A Comprehensive Performance Analysis of IEEE 802.11p based MAC for Vehicular Communications Under Non-saturated Conditions

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Abstract. Reliable and efficient data broadcasting is essential in vehicular networks to provide safety-critical and commercial service messages on the road. There is still no comprehensive analysis of IEEE 802.11p based MAC that portrays the presence of buffer memory in vehicular networks. Besides, most of the analytical works do not fulfill some of the IEEE 802.11p specifications, such as short retry limit and back-off timer freezing. This paper proposes a 1-D and 2-D Markov model to analyze mathematically IEEE 802.11p based MAC for safety and non-safety messages respectively. The work presented in this paper takes into account the traffic arrival along with the first-order buffer memory and freezing of the back-off timer as well, to utilize the channel efficiently and provide higher accuracy in estimation of channel access, yielding more precise results of the system throughput for non-safety messages and lower delay for safety messages. Furthermore, back-off stages with a short retry limit were applied for non-safety messages in order to meet the IEEE 802.11p specifications, guaranteeing that no packet is served indefinitely, avoiding the overestimation of system throughput. A simulation was carried out to validate the analytical results of our model.

Keywords: *back-off freezing timer; buffering; collision probability; frame retry limit; IEEE 802.11p; Markov model; throughput.*

1 Introduction

Recently, the subject of vehicular ad-hoc networks (VANETs) has attracted much attention in governmental sectors, industries, and academic institutions due to the significance of its applications. VANETs is a sub-class of mobile ad-hoc networks (MANETs) with several different characteristics that distinguish it from MANETs, such as a large number of nodes, high mobility, rapid network topology change, no power constraints, and availability of GPS [1]. Mainly, it

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can be utilized to improve vehicle safety, enhance traffic management conditions and provide infotainment in vehicles such as Internet access and video streaming. There are three major types of communication systems in VANETs, i.e. inter-vehicular communication (IVC) systems, roadside-to-vehicle communication systems (RVC), and hybrid vehicular communication systems (HVC), as described in [2]. Moreover, VANET applications use three kinds of priority-based messages, which influence channel assignment by the MAC protocol. In so doing, multiple channels are often designated in VANETs to primarily broadcast the following types of messages: a) event-driven messages (emergency messages usually related to safety, such as electronic brake warnings, post-crash notifications and oncoming traffic warnings); b) periodic messages that give information about the current status of vehicles to control traffic (position, speed, and direction); and c) informational messages (non-safety application messages, such as parking availability notifications, parking payment, electronic toll collection and service announcements). Prioritized access is required for these messages. In VANETs, the MAC layer of 802.11p uses enhanced distributed channel access (EDCA) based on carrier sense multiple access with collision avoidance (CSMA/CA), which is derived from IEEE 802.11e to improve the quality of service (QoS) [3]. Generally, prioritization in the EDCA scheme is achieved by changing the contention window (CW) and the arbitration inter-frame space (AIFS) sizes, which increase the probability of successful medium access for real-time messages [4]. Typically, higher priority is given to safety messages while non-safety messages are lower in priority.

The main goal of this study was to provide an extension of the model presented in [5] by adding back-off freezing and a short retry limit to meet the IEEE 802.11p specifications and evaluate the performance of the IEEE 802.11p based MAC layer comprehensively. For this reason, we used 1D and 2D Markov models under unsaturated traffic to analyze safety and non-safety messages respectively. The reason for choosing unsaturated traffic in our model was to take into consideration the inter arrival time and burstiness in the network; real networks are often unsaturated and saturated traffic sometimes makes a network unstable [6,7].

The work presented in this paper takes into account the traffic arrival along with first-order buffer memory and freezing of the back-off timer when a vehicle senses a busy channel, so the channel is utilized efficiently and the estimation of channel access has higher accuracy, which yields more precise results of system throughput for non-safety messages and a lower delay for safety messages. In addition, we added an idle state to the model in order to represent the empty buffer when no packets are ready for transmission. Typically, VANETs support broadcast and unicast modes for safety and service applications, respectively.

Therefore, in order to achieve the IEEE 802.11p specifications, back-off stages with a frame retry limit and ACK with RTS/CTS schemes were used in our model during service message analysis. Meanwhile, the back-off stages and ACK mechanism were disabled in safety message analysis because transmission is normally in broadcast mode only.

The rest of this paper is organized as follows: related works are discussed in Section 2. In Section 3, the model used in this study is presented, which includes assumptions, the probability of frame transmission of safety and service messages, and the probability of collision, system throughput and delay. Section 4 contains the results and performance analysis of our model. The paper is concluded in Section 5.

2 Related Works

The principle analysis of IEEE 802.11 distributed coordination function (DCF) was introduced in [8]. Bianchi proposed a bi-directional Markov chain model to analyze the performance of the MAC DCF mechanism by computing the throughput, assuming saturated traffic and an error-free channel. The frame retry limit and back-off freezing were not considered in [8]. Several works followed Bianchi's model, which analyze the throughput and delay of IEEE 802.11 DCF under saturated traffic with some improvement of the principle [9,10]. In [9], the authors extended Bianchi's model by taking the frame retry limits into consideration. The prediction of throughput of 802.11 DCF was more precise with this model. Freezing of the back-off timer was not taking into consideration in [9], which means that the nodes were not aware of channel status and the estimation of channel access was not accurate. Bianchi's model was also extended in [10] to analyze the saturation throughput, taking into account channel errors and capture effects.

Unlike saturated traffic, the analytical performance of the IEEE 802.11 DCF under non-saturated traffic is presented in [11,12]. The authors in [11] adjusted the multi-dimensional Markov chain model by adding one more state, which describes the model when there are no packets available in the buffer to be transmitted, known as the post back-off state. Throughput and channel load analyses are described in [12], taking into account a short retry limit. However, freezing of the back-off timer was not taken into consideration. Likewise, IEEE 802.11e enhanced distributed channel access (EDCA) is analyzed theoretically under saturation throughput in [13]. The model offered ACK and RTS/CTS mechanisms under a channel error transmission with priority scheme in order to meet the EDCA specifications.

