Performance Analysis and Enhancement of the DSRC for VANET's Safety Applications

Khalid Abdel Hafeez, *Student Member, IEEE*, Lian Zhao, *Senior Member, IEEE*, Bobby Ma, *Senior Member, IEEE*, and Jon W. Mark, *Life Fellow, IEEE*

***Abstract*—An analytical model for the reliability of a dedicated short-range communication (DSRC) control channel (CCH) to handle safety applications in vehicular ad hoc networks (VANETs) is proposed. Specifically, the model enables the determination of the probability of receiving status and safety messages from all vehicles within a transmitter's range and vehicles up to a certain distance, respectively. The proposed model is built based on a new mobility model that takes into account the vehicle's follow-on safety rule to derive accurately the relationship between the average vehicle speed and density. Moreover, the model takes into consideration 1) the impact of mobility on the density of vehicles around the transmitter, 2) the impact of the transmitter's and receiver's speeds on the system reliability, 3) the impact of channel fading by modeling the communication range as a random variable, and 4) the hidden terminal problem and transmission collisions from neighboring vehicles. It is shown that the current specifications of the DSRC may lead to severe performance degradation in dense and high-mobility conditions. Therefore, an adaptive algorithm is introduced to increase system reliability in terms of the probability of successful reception of the packet and the delay of emergency messages in a harsh vehicular environment. The proposed model and the enhancement algorithm are validated by simulation using realistic vehicular traces.**

***Index Terms*—Connectivity, dedicated short-range communication (DSRC), IEEE 802.11p, Markov chain, medium access control (MAC), mobility, reliability, vehicular ad hoc network (VANET).**

I. INTRODUCTION

THE RESEARCH and application development in vehicular ad hoc networks (VANETs) have been driven by dedicated short-range communication (DSRC) technology or IEEE 802.11p [1], which is designed to help drivers travel more safely and reduce the number of fatalities due to road accidents. The IEEE 802.11p medium access control (MAC) uses carrier sense multiple access with collision avoidance and some concepts from the enhanced distributed channel access (EDCA) [2]. In this technology, there are four access classes (ACs) with different arbitration interframe space numbers (AIFSNs) to insure less waiting time for high-priority packets, as listed in Table I.

TABLE I
CONTENTION PARAMETERS FOR IEEE802.11p CCH [4]

AC No.	Access Class	CWmin	CWmax	AIFSN
0	Background Traffic (BK)	15	1023	9
1	Best Effort (BE)	7	15	6
2	Voice (VO)	3	7	3
3	Video (VI)	3	7	2

The DSRC is licensed at 5.9 GHz with a 75-MHz spectrum, which is divided into seven 10-MHz channels and a 5-MHz guard band. The control channel (CCH) will be used for safety applications, whereas the other six channels, called service channels (SCHs), will be used for infotainment or commercial applications to make this technology more cost effective. Vehicles will synchronize the switching between the CCH and one or more of the SCHs; hence, safety-related messages would not be missed or lost. The synchronization interval (SI) contains a CCH interval (CCI), followed by a SCH interval [3]. Increasing the CCI will enhance the reliability of safety applications and challenge the coexistence of both safety and nonsafety applications on the DSRC.

The VANET is a self-organizing network that works on both intervehicle communication (IVC) and vehicle-to-infrastructure communication. In this paper, IVC is taken into consideration, where vehicles will be equipped with sensors and Global Positioning Systems to collect information about their position, speed, acceleration, and direction to be broadcasted to all vehicles within their range. These status messages should be periodically broadcasted in every CCI. In IEEE 802.11p, vehicles will not send any acknowledgement for the broadcasted packets. Therefore, the transmitter cannot detect the failure of the packet reception; hence, the transmitter will not retransmit it. This is a serious problem in collision warning applications where all vehicles behind the accident have to receive the warning message successfully in a short time to avoid chain collisions. This problem motivates us to propose an analytical model for assessing the DSRC reliability and delay, taking into account the multipath fading channel in VANETs, vehicles' high mobility, hidden terminal problems, and transmission collisions. More specifically, the probability of successfully receiving the status messages from all vehicles around the tagged vehicle, the probability of receiving the safety (or emergency) messages from all vehicles up to a certain distance behind the accident scene, and the delay for

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K. A. Hafeez is with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada, and also with University of Ontario Institute of Technology, Oshawa, ON L1H 7K4, Canada (e-mail: kabdelha@ee.ryerson.ca).

L. Zhao and B. Ma are with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada (e-mail: kabdelha@ee.ryerson.ca; lzhao@ee.ryerson.ca; bma@ee.ryerson.ca).

J. W. Mark is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: jwmark@uwaterloo.ca).

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that safety messages to reach their intended recipients will be studied, assuming unsaturated conditions. The proposed model is built based on a new mobility model that takes into account the vehicle's follow-on safety rule to derive accurately the relationship between vehicle's speed and network density.

It is shown that the current specifications of the DSRC may lead to severe performance degradation in dense and high-mobility conditions. Therefore, a new adaptive and mobility-based algorithm (AMBA) is introduced to increase the system reliability in terms of the probability of successful reception of packets and the time delay of emergency messages in a harsh vehicular environment.

II. Related Work

The MAC protocol of IEEE 802.11p [1] is based on the distributed coordination function of IEEE 802.11, which has been investigated extensively in the literature, analytically, and by simulations. Simulation-based analysis of the IEEE 802.11p shows that, as the network density increases, the system latency increases, and the packet successful reception rate decreases [5]–[10]. To ensure a successful reception of emergency messages, Torrent-Moreno *et al.* [7] and Vaneenennaam *et al.* [8] introduced an algorithm to control the load of periodic status messages. The channel access delay of the DSRC has been analyzed in [9] and compared with a self-organizing time-division multiple-access scheme, which has been proven more suitable for VANETs' real-time applications. In [10], Wang and Hassan proposed a framework for sharing the DSRC between vehicular safety and nonsafety applications. By assuming uniform distribution of vehicles on the road, their simulations show that nonsafety applications may have to be severely restricted, such that safety applications are not compromised, particularly in high-density networks.

