Performance Analysis of IEEE 802.11p MAC Protocol in Vehicular Ad hoc Networks

Duc Ngoc Minh Dang, Sungwon Lee and Choong Seon Hong*
Department of Computer Engineering, Kyung Hee University
dnmduc@khu.ac.kr, drsungwon@khu.ac.kr, cshong@khu.ac.kr

Abstract

Vehicular Ad hoc Network (VANET) is developed to enhance the safety, comfort and efficiency of driving. IEEE 802.11p/WAVE [1] is a standard intended to support wireless access in VANETs. In this paper, we propose an analytical model to evaluate the performance for safety and non-safety applications under saturation condition.

Key word: IEEE 802.11p, MAC protocol, Vehicular Ad hoc networks.

1. Introduction

The main goal of the Intelligent Transportation System (ITS) is to improve the quality, effectiveness and safety of the future transportation systems. VANET is developed as a part of ITS with 2 types of communications: Vehicle-to-vehicle (V2V) and Vehicle-to-Infrastructure (V2I). The applications of VANETs fall into two categories, namely safety applications and non-safety applications. Safety applications, providing drivers information about critical situation in advance, have strict requirements on communication reliability and delay. On the other hand, non-safety applications are used for improving driving comfort and the efficiency of transportation system which are more throughput-sensitive.

The IEEE 802.11p uses an Enhanced Distributed Channel Access (EDCA) MAC sublayer based on IEEE 802.11e. The performance of IEEE 802.11e EDCA has been analyzed in [2, 3] under saturation condition. In the literature, there are some studies about the performance of VANET [4-6]. The authors in [4, 5] studied only about the broadcasting in VANETs while Han *et al.* [6] analyzed the IEEE 802.11p with 4 different access categories. In this paper, we consider 2 types of traffic: emergency traffic with high priority and service traffic with low priority. The 2-D Markov chain is used to model the back-off procedure for each traffic type.

Fig. 1 Emergency and service transmission.

2. Analytical Model

In our analytical model, we consider the emergency and service applications as shown in Fig. 1. The service provider broadcast WSA message, node replies with RES (Reserve). Then the Service Data is transmitted. There are *N* vehicle nodes in the network; each node always has both emergency and service messages to transmit. The vehicle node will not send an acknowledgement for the received emergency messages. The sender could not detect the failure of the emergency transmission and hence there is no retransmission.

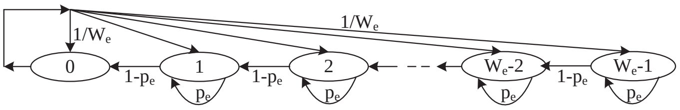

Fig. 2: Markov Chain of emergency traffic.

Let $b_e(t)$ be the random process representing the back-off counter value at slot time t; p_e be the collision probability. The state transition diagram is shown in Fig. 2. The non-null transition probabilities are given as

$$\begin{cases} P\{k\,|\,0\} = 1/W_e, \text{for } 0 \le k \le W_e - 1 \\ P\{k\,|\,k\} = p_e, \text{for } 1 \le k \le W_e - 1 \\ P\{k\,|\,k+1\} = 1 - p_e, \text{for } 0 \le k \le W_e - 2 \end{cases} \quad (1)$$

Let $b_{e,k} = \lim_{t\to\infty} P\{b_e(t) = k\}, \text{for } 0 \le k \le W_e - 1$ be the stationary distribution of the Markov chain, where W_e is the contention window of emergency traffic. From the Markov chain, we can obtain

$$b_{e,k} = \frac{W_e - k}{W_e}\frac{1}{1 - p_e} b_{e,0}, 1 \le k \le W_e - 1 \quad (2)$$

Using Eq. 2 and normalization condition $1 = \sum_{k=0}^{W_e - 1} b_{e,k}$,

we have $b_{e,0} = 2(1 - p_e)(1 - 2p_e + W_e)^{-1}$ (3)

Let τ_e be the probability that a node transmits an emergency message in a time slot

$$\tau_e = b_{e,0} = \frac{2(1-p_e)}{1-2p_e+W_e} \tag{4}$$

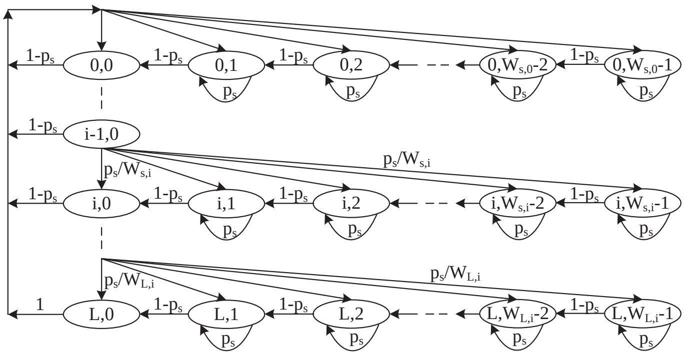

Fig. 3: Markov Chain of service traffic.