Since vital communication in VANETs is a broadcasting mode, several works on the theoretical performance of VANETs have employed high priority-based broadcast for safety applications [14-17]. While the analytical model of a VANET for service applications was introduced in [18-19], the model in [5] is based on a Markov chain model. In [18], the author analyzes the transmission of WAVE service announcements (WSAs) in a VANET under saturated condition.

A short retry limit was not investigated in this study. More analytical investigations of throughput are presented in [19], which take into account the EDCA mechanism specifications, such as different CWs and AIFS for each AC and internal collisions. In [5] the performance of the IEEE 802.11p based MAC is analyzed for both safety and service applications under non-saturated traffic. The analyses of delay, packet delivery ratio and throughput are included in this model. Freezing of the back-off timer and a short retry limit were not considered in [5], which means that the vehicles were not aware of channel status and the estimation of channel access was inaccurate. Our model is an extension of the model in [5], taking into account freezing of the back-off timer and a short retry limit in order accommodate the IEEE 802.11p specifications and to obtain accurate results for system throughput.

3 The Analytical Model of IEEE 802.11p

3.1 Probability of Frame Transmission τ_e

In this section, the one-dimensional process $b_e(t)$ of safety applications is analyzed with a discrete-time Markov chain in which the channel status changes. The term $b_e(t)$ describes the random variable representing the value of the back-off timer $(0, 1, 2, \ldots, W_e - 1)$ for a given station at time slot t. Since the transmission of safety messages is in broadcast mode and has the highest priority, the back-off stage is disabled. The state of this process is denoted by (k). We assumed n vehicles in the network that compete to access the channel. Let p_e and q_e be the probability of collision and the probability of at least one packet in the buffer for a safety application, respectively. Meanwhile, 1-p_e indicates the probability of successfully transmitting the safety packets and 1-q_e is the probability that there is no safety packet in the buffer for transmission. From Figure 1 depicting the state transition diagram of the Markov chain for the safety applications process, the non-null transition probabilities are written as following Eq. (1):

$$\begin{cases} P(k \mid 0) = q_e / W_e, & 0 \le k \le W_e - 1 \\ P(k \mid k) = p_e, & 1 \le k \le W_e - 1 \\ P(k \mid k+1) = 1 - p_e, & 0 \le k \le W_e - 2 \end{cases} \tag{1}$$

Here are the non-null transition probabilities to describe the unavailability of packet transmission in the buffer, hence changing the station to idle (I_e) state after successful transmission as given in Eq. (2).

$$\begin{cases} P(I_e \mid 0) = 1 - q_e \\ P(I_e \mid I_e) = 1 - q_e \\ P(k \mid I_e) = q_e/W_e, \qquad 0 \le k \le W_e - 1 \end{cases} \tag{2}$$

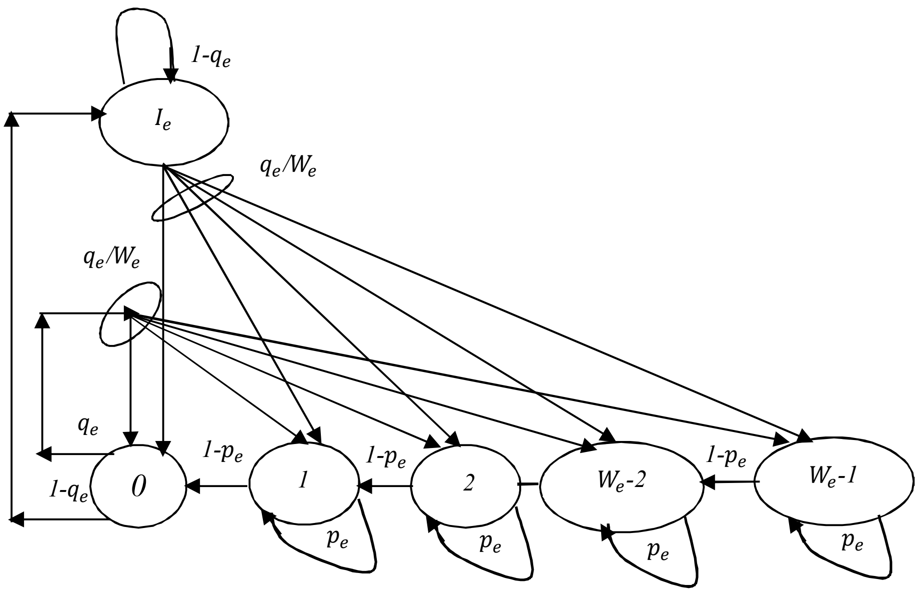

Figure 1 Markov chain model of the safety applications.

Let $b_{e,k} = lim_{t\to\infty} \mathrm{P}\,\{b_e(t) = k\}$ be the stationary distribution of the Markov chain, given that $k \in (0, W_e - 1)$, where W_e is the contention window of the safety process. From the Markov chain, the stationary distribution of b_{I_e} and $b_{e,k}$ is calculated with Eqs. (3) to (5) as follows:

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

$$b_{I_e} = \frac{1-q_e}{q_e} b_{e,0} \tag{4}$$

$$b_{e,k} = \frac{W_e-k}{W_e}\frac{1}{1-p_e} b_{e,0} \quad for \;\; 1 \le k \le W_e - 1 \tag{5}$$

Therefore, by using the normalization condition for stationary distribution, we have:

$$
\begin{aligned}
1 &= b_{I_e} + \sum_{k=0}^{W_e-1} b_{e,k} \\
1 &= b_{I_e} + b_{e,0} + \sum_{k=1}^{W_e-1} b_{e,k} \\
1 &= b_{I_e} + b_{e,0} + \sum_{k=1}^{W_e-1} \frac{w_e - k}{w_e} \frac{1}{1-p_e} b_{e,0} \\
1 &= b_{I_e} + b_{e,0} + \frac{1}{1-p_e} \frac{W_e - 1}{2} b_{e,0} \\
1 &= \frac{1-q_e}{q_e} b_{e,0} + b_{e,0} + \frac{1}{1-p_e} \times \frac{W_e - 1}{2} b_{e,0}
\end{aligned}
\tag{6}
$$