Many analytical models have been proposed to study the DSRC or, in general, the IEEE 802.11 MAC protocol. Although DSRC is based on IEEE 802.11 and EDCA, the unicast analytical models for IEEE 802.11 [11] and EDCA [12], [13] cannot be used for broadcast communication mode in IEEE 802.11p because no acknowledgment is communicated. Therefore, the transmitter cannot detect a collision from a successful transmission. In [14], a 1-D Markov chain has been used to calculate the delay and the reception rate in VANETs without including the delay in each stage due to a busy channel. Eichler [15] analyzed the DSRC based on the average delay for each AC without taking into account the back-off delay. An analytical model that accounts for the mutual influence among nodes in a multichannel environment and the broadcast message frequency has been proposed in [16]. In this model, Campolo *et al.* assumed the static distribution of vehicles on the road with no hidden terminals. Moreover, they did not take into account how the vehicle speed affects the network density; hence, there is a need to throttle the message transmission frequency to increase the successful reception rate. In [17], an analytical model for the performance of delivering vehicular safety messages is proposed, without taking into account the mobility of vehicles. This model considers only the neighborhood of a single roadside unit operating in a nonsaturation traffic regime. A 2-D Markov chain is used in [18] to model the impact of the differentiated AIFS on a stationary vehicular scenario in an urban intersection. They assume a fixed number of vehicles within the range of the transmitter and have not included vehicle mobility in their model. In [19] and [20], Ma and Chen and Ma and Wu studied the saturation performance of the broadcast scheme in VANETs, taking into account the consecutive freeze situation of the back-off counter. They assume saturation conditions, i.e., stationary distribution without considering the impact of vehicle mobility on the system performance. In [21], an analytical model for delivering safety messages within IVC is derived. They assume a perfect channel access and have not accounted for the hidden terminal problem, collision probability, and vehicle mobility. Hassan *et al.* [22] studied the performance of IEEE 802.11p based on the delay of status packets by modeling each vehicle as an M/G/1 queue with an infinite buffer, without taking vehicle mobility into consideration. In [23], Fallah *et al.* analyzed the effect of different sets of data rates and communication ranges on the performance of the DSRC safety applications. They derive the probability of successful reception without taking the busy channel probability in each back-off stage. They introduced a power control algorithm based only on the average channel occupancy to change only the used communication range. As the channel occupancy increases, they decrease the communication range to maintain an acceptable channel capacity. We will compare their algorithm and the one we have proposed in the analysis and simulation sections.

The connectivity in VANETs has been studied in [24]–[26] based on the assumption that vehicles have a uniform stationary distribution without including VANET mobility. By assuming that vehicle positions are known by either simulation or observation, Jim and Recker in [27] presented an analytical model for VANETs. A mobility model has been derived in [28], considering the arrival of vehicles to a service area as a Poisson distribution. Abuelela *et al.* [29] derived the probability of the end-to-end connectivity between clusters of vehicles distributed uniformly on the road. They introduce a new opportunistic packet-relaying protocol that switches between data muling and local routing with the help of vehicles on the other direction. In contrast to our mobility model, all of these models do not consider how the speed of transmitters and receivers affect the connectivity and the packet reception rates.

The mobility model is a crucial part in analyzing and testing VANET applications. Modeling vehicle mobility is quite challenging since the movement of each vehicle is constrained by many factors such as road topology, movements of neighbor vehicles, information on the messaging signs along the road, and driver's reactions to these factors. In [30], a set of movement changes is introduced, such as changing lanes, slowing down, or even changing routes, to allow a micromobility behavior control. In [31], Sommer and Dressler argued that coupling more than one simulator is an important step toward a realistic VANET mobility model. Therefore, we built our simulations by coupling the mobility model (MOVE) [32] with the micro-traffic simulator Simulation of Urban MObility (SUMO) [33], to produce realistic vehicle movement traces for the network simulator ns-2 [34].

In this paper, we propose an analytical model for the analysis of broadcast services in the DSRC protocol, taking into account the high dynamics of vehicles, the hidden terminal problem, collision probability, and nonsaturation conditions. We also derive the delay for emergency messages to reach their intended recipients. The new analysis is based on a new mobility model that takes into account the vehicle's follow-on safety rule to derive accurately the relationship between the vehicles' density and their speeds. The new mobility model considers how the speeds of transmitters and receivers affect the connectivity and the packet reception rates. It also has the capacity to handle the sudden increase in vehicles' density (from jam, accident, or other events) to keep safe distance between vehicles. The packet reception rate is derived, taking into account the interdistance between the transmitter and all potential receivers and their speeds. The proposed model uses a Markov chain approach, which includes the probability of a busy channel in each state, to derive the probability of transmitting status packets and their delay. An adaptive and mobility-aware algorithm is introduced to enhance the performance of VANETs. Simulation results show that the proposed model is quite accurate, and the proposed algorithm enhances the DSRC performance compared with other algorithms in the literature.

TABLE II
MAIN NOTATIONS FOR THE ANALYTICAL MODEL

Notation	Definition
CCH	Control Channel
SCH	Service Channel
CCI	Control Channel Interval
SCI	Service Channel Interval
SI	Synchronization Interval
AC	Access Class
λ_s	Status message generation rate
L	status packet length in bits
P_t	Transmission power
P_{th}	received power threshold at the communication range
$E[R]$ or $\overline{R}$	Average communication range
$E[L_{CS}]$	Average carrier sense range
P_{CS}	received power threshold at the carrier sense range
$\rho \in (0,1]$	$P_{CS} = \rho P_{th}$
μ	Average vehicle speed
V_{min}	minimum vehicle speed
V_{max}	maximum vehicle speed
N_c	Number of vehicles within the communication range
N_h	Number of hidden terminals
N_l	Number of lanes
d_{th}	Safety distance between two vehicles
β_i	Vehicles arriving rate in the i^{th} lane
β	Total vehicles arriving rate
$\varepsilon \in (0,1]$	fraction of vehicles that follow the following distance safety rule
t_s	Safety time needed to cross the safety distance
ϱ	slot time
$AIFS$	Arbitration Inter frame space
W_s	Minimum contention window for statu message

III. System Model and Performance Parameters

In the safety applications of VANETs, vehicles broadcast two types of messages: warning (event driven) and status messages. While warning messages usually contain safety-related information, status messages are periodically sent to all vehicles within their range and contain vehicle's state information such as speed, acceleration, direction, and position. Therefore, emergency messages will use AC3 since it has the highest priority, as listed in Table I, whereas status messages will use AC0.

