International Journal of Electrical and Computer Engineering (IJECE)
Vol. 7, No. 2, April 2017, pp. 999~1011
ISSN: 2088-8708, DOI: 10.11591/ijece.v7i2.pp999-1011

An Accurate Performance Analysis of Hybrid Efficient and Reliable MAC Protocol in VANET under Non-Saturated Conditions

Akram A. Almohammedi[1], Nor K. Noordin[2], A. Sali[3], Fazirulhisyam Hashim[4], Abdulmalek Al-Hemyari[5]
[1,2,3,4]Department of Computer and Communication Engineering, Universiti Putra Malaysia, Malaysia
[2,3,4]Wireless and Photonics Networks Laboratoratory, Universiti Putra Malaysia, Malaysia
[5]Department of Communication Systems Engineering, Al-hikma University, Taiz-Yemen

Article Info

Article history:

Received Nov 26, 2016
Revised Mar 3, 2017
Accepted Mar 21, 2017

Keyword:

Backoff freezing timer
Frame retry limit
Markov model
Packet delivery ratio
Performance analysis

ABSTRACT

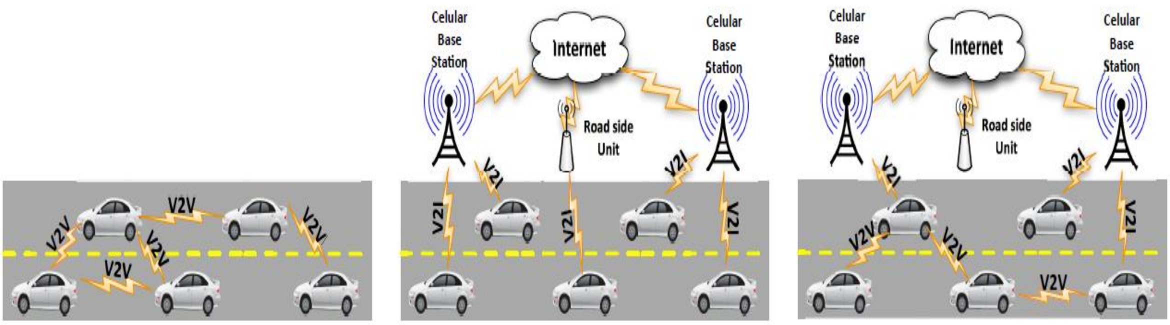
Vehicular Ad Hoc Networks (VANETs) is a technology supporting two types of applications, safety and service applications with higher and lower priorities respectively. Thereby, Medium Access Control (MAC) protocol is designed to provide reliable and efficient data broadcasting based on prioritization. Different from the IEEE 1609.4 (legacy), HER-MAC protocol is a new multi-channel MAC proposed for VANETs, offering remarkable performance with regards to safety applications transmission. This paper focuses on the analysis of packet delivery ratio of the HER-MAC protocol under non-saturated conditions. 1-D and 2-D Markov chains have been developed for safety and non-safety applications respectively, to evaluate mathematically the performance of HER-MAC protocol. The presented work has taken into account the freezing of the backoff timer for both applications and the backoff stages along with short retry limit for non-safety applications in order to meet the IEEE 802.11p specifications. It highlights that taking these elements into consideration are important in modeling the system, to provide an accurate estimation of the channel access, and guarantees that no packet is served indefinitely. More precise results of the system packet delivery ratio have been yield. The probability of successful transmission and collisions were derived and used to compute the packet delivery ratio. The simulation results validate the analytical results of our models and indicate that the performance of our models outperformed the existing models in terms of the packet delivery ratio under different number of vehicles and contention window.

Corresponding Author:

Akram A. Almohammedi,
Department of Computer and Communication Systems Engineering,
Universiti Putra Malaysia,
43300 Serdang, Malaysia.
Email: akrama2810@gmail.com

1. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) are a sub-class of Mobile Ad-hoc Networks (MANETs) with several different characteristics that distinguish them from MANETs. VANETs differ in terms of large number of nodes, high mobility, rapid network topology change, no power constraints, and availability of GPS [1]. Dedicated Short Range Communication (DSRC) is the wireless technology developed for VANETs based on Wi-Fi to use in a very high dynamic network in order to provide reliable communication and minimum latency. Thus, DSRC supports vehicle speed up to 190 km/h, while the transmission range up to 1 km. VANETs support Vehicle-to-Vehicle (V2V), Vehicle to infrastructure (V2I), and Hybrid Vehicular (HV) communications, as shown in Figure 1 [2]. The communication in VANETs is either directly if the vehicles are within the transmission range of each other, or they cooperate in a multi-hop fashion in order to send packets from the source to destination. Moreover, VANETs applications are separated into two categories based on prioritization, safety applications with higher priority and service applications with lower priority. The safety applications include 1) event-driven messages (emergency messages usually related to safety such as electronic brake warning, post-crash notification and oncoming traffic warning); and 2) periodic messages which give information on the current status of vehicles to control the traffic (position, speed, and direction). Meanwhile, the service applications aim to improve driving comfort and the efficiency of transportation such as parking availability notification, parking payment, electronic toll collect and service announcements. Therefore, safety applications require assurance in terms of communication reliability and delay. On the other hand, service applications are more throughput-sensitive instead of delay-sensitive.



(a) Vehicle-to-Vehicle Ad Hoc Network (b) Vehicle-to-Infrastructure Network (c) Hybrid Architecture

Figure 1. VANET Architectures

However, in order to provide different types of application in VANETs, Federal Communications Commission (FCC) has allocated a frequency band of 5.9 GHz on a total bandwidth of 75 MHz to support 7 channels of 10MHZ for each channel, and 5 MHz for guard band under DSRC protocol, as in Figure 2 [3]. These channels are divided functionally into one control channel (CCH_178), and up to six are service channels (SCHs). The CCH is used to broadcast safety-critical messages and regular traffic like beacons and WAVE Service Announcement (WSAs), while the six other channels, SCHs, are dedicated to transmit service messages. The repeating synchronization intervals (SI) for the channels to transmit the packet is *100 ms*, and each SI is divided into CCH Intervals (CCHI) of *50 ms* and SCH Intervals (SCHI) of *50 ms.* as illustrated in Figure 3. Based on the IEEE 1609.4 (legacy), during the interval of CCH, the channel activity on all SCHs is suspended and vice versa. Synchronization between vehicles is achieved by receiving the coordinated universal time (UTC) provided by the navigation satellite system (GPS) equipped in each vehicle. In VANETs, the Medium Access Control (MAC) layer of 802.11p uses the enhanced distributed channel access (EDCA) based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism which is derived from IEEE 802.11e to improve the Quality of Service (QoS) [3],[4]. Generally, prioritization of EDCA scheme is achieved by changing the Contention Windows (CWs) and the Arbitration Inter-Frame Spaces (AIFS) sizes, which increase the probability of successful medium access for real-time messages [5].

