Performance Analysis of the IEEE 802.11p under Finite Traffic Conditions

Duc Ngoc Minh Dang[1], Hanh Ngoc Dang[2], The Cuong Do[1], and Choong Seon Hong[1]

[1] Department of Computer Engineering, Kyung Hee University,
1732 Deokyoungdaero, Giheung-gu, Yongin-si, Gyeonggi-do, 446-701, Korea
{dnmduc,dtcuong,cshong}@khu.ac.kr
[2] Department of Telecommunications Engineering,
Ho Chi Minh City University of Technology,
268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam
hanhdn@hcmut.edu.vn

Abstract. Vehicular Ad hoc Network (VANET) is developed for more driving efficicency, comfort and safety. The IEEE 802.11p/WAVE is a standard intended to support wireless access in VANETs. In this paper, we propose an analytical model to evaluate the performance of the IEEE 802.11p based MAC for VANETs under non-saturation condition through the packet delivery ratio, the average delay of emergency message and the throughput of service message. The 2-D Markov model is used to model two access categories in the IEEE 802.11p. The analytical model is validated by the extensive simulation, and it shows the impact of different parameters on the performance of network.

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 an important part of the ITS with two types of communication: 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 the 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 instead of delay-sensitive. Safety messages have higher priority than non-safety messages. The IEEE 802.11p [1] and the IEEE 1609 standard family are standard for VANETs. Some recent studies [2–5] try to improve the performance of VANETs.

The performance analysis of the IEEE 802.11 Distributed Coordination Function (DCF) is presented by Bianchi [6]. The Bianchi's model employs 2-D Markov chain analysis to compute the saturation throughput under ideal channel conditions. The delay analysis of the IEEE 802.11 protocol is studied in [7]. By taking account of the busy medium conditions, Ziouva *et al.* present a more analytical study of throughput and delay of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [8]. Different from above models, the non-saturation condition is considered

I. Zelinka et al. (eds.), *AETA 2013: Recent Advances in Electrical Engineering and Related Sciences*, Lecture Notes in Electrical Engineering 282,
DOI: 10.1007/978-3-642-41968-3_20,

in [9]. The delay in idle state is geometric with parameter λ, which has no relationship with the load on the system. In [10], Malone *et al.* model the IEEE 802.11 DCF under non-saturated heterogeneous conditions with the post-backoff consideration. The relationship between the offered load and the model parameters is also presented in this study. For the broadcast analysis, Ma *et al.* evaluate the saturation performance of broadcast service in the IEEE 802.11 in [11].

To support MAC-level QoS, the IEEE 802.11e is proposed with the Hybrid Coordination Function (HCF). It combines the contention based Enhanced Distributed Channel Access (EDCA) and the contention-free HCF Controlled Channel Access (HCCA). The EDCA provides a priority scheme by differentiating the inter-frame space (IFS), the initial window size and the maximum window size. Yang analyzed the priority scheme with differentiating the minimum backoff window size, the backoff window-increasing factor and the retransmission limit in [12]. In [13], Wu *et al.* studied about the throughput analysis of the IEEE 802.11p EDCA by taking into account different Contention Window (CW), Arbitration Inter-frame Space (AIFS) values for each Access Categories (AC) and the internal collision.

The IEEE 802.11p uses an Enhanced Distributed Channel Access (EDCA) MAC sublayer based on the IEEE 802.11e. In the literature, there are some studies about the performance of VANET [14–16]. Broadcasting is one of the essential communication techniques in ad hoc network. The broadcast reliability is important in VANETs. While in [14, 15], the authors studied only about the broadcasting in VANETs, Han *et al.* [16] analyzed the IEEE 802.11p with four different Access Categories. In this paper, we consider two 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. The probabilities of transmitting an emergency and service messages are derived. The packet delivery ratio (PDR), the average delay of emergency message and the throughput of service message are also derived to evaluate the performance of the IEEE 802.11p.

2 Analytical Model

In our analytical model, we consider the emergency and service applications as shown in Fig. 1. There are N vehicle nodes in the network, the packet arrival rate of emergency and service traffics at each node are λ_e and λ_s, respectively. Since the emergency messages are sent by broadcast mechanism, the vehicle node will not send any acknowledgement for the received emergency messages. The sender could not detect the failure of the emergency transmission and hence there is no retransmission.