Hence, from Eq. (6) we get Eq. (7):

$$b_{e,0} = \frac{2q_e(1-p_e)}{2(1-p_e)+q_e(W_e-1)} \tag{7}$$

Now we can express the probability τ_e that a vehicle can transmit a safety packet in a randomly chosen time slot. The vehicle can only transmit when the back-off time counter is zero ($b_{e,0}$). (See Eq. (8))

$$\tau_e = b_{e,0} = \frac{2q_e(1-p_e)}{2(1-p_e)+q_e(W_e-1)} \tag{8}$$

3.2 Probability of Frame Transmission τ_s

In order to analyze the probability of frame transmission τ_s of service applications, let $s_s(t)$ be the random variable representing the back-off stage $(0, 1, 2, \ldots, m)$ for a given station at time slot t. Note that $b_s(t)$ is the random variable representing the value of the back-off timer $(0, 1, 2, \ldots, W_{s,i} - 1)$ for a given station at time slot t. Typically, the maximum value of the back-off timer relies on the back-off stage. Hence, these random variables are not independent. (See Eq. (9)).

$$W_{s,i} = \begin{cases} 2^i W_s, & i \le m' \\ 2^{m'} W_s, & i > m' \end{cases} \tag{9}$$

W_s is the initial size of the contention window of service applications, $W_s = (CW_{min} + 1)$, while m' is the maximum number with which the contention window can be doubled, $2^{m'} W_s = (CW_{max} + 1)$. We used $m' = 5$ and the maximum value of back-off stages is denoted by m. Nevertheless, the two-dimensional $(s_s(t), b_s(t))$ processes for service applications is analyzed here with a discrete-time Markov chain at which the channel state changes. The state of this process is denoted by (i, k). We assumed n vehicles in the network that compete to access the channel. Let p_s and q_s be the probability of collision and the probability of at least one packet in the buffer for service applications, respectively. While 1-p_s indicates the probability of successfully transmitting the service packet and 1-q_s is the probability that there is no service packet in the buffer for transmission.

From Figure 2, showing the state transition diagram of the Markov chain for the service applications process, the non-null transition probabilities are written as following Eq. (10):

$$\begin{cases} P(i,k \mid i,k+1) = 1-p_s, & 0 \le k \le W_{s,i}-2, \ 0 \le i \le m \\ P(i,k \mid i,k) = p_s, & 1 \le k \le W_{s,i}-1, \ 0 \le i \le m \\ P(i,k \mid i-1,0) = p_s/W_{s,i}, & 0 \le k \le W_{s,i}-1, \ 1 \le i \le m \\ P(0,k \mid i,0) = (1-p_s)/W_s, & 0 \le k \le W_s-1, \ 0 \le i \le m \\ P(0,k \mid m,0) = 1/W_s, & 0 \le k \le W_s-1, \end{cases} \quad (10)$$

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

$$\begin{cases} P(I_s \mid i,0) = (1-p_s)(1-q_s), & 0 \le i \le m-1 \\ P(I_s \mid m,0) = 1-q_s \\ P(I_s \mid I_s) = 1-q_s \\ P(0,k \mid I_s) = q_s/W_s, & 0 \le k \le W_s-1 \end{cases} \quad (11)$$

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, where $i \in (0, m), k \in \left(0, w_{s,i}-1\right)$. First, note that:

$$b_{s,i-1,0} \cdot p_s = b_{s,i,0} \rightarrow b_{s,i,0} = {p_s}^i \cdot b_{s,0,0} \qquad 0 < i \le m \quad (12)$$

$$b_{s,m,0} = p_s b_{s,m-1,0}$$

Due to the chain regularities, for each $k \in (1, W_{s,i}-1)$, the stationary distribution of b_{I_s} and $b_{s,i,k}$ is calculated with Eqs (13) to (16), as follows:

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}(1-p_s)} \begin{cases} q_s(1-p_s)\sum_{i=0}^{m-1} b_{s,i,0} + q_s b_{s,m,0} + q_s b_{I_s} & i = 0 \\ p_s \cdot b_{s,i-1,0} & 0 < i \le m \end{cases} \quad (13)$$

or

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}} \frac{1}{(1-p_s)} b_{s,i,0} \quad for \ 0 \le i \le m, \ 1 \le k \le W_{s,i}-1 \quad (14)$$

$$b_{I_s} = (1-q_s)(1-p_s)\sum_{i=0}^{m-1} b_{s,i,0} + (1-q_s)b_{s,m,0} + (1-q_s)b_{I_s} \tag{15}$$