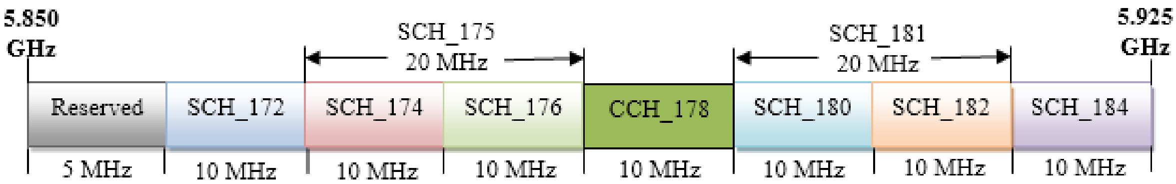


Figure 2. DSRC Spectrum Band and Channels in The U.S.

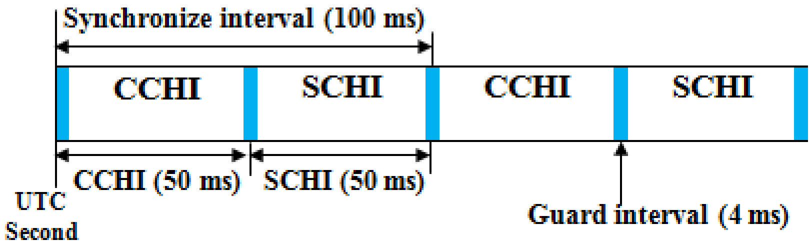


Figure 3. Synchronization Interval, Guard Interval, CCH Interval, and SCH Interval

This paper aims to provide an extension to the existing model, by adding back-off freezing timer to the safety and service application models and back-off stages, along with short retry limit to the service applications models to accommodate the IEEE 802.11p specifications. Therefore, we used 1-D and 2-D Markov chain models to analyze the safety and non-safety applications respectively, under non-saturated conditions. We added an idle state to the models to represent the empty buffer when no packet is ready for transmission. The reason for choosing unsaturated traffic in our models is to simply control the traffic arrival rate on the network based on the situation; the real network conditions are mostly unsaturated, and saturated traffic sometimes makes the network unstable [6], [7]. Typically, VANETs support broadcast mode and acknowledgement (ACK) mechanism for safety and service applications, respectively. The presented work in this paper took into account the freezing of back-off timer for both safety and service applications models, and back-off stages along with short retry limit for the service applications model in order to accommodate the IEEE 802.11p specifications. Hence, taking these elements into consideration are important in modeling the system to provide an accurate estimation of the channel access, and guarantees that no packet is served indefinitely. Consequently, it yields more precise results of the system packet delivery ratio.

The rest of the paper is organized as follows. The related works are presented in section 2. In section 3, we demonstrate the analytical model used in this study that includes probability of frame transmission $\boldsymbol{\tau_e}$ using TDMA access method and probability of frame transmission τ_s using CSMA/CA access method. Section 4 elaborates the results and performance analysis of the models. The paper is concluded in Section 5.

2. RELATED WORK

The principle analysis of IEEE 802.11 Distributed Coordination Function (DCF) was introduced by [8]. Bianchi proposed bi-directional Markov Chain model to analyze the performance of MAC DCF mechanism by computing the throughput, assuming saturated traffic and error free channel. The frame retry limit and back-off freezing has not been considered in [8]. Several works such as [9], [10] followed Bianchi's model by analyzing the throughput and delay of IEEE 802.11 DCF under saturated traffic with some improvements to the principle. 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 in this model. The authors in [10] analyzed the saturation throughput, taking into account the channel errors and capture effects. Unlike saturated traffic, the analytical performance of IEEE 802.11 DCF under non-saturated traffic was presented by [11], [12]. The authors in [11] adjusted the multi-dimensional Markov Chain model by adding one more state which describes the model when there is no packet available in the buffer to be transmitted, known as the post-back-off state. The throughput and channel load analysis have been described by [12], taking into account the short retry limit. However, freezing of the back-off timer was not taken into consideration in [12]. Likewise, IEEE 802.11e enhanced distributed channel access (EDCA) was analyzed theoretically under saturation throughput by [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 the vital communication in VANETs is a broadcasting mode, [14-17] discussed VANETs' theoretical performance which employed high priority-based broadcast for safety applications based on one-dimensional (1-D) Markov chain model to calculate the throughput and delay for emergency, and routine applications. Unlike the analysis of IEEE 802.11p for safety applications, the analytical model of VANETs for service applications was introduced by [18-20] based on bi-dimensional Markov chain model. More analytical study of throughput was represented by [19], taking into account the EDCA mechanism specification such as different CWs and AIFS for each ACs and internal collisions. Unlike saturated traffic, [20] analyzed the performance of IEEE 802.11p based on MAC for both safety and service applications under non-saturated traffic. The analyses of delay, packet delivery ratio and throughput were included in the model. However, in order to improve the reliability of the safety applications among vehicles, the HER-MAC protocol [21] allows vehicles to broadcast their safety applications in the reserved slot time, utilizing whole the SI (*100 ms*); this makes the HER-MAC protocol exploits the channels efficiently. The authors proposed 1-D and 2-D Markov chain models to analyze and evaluate the performance of HER-MAC protocol under non-saturated conditions in term of packet delivery ratio. However, the frame retry limit for service applications and the freezing of the back-off timer for both applications were not considered in model, which means that the vehicles were not aware of the channel status that led to inaccurate estimation of the channel access. Our models are an extension of models, taking into account the freezing of back-off timer and short retry limit in order to accommodate the legacy specifications and to obtain accurate results of the packet delivery ratio.

