

Modeling and analysis of IEEE 1609.4 MAC in the presence of error-prone channels

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ABSTRACT

Vehicular Ad Hoc Networks (VANETs) have been developed to improve the safety, comfort and efficiency of driving on the road. The IEEE 1609.4 is a standard intended to support multi-channel in VANETs. These channels include one control channel for safety applications and six service channels for service applications. However, there is still no comprehensive analysis for the average delay and system throughput of IEEE 1609.4 MAC in VANETs considering error-prone channel under non-saturated conditions. In this paper, we propose an analytical models based on 1-D and 2-D Markov chain to evaluate the performance analysis of IEEE 1609.4-based MAC in the presence of error-prone channels. Besides, freezing of the back-off timer is taken into consideration to provide an accurate estimation of access to the channel. The simulation results have been carried out to validate the analytical results of our model. The results show that the performance of our model outperforms the existing model in terms of packet delivery ratio and average delay of safety packets over CCH, and system throughput of service packets over SCHs.

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1. INTRODUCTION

Recently, with increasing the population, the number of registered vehicles has dramatically increased over all the world, and this leads to a high rate of traffic accidents on the roads. In order to prevent such accidents, an Intelligent Transportation Systems (ITSs) are needed. ITSs typically has the ability to improve the quality, effectiveness and safety of the future transportation systems. However, VANETs are the key component of ITSs which integrate wireless networks into vehicles. VANETs support three types of communications including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Hybrid Vehicular (HV) communications. The applications of VANETs are divided into two categories, safety applications and service applications. Safety applications are used to notify drivers about the critical situation in advance. On the other hand, service applications are used for improving driving comfort and the efficiency of transportation. As a result, safety applications are delay-sensitive and have a higher priority, while service applications are throughput-sensitive and have lower priority. The US Federal Communications Commission (FCC) has allocated a frequency band of 5.9 GHz in a total bandwidth of 75 MHz under DSRC to support 7-channels each of which is 10 MHz wide and the guard band is 5 MHz wide. These channels are functionally divided into one control channel (CCH₁₇₈), and up to six are service channels (SCHs) [1-3].

The CCH is exclusively used to broadcast safety-critical applications and regular traffics, while the six other channels, SCHs, are dedicated to transfer service data applications. Wireless Access in Vehicular Environment (WAVE) has been designed for VANETs based on the IEEE 802.11p and IEEE 1609.x standards family. The IEEE 802.11p standard supports both the physical (PHY) and medium access control (MAC) layers of DSRC. The IEEE 1609.4 is the standard (legacy) intended to support multi-channel operation in VANETs [1-3]. The repeating synchronization intervals (SI) among the channels to transmit the packets are 100 ms , and each SI is evenly divided into 50 ms for CCH Interval (CCHI) and 50 ms SCH Interval (SCHI) as shown in Figure 1 [1-5].

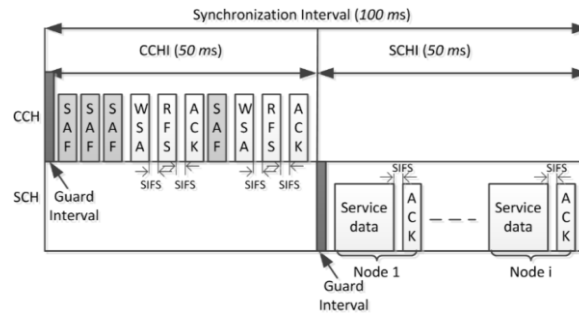


Figure 1. Multi-channel MAC operation in VANETs-IEEE 1609.4

For SCHs reservation in IEEE 1609.4, vehicle (provider) initially broadcasts WAVE Service Advertisement (WSA) packet on the CCH during CCHI to advertise its service and select an appropriate SCH for this service. If other vehicles (users) interest to join the service, which is advertised by a provider, will reply by Request for Service (RFS). Then, the provider replies the users by Acknowledgment (ACK) either for acceptance or rejection. Typically, packets collision may occur if more than one vehicle starts transmitting a packet simultaneously within the same time slot. Whereas, transmission error may manifest due to the complex condition of a wireless channel in VANETs such as path loss, thermal noise, channel fading, or interference from other radio resources.

The principle analysis of IEEE 802.11 Distributed Coordination Function (DCF) was introduced by Bianchi [6]. Bianchi proposed 2-D Markov Chain model to analyze the performance of MAC DCF mechanism by computing the throughput, assuming saturated traffic and error free channel. Several works such as [7-9] followed Bianchi's model by analyzing the throughput and delay of IEEE 802.11 DCF under saturated traffic taking into consideration frame retry limits, error-prone channels and freezing of the back-off timer. Unlike saturated traffic, the analytical model for the throughput and delay of IEEE 802.11 DCF performance under non-saturated traffic was studied by [10-11]. For the broadcast analysis in VANETs, several works such as [12-14] have evaluated the saturation performance of safety messages broadcast in VANETs to calculate the throughput and delay for emergency and routine messages. Different from broadcast analysis in VANETs, the unicast performance analysis of IEEE 802.11p in the presence of hidden terminals under both saturated and unsaturated traffics was presented in [15]. The analytical model of VANETs including both broadcast and unicast analysis for safety and service applications, respectively, based on Markov chain model were introduced in [16]. The authors in [16] analyzed the performance of IEEE 802.11p based MAC under non-saturated traffic and error free channels. The performance metrics of delay, packet delivery ratio and system throughput were investigated in [16]. The authors in [17-18] offered the analytical study of the IEEE 1609.4 MAC in VANETs under non-saturated condition. The performance metrics of delay, packet delivery ratio and system throughput were studied in [17-18]. However, freezing of the back-off timer and error-prone channels were not taken into consideration in [17].