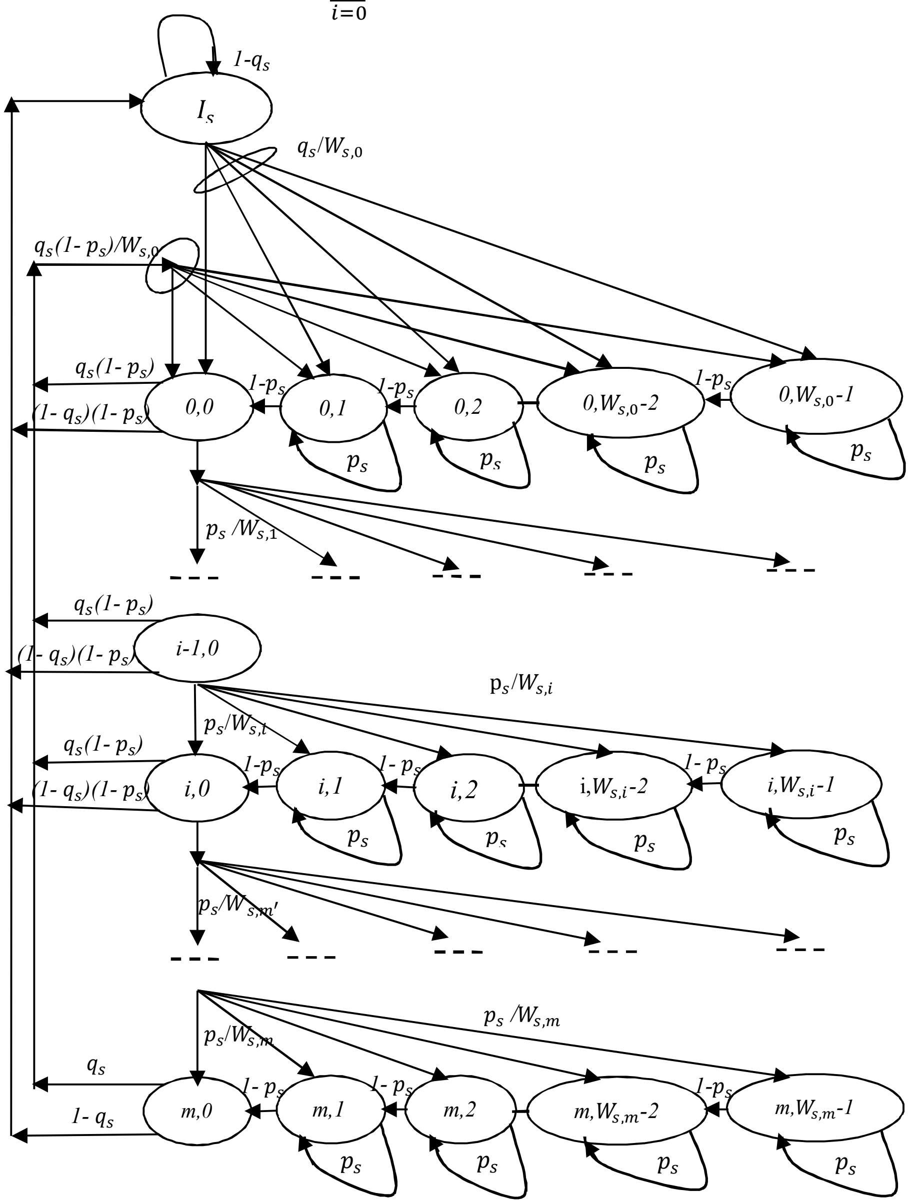

Figure 2 Markov chain model of the service applications.

Mathematically solving Eq. (15), we obtain:

$$b_{I_s} = \frac{1-q_s}{q_s} b_{s,0,0} \tag{16}$$

Thereby the normalization condition of a stationary distribution is used as elaborated in Eq. (17), as follows:

$$\begin{aligned}
1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_{s,i}-1} b_{s,i,k} + b_{s,I_s} \\
1 &= \sum_{i=0}^{m} b_{s,i,0} + \sum_{i=0}^{m} \sum_{k=1}^{W_{s,i}-1} b_{s,i,k} + b_{I_s} \\
1 &= \sum_{i=0}^{m} b_{s,i,0} + \sum_{i=0}^{m} \sum_{k=1}^{W_{s,i}-1} \frac{W_{s,i}-k}{W_{s,i}} \frac{1}{(1-p_s)} b_{s,i,0} + b_{I_s} \\
1 &= \sum_{i=0}^{m} b_{s,i,0} + \frac{1}{1-p_s} \sum_{i=0}^{m} b_{s,i,0} \frac{W_{s,i}-1}{2} + b_{I_s} \\
1 &= \sum_{i=0}^{m} b_{s,i,0} + \frac{1}{1-p_s} \sum_{i=0}^{m} b_{s,i,0} \frac{W_{s,i}-1}{2} + \frac{1-q_s}{q_s} b_{s,0,0} \\
1 &= \sum_{i=0}^{m} {p_s}^i b_{s,0,0} + \frac{1}{2(1-p_s)} \left[\sum_{i=0}^{m} (2p_s)^i W_s b_{s,0,0} - \sum_{i=0}^{m} {p_s}^i b_{s,0,0} \right] \\
&\quad + \frac{1-q_s}{q_s} b_{s,0,0}
\end{aligned} \tag{17}$$

Mathematically solving Eq. (17), we obtain Eq. (18):

$$b_{s,0,0} = \begin{cases} \frac{2(1-p_s)^2(1-2p_s)q_s}{£}, & m \le m' \\ \frac{2(1-p_s)^2(1-2p_s)q_s}{¥}, & m > m' \end{cases} \tag{18}$$

where:

$$£ = (1-2p_s)^2(1-{p_s}^{m+1})q_s + W_s(1-p_s)(1-(2p_s)^{m+1})q_s + 2(1-p_s)^2(1-2p_s)(1-q_s) \tag{19}$$

$$¥ = (1-2p_s)^2(1-{p_s}^{m+1})q_s + W_s(1-p_s)\left(1-(2p_s)^{m'+1}\right)q_s + 2^{m'} w_s {p_s}^{m'+1}\left(1-{p_s}^{m-m'}\right)(1-2p_s)q_s + 2(1-p_s)^2(1-2p_s)(1-q_s) \tag{20}$$

Eq. (21) expresses the probability τ_s that a node can transmit a service packet in a randomly chosen time slot. The node can only transmit when the back-off time counter is zero ($b_{s,i,0}$) regardless of the back-off stage.

$$\tau_s = \sum_{i=0}^{m} b_{s,i,0} = b_{s,0,0} \frac{1-p_s{}^{m+1}}{1-p_s} \tag{21}$$

We notice in Eqs. (8) and (21) that the values of τ_e, τ_s depend on the conditional collision p_e, p_s probabilities and the probability of at least one packet in buffer q_e, q_s for safety and service applications, respectively. The collision probability occurs when more than one vehicle is transmitting in the same time slot.