In our model, vehicles generate their status messages at a rate of λ_s, which implies that the length of the SI is $\mathrm{SI} = 1/\lambda_s$ [8]. We assume that all packets have the same length of L bits, and the whole SI is dedicated to safety applications, i.e., CCI = SI. Each vehicle will randomly choose a slot within the SI to transmit its status packet, whereas emergency packets are sent only during emergencies, such as an accident or warning from hazards or jam on the road ahead. Based on these assumptions, we analyze the DSRC protocol to find the smallest channel interval that maximizes the reliability of safety applications, resulting in achieving high probability of successfully receiving a status message from each vehicle within this interval.

It is assumed that all vehicles have the same transmitting power P_t, and each vehicle successfully receives the signal if the received power is higher than a certain threshold P_{th}. Since fading is a major characteristic of the VANET channel, the received signal power is random; therefore, the communication range is also a random variable. The cumulative distribution function (cdf) of the communication range $F_R(r)$ and its mean $E[R]$ will be derived in the following. Table II lists all notations for the proposed analytical model.

In the following, different parameters that affect the IEEE802.11p performance will be analyzed. The communication range and the mobility model are first studied to derive the distribution of vehicles on the road that will affect the link availability and duration of connection between vehicles. It also determines the population size of vehicles within the transmitter's range and the number of vehicles in the two interfering (hidden terminal) areas. The effect of the transmitter's and receiver's speed, the contention window, and the carrier sense range on the successful reception rate of packets is then derived.

A. Communication Range

Since VANETs have many moving and stationary objects that can reflect, scatter, diffract or even block the signals, the received signal by any vehicle is composed of many reflected signals with randomly distributed amplitudes and phases. Recently, many studies have paid more attention to the vehicle-to-vehicle channel propagation models. In [5], we showed that the fading channel in VANETs can be characterized by Rician distribution for short distances and tends toward Rayleigh distribution for large distances. Therefore, the Nakagami fading distribution whose parameters can be adjusted to fit a variety of empirical measurements and can model Rayleigh and Rician distributions is used. The Nakagami model has a probability density function (pdf) of the received signal power x [35] as

$$P_{z^2}(x) = \left(\frac{m}{P_r}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m\,x}{P_r}}, \quad \text{for } x \geq 0 \qquad (1)$$

where $\Gamma(\cdot)$ is the Gamma function; $P_r = P_t K / r^\alpha$ is the average received power; r is the distance in meters; α is the path-loss exponent; $K = G_t G_r (C/(4\pi f_c))^2$; C is the speed of light; $f_c = 5.9$ GHz is the carrier frequency, and G_t and G_r are the transmitter's and receiver's antenna gains, respectively; and m is the fading factor. For $m = 1$, the Nakagami distribution reduces to Rayleigh distribution, and for $m = (k+1)^2/(2k+1)$, it approximates a Rician distribution with parameter k, which is the ratio of power in the line of sight to the power in the non-line of sight.

From (1), we can calculate the cdf of the communication range when the received power is greater than the threshold $P_{\rm th}$ as

$$F_R(r) = 1 - P(x \geq P_{\rm th}) = 1 - \int_{P_{\rm th}}^{\infty} P_{z^2}(x)dx. \quad (2)$$

Substituting (1) in (2) and let $u = (mx)/P_r$, the cdf can be written as

$$F_R(r) = 1 - \frac{1}{\Gamma(m)} \int_{\frac{mP_{\rm th}}{P_r}}^{\infty} u^{m-1}e^{-u}du. \quad (3)$$

By using

$$\int x^n\, e^{cx}dx = \left(\frac{d}{dc}\right)^n \frac{e^{cx}}{c}$$

the cdf can be written as

$$F_R(r) = 1 - \frac{1}{\Gamma(m)} \sum_{i=0}^{m-1} \frac{(m-1)!}{(m-1-i)!} \left(\frac{mP_{\rm th}}{P_r}\right)^{m-1-i} e^{-\frac{mP_{\rm th}}{P_r}}. \quad (4)$$

The average value of the communication range $E[R]$ (or $\overline{R}$) can be derived as

$$E[R] = \int_0^{\infty} (1 - F_R(r))\, dr. \quad (5)$$

Substituting (4) in (5) and integrating over the limits, we have

$$E[R] = \frac{1}{\alpha\Gamma(m)} \sum_{i=0}^{m-1} \frac{(m-1)!}{(m-1-i)!} \times \Gamma\left(m-1-i+\frac{1}{\alpha}\right) \left(\frac{mP_{\rm th}}{P_tK}\right)^{-\frac{1}{\alpha}}. \quad (6)$$

To derive the average carrier sense range $E[L_{\rm CS}]$ where nodes can sense the packet but could not receive it, the same procedure as in (6) is followed, except for the received power threshold $P_{\rm CS}$, which will be defined as a percentage of the threshold $P_{\rm th}$ as $P_{\rm CS} = \rho P_{\rm th}$, where $\rho \in (0, 1]$. Therefore, the expected carrier sense range will be

$$E[L_{\rm CS}] = \frac{E[R]}{\sqrt[\alpha]{\rho}}. \quad (7)$$

B. Mobility Model

Although some of the previous models in the literature neglect the effect of vehicle speed on the successful reception of a single packet, it is still of paramount importance to consider it on the successful reception of status and emergency packets.

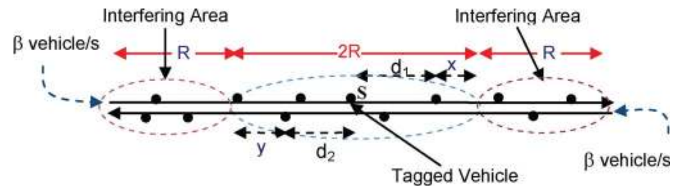

Fig. 1. Simplified 1-D highway scenario.