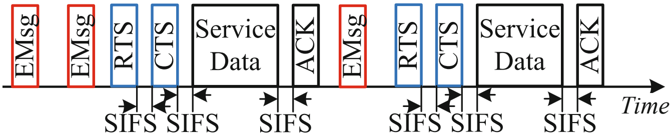

Fig. 1. Emergency and service transmissions

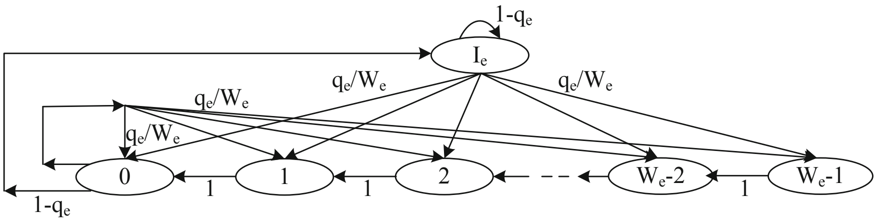

Fig. 2. Markov chain of the emergency traffic

Let $b_e(t)$ be the random process representing the back-off counter value at slot time t; p_e be the collision probability and q_e be the probability of at least one emergency message waiting for transmitting in the buffer. The state transition diagram is shown in Fig.2. The non-null transition probabilities are

$$\begin{cases} P\{I_e|I_e\} = 1 - q_e \\ P\{I_e|0\} = 1 - q_e \\ P\{k|I_e\} = q_e/W_e, \text{for } 0 \le k \le W_e - 1 \\ P\{k|0\} = q_e/W_e, \ \text{for } 0 \le k \le W_e - 1 \\ P\{k|k+1\} = 1, \quad \text{for } 0 \le k \le W_e - 2. \end{cases} \tag{1}$$

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

$$(1 - q_e)b_{e,0} = q_e b_{I_e} \tag{2}$$

$$b_{e,k} = \frac{W_e - k}{W_e} b_{e,0}, \ 1 \le k \le W_e - 1 \tag{3}$$

Using Eq. 3 and normalization condition $1 = b_{I_e} + \sum_{k=0}^{W_e-1} b_{e,k}$, we have

$$b_{e,0} = \left[\frac{1-q_e}{q_e} + \frac{W_e+1}{2}\right]^{-1} \tag{4}$$

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

$$\tau_e = b_{e,0} = \left[\frac{1-q_e}{q_e} + \frac{W_e+1}{2}\right]^{-1} \tag{5}$$

Let $b_s(t)$ and $s_s(t)$ be the stochastic process representing the backoff counter and backoff 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 $W_{s,i} = 2^i W_{s,0}$ be the contention window (CW) of i^{th} backoff stage, where $i \in [0, L]$. We assume the collision probability p_s is constant and independent. Let q_s be the probability of at least one new

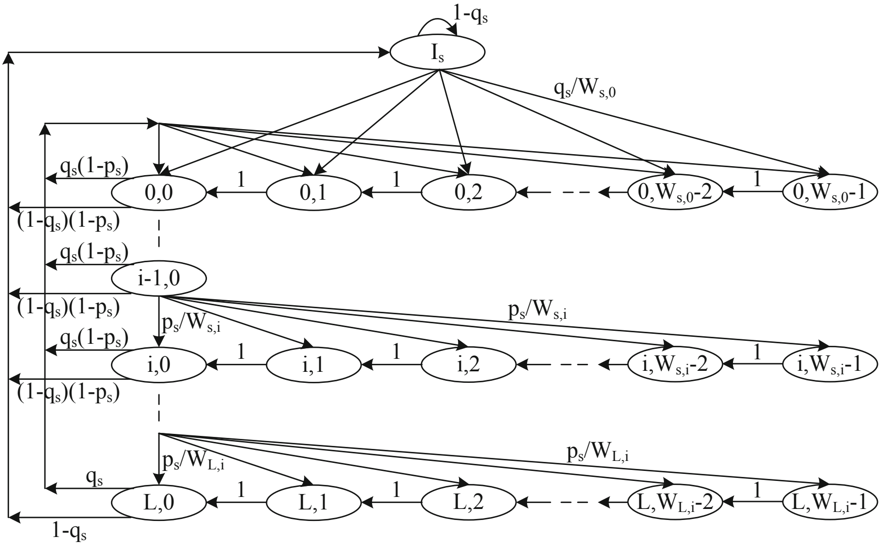

Fig. 3. Markov chain of the service traffic

service message in the buffer. So, we can model the bidimensional 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