Our model is extension of the existing model in [17]. Freezing of the back-off timer with the $M/M/1$ queue and error-prone channels are taken into considered in our model. Taking these elements into account will provide an accurate estimation of access to the channel and also avoid the overestimation of the system throughput. However, this paper focuses on analyzing two types of traffics; safety and service traffics with higher and lower priorities respectively. 1-D and 2-D Markov chain are employed to model the back-off procedures for each traffic type in the presence of error-prone channels under non-saturated conditions. Gaussian wireless error channel is adopted in this model, in which a constant channel bit error rate (BER) is supposed to be identified in advance and each bit has the same bit error probability. The performance metric PDR, average delay of safety applications and system throughput of service applications are investigated in this paper to evaluate the performance analysis of the IEEE 1609.4.

2. ANALYTICAL MODEL

2.1. Multi-priority transmission model

This analytical model considers the IEEE 1609.4 standard specifications for the safety and service applications as displayed in Figure 1. There are n vehicles in the network contending to access the channel based on the EDCA scheme. All vehicles are in the transmission range of each other and there are no hidden terminals in the system. However, according to the IEEE 1609.4 standard, safety and WSAs packets are only transmitted over CCH during CCHI as shown in Figure 1. If safety or WSAs packets arrive at MAC layer during the SCHI at rate λ , they have to queue at MAC layer buffer waiting for the subsequent CCHI to be transmitted. Thus, under heavy traffic, many packets will be queued at MAC layer buffer waiting for transmission at the beginning of the next CCHI. This will increase collision and delay of transmitted safety packets, and decrease the PDR and accordingly the performance of VANETs will be degraded. The critical solution to achieve a reliable dissemination of safety packet on the road is to mitigate the conflict when accessing the CCH. Thus, in order to mitigate the collision probability over CCH, the considered application layer has to schedule the generated packets to arrive at MAC layer with Poisson manner by delaying a time of SCHI (50 ms). Meaning that there will be two queues with the same arrival rate λ during the CCHI. The total of two independent Poisson process with rate λ is 2λ . Thereby, the packet arrival rate for safety and WSAs traffic during the CCHI are denoted by λ_e and λ_s , respectively, and they follow the Poisson distribution.

Let $b_e(t)$ be the random process representing the back-off timer value $(0, 1, 2, \dots, W_e - 1)$ at time slot t , while The back-off state process is denoted by (k) . $p_{e,f}$ and q_e are the transmission failure probability and the probability of at least one packet in the buffer for a safety application, respectively. The state transition diagram of the 1-D Markov chain for the safety applications process is shown in Figure 2. The non-null transition probabilities are given by:

$$\begin{cases} P(k | 0) = q_e / W_e, & 0 \leq k \leq W_e - 1 \\ P(k | k) = p_{e, coll}, & 1 \leq k \leq W_e - 1 \\ P(k | k + 1) = 1 - p_{e, coll}, & 0 \leq k \leq W_e - 2 \end{cases} \quad (1)$$

Here, the non-null transition probabilities describe the unavailability of safety packets transmission in the buffer, hence changing the station into idle (I_e) state after successful transmission is as follows;

$$\begin{cases} P(I_e | 0) = 1 - q_e \\ P(I_e | I_e) = 1 - q_e \\ P(k | I_e) = q_e / W_e, & 0 \leq k \leq W_e - 1 \end{cases} \quad (2)$$