3.3 Load Equation

Generally, most of the work on VANETs have satisfied the Poisson distribution model, in which the inter arrival times of safety and service traffic are exponentially distributed, denoted by λ_e, λ_s, while *M/G/1* is the queue of each station. The load equation of queue probability, q_e and q_s for safety and service applications respectively, as given in [11], is as follows:

$$q_e = 1 - e^{-\lambda_e T_{slot}} \tag{22}$$

$$q_s = 1 - e^{-\lambda_s T_{slot}} \tag{23}$$

Eqs. (22) and (23) consider only the traffic arrival rate while overlooking the existence of buffer memory. The load equations that represent the traffic arrival along with the presence of buffer memory for safety and service applications respectively, as given in [6], are as following Eqs. (24) and (25):

$$q_e = (1 - e^{-\lambda_e T_{slot}})(1 + q_{tmpe})/(1 + (1 - e^{-\lambda_e T_{slot}})q_{tmpe}) \tag{24}$$

$$q_s = (1 - e^{-\lambda_s T_{slot}})(1 + q_{tmps})/(1 + (1 - e^{-\lambda_s T_{slot}})q_{tmps}) \tag{25}$$

where $q_{tmpe} = (p_e + (1 - p_e)p_e)/\ (1 - p_e)^2$

and $q_{tmps} = (p_s + (1 - p_s)p_s)/\ (1 - p_s)^2$

3.4 System Throughput and Average Delay

The collision probabilities p_e and p_s of safety and service applications are defined in Eqs. (26) and (27) as follows:

$$p_e = 1 - (1 - \tau_e)^{n-1}(1 - \tau_s)^n \tag{26}$$

$$p_s = 1 - (1 - \tau_s)^{n-1}(1 - \tau_e)^n \tag{27}$$

From Eqs. (8), (21), (26), and (27), we solve the unknown τ_e, τ_s using numerical techniques in order to calculate the delay and system throughput. The probabilities p_i , p_b during an idle or busy channel in a given time slot respectively, are computed with Eqs. (28) and (29) as follows:

$$p_i = (1-\tau_e)^n(1-\tau_s)^n \tag{28}$$

$$p_b = 1-(1-\tau_s)^n(1-\tau_e)^n \tag{29}$$

The probabilities that a time slot is occupied by a successful transmission for safety and service applications are given by Eqs. (30) and (31):

$$p_{e,s} = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n \tag{30}$$

$$p_{s,s} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n \tag{31}$$

In general, the system in a VANET can be either in broadcast mode or ACK with RTS/CTS access mechanism for safety and service application transmissions respectively. Thus, let $H = PHY_{hdr} + MAC_{hdr}$ be the packet header, while σ is the duration of the time slot, and δ is the propagation delay. $T_{e,s}$, $T_{s,s}$, $T_{e,c}$ and $T_{s,c}$ are the average times that the channel is sensed as busy due to a successful transmission of a safety and service application, and the average time that the channel is sensed as busy by each node during a collision because of a safety and service application respectively (see Eqs. (32) to (34)). $E[P_e]$, $E[P_s]$ are packet payload sizes for safety and service applications, respectively.

$$T_{e,s} = T_{e,c} = H + E[P_e] + DIFS + \delta \tag{32}$$

$$T_{s,s} = RTS + 3SIFS + 4\delta + CTS + H + E[P_s] + DIFS + ACK \tag{33}$$

$$T_{s,c} = DIFS + RTS + \delta \tag{34}$$

Perhaps a collision transmission could happen from safety messages only, service messages only, or from both with probability derived in Eqs. (35) to (37):

$$p_{e,c} = (1-\tau_s)^n(1-(1-\tau_e)^n - n\tau_e(1-\tau_e)^{n-1}) \tag{35}$$

$$p_{s,c} = (1-\tau_e)^n(1-(1-\tau_s)^n - n\tau_s(1-\tau_s)^{n-1}) \tag{36}$$

$$p_{es,c} = p_b - p_{e,s} - p_{s,s} - p_{e,c} - p_{s,c} \tag{37}$$

Thus, in order to figure out the system throughput, the average duration of the logical time slot T_{slot} that might be spent for each process in the system (successful transmission, collision, or idle) is necessarily calculated, which is given by Eq. (38):

$$T_{slot} = (1 - p_b)\sigma + p_{e,s}T_{e,s} + p_{s,s}T_{s,s} + p_{e,c}T_{e,c} + p_{s,c}T_{s,c} + p_{es,c}max(T_{e,c}, T_{s,c}) \quad (38)$$

The packet delivery ratio (PDR) of a safety message is derived as the probability of having a successful transmission, given that the time slot is busy, as given in Eq. (39) [20]:

$$PDR = \frac{p_{e,s}}{n_e\tau_e} = (1 - \tau_e)^{n-1}(1 - \tau_s)^n \quad (39)$$

The average time for a safety message to finish the back-off, which takes the average time slot of $\frac{(w_e-1)}{2}$, is calculated with Eq. (40):

$$\mu_e = \frac{(w_e-1)}{2} * T_{slot} \quad (40)$$

In this model, each node is modeled as an *M/M/1* queue under an infinite buffer size. Consequently, the average delay of safety messages comprising queuing and transmission delays along with packet arrival and service rates λ_e, μ_e respectively is given as in Eq. (41):

$$E[d_e] = \frac{\mu_e}{1-\lambda_e\mu_e} + E[T_e] \quad (41)$$

Finally, the saturation throughput *S* of the service applications is computed as in Eq. (42) [8]:

$$S = \frac{P_{s,s} * E[P_s]}{T_{slot}} \quad (42)$$

4 Performance Analysis

In the following sections, we analyze and discuss the simulation and numerical results to gain a better understanding of the behavior of broadcasting safety and non-safety messages in a VANET based MAC layer, with respect to our Markov model and the previous model in [5]. Network simulator (ns-2) version 2.34 was used for the simulation to validate our model, while the numerical calculations were carried out in MATLAB. An unsaturated condition was assumed by adding an idle state to the model to represent the empty queues in the MAC layer when no more packets are available in the buffer for transmission. In this model, λ_e and λ_s denote the traffic arrival rates of emergency and service packets, respectively. Both traffic arrival rate and first-order buffer memory follow a Poisson distribution. There were n vehicles in the network that competed for the medium access. All vehicles were in the same transmission range and there were no hidden terminals. The data rate, R, for the MAC data frames for all vehicles was set to 6 Mbps. More parameters for our model are presented in Table 1. Generally, the dissemination of safety messages should be in broadcast mode, so the transmitter will not receive any ACK from the receiver. Otherwise for transmissions of service messages, the ACK with RTS/CTS mechanisms was employed between sender and receiver. Vehicle communications were ad hoc (basic service set) with ideal channel. Finally, a performance evaluation of the VANET based MAC layer with respect to different traffic arrival rates and numbers of vehicles was conducted in this work.