$$\begin{cases} P\{I_s|I_s\} = 1-q_s, & \\ P\{I_s|i,0\} = (1-q_s)(1-p_s), & \text{for } 0 \le k \le W_{s,0}-1,\ 0 \le i \le L-1, \\ P\{I_s|L,0\} = 1-q_s, & \\ P\{0,k|I_s\} = q_s/W_{s,0}, & \text{for } 0 \le k \le W_{s,0}-1, \\ P\{0,k|i,0\} = q_s(1-p_s)/W_{s,0}, & \text{for } 0 \le k \le W_{s,0}-1,\ 0 \le i \le L-1, \\ P\{0,k|L,0\} = q_s/W_{s,0}, & \text{for } 0 \le k \le W_{s,0}-1, \\ P\{i,k|i-1,0\} = p_s/W_{s,i}, & \text{for } 0 \le k \le W_{s,i}-1,\ 1 \le i \le L, \\ P\{i,k|i,k+1\} = 1, & \text{for } 0 \le k \le W_{s,i}-2,\ 0 \le i \le L. \end{cases} \tag{6}$$

Let $b_{s,i,k} = \lim_{t\to\infty} P\{s_s(t) = i, b_s(t) = k\},\ 0 \le i \le L,\ 0 \le k \le W_{s,i}-1$ be the stationary distribution of the Markov chain. From the Markov chain, we can obtain

$$b_{s,i,0} = b_{s,i-1,0} \cdot p_s \rightarrow b_{s,i,0} = p_s^i \cdot b_{s,0,0},\ \text{for } 1 \le i \le L \tag{7}$$

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

Since the chain is regularity, for each $k \in (1, W_{s,i-1})$, we have

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}} b_{s,i,0},\ \ \text{for } 0 \le i \le L, 1 \le k \le W_i - 1 \tag{9}$$

All $b_{s,i,k}$ are expressed in terms of $b_{s,0,0}$ which is determined through the normalization condition $1 = b_{I_s} + \sum_{i=0}^{L} \sum_{k=0}^{W_{s,i}-1} b_{s,i,k}$ as follows

$$\begin{aligned} b_{s,0,0} &= \left[\frac{1-q_s}{q_s} + \sum_{i=0}^{L} p_s^i \left(\frac{W_{s,i}+1}{2} \right) \right]^{-1} \\ &= \left[\frac{1-q_s}{q_s} + \frac{1}{2} \left(\frac{1-p_s^{L+1}}{1-p_s} + \frac{1-(2p_s)^{L+1}}{1-2p_s} W_{s,0} \right) \right]^{-1} \end{aligned} \tag{10}$$

As a packet is transmitted when the backoff counter is zero, regardless of the backoff stage, the probability τ_s that node transmits in a time slot is given as

$$\begin{aligned} \tau_s &= \sum_{i=0}^{L} b_{s,i,0} = \frac{1-p_s^{L+1}}{1-p_s} b_{s,0,0} \\ &= \frac{1-p_s^{L+1}}{1-p_s} \left[\frac{1-q_s}{q_s} + \frac{1}{2} \left(\frac{1-p_s^{L+1}}{1-p_s} + \frac{1-(2p_s)^{L+1}}{1-2p_s} W_{s,0} \right) \right]^{-1} \end{aligned} \tag{11}$$

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

$$\begin{aligned} p_e &= 1-(1-\tau_e)^{N-1}(1-\tau_s)^{N} \\ p_s &= 1-(1-\tau_e)^{N}(1-\tau_s)^{N-1} \end{aligned} \tag{12}$$

From Eqs. 5, 11 and 12, we can solve the unknowns τ_e, τ_s. The probability P_b that the channel is busy is given by

$$P_b = 1-(1-\tau_e)^{N}(1-\tau_s)^{N} \tag{13}$$

The probabilities of successful transmission for emergency and service traffic are

$$\begin{cases} P_{e,suc} = N\tau_e(1-\tau_e)^{N-1}(1-\tau_s)^{N} \\ P_{s,suc} = N\tau_s(1-\tau_e)^{N}(1-\tau_s)^{N-1} \end{cases} \tag{14}$$

Let σ be the duration of slot time, $H = PHY_{hdr} + MAC_{hdr}$ be the packet header and δ be the propagation delay. Let $T_{e,suc}, T_{s,suc}, T_{e,col}$ and $T_{s,col}$ be 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

$$\begin{cases} T_{e,suc} = T_{e,col} = T_e = H + E[P_e] + DIFS + \delta \\ T_{s,suc} = RTS + SIFS + \delta + CTS + SIFS + \delta \\ \quad + H + E[P_s] + SIFS + \delta + ACK + DIFS + \delta \\ T_{s,col} = RTS + DIFS + \delta \end{cases} \tag{15}$$