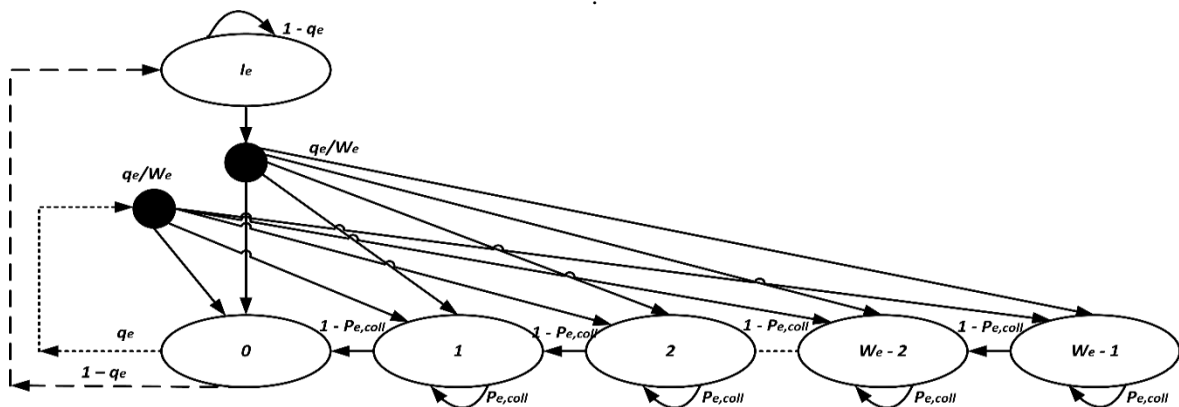


Figure 2. Markov chain model of safety applications

Let $b_{e,k} = \lim_{t \rightarrow \infty} P\{b_e(t) = k\}$ for $k \in (0, W_e - 1)$ be the stationary distribution of the 1-D Markov chain, where W_e is the contention window of safety process. From the Markov chain model in Figure 2, we can get:

$$b_{I_e} = (1 - q_e)b_{e,0} + (1 - q_e)b_{I_e} \quad (3)$$

$$b_{I_e} = \frac{1-q_e}{q_e} b_{e,0} \quad (4)$$

$$b_{e,k} = \frac{W_e - k}{W_e} \frac{1}{1-p_{e,coll}} b_{e,0} \quad \text{for } 1 \leq k \leq W_e - 1 \quad (5)$$

Therefore, by using the normalization condition $1 = b_{I_e} + \sum_{k=0}^{W_e-1} b_{e,k}$ for stationary distribution, we can derive $b_{e,0}$ as follows:

$$b_{e,0} = \frac{2q_e(1-p_{e,coll})}{2(1-p_{e,coll})+q_e(W_e-1)} \quad (6)$$

Let τ_e be the transmission probability of safety applications that a vehicle can transmit in a random chosen time slot. The vehicle can only transmit when the back-off time counter is zero ($b_{e,0}$).

$$\tau_e = b_{e,0} = \frac{2q_e(1-p_{e,coll})}{2(1-p_{e,coll})+q_e(W_e-1)} \quad (7)$$

To analyze τ_s , let $s_s(t)$ and $b_s(t)$ be the random variables representing the back-off stage ($0,1,2,\dots,m$) and the value of the back-off timer ($0,1,2,\dots,W_{s,i}-1$) for a given station at time slot t , respectively. Typically, the maximum value of the back-off timer relies on the back-off stage; thereby, these random variables are not independent.

$$W_{s,i} = \begin{cases} 2^i W_{s,0}, & i \leq m' \\ 2^{m'} W_{s,0}, & i > m' \end{cases} \quad (8)$$

where $W_{s,0}$ is the initial contention window size, $W_{s,0} = (CW_{min} + 1)$, and m' is the maximum number of trials before the packet is dropped according to $W_{s,m'} = 2^{m'} W_{s,0} = (CW_{s,max} + 1)$. The value of m' is assumed to be 5. The maximum value of back-off stages is denoted by m . The transmission failure probability $p_{s,f}$ is constant and independent in this analysis. So, the two-dimensional ($s_s(t), b_s(t)$) processes are analyzed here with a discrete-time Markov chain at which the channel state changes, as shown in Figure 3. The state of this process is denoted by (i, k) . Thus, the non-null transition probabilities are given by

$$\begin{cases} P(i, k | i, k+1) = 1 - p_{s,coll}, & 0 \leq k \leq W_{s,i} - 2, & 0 \leq i \leq m \\ P(i, k | i, k) = p_{s,coll}, & 1 \leq k \leq W_{s,i} - 1, & 0 \leq i \leq m \\ P(i, k | i-1, 0) = p_{s,f}/W_{s,i}, & 0 \leq k \leq W_{s,i} - 1, & 1 \leq i \leq m \\ P(0, k | i, 0) = (1 - p_{s,f})/W_{s,0}, & 0 \leq k \leq W_{s,0} - 1, & 0 \leq i \leq m \\ P(0, k | m, 0) = 1/W_{s,0}, & 0 \leq k \leq W_{s,0} - 1, & \end{cases} \quad (9)$$

Here, the non-null transition probabilities describe the unavailability of packet transmissions in the buffer which is redirected into idle state (I_s) after a successful transmission.

$$\begin{cases} P(I_s | i, 0) = (1 - p_{s,f})(1 - q_s), & 0 \leq i \leq m - 1 \\ P(I_s | m, 0) = 1 - q_s \\ P(I_s | I_s) = 1 - q_s \\ P(0, k | I_s) = q_s/W_{s,0}, & 0 \leq k \leq W_{s,0} - 1 \end{cases} \quad (10)$$

Let $b_{s,i,k} = \lim_{t \rightarrow \infty} P\{s_s(t) = i, b_s(t) = k\}$ be the stationary distribution of the Markov chain, where $i \in (0, m), k \in (0, W_{s,i} - 1)$. First, note that:

$$b_{s,i-1,0} \cdot p_{s,f} = b_{s,i,0} \rightarrow b_{s,i,0} = p_{s,f}^i \cdot b_{s,0,0} \quad 0 < i \leq m \quad (11)$$

$$b_{s,m,0} = p_{s,f} b_{s,m-1,0}$$

Due to the chain regularities, for each $k \in (1, W_{s,i} - 1)$, the stationary distribution of idle and back-off states of service packets are denoted by b_{I_s} and $b_{s,i,k}$ and calculated as follows:

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}(1-p_{s, coll})} \begin{cases} q_s(1-p_{s,f}) \sum_{i=0}^{m-1} b_{s,i,0} + q_s b_{s,m,0} + q_s b_{I_s} & i = 0 \\ p_{s,f} \cdot b_{s,i-1,0} & 0 < i \leq m \end{cases} \quad (12)$$

or

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}} \frac{1}{(1-p_{s, coll})} b_{s,i,0} \quad \text{for } 0 \leq i \leq m, \quad 1 \leq k \leq W_{s,i} - 1 \quad (13)$$

$$b_{I_s} = (1 - q_s)(1 - p_s) \sum_{i=0}^{m-1} b_{s,i,0} + (1 - q_s) b_{s,m,0} + (1 - q_s) b_{I_s} \quad (14)$$

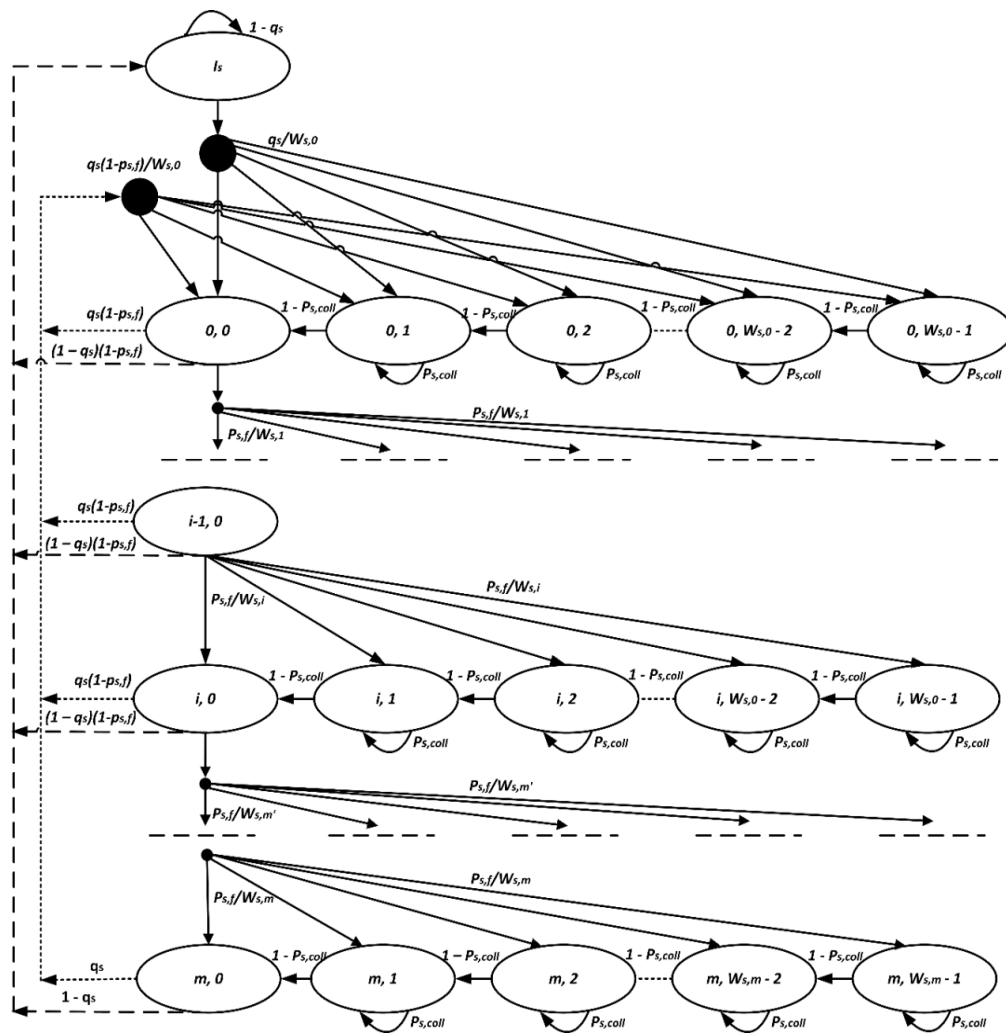


Figure 3. Markov chain model of service applications

By using the normalization condition $1 = \sum_{i=0}^m \sum_{k=0}^{W_{s,i}-1} b_{s,i,k} + b_{I_s}$ for stationary distribution, then $b_{s,0,0}$ is given by

$$b_{s,0,0} = \begin{cases} \frac{2(1-p_{s,f})(1-p_{s, coll})(1-2p_{s,f})q_s}{\epsilon}, & m \leq m' \\ \frac{2(1-p_{s,f})(1-p_{s, coll})(1-2p_{s,f})q_s}{\varkappa}, & m > m' \end{cases} \quad (15)$$