Table 1 Parameter values.

Parameter	Value
Channel capacity	6 Mbps
Safety packet payload	2000 bits
Service packet payload	8000 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits
RTS	160 bits
CTS	112bits
SIFS	16 μs
Time slot σ	9 μs
DIFS	34 μs
Propagation delay δ	1 μs
Minimum W_e	8
Minimum W_s	16
Maximum retry limit	5

4.1 Performance Analysis of Safety Applications

Safety messages are one type of VANET applications, thus, in this study we examined the behavior of broadcasting safety messages under different traffic loads. As the safety applications were in broadcast mode, the ACK mechanism and retransmission were disabled. Typically, the safety applications in VANETs are delay-sensitive and have the highest priority in the EDCA mechanism in order to disseminate the safety-critical messages rapidly and accurately on the road. Therefore, the average delay and collision probabilities were the two performance metrics chosen, which are discussed in this sub-section. We assumed a fixed payload size of $E[P_e] = 250\ bytes$, number of vehicles n = 20, different traffic arrival rates, λ_e, from 10 to 100 pkts/s, contention window size W_e = 8 and 16 time slots for minimum and maximum respectively. The other parameters are summarized in Table 1. The traffic arrival rate λ_e is a Poisson process increasing gradually from 10-100 pkts/s. This increasing traffic arrival causes higher delay and collision probability. Figures 3 and 4 describe the average delay and collision probabilities versus different traffic loads for the analytical and simulation results based on our model. It can be observed from Figure 3 that at light traffic loads there is no significant effect on the delay, particularly when $W_e = 8$. When the traffic load increases from moderate to heavy, the medium becomes congested, which leads to increasing delay. This is because of the directly proportional relationship between the packets in the buffer and the service times. It is believed that the queue and service time increase with the increment of the traffic arrival rate, and thus definitely cause a longer delay. Figure 3 also shows the effect of the various initial contention windows sizes W_e on the delay. The delay is short when a shorter contention window size is chosen; this is owing to the higher priority of using the channel, which is typically given to a shorter contention window size based on the EDCA scheme conditions. The analytical results matched the simulation results, which means that our mathematical model is accurate.

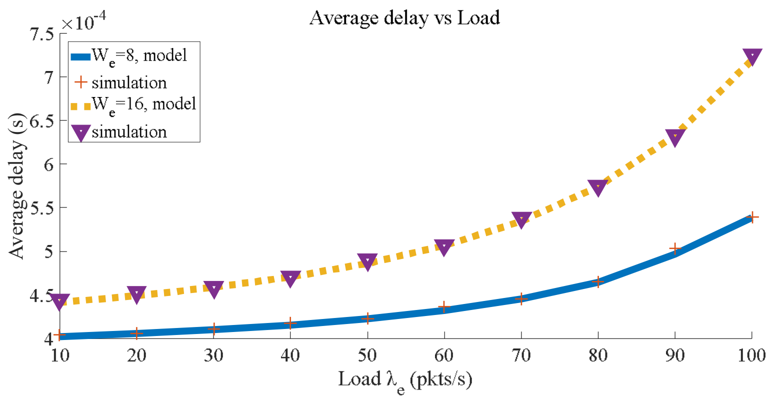

Figure 3 Average delay versus offered load (packets/s), $n = 20$ *vehicles*.

Figure 4 illustrates the collision probability of broadcasting safety messages in a VANET based MAC layer, which strongly depends on the traffic load in the network. In particular, the figure shows that when the traffic load was light (less than the moderate), the collision probability stayed at a lower level and the network was stable. In contrast, when the traffic load increased from moderate to heavy, the collision probability was high and increased linearly, which is due to the higher contention-based broadcast among the vehicles in the network, which essentially leads to a higher collision probability. Besides that, Figure 4 demonstrates the effect of the various initial contention windows sizes W_e on the collision probability. The collision probability was slightly lower when a longer contention window size was chosen, which is because of the longer interval back-off time among vehicles for broadcasting message, which leads to a lower probability of choosing the same timeslot value by more than one vehicle. In this figure we can see that the analytical results matched the simulation results, which supports the accuracy of our mathematical model.

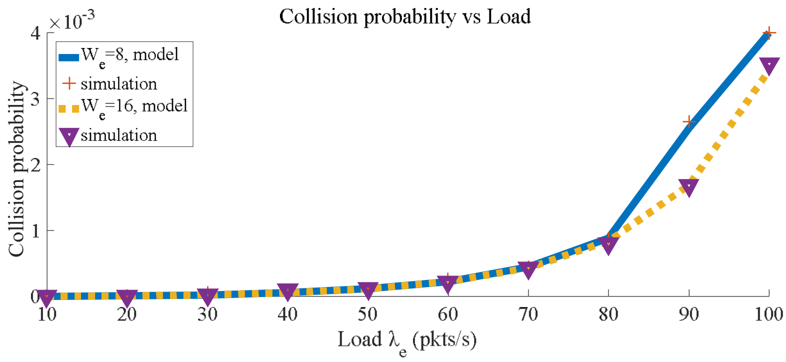

Figure 4 Collision probability versus offered load (packets/s), $n = 20\ vehicles$.

4.2 Performance Analysis of Non-safety Applications

In this subsection, we elaborate the behavior of the transmission of service messages under different numbers of vehicles and traffic arrivals. Usually, the service applications in VANETs are throughput-sensitive in order to improve driving comfort and efficiency of commercial service message transportation systems on the road. Therefore, the throughput, collision and transmission probability were the three performance metrics chosen, which are discussed in this sub-section. We assumed fixed payload size $E[P_s] = 1000\ bytes$, various numbers of vehicles from 10-100 vehicles, different traffic arrival rates and contention window sizes. The other parameters are summarized in Table 1. Traffic arrival λ_s satisfies a Poisson process. As the service applications follow the ACK and RTS/CTS mechanisms, the back-off stages and the frame retry limits are considered in this part. The maximum back-off stage (retransmission count) is represented by m while the maximum values of the frame retry limits $m' = 5$ as in [9,12].