3. THE ANALYTICAL MODEL OF THE HER-MAC PROTOCOL

We proposed 1-D and 2-D Markovian models for safety and service applications respectively, to analyze and evaluate the performance of HER-MAC protocol in terms of packet delivery ratio. Our proposed models are an extension of model, taking into account the freezing of back-off timer for both models, and also the back-off stages along with a short retry limit in our service applications model in order to meet the IEEE 802.11p specifications. We assumed non-saturated conditions by adding Idle state to the models to represent the empty queues in the MAC layer when no more packets are available in the buffer for transmission. In the analytical model, the CCH is divided into two parts: reservation period (*RP*) and contention period (*TP*) based on the HER-MAC protocol, more details refer to [21]. In order to transmit safety packets in HER-MAC protocol, two access methods are used. Time division multiple access (TDMA) is the first access method along with retransmission mechanism used to broadcast the safety packets. On the other hand, Distributed Coordination Function (DCF) based on CSMA/CA technique with binary slotted exponential back-off is used as the second access method, more details refer to [21]. Since the dissemination of safety packets are in broadcast mode, the binary exponential back-off is disabled, and the vehicles will not send any acknowledgement (ACK) for the received safety packets. Thus, the sender will not discover the failure of safety packets and there is no retransmission. According to the HER-MAC protocol, on the CCH, the packets transmissions are divided into two categories: safety packet and WAVE Service Announcement/Request for Service (WSA/RES) packet transmission. In the models, λ_e and λ_s denote the packets arrival rate of both safety and service traffics respectively. Packets arrival rate satisfies Poisson distribution. There are n vehicles in the network competing for the medium access. In the HER-MAC protocol, there are two queues with the same traffic arrival rate during the CCHI: CCHI and SCHI queues. Thus, the traffic arrival rate of safety and WSA/RES packets at each vehicle are $2\lambda_e$ and $2\lambda_s$ respectively, for more details refer to.

3.1. Case 1: Probability of Frame Transmission τ_e uses TDMA access method

In this subsection, the TDMA access method along with retransmission mechanism is used to transmit a safety packet. All vehicles broadcast a SAFE packet to reserve the Emergency Slots (EmgSlots) on reservation period. Once a vehicle reserved an EmgSlot successfully, it is able to broadcast a safety packet during its reserved EmgSlots without any collision. The main field of each safety packet is divided into five fields which include: an ID, a serviced slot, the IDs of neighbor nodes, the time slot of each neighbor node, safe applications, as shown in Figure 4. The vehicle may occupy an EmgSlot successfully when it transmits a safety packet on the reservation period and all neighbor vehicles confirm an ID and serviced EmgSlot of this contended vehicle. Otherwise, a vehicle fails to occupy an EmgSlot successfully. Thus, if the vehicles could not reserve the EmgSlots successfully, they should broadcast HELLO packets in the next SI to reserve the Emgslots. In this study, we assumed each vehicle has only a safety application packet to broadcast in the CCHI. Since safety packet broadcast and HELLO packet broadcast use the same mechanism to be disseminated, we used the same Markov chain model to analyze both safety and HELLO packets broadcast, as shown in Figure 5. We assumed the payload of both safety and HELLO packets have the same length.

ID	SerSlot	IDs of neighbor nodes	The time slot used by each neighbor node	Safety applications

Figure 4. Safety Packet Frame

However, the unidimensional process $b_e(t)$ of safety and HELLO packets are 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 $(0, 1, 2, \dots, W_i - 1)$ for a given station at slot time t. Since the transmission of safety and HELLO packets are in broadcast mode, and have the highest priority, the back-off stages are disabled. The state of this process is denoted by (k). From Figure 5 of state transition diagram of Markov chain for the safety process, the non-null transition probabilities are written as follows:

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

Here are the non-null transition probabilities to describe the unavailability of packets transmission in the buffer, hence changing the station into idle ($b_{\mathrm{e,Idle}}$) state after a successful transmission.

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

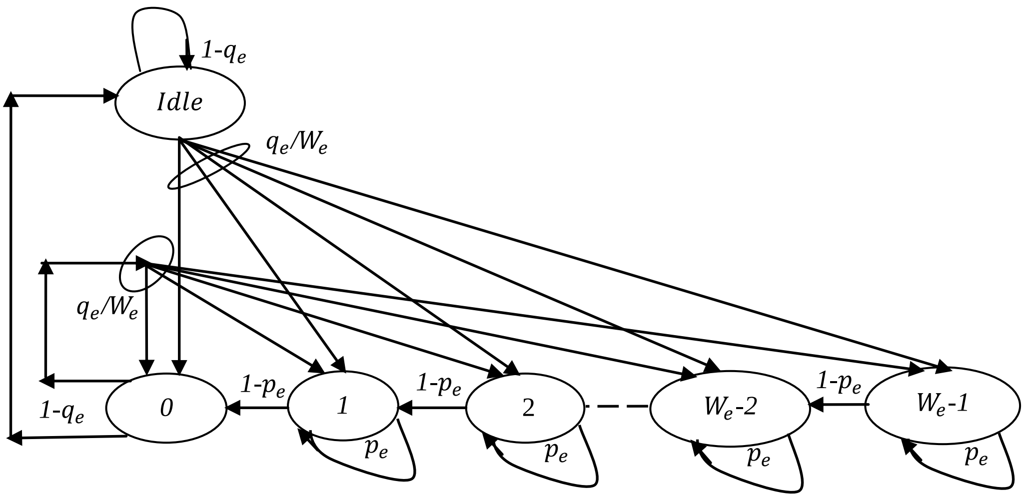


Figure 5. Markov Chain Model of The Safety Applications

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 safety process. From the Markov chain, the stationary distribution of $b_{e,Idle}$ and $b_{e,k}$ are calculated as follows:

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

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

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

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

$$1 = b_{e,Idle} + \sum_{k=0}^{W_e-1} b_{e,k}$$

$$1 = b_{e,Idle} + b_{e,0} + \sum_{k=1}^{W_e-1} b_{e,k}$$

$$1 = b_{e,Idle} + b_{e,0} + \sum_{k=1}^{W_e-1} \frac{w_e - k}{w_e} \frac{1}{1-p_e} b_{e,0}$$

$$1 = b_{e,Idle} + b_{e,0} + \frac{1}{1-p_e}\frac{W_e-1}{2}b_{e,0}$$

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

Hence, from (6), we obtain (7)

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

Now we can express the probability τ_e that a vehicle can transmit safety or HELLO packet in an arbitrary slot time. The vehicle can only transmit when the back-off time counter is zero ($b_{e,0}$).