where:

$$\mathcal{E} = (1 - 2p_{s,f})(1 - 2p_{s,coll})(1 - p_{s,f}^{m+1})q_s + W_{s,0}(1 - p_{s,f})(1 - (2p_{s,f})^{m+1})q_s + 2(1 - p_{s,f})(1 - p_{s,coll})(1 - 2p_{s,f})(1 - q_s) \quad (16)$$

and:

$$\mathcal{Y} = (1 - 2p_{s,f})(1 - 2p_{s,coll})(1 - p_{s,f}^{m+1})q_s + W_{s,0}(1 - p_f)(1 - (2p_{s,f})^{m+1})q_s + 2^{m'}W_{s,0}p_{s,f}^{m'+1}(1 - p_{s,f}^{m-m'}) (1 - 2p_{s,f})q_s + 2(1 - p_{s,f})(1 - p_{s,coll})(1 - 2p_{s,f})q_s \quad (17)$$

Let τ_s be the transmission probability of service applications that a vehicle can transmit a service packet in a random chosen time slot. The vehicle can only transmit the packet when the back-off time counter is zero ($b_{s,i,0}$) regardless of the back-off stage.

$$\tau_s = \sum_{i=0}^m b_{s,i,0} = b_{s,0,0} \frac{1 - p_{s,f}^{m+1}}{1 - p_{s,f}} \quad (18)$$

2.2. Failure p_f and collision p_{coll} probabilities

The transmission failure probabilities $p_{e,f}$ and $p_{s,f}$ of safety and service packets are respectively derived as follows:

$$\begin{cases} p_{e,f} = 1 - (1 - p_{e,coll})(1 - p_{e,err}) \\ p_{s,f} = 1 - (1 - p_{s,coll})(1 - p_{s,err}) \end{cases} \quad (19)$$

where $p_{e,err}$ and $p_{s,err}$ denote the probability of frame error for safety and service packets, respectively.

$$\begin{cases} p_{e,err} = 1 - (1 - p_{e,saf_err}) \\ p_{s,err} = 1 - (1 - p_{s,wsa_err})(1 - p_{s,rfs_err})(1 - p_{s,ack_err}) \end{cases} \quad (20)$$

where p_{e,saf_err} , p_{s,wsa_err} , p_{s,rfs_err} , and p_{s,ack_err} denote the Frame Error Rate (FERs) for safety and WSA/RFS/ACK frames error, respectively. The probability of these errors can be computed from bit error probability (i.e. BER) p_{BER} as follows [9]:

$$\begin{cases} p_{e,saf_err} = 1 - (1 - p_{BER})^{L_{saf}} \\ p_{s,wsa_err} = 1 - (1 - p_{BER})^{L_{wsa}} \\ p_{s,rfs_err} = 1 - (1 - p_{BER})^{L_{rfs}} \\ p_{s,ack_err} = 1 - (1 - p_{BER})^{L_{ack}} \end{cases} \quad (21)$$

where L_{saf} , L_{wsa} , and L_{ack} represents the size of safety and WSA/RFS/ACK frames respectively. The probabilities of collision for safety $p_{e,coll}$ and service $p_{s,coll}$ packets are respectively defined as follows:

$$\begin{cases} p_{e,coll} = 1 - (1 - \tau_e)^{n-1}(1 - \tau_s)^n \\ p_{s,coll} = 1 - (1 - \tau_s)^{n-1}(1 - \tau_e)^n \end{cases} \quad (22)$$

then,

$$\begin{cases} p_{e,f} = 1 - (1 - \tau_e)^{n-1}(1 - \tau_s)^n(1 - p_{e,err}) \\ p_{s,f} = 1 - (1 - \tau_s)^{n-1}(1 - \tau_e)^n(1 - p_{s,err}) \end{cases} \quad (23)$$

From (7), (18), and (23), we can solve the two unknown variables, τ_e , τ_s , $p_{e,f}$ and $p_{s,f}$ by using numerical techniques in order to calculate the transmission and failure probabilities for safety and service applications respectively.

2.3. Time analysis for safety and WSA transmission

In every time slot during the contention-based MAC scheme (CCH), the state of the channel could be idle $p_{es,i}$, successful transmission, collision transmission or failure transmission due to the frame error. Thus, the probabilities of channel states are expressed by (24).