A small fraction of a second could prevent a fatal accident to occur if the following vehicle managed to stop at least 1 mm from the front vehicle. Vehicles continuously go in and out of the tagged vehicle's communication range. Moreover, in some cases and due to the large number of vehicles, the message could be propagated to all recipients in a multihop fashion, which may increase the time that the message could spend on the MAC layer before it can be delivered without collisions.

The proposed VANET mobility model is built based on a one-way multilane highway segment [36]. Since the communication range is much larger than the width of the road, the network in each direction of the road is simplified as a 1-D VANET, as shown in Fig. 1. Vehicles will follow the direction of the road with a speed uniformly distributed between $V_{\min}$ and $V_{\max}$ with mean $\mu = (V_{\min} + V_{\max})/2$ and variance $\sigma^2 = (v_{\max} - v_{\min})^2/12$. In this model, we are interested in the distribution of vehicles on the road, number of vehicles N_c around the transmitter (contention region), and the number of vehicles N_h in the hidden terminal areas (interference region).

In this model, an arbitrary starting point of the highway is first defined. The number of vehicles that cross the starting point in each lane (assume the road has N_l lanes) is modeled as a Poisson process with average rate β_i vehicles/s for the ith lane, and $\beta = \sum_{i=0}^{N_l} \beta_i$ is the total number of vehicles per second that cross that point. Empirical studies [37] show that the Poisson process is a sufficiently accurate assumption for modeling the vehicle arrival process in a highway scenario. It is assumed that vehicles independently move of each other; hence, according to the central limit theorem, the total distance that a vehicle travels during an interval of $(0, t)$ approaches a normal distribution, and the distance between two vehicles crossing the starting point with time difference τ_d also has normal distribution. Based on this conclusion, the probability of having two vehicles within the communication range of each other is derived [36].

To find the probability of having N_c vehicles within the range of any tagged vehicle, the mobility model is extended to include the minimum safety distance between vehicles in each lane (t_s-second rule). This means that the following vehicle traveling with speed V_j has to keep a safe distance $d_{\rm th}$ from the vehicle in front, such that $d_{\rm th} > V_j t_s$, to avoid an accident if the vehicle in front suddenly stops. This minimum distance is a random variable and depends on the following vehicle's speed V_j if fixed t_s is assumed, which is the response time for a driver to react on a sudden incident. Moreover, the following two cases are considered.

The first case is when the number of vehicles that cross the defined reference point is small such that the interarrival time ($\tau_d = 1/\beta_i$) between vehicles in the ith lane is larger than t_s.

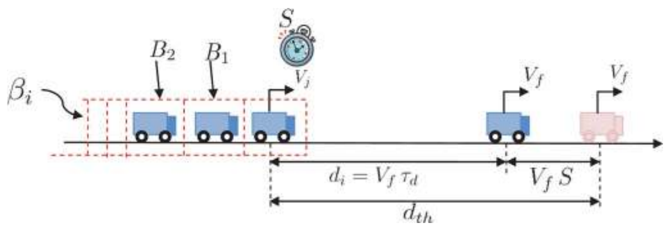

Fig. 2. Single-server queue model.

In this case, the probability of having $N_{c_i} = k$ vehicles within the communication range of the tagged vehicle (i.e., within a distance of $2\overline{R}$) in the ith lane is Poisson distributed [36] as

$$P_{2\overline{R}}(N_{c_i} = k) = \frac{\left(\frac{2\beta_i \overline{R}}{\mu}\right)^k}{k!} e^{-\frac{2\beta_i \overline{R}}{\mu}} \tag{8}$$

and the average number of vehicles around the tagged vehicle in the ith lane is

$$\overline{N_{c_i}} = \frac{2\beta_i \overline{R}}{\mu}. \tag{9}$$

The probability of having $N_{h_i} = k$ vehicles within the carrier sense range of the tagged vehicle is

$$P_{2L_{\mathrm{CS}}}(N_{h_i} = k) = \frac{\left(\frac{2\beta_i \overline{R}}{\mu \sqrt[\alpha]{\rho}}\right)^k}{k!} e^{-\frac{2\beta_i \overline{R}}{\mu \sqrt[\alpha]{\rho}}}. \tag{10}$$

The second case is when the number of vehicles that cross the reference point is large such that the interarrival time between the two following vehicles is less than the safety time t_s. As a consequence, the interdistance between two neighboring vehicles in one lane is less than the threshold distance as

$$d_i = V_f\, \tau_d < V_j\, t_s \tag{11}$$

where V_f and V_j are the in-front and following vehicles' speeds on the ith lane, respectively. In this case, the following vehicle has to reduce its speed to avoid an accident. To derive an expression for this reduction in speed, the system is modeled as a single-server Poisson arrival queue, as shown in Fig. 2. A vehicle is immediately served if the server is empty, and its service time S will be $(S + 1/\beta_i) \cdot V_f = V_j t_s$; therefore

$$S = \frac{V_j}{f} t_s - \frac{1}{\beta_i}. \tag{12}$$

On the other hand, if a vehicle finds that another one is being served (i.e., reducing its speed to maintain the threshold distance), the new vehicle would wait in the queue for time B_1 until the first one finishes the service, i.e., the distance that the vehicle traveled is equal to d_{th}. If another vehicle arrives during time S, it will wait in the queue until all vehicles in front of it have been served, i.e., the distance between any two neighboring vehicles is at least equal to d_{th}. After that, vehicles would move according to new speed limits, which reflect this increase in the interdistances between vehicles. Since the arrival time is Poisson with rate β_i, the number of vehicles $N(s)$ that will arrive during the time S has Poisson distribution, and the server busy time can be modeled as

$$B = E[S] + \sum_{i=1}^{N(S)} B_i. \tag{13}$$

However, for given S, $\sum_{i=1}^{N(S)} B_i$ is a compound Poisson distribution, and its mean $E[B]$ can be derived as

$$E[B] = \frac{E[S]}{1 - \beta_i E[S]}. \tag{14}$$

To derive $E[S]$, it is seen from (12) that S has a ratio distribution, and its mean value is

$$E[S] = E\left[\frac{V_j}{V_f}\right] t_s - \frac{1}{\beta_i}. \tag{15}$$

Define a random variable $Z = V_j/V_f$, which has values in the interval $(V_{\min}/V_{\max}, V_{\max}/V_{\min})$; hence, the pdf of Z can be written as

$$f_Z(z) = \begin{cases} \frac{1}{2(V_{\max}-V_{\min})^2}\left(V_{\max}^2 - \frac{V_{\min}^2}{z^2}\right), & \frac{V_{\min}}{V_{\max}} \leq z < 1 \\ \frac{1}{2(V_{\max}-V_{\min})^2}\left(\frac{V_{\max}^2}{z^2} - V_{\min}^2\right), & 1 \leq z < \frac{V_{\max}}{V_{\min}} \\ 0, & \text{otherwise.} \end{cases} \tag{16}$$