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

The collision probability p_e when more than one vehicle transmits a packet at the same slot time is given by

$$p_e = 1-(1-\tau_e)^{n-1} \quad (9)$$

We notice that the value of τ_e depends on the conditional collision probability p_e and probability of at least one safety or HELLO packet in buffer q_e. The collision probability occurs when more than one vehicle is transmitting in the same time slot. From equations (8) and (9), we can solve the unknowns τ_e and p_e by using numerical techniques in order to calculate the packet delivery ratio (PDR). Note that $0 \le \tau_e \le 1$ and $0 \le p_e \le 1$. The PDR of the safety applications in the legacy is

$$PDR_{\text{legacy}} = \frac{p_{e,s}}{n\tau_e} = (1-\tau_e)^{n-1} \quad (10)$$

During the safety or HELLO packet interval, let $p_{e,i}$, $p_{e,b}$, $p_{e,s}$, and $p_{e,c}$ denote the probability of an idle channel, the probability of a busy channel, the probably of successful transmission, and the probability of collision transmission respectively, which are computed with

$$\begin{cases} p_{e,i} = (1-\tau_e)^n \\ p_{e,b} = 1-(1-\tau_e)^n \\ p_{e,s} = n\tau_e(1-\tau_e)^{n-1} \\ p_{e,c} = p_{e,b} - p_{e,s} \end{cases} \quad (11)$$

Let $T_{e,s}$, $T_{e,c}$, σ, and δ are the average times that the channel is sensed busy due to a successful transmission of safety or HELLO packet, and the average time that the channel is sensed busy by each vehicle during a collision because of the safety or HELLO packet, the duration of the slot time, and the propagation delay respectively.

$$T_e = T_{e,s} = T_{e,c} = T_{safe} + DIFS + \delta = T_{HELLO} + DIFS + \delta \quad (12)$$

The average duration of the logical slot T_{slot} that might be spent for each process (successful transmission, collision or idle) in the system is given by

$$T_{slot} = (1-p_{e,b})\sigma + p_{e,b}(1-p_{e,s})T_e + p_{e,b}p_{e,s}p_{e,c}T_e + p_{e,b}p_{e,s}(1-p_{e,c})T_e \quad (13)$$

The traffic arrival rate for safety applications in VANETs satisfy the Poisson distribution, which is denoted by λ_e, while *M/G/1* is the queue of each station. The load equation of probability of at least one safety packet q_e in the buffer is given by

$$q_e = 1 - e^{-2\lambda_e T_{slot}} \quad (14)$$

As mentioned earlier, based on the HER-MAC protocol, in case vehicles couldn't reserve the EmgSlots successfully, they will broadcast HELLO packets in the next SI to reserve Emgslots. HER-MAC protocol exploits the whole SI (*100ms*) to transmit safety and HELLO packets concurrently, while the legacy takes half of SI (*50ms*) to transmit safety packets. Thus, after *50ms*, in HER-MAC protocol, the average number of vehicle that fails to transmit HELLO packets successfully is $n_2 = np_e$. By substituting n_2 for *n* in equation (9), we can solve the unknowns τ_{e2} and p_{e2}. The PDR of safety packet in the second SI is $PDR_2 = (1-\tau_{e2})^{n_2-1}$. The PDR of HELLO packets of HER-MAC protocol through the SI (*100 ms*) is defined by

$$PDR_{HER-MAC} = 1 - \left(1 - PDR_{legacy}\right)(1 - PDR_2) \tag{15}$$

3.2. Case 2: Probability of Frame Transmission τ_e Uses CSMA/CA Access Method

Typically the transmission of safety applications are in broadcast mode and independent of transmission of service application, thus, we keep using the Markov model in case 1 to analyze the transmission of safety applications. In order to analyze the probability of frame transmission τ_s of service applications (WSA/RES), let $s_s(t)$ be the random variable representing the back-off stage $(0, 1, 2, \dots, m)$ for a given station at slot time t. Note that, $b_s(t)$ is the random variable representing the value of the back-off timer $\left(0, 1, 2, \dots, W_{s,i} - 1\right)$ for a given station at slot time t. Typically, the maximum value of the back-off timer relies on the back-off stage. Hence, these random variables are not independent.

$$W_{s,i} = \begin{cases} 2^i W_s, & i \le m' \\ 2^{m'} W_s, & i > m' \end{cases} \tag{16}$$

W_s is the initial size of the contention window of service application, $W_s = (CW_{min} + 1)$, while m' is the maximum number in 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. Let p_s denotes the probability of collision that more than one vehicle transmits in the same slot time simultaneously, and q_s be the probability of at least one new WSA/RES packet in the buffer.

Nevertheless, the bi-dimensional $(s_s(t), b_s(t))$ processes for service applications are analyzed here with a discrete-time Markov chain at which the channel state changes. The state of this process is denoted by (i, k). Figure 6 exhibits the state transition diagram of Markov chain for the service process, and the non-null transition probabilities are written as follows:

$$\begin{cases} P(i,k \mid i,k+1) = 1 - p_s, & 0 \le k \le W_{s,i} - 2, \quad 0 \le i \le m \\ P(i,k \mid i,k) = p_s, & 1 \le k \le W_{s,i} - 1, \quad 0 \le i \le m \\ P(i,k \mid i-1,0) = p_s/W_{s,i}, & 0 \le k \le W_{s,i} - 1, \quad 1 \le i \le m \\ P(0,k \mid i,0) = (1 - p_s)/W_s, & 0 \le k \le W_s - 1, \quad 0 \le i \le m \\ P(0,k \mid m,0) = 1/W_s, & 0 \le k \le W_s - 1, \end{cases} \tag{17}$$

Here are the non-null transition probabilities to describe the unavailability of packet transmissions in the buffer which are redirected into idle ($b_{s,Idle}$) state after successful transmission.

$$\begin{cases} P(Idle \mid i,0) = (1 - p_s)(1 - q_s), & 0 \le i \le m - 1 \\ P(Idle \mid m,0) = 1 - q_s \\ P(Idle \mid Idle) = 1 - q_s \\ P(0,k \mid Idle) = q_s/W_s, & 0 \le k \le W_s - 1 \end{cases} \tag{18}$$

Let $b_{s,i,k} = lim_{t\to\infty} \mathrm{P}\{s_s(t) = i, b_s(t) = k\}$ 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

$$\begin{aligned} &b_{s,i-1,0} \cdot p_s = b_{s,i,0} \rightarrow b_{s,i,0} = {p_s}^i \cdot b_{s,0,0} \qquad 0 < i \le m \\ &b_{s,m,0} = p_s b_{s,m-1,0} \end{aligned} \tag{19}$$

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

$$b_{s,i,k} = \frac{W_{s,i} - k}{W_{s,i}(1-p)} \begin{cases} q_s(1 - p_s)\sum_{i=0}^{m-1} b_{s,i,0} + q_s b_{s,m,0} + q_s b_{s,Idle} & i = 0 \\ p_s \cdot b_{s,i-1,0} & 0 < i \le m \end{cases} \tag{20}$$

Or

$$b_{s,i,k} = \frac{W_{s,i}-k}{W_{s,i}} \frac{1}{(1-p_s)} b_{s,i,0} \quad for\ 0 \le i \le m,\ \ 1 \le k \le W_{s,i}-1 \tag{21}$$

$$b_{s,idle} = (1-q_s)(1-p_s)\sum_{i=0}^{m-1} b_{s,i,0} + (1-q_s)b_{s,m,0} + (1-q_s)b_{s,idle} \tag{22}$$