Let $b_s(t)$ and $s_s(t)$ be the stochastic process representing the back-off counter and back-off stage for the service data at slot time t, respectively. Let L be the retry limit, the maximum number of trials before the packet is dropped and $W_{s,i}=2^iW_{s,0}$ be the contention window (CW) of i^{th} back-off stage, where $i\in[0,L]$. We assume the collision probability p_s is constant and independent. So, we can model the bi-dimensional process $\{s_s(t),b_s(t)\}$ with the discrete-time Markov chain, as shown in Fig. 3. The only non-null one-step transition probabilities are

$$\begin{cases} P\{0,k\,|\,i,0\} = (1-p_s)/W_{s,0}, k\in[0,W_{s,0}-1], i\in[0,L-1], \\ P\{0,k\,|\,L,0\} = 1/W_{s,0}, k\in[0,W_{s,0}-1], \\ P\{i,k\,|\,i-1,0\} = p_s/W_{s,i}, k\in[0,W_{s,0}-1], i\in[1,L-1], \\ P\{i,k\,|\,i,k+1\} = 1-p_s, k\in[0,W_{s,0}-2], i\in[0,L], \quad (5) \\ P\{i,k\,|\,i,k\} = p_s, k\in[1,W_{s,0}-1], i\in[0,L], \end{cases}$$

Let $b_{s,i,k} = \lim_{t\to\infty} P\{s_s(t)=i, b_s(t)=k\}$ be the stationary distribution of the Markov chain. Since the chain is regularity, for each $k\in[1,W_{s,i-1}]$, we have

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}}\frac{1}{1-p_s}b_{s,i,0}, 0\le i\le L, 1\le k\le W_i-1 \tag{6}$$

From Eq. 6 and the normalization condition $1=\sum_{i=0}^{L}\sum_{k=0}^{W_{s,i}-1} b_{s,i,k}$, $b_{s,0,0}$ is determined as follows

$$b_{s,0,0} = \left(\sum_{i=0}^{L} p_s^i\left(1+\frac{1}{1-p_s}\frac{W_{s,i}-1}{2}\right)\right)^{-1} \tag{7}$$

As a packet is transmitted when the back-off counter is zero, regardless of the back-off stage, the probability τ_s that node transmits in a time slot

$$\begin{aligned}\tau_s &= \sum_{i=0}^{L} b_{s,i,0} \\ &= \frac{2(1-p_s^{L+1})(1-p_s)(1-2p_s)}{(1-2p_s)^2(1-p_s^{L+1})+W_{s,0}(1-(2p_s)^{L+1})(1-p_s)} \end{aligned} \tag{8}$$

A transmitted frame collides when one more node also transmits during a slot time. The collision probabilities p_e, p_s are given as

$$\begin{aligned} p_e &= 1-(1-\tau_e)^{N-1}(1-\tau_s)^N \\ p_s &= 1-(1-\tau_e)^N(1-\tau_s)^{N-1} \end{aligned} \tag{9}$$

From Eqs. 4, 8 and 9, we can solve the unknowns τ_e, τ_s. The probability P_b that the channel is busy

$$P_b = 1-(1-\tau_e)^N(1-\tau_s)^N \tag{10}$$

The probabilities of successful transmission for emergency and service traffic are

$$\begin{cases} P_{e,suc} = N\tau_e(1-\tau_e)^{N-1}(1-\tau_s)^N \\ P_{s,suc} = N\tau_s(1-\tau_e)^N(1-\tau_s)^{N-1} \end{cases} \tag{11}$$

The packet delivery rate (PDR) of the emergency traffic can be calculated as

$$PDR_e = \frac{P_{e,suc}}{N_e\tau_e} = (1-\tau_e)^{N-1}(1-\tau_s)^N \tag{12}$$

Let σ, $T_{e,suc}$, $T_{s,suc}$, $T_{e,col}$ and $T_{s,col}$ be the duration of slot time, the average time the channel is sensed busy because of the successful transmission of emergency and service traffic, the average time the channel is sensed busy during the collision caused by the emergency and service traffic, respectively. The collision transmission may from only emergency traffic; only service traffic or both with the probability

$$\begin{cases} P_{e,col} = (1-\tau_s)^N\left(1-(1-\tau_e)^N - N\tau_e(1-\tau_e)^{N-1}\right) \\ P_{s,col} = (1-\tau_e)^N\left(1-(1-\tau_s)^N - N\tau_s(1-\tau_s)^{N-1}\right) \quad (13) \\ P_{es,col} = P_b - P_{e,suc} - P_{s,suc} - P_{e,col} - P_{s,col} \end{cases}$$