Therefore, $E[Z]$ can be derived as

$$E[Z] = \frac{V_{\max} + V_{\min}}{2(V_{\max} - V_{\min})} \ln\left(\frac{V_{\max}}{V_{\min}}\right). \tag{17}$$

Substituting (17) in (15), we have

$$E[S] = \frac{V_{\max} + V_{\min}}{2(V_{\max} - V_{\min})} \ln\left(\frac{V_{\max}}{V_{\min}}\right) t_s - \frac{1}{\beta_i}. \tag{18}$$

Substituting (18) in (14), the average server busy time is

$$E[B] = \frac{\frac{V_{\max}+V_{\min}}{2(V_{\max}-V_{\min})} \ln\left(\frac{V_{\max}}{V_{\min}}\right) t_s - \frac{1}{\beta_i}}{1 - \beta_i \left[\frac{V_{\max}+V_{\min}}{2(V_{\max}-V_{\min})} \ln\left(\frac{V_{\max}}{V_{\min}}\right) t_s - \frac{1}{\beta_i}\right]}. \tag{19}$$

Equation (19) represents the average time that a vehicle will wait in the queue, such that the interdistance between two following vehicles in one lane is greater than or equal to the threshold distance d_{th}. To reflect this waiting time on the real scenario on the road, vehicles in our model will proportionally reduce their speed with $E[B]$, which is normalized by the number of lanes, and the maximum and current average speeds as $\mu_v = (N_l \mu)/\mu_{\mathrm{new}}$. Initially, $\mu_{\mathrm{new}} = \mu$ and will decrease as the vehicle density increases. Intuitively, increasing the number of lanes on the road will give the drivers more options to change lane and to keep the same speed. At the same time, decreasing the vehicles speed compared with the initial average speed will increase the interarrival time between vehicles, resulting to a decrease in the server busy time. It is clear that the more waiting time, the more reduction in the average speed of all following vehicles until it reaches zero speed, defined as a jam state. In this state, vehicles will come to a complete stop or move at a speed close to zero. Therefore, it is assumed that each vehicle occupies a space of 10 m on average, which is the maximum vehicle density a road lane can handle. The new speeds and their mean are given, respectively, as

$$V_{\max}[\text{new}] = V_{\max} e^{-\varepsilon \frac{E[B]}{\mu_v}} \tag{20}$$

$$V_{\min}[\text{new}] = V_{\min} e^{-\varepsilon \frac{E[B]}{\mu_v}} \tag{21}$$

$$\mu_{\text{new}} = \frac{V_{\max}[\text{new}] + V_{\min}[\text{new}]}{2} \tag{22}$$

where $\varepsilon \in (0, 1]$ is the fraction of vehicles that follow the following distance safety rule. For example, if $\varepsilon = 0.8$, this means that 80% of the vehicles on the road will follow this rule. This percentage will vary from country to country and from city to city; even each lane on a road could have a different value.

From the new values of the maximum and minimum vehicle speeds in (20) and (21), respectively, it is required to calculate a new value of $E[S]$ as $E[S]_{\text{new}}$ and to substitute it in (19) to calculate a new value of $E[B]$ as $E[B]_{\text{new}}$. The new distribution of vehicles will be a new Poisson but with different mean $(2\overline{R}\beta_i)/\mu_{\text{new}}$ if the condition $\beta_i E[S]_{\text{new}} < 1$ is satisfied. Otherwise, the road reaches the jam state. Therefore, the average number of vehicles N_{c_i} within the communication range of any tagged vehicle in the ith lane will be

$$N_{c_i} = \begin{cases} \frac{2\overline{R}\beta_i}{\mu}, & E[S] = 0 \\ \frac{2\overline{R}\beta_i}{\mu_{\text{new}}}, & E[S] \neq 0, \beta_i E[S]_{\text{new}} < 1 \\ \frac{2\overline{R}}{10}, & E[S] \neq 0, \beta_i E[S]_{\text{new}} \geq 1. \end{cases} \tag{23}$$

From (23), it is clear that the proposed mobility model has the capacity to handle sudden reduction of interdistances between vehicles (from jams or other events) to keep the safe distance between vehicles to avoid accidents.

The vehicles' arrival rate and average speed could vary from lane to lane. The leftmost lane could have higher average speed and arrival rate than the rightmost lane. To find the total number of vehicles within the communication range of the transmitter, one can use (23) to calculate the number of vehicles N_{c_i} in each lane and sum them all, such that $N_c = \sum_{i=1}^{N_l} N_{c_i}$. Without loss of generality, assuming that all lanes have the same arrival rate and average speed, then the total number of vehicles that are located within the range of the transmitter is

$$N_c = \begin{cases} \frac{2\overline{R}\beta}{mu}, & E[S] = 0 \\ \frac{2\overline{R}\beta}{\mu_{\text{new}}}, & E[S] \neq 0, \beta E[S]_{\text{new}} < 1 \\ \frac{2\overline{R}}{10} N_l, & E[S] \neq 0, \beta E[S]_{\text{new}} > 1. \end{cases} \tag{24}$$