The collision transmission may from only emergency traffic; only service traffic or both with the probability given as

$$\begin{cases} P_{e,col} = (1-\tau_s)^N \left(1-(1-\tau_e)^N - N\tau_e(1-\tau_e)^{N-1}\right) \\ P_{s,col} = (1-\tau_e)^N \left(1-(1-\tau_s)^N - N\tau_s(1-\tau_s)^{N-1}\right) \\ P_{es,col} = P_b - P_{e,suc} - P_{s,suc} - P_{e,col} - P_{s,col} \end{cases} \tag{16}$$

Each state may be a successful transmission, a collision or the medium being idle. The expect time spent per state E_S is given

$$\begin{aligned} E_S = {} & (1-P_b)\sigma + P_{e,suc}T_{e,suc} + P_{s,suc}T_{s,suc} + P_{e,col}T_{e,col} \\ & + P_{s,col}T_{s,col} + P_{es,col}\max(T_{e,col}, T_{s,col}) \end{aligned} \tag{17}$$

From the average time slot E_S, the probability q_e and q_s can be approximated as [10, 17]

$$\begin{aligned} q_e &= 1 - e^{-\lambda_e \cdot E_S} \\ q_s &= 1 - e^{-\lambda_s \cdot E_S} \end{aligned} \tag{18}$$

The packet delivery ratio (PDR) of the emergency traffic can be calculated as [11]

$$PDR_e = \frac{P_{e,suc}}{N_e \tau_e} = (1-\tau_e)^{N-1}(1-\tau_s)^N \tag{19}$$

It takes the average slot of $\frac{(W_e-1)}{2}$ for the back-off. The average time for an emergency message to finish back-off can be estimated by

$$\mu_e = E_E = \frac{(W_e-1)}{2} E_S \tag{20}$$

For simplicity, each node can be modeled as an M/M/1 queue with an infinitive buffer size. With the packet arrival rate λ_e and service rate μ_e, the average delay of the emergency traffic including the queueing delay and the transmission delay is

$$E[D_e] = \frac{\mu_e}{(1-\lambda_e \mu_e)} + T_e \tag{21}$$

The saturation throughput of the service traffic is calculated as

$$S_s = \frac{P_{s,suc} \cdot E[P_s]}{E_S} \tag{22}$$

3 Model Validation

To validate our model, we use the event-driven simulation program written in Matlab. Our program follows the IEEE 802.11 standard with the time resolution of microsecond. The parameters value used to obtain the numerical results for both the analytical model and simulation runs, are summarized in Table. 1. We fix the service packet arrival rate λ_s at 100 packets/second, and vary the emergency packet arrival rate λ_e and the number

Table 1. MAC parameters

Parameters	Value
Data rate	6 Mbps
RTS	20 bytes
CTS	14 bytes
Service data P_s	1000 bytes
ACK	14 bytes
Emergency data	100 bytes
Slot time σ	9 μs
SIFS	16 μs
DIFS	34 μs
Propagation time δ	1 μs
W_e	8
$W_{s,0}$	16
Retry limit L	6

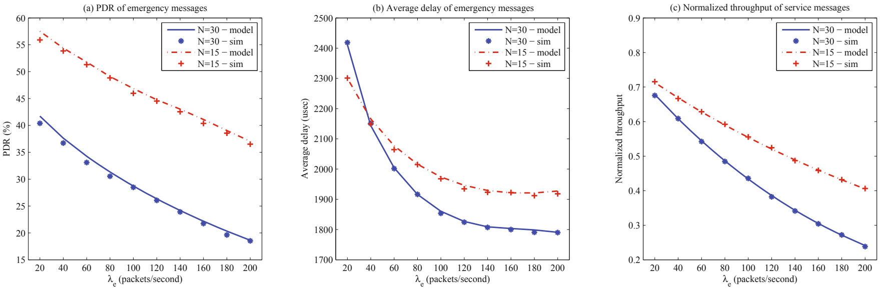

Fig. 4. Performance analysis of the IEEE 802.11p

of nodes N to evaluate the PDR and the average delay of the emergency messages and the throughput of service messages.

Fig. 4 shows the performance of the IEEE 802.11p based MAC for VANET with varying the packet arrival rate of emergency messages when the number of nodes is 15 nodes and 30 nodes. The analytical results (lines) closely match the simulation results (symbols). Obviously, when the number of nodes in the network increases, the collision probability increases and therefore, the performance of the network decreases. And as the packet arrival rate of emergency message increases, there are more nodes having emergency messages to send, thus the collision probability also increases. That is the reason why the PDR of the emergency messages and the normalized throughput of the service messages decrease (Fig. 4(a), Fig. 4(c) respectively).

