Analytical Study of the IEEE 1609.4 MAC in Vehicular Ad Hoc Networks

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Abstract. Vehicular Ad hoc Network (VANET) is developed to enhance the safety, comfort and efficiency of driving. The IEEE 802.11p/WAVE [1] is a standard intended to support wireless access in VANETs. The IEEE 1609.4 [2] is a MAC extension of IEEE 802.11p [1] to support multi-channel operations. In this paper, we propose an analytical model to evaluate the performance for safety and non-safety applications of IEEE 1609.4 under non-saturation condition. The 2-D Markov model is used to model two access categories in the IEEE 1609.4. The analytical model is validated by the extensive simulation, and it shows the effect of different parameters to the network performance.

Keywords: IEEE 1609.4 · WAVE · MAC · VANET · Performance analysis

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 provides drivers information about critical situation in advance while non-safety applications are used for improving driving comfort and the efficiency of transportation system. So, safety applications have strict requirements on communication reliability and delay. On the other hand, non-safety applications are more throughput-sensitive. The US Federal Communication Commission (FCC) has allocated 75 MHz of the spectrum in the 5.9 GHz band,

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including one control channel (CCH) and six service channels (SCHs) for safety and non-safety applications, respectively.

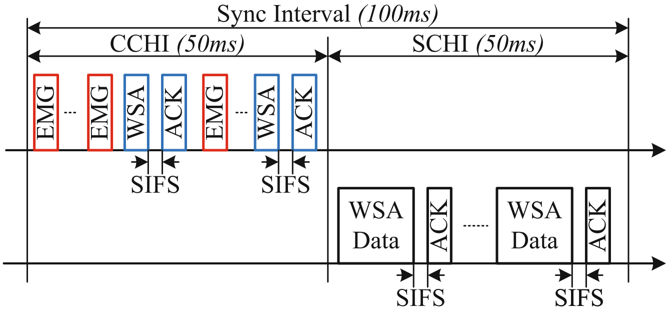


Fig. 1. Multi-channel MAC of VANET - IEEE 1609.4.

Wireless Access in Vehicular Environment (WAVE) is designed for an ITS on 5.9 GHz band with the IEEE 802.11p and IEEE 1609 standard family. The IEEE 802.11p standard is set for both the physical (PHY) and the medium access control (MAC) layer of DSRC. The IEEE 1609.4 is the standard of the multi-channel operation for WAVE MAC. As shown in Fig. 1, each 100 ms Sync Interval (SI) allocates 50 ms for the CCHI and 50 ms for the SCHI. This scheme is similar to some multi-channel MAC proposals [3–5] in Wireless Ad hoc Network with control interval and data interval. Nodes broadcast EMGs or transmit WSA packets to negotiate the SCHs on the CCH during the CCHI. Then, nodes switch to the negotiated SCHs for their non-safety message transmissions.

The performance analysis of the IEEE 802.11 Distributed Coordination Function (DCF) are studied in [6–11]. The Bianchi's model [6] employs 2-D Markov chain analysis to compute the saturation throughput under ideal channel conditions. The delay analysis of 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 in [9,10]. 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 and Chen evaluate the saturation performance of broadcast service in the IEEE 802.11 in [11].

The IEEE 802.11e is proposed with the Hybrid Coordination Function (HCF) to support MAC-level QoS. It combines the contention based Enhanced Distributed Channel Access (EDCA) and 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 by 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.

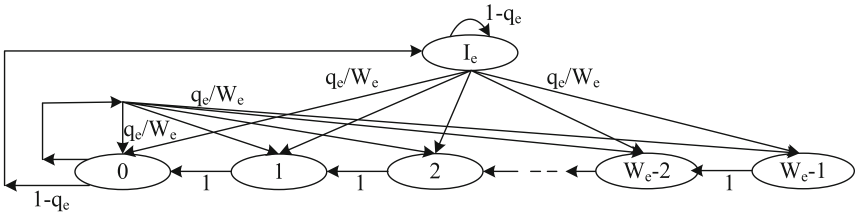
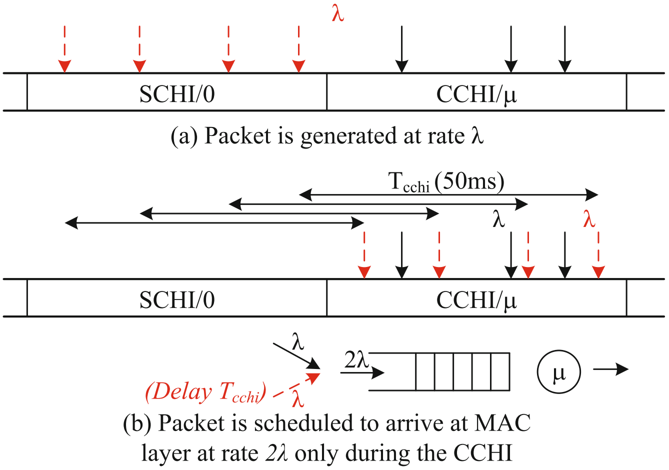


Fig. 2. Markov chain of the emergency traffic.