Mathematically solving (22), we obtain (23)

$$b_{s,idle} = \frac{1-q_s}{q_s} b_{s,0,0} \tag{23}$$

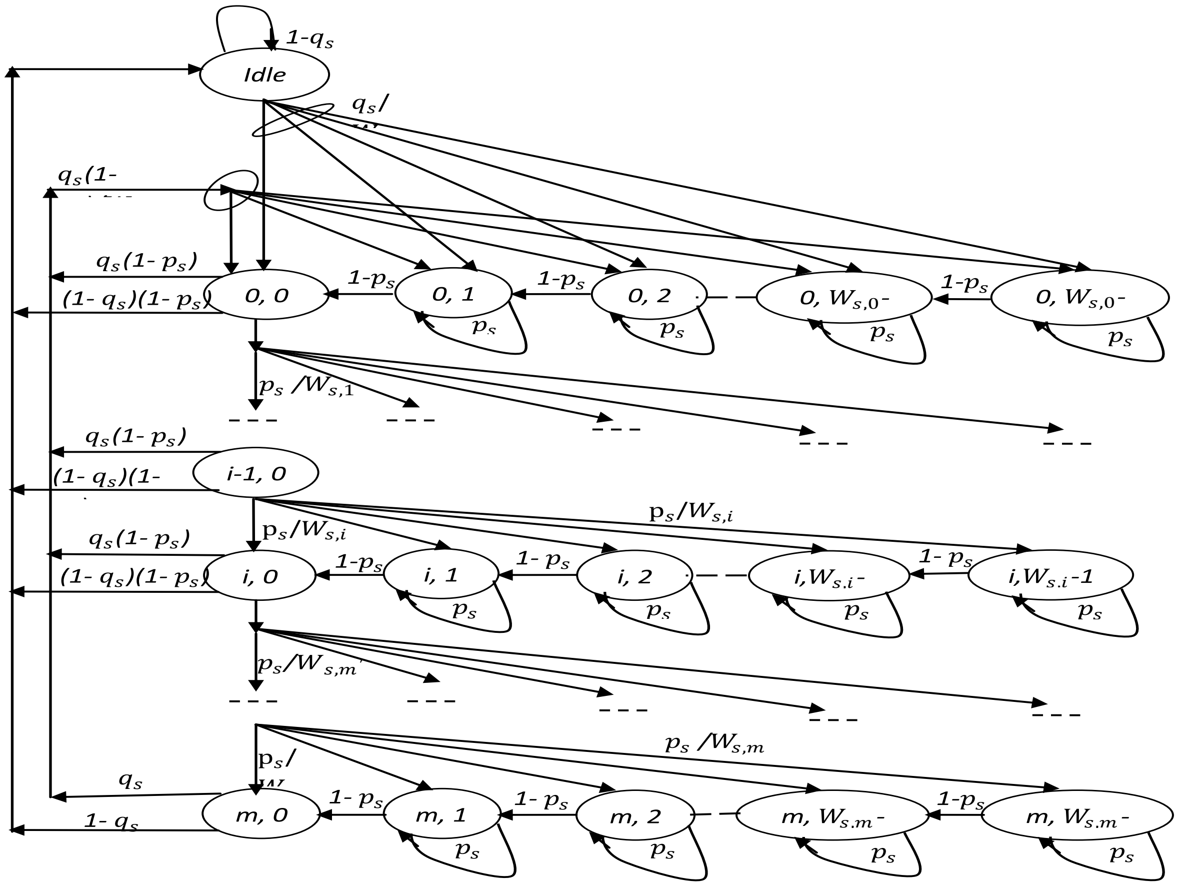


Figure 6. Markov Chain Model of the Service Applications

Thereby, the normalization condition of stationary distribution is used which is elaborated as the following:

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_{s,i}-1} b_{s,i,k} + b_{s,idle}$$
$$1 = \sum_{i=0}^{m} b_{s,i,0} + \sum_{i=0}^{m} \sum_{k=1}^{W_{s,i}-1} b_{s,i,k} + b_{s,idle}$$
$$1 = \sum_{i=0}^{m} b_{s,i,0} + \sum_{i=0}^{m} \sum_{k=1}^{W_{s,i}-1} \frac{W_{s,i}-k}{W_{s,i}} \frac{1}{(1-p_s)} b_{s,i,0} + b_{s,idle}$$
$$1 = \sum_{i=0}^{m} b_{s,i,0} + \frac{1}{1-p_s}\sum_{i=0}^{m} b_{s,i,0} \frac{W_{s,i}-1}{2} + b_{s,idle}$$
$$1 = \sum_{i=0}^{m} b_{s,i,0} + \frac{1}{1-p_s}\sum_{i=0}^{m} b_{s,i,0} \frac{W_{s,i}-1}{2} + \frac{1-q_s}{q_s} b_{s,0,0}$$
$$1 = \sum_{i=0}^{m} {p_s}^i b_{s,0,0} + \frac{1}{2(1-p_s)}\left[\sum_{i=0}^{m} (2p_s)^i W_s b_{s,0,0} - \sum_{i=0}^{m} {p_s}^i b_{s,0,0}\right] + \frac{1-q_s}{q_s} b_{s,0,0} \tag{24}$$

Mathematically solving (24), we obtain (25)

$$b_{s,0,0} = \begin{cases} \frac{2(1-p_s)^2(1-2p_s)q_s}{£}, & m \le m' \\ \frac{2(1-p_s)^2(1-2p_s)q_s}{¥}, & m > m' \end{cases} \quad (25)$$

where

$$£ = (1-2p_s)^2(1-{p_s}^{m+1})q_s + W_s(1-p_s)(1-(2p_s)^{m+1})q_s \\ +2(1-p_s)^2(1-2p_s)(1-q_s) \quad (26)$$

$$¥ = (1-2p_s)^2(1-{p_s}^{m+1})q_s + W_s(1-p_s)\left(1-(2p_s)^{m'+1}\right)q_s + 2^{m'}w_s {p_s}^{m'+1}\left(1-{p_s}^{m-m'}\right) \\ (1-2p_s)q_s + 2(1-p_s)^2(1-2p_s)(1-q_s) \quad (27)$$

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

$$\tau_s = \sum_{i=0}^{m} b_{s,i,0} = b_{s,0,0}\frac{1-{p_s}^{m+1}}{1-p_s} \quad (28)$$

We notice that the values of τ_s depend on the conditional collision probability p_s and the probability of at least one WSA/RES packet in the buffer q_s respectively. The collision probability occurs when more than one vehicle is transmitting in the same time slot simultaneously.