Since the average delay of the emergency messages including queueing delay is considered for both the successful and failed broadcast. This delay is calculated from the time the emergency message arrived at a node until the time this emergency message is transmitted. The average delay is the total delay over the number of transmitted emergency messages. When the collision probability is low, the successful broadcast probability is high. In this case, an emergency message has to wait long time until it is transmitted, and the total delay increases. On the other hand, as the collision probability increases, there are more collided emergency messages and it makes the total delay decreased. So, the average delay of emergency messages decreased when the number of nodes increases and the packet arrival rate of emergency messages increases as given in Fig. 4(b).

4 Conclusion

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 packet arrival rate affect the network performance. According to the performance analysis, the IEEE 802.11p does not provide the emergency broadcast reliability and the high service throughput.

Acknowledgement. This research was supported by the MSIP (Ministry of Science, ICT & Future Planning), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency)" (NIPA-2013-(H0301-13-2001)). Dr. CS Hong is the corresponding author.

References

1. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments (July 2010)
2. Dang, D.N.M., Dang, H.N., Do, C.T., Hong, C.S.: An enhanced multi-channel mac for vehicular ad hoc networks. In: 2013 IEEE Wireless Communications and Networking Conference (WCNC), pp. 351–355 (2013)
3. Wang, Q., Leng, S., Fu, H., Zhang, Y.: An IEEE 802.11 p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks. IEEE Transactions on Intelligent Transportation Systems 13(2), 449–458 (2012), doi:10.1109/TITS.2011.2171951
4. Han, C., Dianati, M., Tafazolli, R., Liu, X., Shen, X.: A novel distributed asynchronous multichannel mac scheme for large-scale vehicular ad hoc networks. IEEE Transactions on Vehicular Technology 61(7), 3125–3138 (2012)
5. Dang, D.N.M., Dang, H.N., Do, C.T., Hong, C.S.: An efficient and reliable mac for vehicular ad hoc networks. In: 2013 15th Asia-Pacific Network Operations and Management Symposium, APNOMS (2013)
6. Bianchi, G.: Performance analysis of the ieee 802.11 distributed coordination function. IEEE Journal on Selected Areas in Communications 18(3), 535–547 (2000)
7. Chatzimisios, P., Boucouvalas, A., Vitsas, V.: Packet delay analysis of ieee 802.11 mac protocol. Electronics Letters 39(18), 1358–1359 (2003)
8. Ziouva, E., Antonakopoulos, T.: Csma/ca performance under high traffic conditions: throughput and delay analysis. Computer Communications 25(3), 313–321 (2002)
9. Ergen, M., Varaiya, P.: Throughput analysis and admission control for ieee 802.11a. Mobile Networks and Applications 10(5), 705–716 (2005)
10. Malone, D., Duffy, K., Leith, D.: Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions. IEEE/ACM Transactions on Networking 15(1), 159–172 (2007)

11. Ma, X., Chen, X.: Performance analysis of ieee 802.11 broadcast scheme in ad hoc wireless lans. IEEE Transactions on Vehicular Technology 57(6), 3757–3768 (2008)
12. Xiao, Y.: Performance analysis of priority schemes for ieee 802.11 and ieee 802.11e wireless lans. IEEE Transactions on Wireless Communications 4(4), 1506–1515 (2005)
13. Wu, H., Wang, A., Zhang, Q., Shen, X.: Ieee 802.11e enhanced distributed channel access (edca) throughput analysis. In: IEEE International Conference on Communications, ICC 2006, vol. 1, pp. 223–228 (2006)
14. Hafeez, K., Zhao, L., Liao, Z., Ma, B.: Performance analysis of broadcast messages in vanets safety applications. In: 2010 IEEE Global Telecommunications Conference (GLOBECOM 2010), pp. 1–5 (2010)
15. Campolo, C., Vinel, A., Molinaro, A., Koucheryavy, Y.: Modeling broadcasting in ieee 802.11 p/wave vehicular networks. IEEE Communications Letters 15(2), 199–201 (2011)
16. Han, C., Dianati, M., Tafazolli, R., Kernchen, R., Shen, X.: Analytical study of the ieee 802.11p mac sublayer in vehicular networks. IEEE Transactions on Intelligent Transportation Systems 13(2), 873–886 (2012)
17. Daneshgaran, F., Laddomada, M., Mesiti, F., Mondin, M.: Unsaturated throughput analysis of ieee 802.11 in presence of non ideal transmission channel and capture effects. IEEE Transactions on Wireless Communications 7(4), 1276–1286 (2008)