C. Link Availability Probability

Two vehicles can communicate only if they are within the communication range of each other. Therefore, the probability of successfully receiving a packet depends on the relative speed between the sender and the receiver, the packet transmission time, and the transmitter's range $\overline{R}$. Assume initially that the receiver is at an arbitrary distance from the transmitter but within the communication range at the beginning of the packet transmission. Let d_1 be the distance of the receiver from the sender, which is moving in the same direction of the sender, as shown in Fig. 1. Then, the pdf of this distance is $f_{d_1}(x) = 1/2\overline{R}$. Since the status packet transmission time T_t is very short, assume that the vehicle's speed will not change during this time period. If the receiver is at distance d_1 from the sender, then its new location from the sender at the end of the packet transmission is $d_n = d_1 + (v_x - v_t)T_t$, where v_t and v_x are the transmitter's and receiver's speeds, respectively. Therefore, the probability P_l that a vehicle, which is traveling in the same direction, will successfully receive the packet is when its d_n is still within the transmitter's range as

$$P_l = P\left(-\overline{R} \leq d_1 + (v_x - v_t)T_t \leq \overline{R}\right). \tag{25}$$

From (25), if the receiver's speed $v_x \geq v_t$, then the vehicles located at distances less than $-R$ at the time of transmission are not considered. Therefore, the probability P_{l1} that a vehicle traveling at a higher speed than the transmitter will successfully receive the packet is given by

$$\begin{aligned} P_{l1}(v_t) &= P\left(-\overline{R} \leq d_1 \leq \overline{R} - (v_x - v_t)T_t\right) \\ &= \int_{v_t}^{v_{\max}} \int_{-\overline{R}}^{\overline{R}-(v_x-v_t)T_t} \frac{1}{2\overline{R}} \frac{1}{v_{\max} - v_t} \, dx \, dv_x \\ &= 1 - \frac{v_{\max} - v_t}{4\overline{R}} T_t. \end{aligned} \tag{26}$$

On the other hand, if the receiver's speed $v_x < v_t$, then vehicles located at distances greater than $\overline{R}$ at the time of transmission are not considered. Therefore, probability P_{l2} that a vehicle traveling in lower speed than the transmitter will successfully receive the packet is given by

$$\begin{aligned} P_{l2}(v_t) &= P\left(-\overline{R} + (v_x - v_t)T_t \leq d_1 \leq \overline{R}\right) \\ &= \int_{v_{\min}}^{v_t} \int_{-\overline{R}+(v_x-v_t)T_t}^{\overline{R}} \frac{1}{2\overline{R}} \frac{1}{v_t - v_{\min}} \, dx \, dv_x \\ &= 1 - \frac{v_t - v_{\min}}{4\overline{R}} T_t. \end{aligned} \tag{27}$$

Since a vehicle traveling at a speed lower than the transmitting vehicle's speed with probability $\gamma = (v_t - v_{\min})/(v_{\max} - v_{\min})$, the probability $P_{ls}(v_t)$ that a vehicle traveling in the same direction as the transmitting vehicle will successfully receive the packet is given by

$$P_l(v_t) = P_{l1}(v_t)(1 - \gamma) + P_{l2}(v_t)\gamma. \tag{28}$$

Integrating (28) over the range $v_t \in [v_{\min}, v_{\max}]$ yields the average probability P_l as

$$P_l = 1 - \frac{v_{\max} - v_{\min}}{8\overline{R}} T_t. \tag{29}$$

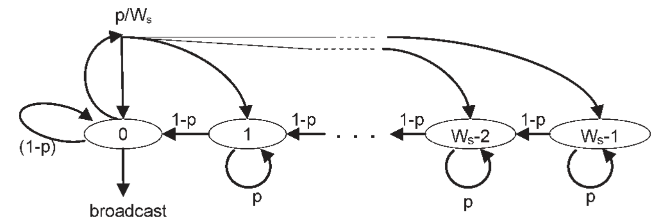

Fig. 3. Markov chain for emergency and status packets.

D. Back-Off Process and Contention Window

In [38], we constructed a model for the back-off counter process of the IEEE 802.11p, assuming unsaturated conditions, as shown in Fig. 3. If a vehicle has a status packet, it will initially wait for a period of AIFS $=$ AIFSN $\cdot\, \varrho$ before it can broadcast the packet, where AIFS is the arbitration interframe space for status packet's AC (chosen here as AC_0); AIFSN is the AIFSN associated with this class, as listed in Table I; and $\varrho = 13\ \mu$s is the length of the time slot [1]. If the channel is sensed busy (with probability p) during the AIFS time, the AC will uniformly and randomly choose contention window W_o from $[0, \ldots, W_s]$ as a back-off counter, where W_s is the minimum contention window associated with this class (AC_0). At any time slot during the back-off process with probability $(1-p)$, the AC decrements its back-off counter if it senses an idle channel; otherwise, it freezes the counter and waits for the whole period of the ongoing transmission ($T_t = L/r_d +$ AIFS $\cdot\, \varrho + \delta$) until the channel is idle again before decrementing its counter, where p is the conditional busy channel probability seen by a packet about to be transmitted and independent from any other vehicle, δ is the propagation delay, and r_d is the data rate. Once the back-off counter reaches the zero state, the AC broadcasts the packet. There will be no subsequent retransmissions if the packet collides; hence, the packet is lost.

By solving the discrete Markov chain in [38], it is found that the probability τ_s that a vehicle transmits a status packet in a randomly selected slot is

$$\tau_s = \frac{2(1-p)^2}{2 + pW_s - 3p}(\varrho\lambda_s) \tag{30}$$

where $\varrho\lambda_s$ is the probability that a vehicle is ready to transmit in that time slot.

If at least one vehicle within the carrier sense range is transmitting a packet in the same time slot when the channel is sensed busy, p can be expressed as

$$p = 1 - \sum_{k=0}^{\infty}(1-\tau_s)^k P_{2L_{\mathrm{CS}}}(k) = 1 - e^{-\frac{2\beta\overline{R}}{\mu\sqrt[\alpha]{\rho}}\tau_s}. \tag{31}$$

The Newton–Raphson method is used to solve (30) and (31) since the system has a unique solution in the range of $p \in [0, 1]$, as shown in Section VI.