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. The authors in [14,15] studied only about the broadcasting in VANETs. Han *et al.* [16] 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. We use the packet delivery ratio (PDR), the average delay of emergency packet and the throughput of service packet as the performance metric to evaluate the performance of the IEEE 1609.4.

2 Analytical Model

In our analytical model, we consider the IEEE 1609.4 for 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. However, according to the IEEE 1609.4, the EMG packets and WSA packets are sent on the CCH only during the CCHI. If the packets are generated and arrives at MAC layer during the SCHI at the rate of λ as shown in Fig. 3(a), they have to wait in the MAC buffer until the next CCHI to be transmitted. As there are many packets queued in the MAC buffer at the beginning of the next CCHI, many nodes try to contend the CCH to transmit the queued packets. It results in the high collision probability, many packets might be dropped. The important thing to achieve the reliable emergency dissemination is to reduce the conflict when accessing the control channel. So, in order to reduce the collision probability, the considered application layer has to schedule these packets arrive at MAC layer with the Poisson manner by delaying a time of SCHI (50 ms) as shown in Fig. 3(b). That means there are two queues with the same



(a) Packet is generated at rate λ

(b) Packet is scheduled to arrive at MAC layer at rate *2λ* only during the CCHI

Fig. 3. Packet scheduling scheme.

arrival rate λ during the CCHI. The sum of two independent Poisson processes with rate λ is the Poisson process with rate 2λ. Now, the packet arrival rate of emergency and service traffics are λ_e and λ_s during the CCHI, respectively.

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

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

Let $b_{e,k} = \lim\limits_{t\to\infty} P\{b_e(t) = k\}, \text{for } 0 \leq k \leq W_e - 1$ 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

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

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

Using the normalization condition $1 = b_{I_e} + \sum\limits_{k=0}^{W_e-1} b_{e,k}$, we derive $b_{e,0}$

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

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

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

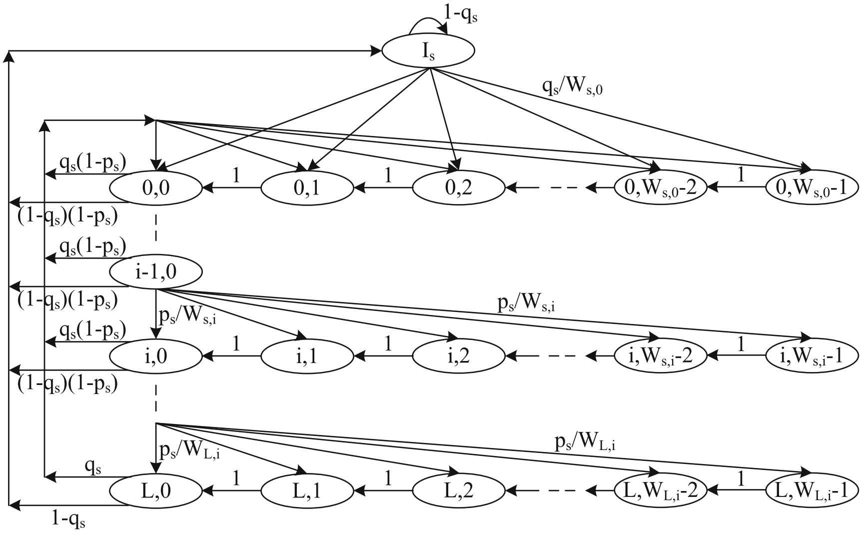


Fig. 4. Markov chain of the service traffic.

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, $W_{s,0}$ be the initial contention window and $W_{s,i} = 2^i W_{s,0}$ be the contention window of i^{th} backoff stage, where $i \in [0, L]$. We assume the collision probability p_s is constant and independent. So, we can model the bidimensional process $s_s(t), b_s(t)$ with the discrete-time Markov chain, as shown in Fig. 4. The only non null one-step transition probabilities are

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

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

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

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

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

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

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

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

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

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

The probabilities of successful transmission for emergency and service traffic are

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

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

$$\begin{cases} P_{e,col} = (1-\tau_s)^N \left(1 - (1-\tau_e)^N - N\tau_e (1-\tau_e)^{N-1} \right) \\ P_{s,col} = (1-\tau_e)^N \left(1 - (1-\tau_s)^N - N\tau_s (1-\tau_s)^{N-1} \right) \\ P_{es,col} = P_b - P_{e,suc} - P_{s,suc} - P_{e,col} - P_{s,col} \end{cases} \tag{15}$$