Figures 5 and 6 depict the throughput and collision probability against different numbers of vehicles and traffic arrival rates for the analytical and simulation results based on our model. It is clear from Figure 5 that the network throughput of the RTS/CTS scheme strongly depends on the number of vehicles and traffic arrival rate. Accordingly, it is notable that as the number of vehicles and traffic arrival increased, the network throughput increased with the increasing number of vehicles and traffic arrival rate when the traffic load was light. Our network size was large; the fast saturation level of occupying the channel is shown in Figure 5. It can be seen that the network throughput reached maximum value and its graph becomes flat when the traffic load is heavy. This is because the possibility to occupy the channel by vehicles also increases. The matching of the analytical results and the simulation results in this figure indicates that our mathematical model is precise.

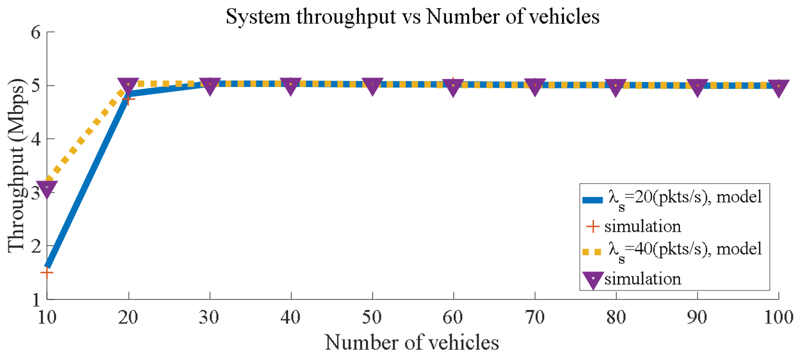

Figure 5 System throughput versus number of vehicles, λs=20 and 40 packets/s.

Figure 6 represents the collision probability of transmitting service messages in the VANET based MAC layer, which depends on the different numbers of vehicles and traffic load in the network. Specifically, Figure 6 shows that when the number of vehicles and traffic arrival increased, the collision probability increased as well, almost linearly. This is because the contention-based transmission among the vehicles in the network increased, which absolutely prompted a higher collision probability. Also, our model has a short retry limit, which means that the vehicles keep contending for the channel. Whenever the packets face collision, the back-off algorithm increases the contention window value to minimize the collision probability with other transmitting vehicles until the contention window value reaches its maximum, $2^{m'}W_s$. In this stage, m', if the packet still fails in transmission, it keeps contending for the channel with the same contention window value $2^{m'}W_s$ until the short retry limit is exhausted. This leads to a higher number of collisions since the back-off value remains the same from stage m' to stage m. In this figure we can see that the analytical results match the simulation results, which means that our mathematical model is accurate.

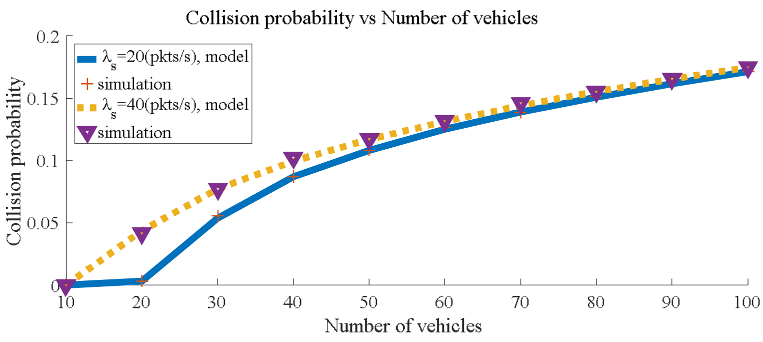

Figure 6 Collision probability versus number of vehicles, λs=20 and 40 packets/s.

Figure 7 shows the transmission probability with respect to different numbers of vehicles and contention window sizes. The figure explains that the transmission probability first increases with the increasing number of vehicles when the traffic load in the network is still light (less than moderate). In exact contrast, the graph of the transmission probability starts going downward when the number of vehicles increases from moderate to heavy; this is due to the fact that as the contention-based transmission among the vehicles in the network increases, the collision probability is high, which leads to a lower transmission probability. Figure 7 also shows the effect of the various initial contention windows sizes W_s on the transmission probability. The value of the transmission probability is low when a longer contention window size is chosen. This is because the waiting time of a vehicle to transmit a packet increases, which usually reduces the transmission probability.

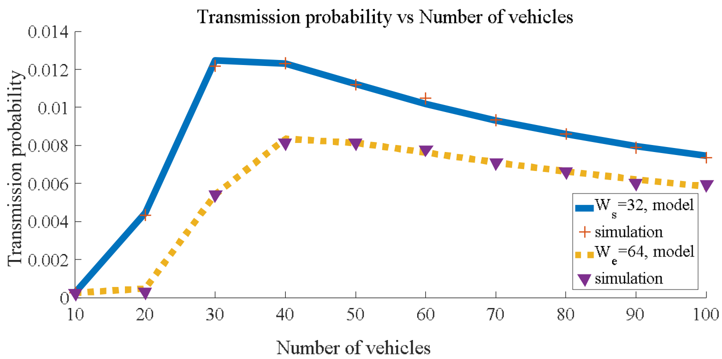

Figure 7 Transmission probability versus number of vehicles, with $\lambda_s =$ 20 packets/s.

4.3 Comparison of the Proposed Model with Existing Model [5]

This subsection presents a comparison between the proposed and an existing model to study the performance of the transmission of service messages with respect to different traffic arrival rates and numbers of vehicles. As we mentioned earlier, our model was designed based on the existing model from [5] by adding some features such as freezing of the back-off timer and a short retry limit to our model to meet the IEEE 802.11p specifications.