The average delay $E[T_{\mathrm{ss}}]$ for status packets to be transmitted from the time it was ready at the MAC layer can be derived from the Markov chain in Fig. 3 and detailed in [38] as

$$E[T_{\mathrm{ss}}] = \sum_{i=0}^{W_s-1} \frac{p}{W_s} \sum_{k=0}^{i}(pT_t) + T_t = \frac{p^2\, T_t(W_s-1)}{2} + T_t. \tag{32}$$

E. Probability of Successful Reception

To derive the probability of successful reception, it is assumed that concurrent transmissions will cause a collision at the receiver. The vehicles that are located at distances higher than the communication range will not cause a collision at the receiver. Therefore, for successful reception by another vehicle located within the tagged vehicle's range $\overline{R}$, it is imperative that no vehicle within its carrier sense range $(2E[L_{\mathrm{CS}}])$ (or within the maximum $4\overline{R}$ if $E[L_{\mathrm{CS}}] > 2R$) will transmit in the same time slot in which the tagged vehicle is transmitting. At the same time, vehicles within the interfering areas, which are at maximum equal to $2(2\overline{R} - E[L_{\mathrm{CS}}])$ if $E[L_{\mathrm{CS}}] < 2R$, should not transmit during the vulnerable interval of unslotted ALOHA, which is equal to two transmission periods weighted by the time slot $T_v = 2T_t/\varrho$. The transmitted packet has also to be error free, and the received signal strength has to be higher than the threshold P_{th} that has been accounted for in the derivation of the average communication and carrier sense ranges in (6) and (7), respectively. Moreover, the vehicle has to stay within the range of the transmitting vehicle for the whole communication period. Putting all these conditions together, the probability of successful reception P_s that a vehicle within the communication range of the tagged vehicle successfully receive the status packet can be written as

$$P_s = P_l \cdot \left(\sum_{k=0}^{\infty}(1-\tau_s)^k P_{d_c}(k)\right) \cdot \left(\sum_{k=0}^{\infty}(1-\tau_s)^k P_{d_h}(k)\right)^{T_v} \tag{33}$$

where $d_c = 2 \cdot \min(E[L_{\mathrm{CS}}], 2\overline{R})$ is the contention area, and $d_h = 2 \cdot \max(2\overline{R} - E[L_{\mathrm{CS}}], 0)$ is the hidden terminal area and can be calculated from (8). Therefore, P_s can be simplified as

$$P_s = \begin{cases} P_l \cdot e^{-(1+T_v(2\sqrt[\alpha]{\rho}-1))\frac{2\beta\overline{R}}{\mu\sqrt[\alpha]{\rho}}\tau_s}, & \rho > 0.5^{\alpha} \\ P_l \cdot e^{-2\frac{2\beta\overline{R}}{\mu}\tau_s}, & \rho \le 0.5^{\alpha}. \end{cases} \tag{34}$$

This probability expresses the reliability of the designed system. The higher the success rate, the more vehicles will successfully receive the emergency and status packets, which will increase the drivers' awareness of potential dangers on the road ahead.

IV. Emergency Time Delay

Here, the case when a vehicle encounters an emergency situation, such as an accident, lane change, or slowing down below a certain threshold speed, is analyzed. The vehicle that is involved in an emergency situation will send an emergency packet to all vehicles behind it who will select another vehicle as a relay node to rebroadcast the message to its neighbors. The emergency message continues to propagate until it reaches a certain distance D defined within the message itself. The vehicle uses the high-priority AC AC3 to send the emergency message after sensing an idle channel for an AIFSN $\cdot\, \varrho$ s, where AIFSN $= 2$ for this class, as listed in Table I. If the channel is sensed busy, the AC selects a contention window from the range $[0, W_e]$, where $W_e = 3$ in this case, and starts decrementing this counter, as in the Markov chain in Fig. 3. Therefore, the probability τ_e that the emergency message will be sent can be derived by analyzing the Markov chain, as in (30), except for changing W_s by W_e as

$$\tau_e = \frac{2(1-p)^2}{2 + pW_e - 3p}. \tag{35}$$

The average delay $E[T_{\mathrm{se}}]$ for the emergency packet to be transmitted from the time it was ready at the MAC layer can also be derived as in (32) as follows:

$$E[T_{\mathrm{se}}] = \sum_{i=0}^{W_e-1} \frac{p}{W_e} \sum_{k=0}^{i} (pT_t) + T_t = \frac{p^2\, T_t(W_e-1)}{2} + T_t. \tag{36}$$

Once the vehicles located within the transmitter's range receive the emergency message, they have to rebroadcast the message to the next hop. The algorithm of selecting the best relay vehicle is based on the network topology persistence protocol (NTPP) algorithm proposed in [39], where vehicles calculate their probability of retransmitting the message and their waiting time based on their distance from the transmitter and the vehicle density. The farthest vehicle from the transmitter will have higher retransmitting probability P_{tr} and less waiting time T_w as

$$P_{\mathrm{tr}}(d) = \frac{1}{2}\left[\left(\frac{d}{\overline{R}}\right) + \left(1 - \frac{\beta/\mu}{N_l/10}\right)\right] \tag{37}$$

$$T_w(d) = \left(1 - \frac{d}{\overline{R}}\right)\left(\frac{\beta/\mu}{N_l/10}\right)(2T_t + \delta) \tag{38}$$

where d is the interdistance between the transmitter and the potential relay vehicle, β/μ is the current vehicle density, and $N_l/10$ is the maximum vehicle density, i.e., the jam scenario (For more information on deriving (37) and (38), see (39), shown at the bottom of the page).

To derive the total travel time for the emergency message to reach the distance D, it is required to find the location of the farthest relay vehicle to the transmitter that successfully receives the message and the time it waits before it retransmits the message to the next hop. Assuming that the relay vehicle is located at distance d from the transmitter as in Fig. 4, then the probability P_{rec} that this relay vehicle will successfully receive the message (assuming that the message is transmitted with probability τ_e) can be derived in two cases. The first case is when $0 \le d \le L_{\mathrm{CS}} - \overline{R}$; in this case, the relay vehicle would successfully receive the message when all vehicles

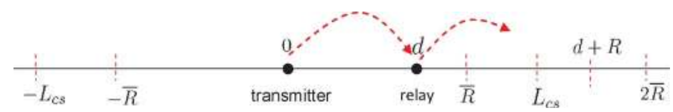

Fig. 4. Relay vehicle distance model.

within the range $[d - L_{\mathrm{CS}}, d + \overline{R}]$ do not use the channel in the same time slot as the transmitter. The second case is when $L_{\mathrm{CS}} - \overline{R} < d \le \overline{R}$; in this case, the vehicles within the range of $[d - L_{\mathrm{CS}}, L_{\mathrm{CS}}]$ should not use the channel in the same time slot as the transmitter and the vehicles within the range $[L_{\mathrm{CS}}, d + \overline{R}]$ should not use the channel for the vulnerable period T_v. Therefore, P_{rec} can be derived in the same way as in (34) as (39).