The collision probabilities, p_e and p_s of safety and service applications are defined as follows:

$$p_e = 1-(1-\tau_e)^{n-1}(1-\tau_s)^n \quad (29)$$

$$p_s = 1-(1-\tau_s)^{n-1}(1-\tau_e)^n \quad (30)$$

From equations (8), (28), (29), and (30), we can solve the unknown τ_e , τ_s by using numerical techniques. Let $p_i^{e,s}$ and $p_b^{e,s}$ denote the probability of an idle and busy channel respectively during a given slot. The probably of successful transmission for safety and service packets are denoted respectively by p_s^e, p_s^s. The collision transmission could happen with safety packet only p_c^e, service packet only p_c^s, or by both $p_c^{e,s}$. Therefore, we have

$$\begin{cases} p_i^{e,s} = (1-\tau_e)^n(1-\tau_s)^n \\ p_b^{e,s} = 1-(1-\tau_s)^n(1-\tau_e)^n \\ p_s^e = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n \\ p_s^s = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n \\ p_c^e = (1-\tau_s)^n(1-(1-\tau_e)^n - n\tau_e(1-\tau_e)^{n-1}) \\ p_c^s = (1-\tau_e)^n(1-(1-\tau_s)^n - n\tau_s(1-\tau_s)^{n-1}) \\ p_c^{e,s} = p_b^{e,s} - p_s^e - p_s^s - p_c^e - p_c^s \end{cases} \quad (31)$$

In general, the system in VANETs can be either in broadcast mode or ACK with RTS/CTS access mechanism for safety and service applications transmission respectively. Thus, let $T_{WSA}, T_{RES}, T_{ACK}$, and T_{safe} be the transmission time of a WSA, RES, ACK, and safety application respectively, assuming that $T_{WSA} = T_{RES}$ and $T_{safe} = T_{WSA}$. T_{SIFS} and T_{DIFS} are the duration time of SIFS and DIFS respectively. The duration of a free slot time, the average time that the channel is sensed busy due to a successful reservation, and the average time that the channel is sensed busy by each node during a transmission collision are denoted respectively by T_i , T_s^s, and T_c^s.

$$\begin{cases} T_i = aSlotTime \\ T_s^s = T_{WSA} + T_{RES} + 2T_{SIFS} + T_{ACK} + 3\delta + T_{DISF} \\ T_c^s = T_{WSA} + \delta + T_{DISF} \\ T_s^e = T_c^e = T_{safe} + \delta + T_{DISF} \end{cases} \quad (32)$$

The average duration of the logical slot T_{slot} that might be spent for each process (successful transmission, collision or idle) in the system is given by

$$T_{slot} = (1 - p_b^{e,s})\sigma + p_s^e T_s^e + p_s^s T_s^s + p_c^e T_c^e + p_c^s T_c^s + p_c^{e,s} \max(T_c^e, T_c^s) \quad (33)$$

The traffic arrival rate for safety and service applications in VANETs satisfy Poisson distribution denoted, which are by λ_e, λ_s, in which the traffic arrival rate for service applications are exponentially distributed, while *M/G/1* is the queue of each station. The load equations of probability of at least one safety q_e or WSA/RES q_s packet in the buffer are given respectively by

$$q_e = 1 - e^{-\lambda_e T_{slot}} \quad (34)$$

$$q_s = 1 - e^{-\lambda_s T_{slot}} \quad (35)$$

The packet delivery ratio (PDR) of the safety packet in the legacy is derived as the probability of having a successful transmission, given that the slot is busy

$$PDR_{legacy} = \frac{p_s^e}{n\tau_e} = (1 - \tau_e)^{n-1}(1 - \tau_s)^n \quad (36)$$

Based on the HER-MAC protocol, the safety packets are transmitted twice and the successful transmission during CCHI is the same with the legacy as in (36). HER-MAC protocol also utilizes the CCH during the SCHI to transmit safety and WSA/RES packets. The PDR of the safety applications is also similar with the legacy. Thereby, the PDR of safety application in HER-MAC protocol is computed as

$$PDR_{HER-MAC} = 1 - \left(1 - PDR_{legacy}\right)^2 \quad (37)$$

4. PERFORMANCE EVALUATION MODEL

In the following sections, we discuss and compare the analysis of the simulation and numerical results of our Markov models and the previous models by [22], to gain better understanding on the behavior of broadcasting safety applications in HER-MAC protocol in VANETs. We validated the simulation results of our models with network simulator (ns-2) version 2.34, while the numerical results were obtained using Matlab. The data rate R for MAC layer channel was set to 6 Mbps for all vehicles. The traffic arrival rate of safety and HELLO packets was fixed at 200 packets/second (pkts/sec), while the traffic arrival rate of service applications was 50 pkts/sec, more parameter values are summarized in Table 1. The performance evaluation of the proposed and existing models in terms of PDR with respect to the number of vehicles *n* and contention window W_e is scrutinized in this paper.

Safety applications are a part of VANETs applications, thus, in this paper we examined the behavior of broadcasting the safety packets according to HER-MAC protocol. As the safety applications are in broadcast mode, the ACK mechanism and retransmission are disabled. In case 1, each vehicle has to reserve an EmgSlot in order to broadcast a safety packet during its reserved EmgSlots without any collision. If a vehicle fails to reserve the EmgSlots successfully and it has safety packets to broadcast, a vehicle should try to broadcast HELLO packets in the next SI to reserve an Emgslot based on HER-MAC protocol. Figure 7 and 8 illustrate the performance of the proposed and existing model in terms of PDR with respect to different number of vehicles, *n* and contention window W_e. It is clear from Figure 7 that the PDR of the network is strongly affected by the number of vehicles and contention window W_e. Accordingly, it is notable from Figure 7 that along with the increase in vehicles, the PDR of the network decreases for both proposed and existing model [22]. This is because of the inversely proportional relationship between the PDR and number of vehicles, thus it is believed that the collision probability at the same time slot increases with the increase of vehicles in the network. This then leads to a lower value of PDR. Between our proposed model derived in this study and the model by [22], Figure 7 clearly marks high values of PDR from our models with percentage increase of 121%. This is due to the freezing of the back-off timer that has been taken into consideration in our model, which provides an accurate estimation of the channel access and yields more precise results of the PDR. On the other hand, Figure 8 offers the effect of various initial contention window sizes W_e on the values of PDR. We can see from the Figure 8 that along with increasing W_e, the values of PDR on the network increase as well for both proposed and existing model [22]. This is because of the longer interval backoff time among vehicles for transmitting a safety packet, which leads to the lower probability of choosing the same timeslot value by more than one vehicle. Figure 8 also displays that higher values of PDR are achieved by our proposed model derived in this paper with percentage increase of 53.1% as compared to the existing model [22].