Figures 8 and 9 depict the system throughput and collision probability against different traffic arrival rates and numbers of vehicles for the analytical result based on a Markov model. It is clear from Figure 8 that the network throughput of the RTS/CTS scheme strongly depends on the traffic arrival rate and number of vehicles in both models. Accordingly, it is notable that as the traffic arrival rate and vehicles number increase, the network throughput for both models increases as well. This is because the possibility to occupy the channel by packets also increases. The saturation level of occupying the channel is shown in Figure 8. It can be seen that the network throughput reached the maximum value and its graph becomes flat very fast. This is because the network size in our work is large. Also, we can observe from Figure 8 that our model outperforms the existing model when the offered traffic load in the network is still light (less than moderate). This is due to applying the new load equation in our model, which considers both the traffic arrival and the first-order buffer memory to keep the channel occupied efficiently in all situations.

Figure 9 shows that the collision probability increased with the increase of both the traffic arrival rate and the number of vehicles when the offered traffic load was still light. Then, when the offered traffic load increased from moderate to heavy, the collision probability metric flow was flat. Nevertheless, when the offered traffic load increased from moderate to heavy, the increasing collision probability will slow down with increasing traffic arrival rate. Comparing the model derived in this study and the model from [5], Figure 9 clearly shows the high values of the collision probability in the [5] model. This is due to the freezing of the back-off timer that is taken into consideration in our model, which always keeps the vehicles aware of the channel status to apply the frozen mechanism when there is a collision in the channel to reduce the collision probability, especially when the traffic load in the network is heavy.

Figure 10 describes the system throughput against different packet sizes and numbers of vehicles for the analytical result based on the Markov model. It is clear from the result that the network throughput of the RTS/CTS scheme strongly depends on the packet size and number of vehicles, and there is an almost linear relationship between them. The system network throughput increases gradually with the increase of the packet size. Figure 10 also shows that a higher throughput is achieved with the proposed model when compared to the existing model. This is because the traffic arrival, the first-order buffer memory and the freezing of the back-off timer are applied in our model, which leads to utilizing the channel efficiently and accurate results of the system throughput.

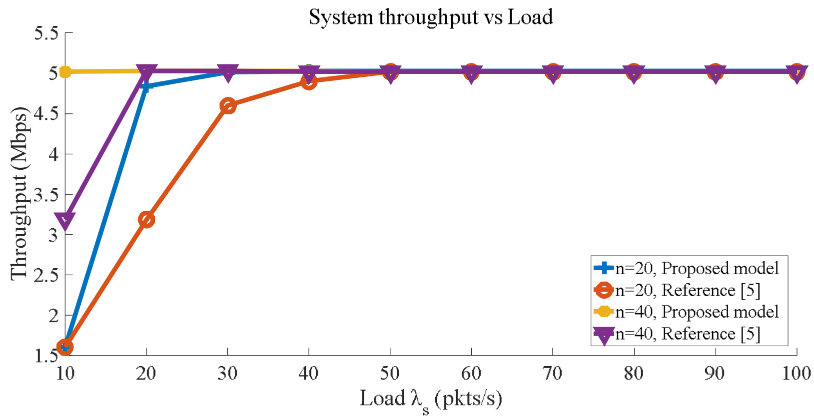

Figure 8 System throughput versus offered load (packets/s), n = 20 and 40 vehicles.

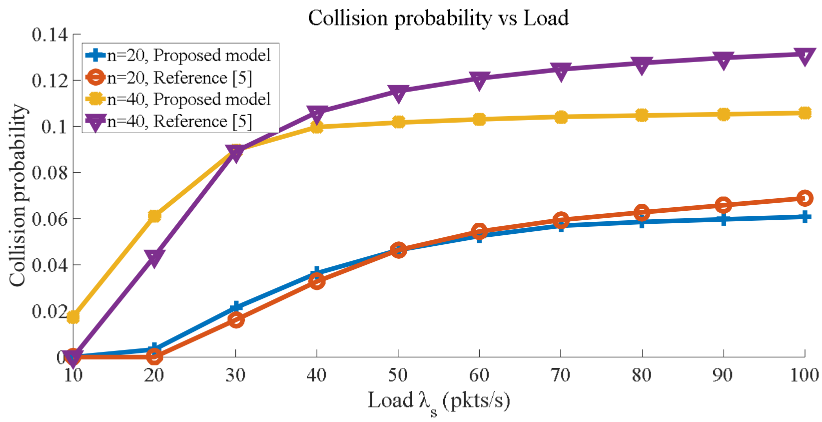

Figure 9 Collision probability versus offered load (packets/s), n = 20 and 40 vehicles.

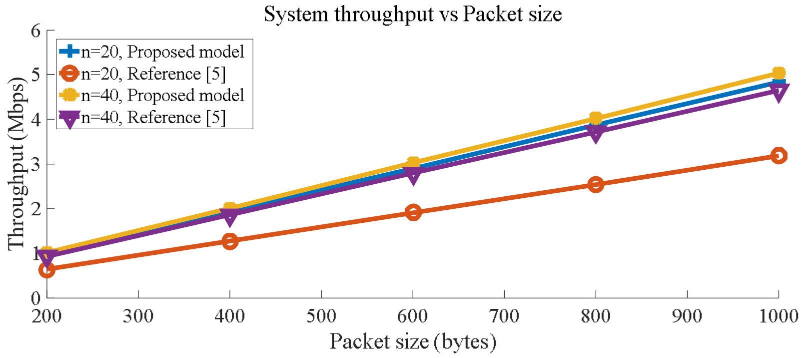

Figure 10 System throughput versus packet size (bytes), $\lambda_s = 20$ packets/s.

5 Conclusion

In this paper, we have presented the improvement of two analytical models for the IEEE 802.11p based MAC layer to analyze safety and non-safety messages concurrently. An elaborate analysis was applied under unsaturated conditions, whereby a buffer was added to hold the packets during traffic arrival when the channel is busy. Traffic arrival rates and the first-order buffer memory were both studied. Additionally, a short retry limit and back-off freezing were presented in our model to accommodate the IEEE 802.11p specifications to obtain accurate system throughput. Since the safety messages are usually delay-sensitive, average delay and collision probabilities were chosen as performance metrics for evaluating safety message transmission under different traffic loads. On the other hand, throughput and collision probability were chosen for evaluating service message transmission, as this is throughput-sensitive. A simulation was carried out to validate the analytical results of our model. The results showed that our model significantly outperformed the model it is based on, both in terms of network throughput and collision probability.

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