Let X_e be the random variable representing the total number of back-off slots without the taking into account the case the counter freezes, and F_e be the random variable representing the total number of slots when the counter freezes

$$E[X_e] = \frac{W_e-1}{2} \qquad E[F_e] = \frac{E[X_e]}{(1-p_e)}p_e \tag{14}$$

$$S_s = \frac{P_{s,suc}E[P_s]}{(1-P_b)\sigma + P_{e,suc}T_{e,suc} + P_{s,suc}T_{s,suc} + P_{e,col}T_{e,col} + P_{s,col}T_{s,col} + P_{es,col}\max(T_{e,col}, T_{s,col})} \qquad (15)$$

$$\begin{cases} T_{e,suc} = T_{e,col} = H + E[P_e] + DIFS + \delta; \qquad T_{s,col} = WSA + DIFS + \delta \\ T_{s,suc} = WSA + SIFS + \delta + RES + SIFS + \delta + H + E[P_s] + SIFS + \delta + ACK + DIFS + \delta \end{cases}$$

$$E[D_e] = E[X_e]\cdot\sigma + E[F_e](P_{e,suc}T_{e,suc} + P_{s,suc}T_{s,suc} + P_{e,col}T_{e,col} + P_{s,col}T_{s,col} + P_{es,col}\max(T_{e,col}, T_{s,col})) + T_{e,suc} \qquad (16)$$

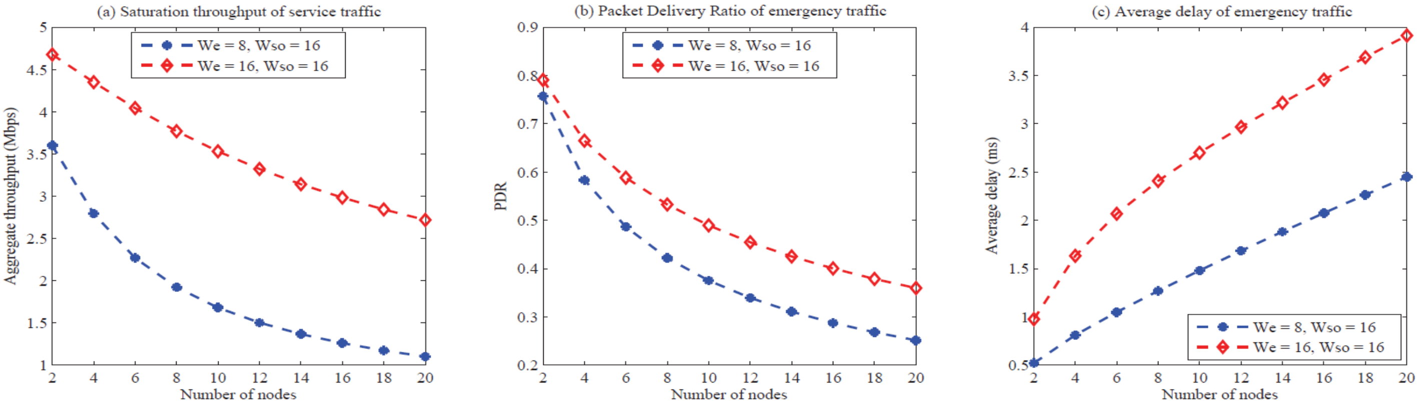

Fig. 4: Performance analysis

Let D_e denote the random variable representing the packet delay. The saturation throughput of the service traffic and the average delay for emergency packet without the queuing delay are given in Eqs. 15 and 16.

3. Numerical results

Fig. 4 shows the performance of the IEEE 802.11p based MAC for VANET under saturation condition. When the number of vehicle nodes increases, the network performance decreases. The saturation throughput of the service traffic when varying the number of vehicle nodes is shown in Fig. 4(a). When the contention window of emergency increases, the collision probability will decrease, the service traffic has more chance to access the channel. It leads to higher throughput when the contention window of emergency is higher. Since the collision probability decreases, the packet delivery ratio of emergency traffic will increase as shown in Fig. 4(b). However, when the service traffic has more chance to access the channel, the average delay of emergency traffic increases as shown in Fig. 4(c). It is because the duration of successful service data transmission is too long compared to the duration of the emergency data transmission.

4. Conclusions

In this paper, we proposed an analytical model to evaluate the performance of the IEEE 802.11p based MAC for VANET using the 2-D Markov chain. The numerical results show how the number of nodes and the contention window size affect the network performance.

4. Acknowledgement

"This research was funded by the MSIP (Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2013". *Dr. CS Hong is the corresponding author.

5. Reference

[1] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 6: Wireless Access in Vehicular Environments, 2010.

[2] H. Wu, A. Wang, Q. Zhang, and X. Shen, *"IEEE 802.11e enhanced distributed channel access (EDCA) throughput analysis,"* IEEE International Conference on Communications (ICC), 2006, pp. 223–228.

[3] Y. Xiao, *"Performance analysis of priority schemes for ieee 802.11 and ieee 802.11e wireless lans,"* IEEE Transactions on Wireless Communications, vol. 4, no. 4, pp. 1506–1515, 2005.

[4] K. Hafeez, L. Zhao, Z. Liao, and B. Ma, *"Performance analysis of broadcast messages in vanets safety applications,"* IEEE Global Telecommunications Conference, 2010, pp. 1–5.

[5] C. Campolo, A. Vinel, A. Molinaro, and Y. Koucheryavy, *"Modeling broadcasting in ieee 802.11 p/wave vehicular networks,"* Communications Letters, IEEE, vol. 15, no. 2, pp. 199–201, 2011.

[6] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, *"Analytical study of the ieee 802.11p mac sublayer in vehicular networks,"* IEEE Transactions on Intelligent Transportation Systems, vol. 13, no. 2, pp. 873–886, 2012.