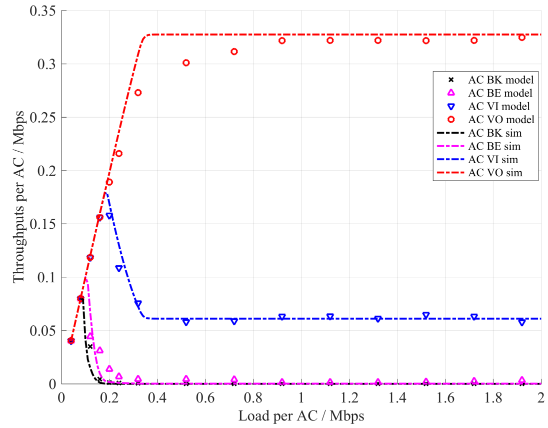

Fig. 3. Throughput vs. load per AC under an error free channel.

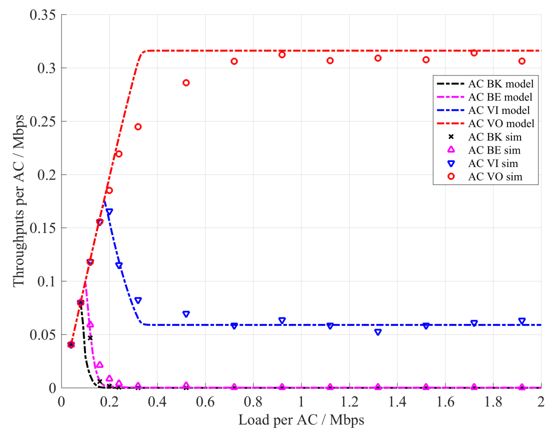

Fig. 4. Throughput vs. load per AC under an error-prone channel with $BER = 10^{-5}$.

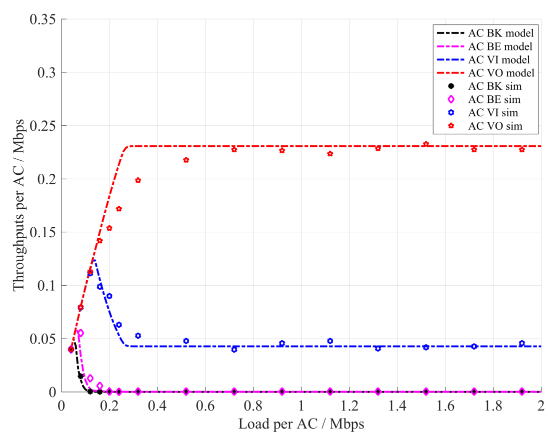

Fig. 5. Throughput vs. load per AC under an error-prone channel with $BER = 10^{-4}$.

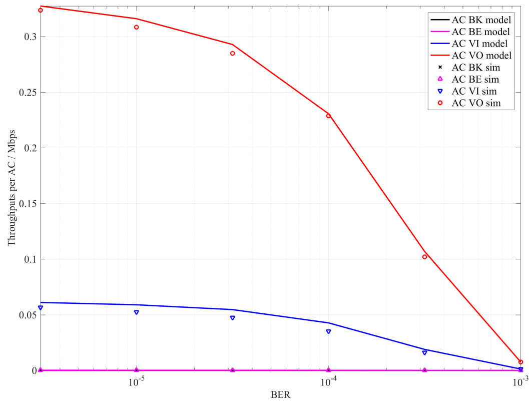

Fig. 6. Throughput vs. Bit Error Rates.

performance of the networks. This is especially important in a vehicular environment due to the high mobility of vehicles and the Doppler spread.

Overall, the results obtained from the simulation experiments through the ns-3 prove the correctness and effectiveness of our model. Meanwhile, the results generated from both the model and the simulation experiments suggest the powerful influences of channel errors on the performance of IEEE 802.11p.

V. Conclusion

In this paper, we proposed a new analytical model based on a 3-D Markov chain and Queuing analysis for IEEE 802.11p EDCA mechanism in Inter-Vehicle communication networks under imperfect channels. This analytical model combined the CW backoff and AIFS deferring procedures within one model. Specially, all of the major factors, including the backoff counter freezing, AIFS defers, and internal collision, have been taken into account under various channel conditions with both saturated and unsaturated traffic. The effectiveness and accuracy of the proposed model have been validated through the ns-3 simulation experiments. In addition, the combined results of the proposed model and the simulation experiments demonstrated the significant impact on the performance due to channel errors.