Table 1. Parameters Values

Parameters	Value
Channel capacity	6 Mbps
Safety application	100 bytes
WSA	100 bytes
HELLO	100 bytes
RES	14 bytes
ACK	14 bytes
SIFS	16 μs
Slot time σ	9 μs
DIFS	34 μs
Propagation delay δ	1μs
Number of SerSlots *M*	5
λ_e	200 pkts/sec
λ_s	50 pkts/sec
Minimum W_e	8
Minimum W_s	16
Maximum Retry limit	5

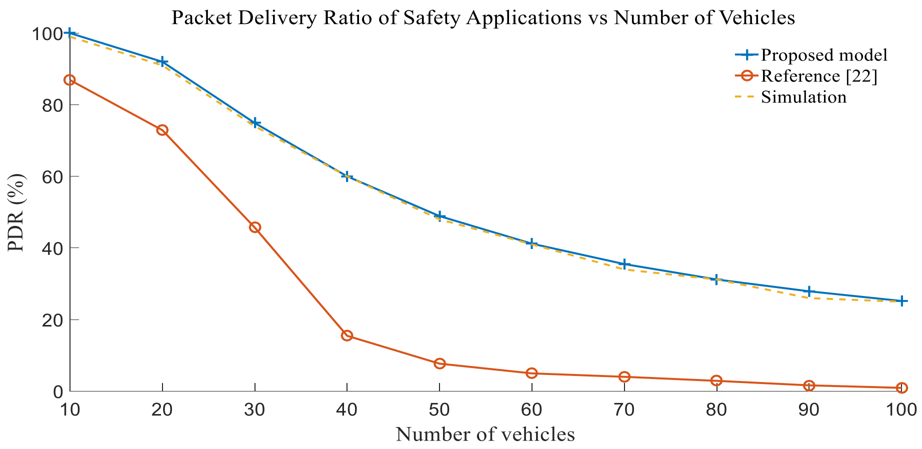


Figure 7. Packet Delivery Ratio of Safety Applications vs Number of Vehicles

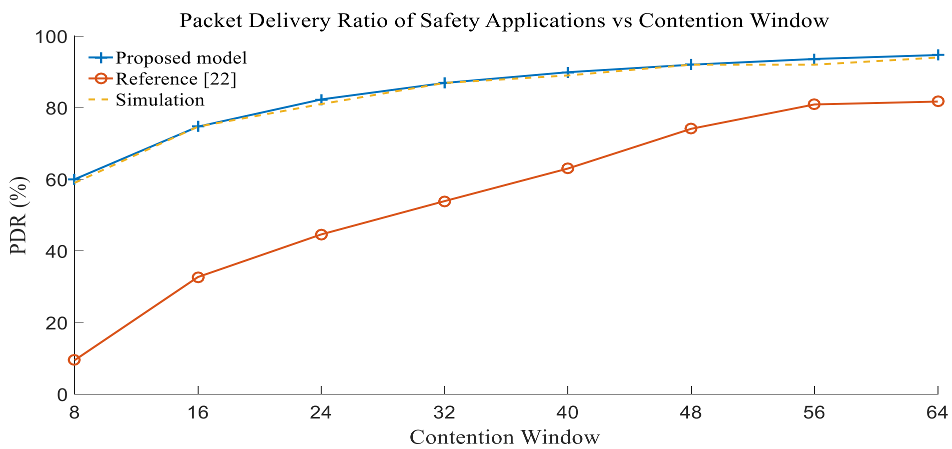


Figure 8. Packet Delivery Ratio of Safety Applications vs Contention Window (W_e)

In case 2, according to HER-MAC protocol, the safety and WSA/RES packets are transmitted simultaneously in the second half of the SI (*50 ms*). Figures 9 and 10 are the same as in case 1, the PDR of the network is affected by the number of vehicles and contention window sizes. Since HER-MAC protocol utilizes this interval to transmit both safety and WSA/RES packets concurrently, by increasing the number of vehicles, probability of choosing the same timeslot value by more than one vehicle is high, which causes higher collision among vehicles and lower PDR in the network compared to case 1. Between the proposed models derived in this study and the model by [22], Figure 9 and 10 clearly mark high values of PDR from our models with percentage increase of 96.2% and 57% respectively. This is due to the freezing of the back-off timer and the frame retry limit of service application that were taken into consideration in our models which provides an accurate estimation of the channel access, and yields more precise results of the PDR.