$$\begin{cases} p_{es,i} = (1 - \tau_e)^n (1 - \tau_s)^n \\ p_{e,suc} = n\tau_e(1 - \tau_e)^{n-1}(1 - \tau_s)^n(1 - p_{e,saf_err}) \\ p_{e,SAF_ERR} = n\tau_e(1 - \tau_e)^{n-1}(1 - \tau_s)^n p_{e,saf_err} \\ p_{s,suc} = n\tau_s(1 - \tau_s)^{n-1}(1 - \tau_e)^n(1 - p_{s,wsa_err})(1 - p_{s,rfs_err})(1 - p_{s,ack_err}) \\ p_{s,WSA_ERR} = n\tau_s(1 - \tau_s)^{n-1}(1 - \tau_e)^n p_{s,wsa_err} \\ p_{s,RFS_ERR} = n\tau_s(1 - \tau_s)^{n-1}(1 - \tau_e)^n(1 - p_{s,wsa_err})p_{s,rfs_err} \\ p_{s,ACK_ERR} = n\tau_s(1 - \tau_s)^{n-1}(1 - \tau_e)^n(1 - p_{s,wsa_err})(1 - p_{s,rfs_err})p_{s,ack_err} \\ p_{es,b} = 1 - p_{es,i} = 1 - (1 - \tau_s)^n(1 - \tau_e)^n \\ p_{e,c} = (1 - \tau_s)^n(1 - (1 - \tau_e)^n - n\tau_e(1 - \tau_e)^{n-1}) \\ p_{s,c} = (1 - \tau_e)^n(1 - (1 - \tau_s)^n - n\tau_s(1 - \tau_s)^{n-1}) \\ p_{es,c} = p_{es,b} - p_{e,suc} - p_{s,suc} - p_{e,c} - p_{s,c} \end{cases} \quad (24)$$

where $p_{e,suc}$ and $p_{s,suc}$ represent the successful transmission probabilities of safety and service packets, respectively. p_{e,SAF_ERR} , p_{s,WSA_ERR} , p_{s,RFS_ERR} and p_{s,ACK_ERR} denote the unsuccessful transmission probabilities of safety and WSA/RFS/ACK packets due to the frames error. The busy channel probability is denoted by $p_{es,b}$. The transmission probability of a safety packet with collision caused by safety packets only is denoted by $p_{e,c}$. The transmission probability of a service packet with collision caused by service packets only is denoted by $p_{s,c}$. The transmission probability of a packet with collision caused by safety and service packets.

Now, let $T_{es,i}$ denotes the idle slot duration. $T_{e,suc}$ and $T_{s,suc}$ represent the successful transmission time of safety and service packets, respectively. $T_{e,c}$ and $T_{s,c}$ denote the transmission time of safety and service packets with collision, respectively. T_{e,SAF_ERR} , T_{s,WSA_ERR} , T_{s,RFS_ERR} , and T_{s,ACK_ERR} denote the unsuccessful transmission times of safety and WAS/RFS/ACK packets due to frames error. T_{saf} , T_{WSA} , T_{RFS} , and T_{ACK} are the time duration to transmit safety, and WSA/RFS/ACK packets respectively. T_{SIFS} , T_{DIFS} , and T_{EIFS} are the time duration of SIFS, DIFS and EIFS respectively. δ is the propagation delay. σ is the idle time slot. Thus, the transmission time with adoption broadcast and unicast mechanisms is calculated by

$$\begin{cases} T_{es,i} = aSlotTime = \sigma \\ T_{e,suc} = T_{e,c} = T_{e,SAF_ERR} = T_{saf} + \delta + T_{DIFS} \\ T_{s,suc} = T_{wsa} + T_{rfs} + T_{ack} + 3\delta + 2T_{SIFS} + T_{DIFS} \\ T_{s,c} = T_{wsa} + \delta + T_{EIFS} \\ T_{s,WSA_ERR} = T_{wsa} + \delta + T_{EIFS} \\ T_{s,RFS_ERR} = T_{wsa} + T_{SIFS} + T_{rfs} + 2\delta + T_{EIFS} \\ T_{s,ACK_ERR} = T_{s,suc} \end{cases} \quad (25)$$

However, assuming that the service data packet size is constant, then the time slot duration to transmit a service data packet over the SCH based on the contention-free MAC scheme is expressed by

$$\begin{cases} T_{data_suc}^{s,sch} = T_h + T_{data} + T_{ack} + 2\delta + T_{SIFS} + T_{DIFS} \\ T_{DATA_ERR}^{s,sch} = T_h + T_{data} + \delta + T_{EIFS} \\ T_{ACK_ERR}^{s,sch} = T_{s,DATA_SUC} \end{cases} \quad (26)$$

where $T_{data_suc}^{s,sch}$ denotes the successful transmission time of service data packet over SCH. $T_{DATA_ERR}^{s,sch}$ is the unsuccessful transmission time of a service data packet over SCH due to frame error. $T_h = PHY_{hdr} + MAC_{hdr}$ is the packet header. $T_{data} = L_{pld}/R$, where L_{pld} represents the payload of the service data packet, and R is the transmission data rate. T_{saf} , T_{wsa} , T_{rfs} and T_{ack} are PHY-layer dependent, and the frame transmissions in the unit of Orthogonal Frequency Division Multiplexing (OFDM) symbols are given by (27) [19]:

$$\begin{cases} T_{saf} = T_{symbol} \left[\frac{L_{ser} + L_{tail} + L_{saf}}{N_{Bps}} \right] \\ T_{wsa} = T_{symbol} \left[\frac{L_{ser} + L_{tail} + L_{wsa}}{N_{Bps}} \right] \\ T_{rfs} = T_{symbol} \left[\frac{L_{ser} + L_{tail} + L_{rfs}}{N_{Bps}} \right] \\ T_{data} = T_{symbol} \left[\frac{L_{ser} + L_{tail} + L_{data}}{N_{Bps}} \right] \\ T_{ack} = T_{symbol} \left[\frac{L_{ser} + L_{tail} + L_{ack}}{N_{Bps}} \right] \end{cases} \quad (27)$$