References

[1] G. S. Khekare and A. V. Sakhare, ”A smart city framework for intelligent traffic system using VANET,” 2013 International Mutli-Conference on Automation, Computing, Communication, Control and Compressed Sensing (iMac4s), 2013, pp. 302-305.

[2] A. Sumalee, H. Ho, Smarter and more connected: Future intelligent transportation system, IATSS Research, Volume 42, Issue 2, 2018, pp. 67-71.

[3] O. Renaudin, V. Kolmonen, P. Vainikainen and C. Oestges, ”Wideband Measurement-Based Modeling of Inter-Vehicle Channels in the 5-GHz Band,” in IEEE Transactions on Vehicular Technology, vol. 62, no. 8, pp. 3531-3540, Oct. 2013.

[4] X. Li, B. Hu, H. Chen, G. Andrieux, Y. Wang and Z. Wei, ”An RSU-Coordinated Synchronous Multi-Channel MAC Scheme for Vehicular Ad Hoc Networks,” in IEEE Access, vol. 3, pp. 2794-2802, 2015.

[5] C. Han, M. Dianati, R. Tafazolli, R. Kernchen and X. Shen, ”Analytical Study of the IEEE 802.11p MAC Sublayer in Vehicular Networks,” in IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 2, pp. 873-886, June 2012.

[6] ”IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments,” in IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009), 15 July 2010 pp.1-51.

[7] F. Zeng, C. Li and H. Wang, ”Performance Evaluation of Different Fading Channels in Vehicular Ad Hoc Networks,” 2018 International Conference on Information and Communication Technology Convergence (ICTC), 2018, pp. 356-361.

[8] J. Hu, G. Min, W. Jia, and M. E. Woodward. Comprehensive QoS analysis of enhanced distributed channel access in wireless local area networks, Information Sciences, 214, 2012, 20–34.

[9] J. R. Gallardo, D. Makrakis and H. T. Mouftah, ”Performance Analysis of the EDCA Medium Access Mechanism over the Control Channel of an IEEE 802.11p WAVE Vehicular Network,” 2009 IEEE International Conference on Communications, 2009, pp. 1-6.

[10] Y. Kim, Y. H. Bae, D. Eom and B. D. Choi, ”Performance Analysis of a MAC Protocol Consisting of EDCA on the CCH and a Reservation on the SCHs for the IEEE 802.11p/1609.4 WAVE,” in IEEE Transactions on Vehicular Technology, vol. 66, no. 6, pp. 5160-5175, June 2017.

[11] J. Zheng and Q. Wu, ”Performance Modeling and Analysis of the IEEE 802.11p EDCA Mechanism for VANET,” in IEEE Transactions on Vehicular Technology, vol. 65, no. 4, pp. 2673-2687, April 2016.

[12] S. Cao, V. C. S. Lee, An accurate and complete performance modeling of the IEEE 802.11p MAC sublayer for VANET, Computer Communications, vol. 149, 2020, pp. 107-120.

[13] M. A. Togou, L. Khoukhi and A. S. Hafid, ”Throughput analysis of the IEEE802.11p EDCA considering transmission opportunity for non-safety applications,” 2016 IEEE International Conference on Communications (ICC), 2016, pp. 1-6.

[14] C. Song, Performance Analysis of the IEEE 802.11p Multichannel MAC Protocol in Vehicular Ad Hoc Networks. Sensors 2017, 17, pp. 2890.

[15] A. A. Almohammedi, N. K. Noordin, A. Sali, F. Hashim and M. Balfaqih, ”An Adaptive Multi-Channel Assignment and Coordination Scheme for IEEE 802.11P/1609.4 in Vehicular Ad-Hoc Networks,” in IEEE Access, vol. 6, pp. 2781-2802, 2018

[16] Y. Harkat, A. Amrouche, E. Lamini, M. Kechadi, Modeling and performance analysis of the IEEE 802.11p EDCA mechanism for VANET under saturation traffic conditions and error-prone channel, AEU - International Journal of Electronics and Communications, Volume 101, 2019, pp 33-43.

[17] ns-3 Network Simulator. Available online: https://www.nsnam.org/ (accessed on 6 June 2021).