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

$$\begin{cases} T_{e,suc} = T_{e,col} = T_e = EMG + DIFS + \delta \\ T_{s,suc} = WSA + SIFS + \delta + ACK + DIFS + \delta \\ T_{s,col} = WSA + DIFS + \delta \end{cases} \tag{16}$$

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]

$$\begin{aligned} q_e &= 1 - e^{-2\lambda_e \cdot E_S} \\ q_s &= 1 - e^{-2\lambda_s \cdot E_S} \end{aligned} \tag{18}$$

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 $(W_e - 1)/2$ for the node to perform the back-off. The average time for an EMG packet 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 modelled as an M/M/1 queue with an infinitive buffer size, the packet arrival rate $2\lambda_e$ and service rate μ_e. Since the CCHI and SCHI are the same duration, the average arrived packets are equal. However, all the packets which arrives during the SCHI have to delay by T_{cchi}. Thus, the average delay of the emergency traffic including the queueing delay and the transmission delay

$$E[D_e] = \frac{2\mu_e}{(1 - 2\lambda_e \mu_e)} + T_e + \frac{T_{cchi}}{2} \tag{21}$$

For the service packets, after nodes exchange the WSA packets successfully, they will switch to the agreed SCH to exchange WSA data. The maximum time the nodes use to transfer data is one SCHI (50 ms). For simplicity, we divided the SCHI into M transmission slots. For the fairness, nodes have to exchange WSA on the CCH during the CCHI to select one transmission slot for their WSA data transmissions. The average number WSA packets exchanged successfully during the CCHI on the CCH

$$N_{s,suc} = \frac{T^{cch}}{E_S} Q_{s,suc} \tag{22}$$

With six services channels, the maximum transmission slots can be utilized is $6M$. Now, we can evaluate the aggregate throughput of the service packets via the number of selected transmission slots

$$S_s = \min\left[N_{s,suc}, 6M\right] \tag{23}$$

3 Model Validation

We use the event-driven simulation program written in MATLAB to validate our model. Our program follows the IEEE 802.11 standard with the time resolution of microsecond. The values of the parameters 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 50 packets/second, and vary the emergency packet arrival rate λ_e and the number of nodes N to evaluate the PDR and the average delay of the emergency packets and the throughput of service packets.

Table 1. MAC parameters

Parameters	Value
Data rate	6 Mbps
RTS	20 bytes
CTS	14 bytes
WSA	100 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
Number transmission slots M	6

Figure 5 shows the performance of the IEEE 1609.4 of VANET with varying the packet arrival rate of emergency packets. The analytical results (lines) closely match the simulation results (symbols). Obviously, when the number of nodes in the network increases, the collision probability increases. As the packet arrival rate of emergency packet increases, there are more nodes have emergency packets to send, therefore the collision probability also increases. That is the reason why

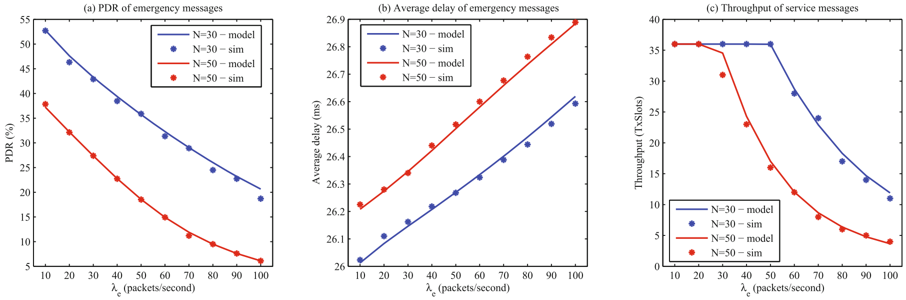


Fig. 5. Performance analysis of the IEEE 1609.4.

the packet delivery ratio of the emergency packets (Fig. 5(a)) and the normalized throughput of the service packets (Fig. 5(c)) decrease.

Since the average delay of the emergency packets including queueing delay is considered for both the successful and failed broadcast. This delay is calculated from the time the emergency packet arrived at a node until the time this emergency packet is transmitted. The average delay is the total delay over the number of transmitted emergency packets. When the collision probability is low, the successful broadcast probability is high. In this case, an emergency packet 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 packets and it makes the total delay decreased. So, the average delay of emergency packets decreased when the number of nodes increases and the packet arrival rate of emergency packets increases.

4 Conclusion

In this paper, we proposed an analytical model to evaluate the performance of the IEEE 1609.4 for VANET using the 2-D Markov chain. The study shows the impact of the number of nodes and the packet arrival rate on the network performance. As the number of nodes and the packet arrival rate increase, the network performance decreases.

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