where T_{symbol} , L_{ser} , L_{tail} , and N_{Bps} denote the duration of a transmission symbol, OFDM PHY layer service field size, OFDM PHY layer tail fields size, and the number of encoded bites per one symbol. In order to figure out the system throughput and delay, the duration of the logical time slots T_{slot} per state in the channel is required and given by:

$$T_{slot} = p_{es,i} T_{es,i} + p_{e,suc} T_{e,suc} + p_{s,suc} T_{s,suc} + p_{e,c} T_{e,c} + p_{s,c} T_{s,c} + p_{e,SAF_ERR} T_{e,SAF_ERR} + p_{s,WSA_ERR} T_{s,WSA_ERR} + p_{s,RFS_ERR} T_{s,RFS_ERR} + p_{s,ACK_ERR} T_{s,ACK_ERR} + p_{es,c} \max(T_{e,c}, T_{s,c}) \quad (28)$$

In this model, the Poisson distribution model is assumed, in which the inter arrival time is exponentially distributed. Then, from the average duration of the logical time slot T_{slot} , the load equation of queue probability, q_e and q_s for safety and service applications is given respectively by [10]:

$$\begin{cases} q_e = 1 - e^{-2\lambda_e T_{slot}} \\ q_s = 1 - e^{-2\lambda_s T_{slot}} \end{cases} \quad (29)$$

The packet delivery ratio (PDR) of the safety application is derived as the probability of having a successful transmission during a given time slot over the average number of vehicles transmitting packets in a generic time slot;

$$PDR = \frac{p_{e,suc}}{n_e \tau_e} = (1 - \tau_e)^{n-1} (1 - \tau_s)^n \quad (30)$$

The average time slot of a safety packet to execute the back-off is given by $\frac{(w_e-1)}{2}$. Thereby, the average total service time $E[X_e]$ of a safety packet, which experiences the average back-off duration, can be estimated by

$$\mu_e = E[X_e] = \frac{(w_e-1)}{2} * T_{slot} \quad (31)$$

In this model, each vehicle is modelled as an M/M/1 queue with an infinitive buffer size, service rate μ_e , and the packet arrival rate $2\lambda_e$. In 1609.4 standard, the CCHI and SCHI have the same duration (50 ms for each interval), thereby, the average arrived packets are equal. However, safety packets which are generated during SCHI have to delay by T_{cchi} . Therefore, the average delay of safety packets $E[D_e]$ including queuing and transmission delays is expressed by

$$E[D_e] = \frac{2\mu_e}{(1-2\lambda_e\mu_e)} + T_{e,suc} + \frac{T_{cchi}}{2} \quad (32)$$

However, the retry limit is considered in the model analysis of the WSAs packets in order to meet the IEEE 802.11p specifications. Thus, the maximum back-off stage for the WSA packet to be transmitted in this model is denoted by m . If the WSA packet faces m collisions in the previous stages, and therefore this packet will be dropped if it experiences another collision. Then, the WSA packet drop probability $P_{s,drop}$ expressed by

$$P_{s,drop} = p_{s,f}^{m+1} \quad (33)$$

For service applications, when the vehicles successfully exchange the WSA packets over CCH, they will tune to the selected SCH during SCHI to transfer service data. The maximum time that vehicles use to

exchange service data is one SCHI (50 ms). In this model, the SCHI is divided into Q transmission slots. Initially, vehicles have to exchange WSA packets over CCH during CCHI to choose suitable transmission slot for their service data transmission over SCHs. Thus, the average number of WSA packets $N_{s,suc}$ successfully transmitted over the CCH during the CCHI is calculated by:

$$N_{s,suc} = \frac{T_{cchi}}{T_{slot}} \times p_{s,suc} \quad (34)$$

According to the 1609.4 standard, the number of service channel is six, thus, the maximum transmission slots can be utilized is $6Q$. Finally, the aggregate throughput of the service packets S_s , is evaluated by considering the number of selected transmission slots, and thus, it can be estimated by [17],

$$S_s = \min[N_{s,suc}, 6Q] \quad (35)$$

3. MODEL VALIDATION

We use MATLAB to carry out the numerical results, while the extensive simulations are conducted to validate the proposed analytical model using NS-2.34. The simulation scenario includes 100 vehicles with a GPS and a single-radio WAVE communication device. The speed of vehicles is 60 km/h. The value of bit error rate p_{BER} for the channel condition is assumed to be 10^{-5} , which is one of the most affected and sensitive values for the channel BER in a comparatively noisy, channel fading and unreliable wireless environment [20-21]. The typical parameters values for both analytical model and simulations are summarized in Table 1 as obtained from [17]. The safety packet arrival rate λ_e is varied up to 100 packets/second (pps), while the service packet arrival rate λ_s and the number of vehicles n are fixed, $\lambda_s = 50$ pps and $n = 30$ vehicle. Performance metrics such as average delay and PDR of safety packets, as well as the network throughput of service packets are investigated in this section.