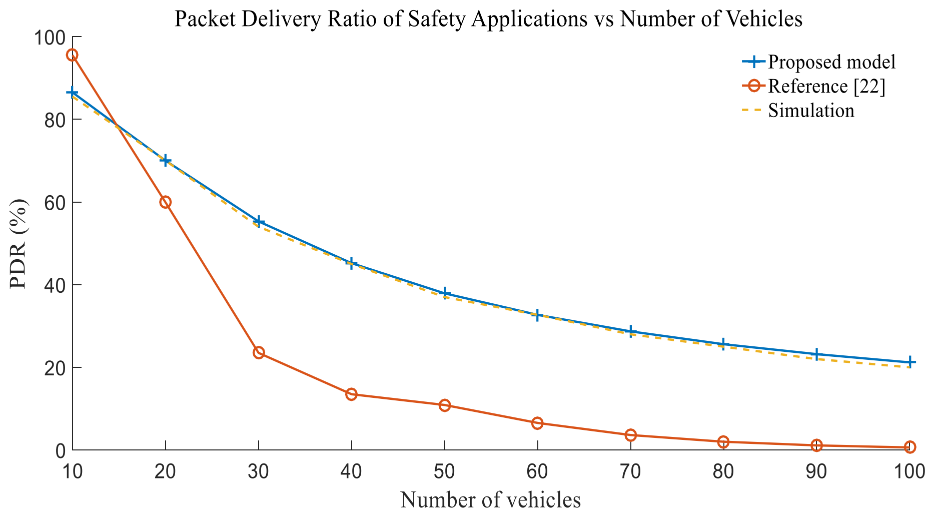


Figure 9. Packet Delivery Ratio of Safety Applications vs Number of Vehicles

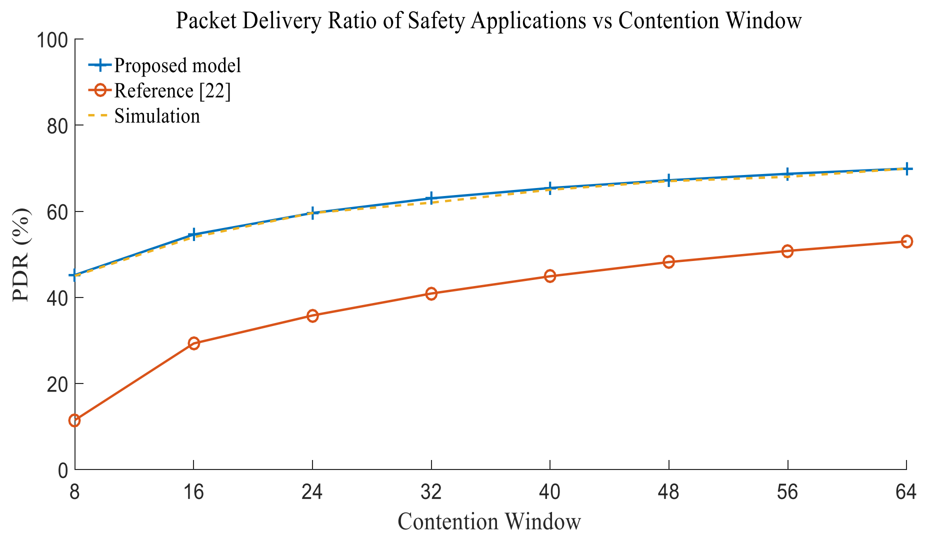


Figure 10. Packet Delivery Ratio of safety applications vs Contention Window (W_e)

5. CONCLUSION

In this paper, we present an improved 1-D and 2-D Markov chain models for both safety and non-safety applications concurrently, to analyze and evaluate the performance of HER-MAC protocol under non-saturated conditions, in which a buffer was added to hold the packets during traffic arrival when the channel is busy. Backoff freezing along with short retry limit were considered in our models to accommodate the IEEE 802.11p specifications to obtain an accurate system packet delivery ratio. The models' performance was evaluated based on TDMA and CSMA/AC access methods. The packet delivery ratio was the only metric chosen to evaluate the models' performance under different number of vehicles and contention window sizes. The simulation results have validated the analytical results of our models. The results show that our models significantly outperform the existing model in terms of the packet delivery ratio.

REFERENCES

[1] Piran M. J., *et al.*, "Vehicular ad hoc and sensor networks; principles and challenges," arXiv preprint arXiv:11082776, 2011.

[2] Sichitiu M. L. and Kihl M., "Inter-vehicle communication systems: a survey," *Communications Surveys & Tutorials, IEEE*, vol/issue: 10(2), pp. 88-105, 2008.

[3] Shuhaimi N. I., *et al.*, "Performance Analysis for Uniform and Binomial Distribution on Contention Window using DSRC and Wi-Fi Direct Standard," *International Journal of Electrical and Computer Engineering*, vol/issue: 5(6), 2015.

[4] Almohammedi A. A., *et al.*, "Evaluating the Impact of Transmission Range on the Performance of VANET," *International Journal of Electrical and Computer Engineering (IJECE)*, vol/issue: 6(2), pp. 800-9, 2016.

[5] Hadded M., *et al.*, "TDMA-Based MAC Protocols for Vehicular Ad Hoc Networks: A Survey, Qualitative Analysis, and Open Research Issues," *Communications Surveys & Tutorials, IEEE*, vol/issue: 17(4), pp. 2461-92, 2015.

[6] Dong W., *et al.*, *"A new load equation for 802.11 MAC performance evaluation under non-saturated conditions,"* Communications in China (ICCC), 2012 1st IEEE International Conference on, IEEE, 2012.

[7] Daneshgaran F., *et al.*, "Unsaturated throughput analysis of IEEE 802.11 in presence of non ideal transmission channel and capture effects," *Wireless Communications, IEEE Transactions on.*, vol/issue: 7(4), pp. 1276-86, 2008.

[8] Bianchi G., "Performance analysis of the IEEE 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*., vol/issue: 18(3), pp. 535-47, 2000.

[9] Wu H., *et al.*, *"Performance of reliable transport protocol over IEEE 802.11 wireless LAN: analysis and enhancement,"* INFOCOM 2002 Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies Proceedings IEEE, 2002.

[10] Daneshgaran F., *et al.*, "Saturation throughput analysis of IEEE 802.11 in the presence of non ideal transmission channel and capture effects," *Communications, IEEE Transactions on*., vol/issue: 56(7), pp. 1178-88, 2008.

[11] Malone D., *et al.*, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Transactions on networking*, vol/issue: 15(1), pp. 159-72, 2007.

[12] Gupta N. and Rai C. S., "Performance Evaluation of IEEE 802.11 DCF in Single Hop Ad Hoc Networks," *Wireless Personal Communications*, vol/issue: 79(3), pp. 2171-93, 2014.

[13] Wen J. H., *et al.*, "The performance study of IEEE 802.11 E EDCF in channel error environments," *Broadband Multimedia Systems and Broadcasting (BMSB), 2010 IEEE International Symposium on*, IEEE, 2010.

[14] Woo R., *et al.*, "Performance analysis for priority-based broadcast in vehicular networks," *International Journal of Distributed Sensor Networks*, 2013.

[15] Hafeez K. A., *et al.*, "Impact of mobility on VANETs' safety applications," *Global Telecommunications Conference (GLOBECOM 2010)*, IEEE, 2010.

[16] Lun T., *et al.*, "Optimized beaconing rate control for vehicular Ad-hoc networks," *The Journal of China Universities of Posts and Telecommunications*, vol/issue: 22(6), pp. 10-50, 2015.

[17] Ghandour A. J., *et al.*, "Dissemination of safety messages in IEEE 802.11 p/WAVE vehicular network: Analytical study and protocol enhancements," *Pervasive and Mobile Computing*, vol. 11, pp. 3-18, 2014.

[18] Wang Q., *et al.*, "An IEEE 802.11 p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks," *Intelligent Transportation Systems, IEEE Transactions on*., vol/issue: 13(2), pp. 449-58, 2012.

[19] Han C., *et al.*, "Analytical study of the IEEE 802.11 p MAC sublayer in vehicular networks," *Intelligent Transportation Systems, IEEE Transactions on*., vol/issue: 13(2), pp. 873-86, 2012.

[20] Dang D. N. M., *et al.*, "Performance Analysis of the IEEE 802.11 p under Finite Traffic Conditions," *AETA 2013: Recent Advances in Electrical Engineering and Related Sciences: Springer*, pp. 191-9, 2014.

[21] Dang D. N. M., *et al.*, "HER-MAC: A hybrid efficient and reliable MAC for vehicular ad hoc networks," *2014 IEEE 28th International Conference on Advanced Information Networking and Applications*, IEEE, 2014.