Table 1. Parameters values

Parameters	value	Parameters	value
Number of CCH	1	δ	1 μ s
Number of SCHs	6	L_{ser}	16 bits
Transmission data rate for each channel	6 Mbps	L_{tail}	6 bits
MAC header	272 bits	p_{BER}	10^{-5}
PHY header	128 bits	T_{symbol} (μ s)	4
Service packet size	8000 bits	N_{BPS}	24
Safety packet size	800 bits	W_e	8
WSA	800 bits	$W_{s,0}$	16
RFS	160 bits	Short retry limit	5
ACK	112 bits	Long retry limit	7
SIFS	16 μ s	Number of transmission slots Q	6
Time slot σ	9 μ s	Frequency	5.9 GHz
DIFS	34 μ s	λ_e	10-100 pps

Figure 4 displays the performance of the IEEE 1609.4 MAC in VANETs under various safety packet arrival rate λ_e . In fact, the value of collision probability increases with increasing the packet arrival rate or the number of vehicles in the network. The reason for this can be attributed to the fact that in the heavy packet arrival rate (traffic load), more broadcasting packets are exchanged, leading to a higher collision probability. In addition, due to the lack of ACK and exponential back-off mechanisms in safety packets broadcast, vehicles with broadcast mode attempts to transmit a packet after the last packet being broadcasted constantly, which results in higher collision probability. According to these facts, we observe the PDR of safety packets in Figure 4(b) and the throughput of service packets in Figure 4(d) decrease with increasing the packet arrival rate in the network. We also notice in Figure 4(c) that the WSA packets drop probability significantly increases with increasing safety packet arrival rate. Figure 4(a) shows that the average delay of safety packets increases linearly with increasing packet arrival rate. This observation explains that the average service time $E[X_e] = \mu_e$ is directly proportional to the packet arrival rate. Explicitly, as the packet arrival rate increases, the packets queue and service time increase as well and this certainly lead to longer delay for packets to be transmitted. In addition, with more safety packets being broadcasted, the back-off time occurs more frequently and the overall back-off time increases for each vehicle in the network due to more frequent freezing of the back-off timer.

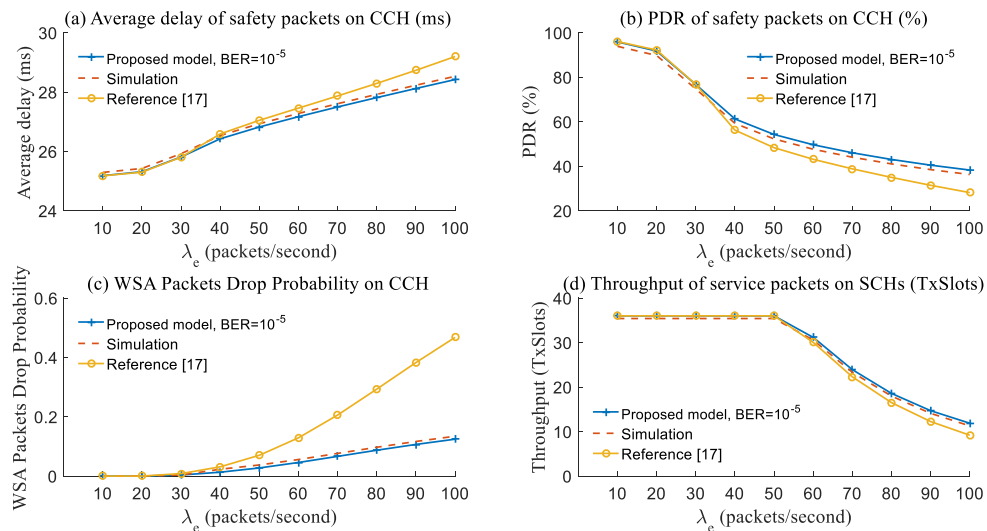


Figure 4. Performance analysis of the IEEE 1609.4, $\lambda_s = 50pps$ and $n = 30$ vehicle

Figure 4 clearly shows that the results of the proposed model outperform the results of the existing model, although the BER is considered in the proposed model. This is due to the freezing of the back-off timer mechanism that is taken into consideration in the proposed model. This mechanism always keeps the vehicles aware of the channel status to apply the freezing of the back-off timer when there is a collision in the channel to reduce the collision probability, especially when the packet arrival rate increases in the network. In addition, the simulation results in Figure 4 are close to the analytical results, which validate the accuracy of the proposed model.

4. CONCLUSION

This paper has proposed analytical models based on 1-D and 2-D Markov chain for safety and service applications, respectively, to evaluate the performance of the IEEE 1609.4 MAC in the presence of error prone channels. The result displays the effect of the packet arrival rate on the network performance. The network performance degrades with increasing the safety packet arrival rate. The study also shows that the results of the proposed model outperform the results of the existing model in terms of average delay and PDR of safety packets over CCH, and network throughput of service packets over SCHs.

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