It is obvious that the farther the relay vehicle is, the less number of hops the emergency message will travel and have less travel delay. However, as d increases, the relay vehicle is more vulnerable to the hidden terminal problem, particularly in high-density scenarios. Therefore, a condition of receiving the emergency message with probability $P_{\mathrm{rec}}(d) \ge 90\%$ is applied to find the average interdistance d of the relay vehicle from the transmitter. Since this relay vehicle has a retransmission probability of $P_{\mathrm{tr}}(d)$, its average waiting time until it transmits the emergency message is $T_w(d)/P_{\mathrm{tr}}(d)$. The average number of hops that the emergency message will travel to reach its intended distance D is $\lfloor D/d \rfloor$. Therefore, the average emergency-message travel time to reach a distance D is

$$T_{travel} = \left\lfloor \frac{D}{d} \right\rfloor \left(E[T_{\mathrm{se}}] + \frac{T_w(d)}{P_{\mathrm{tr}}(d)}\right). \tag{40}$$

V. Adaptive and Mobility-Based Algorithm for Enhancing Vehicular Ad Hoc Network Performance

From the given analysis, it can be seen that there are many conflicting parameters that affect the system reliability and its success rate. Keeping these parameters with fixed values as specified in the standard [1] will result in undesired performance, particularly in a harsh vehicular environment where vehicles are moving in a very high speed and their density on the road is changing very frequently. That is, in a matter of seconds, the vehicle density could change from light density to the jam scenario. Therefore, vehicles have to change their sending rate λ_s, communication range $\overline{R}$ or transmission power, carrier sense range L_{CS}, and/or their minimum contention window size W_s based on the situation on the road to increase the success rate and reliability of VANETs.

Therefore, a new AMBA in which vehicles change their parameters according to their density and average speed on the road, pertaining to the following assumptions, is proposed.

$$P_{\mathrm{rec}}(d) = \begin{cases} P_l \cdot \tau_e \cdot e^{-\frac{\beta \overline{R}}{\mu}(1+\sqrt[\alpha]{\rho})\tau_s}, & 0 < d \le L_{\mathrm{CS}} - \overline{R} \\ P_l \cdot \tau_e \cdot e^{-\frac{\beta}{\mu}\left(2\frac{\overline{R}}{\sqrt[\alpha]{\rho}} - d + \left(d + \overline{R} - \frac{\overline{R}}{\sqrt[\alpha]{\rho}}\right)T_v\right)\tau_s}, & L_{\mathrm{CS}} - \overline{R} < d \le \overline{R} \end{cases} \tag{39}$$

1) The vehicles know their current average speed V_c and their maximum allowed speed $V_{\max}$ on the road.
2) The maximum communication range (or the maximum transmission power) is set to $R_{\max}$, and the minimum communication range is set to $R_{\min}$, which is used in the jam scenario.
3) The carrier sense parameter ρ can take three values $\rho \in [1, 0.5, 0.25]$ when the average vehicle speed is $[30\%, 30\%{-}70\%, 70\%]$ of the maximum speed, respectively. The values 30% and 70% are chosen here based on intensive simulations, and they seem to work well, as can be seen from the simulation results.
4) The vehicles' status packet-sending rate can take the values in the range of [1–10].
5) The minimum contention window size W_s can take on values in the range [15–127] with a step size of 16.
6) The current used vehicle's average speed, range, carrier sense parameter, packet-sending rate and the minimum contention window are denoted by V_c, R_c, ρ_c, λ_{s_c}, W_{s_c}, respectively.

Vehicles will execute the AMBA algorithm every T_{alg} s, where they sense the vehicle's density from their current average speed and compare it with the maximum speed $V_{\max}$. The pseudocode of the AMBA algorithm is shown as Algorithm 1. The smaller the current vehicle's average speed within the previous time period T_{alg}, the higher the vehicle density will be around that vehicle based on the proposed mobility model. The algorithm divides the range $(R_{\max}{-}R_{\min})$ into ten steps. Each time that the vehicle speed is dropped by a tenth of its maximum speed $V_{\max}$, it will reduce its range and set the other parameters accordingly. The vehicle will calculate its delay T_b from the time it was ready to transmit its status packet until the time the packet is transmitted. If the new value of T_b is higher than its previous one by $\psi = 10\%$, the vehicle will increase its minimum contention window size W_{s_c}. On the other hand, if T_b is smaller than its previous value by $\psi = 10\%$, it will decrease its W_{s_c}. Otherwise, it will keep it the same. The carrier sense range is also set according to the sensed density. When the vehicle's density is high (average speed drops below 30% $V_{\max}$), the carrier sense range is decreased to decrease the waiting time for each vehicle to send its status message. Although decreasing the carrier sense range will increase the hidden terminal area, the algorithm deals with this problem by decreasing the communication range. Therefore, the AMBA algorithm allows more vehicles to send their status messages within the SI with a high successful reception rate.

Algorithm 1 AMBA to set VANETs' parameters according to the vehicles' density on the road.

Initial setup
$R_c \leftarrow R_{\max}$
$\rho_c \leftarrow 0.25$
$\lambda_{s_c} \leftarrow 10$
$W_{s_c} \leftarrow 15$
for Every $T_{\text{alg}} = 10 \cdot \text{CCI}$ s **do**
  if $V_c < V_{\max}$ **then**
    $i \leftarrow \lfloor V_c/V_{\max} \cdot 10 \rfloor$ (i represents a step from 1 to 10 in which the current speed falls compared with the maximum speed)
    $R_c \leftarrow R_{\min} + i \cdot R_{\max}{-}R_{\min}/10$ (use a new range based on the step i)
    $\lambda_{s_c} \leftarrow \max(i, 1)$ (use a new sending rate based on the step i)
    if $i \leq 3$ **then**
      $\rho_c \leftarrow 1$ (in high density, $L_{\text{CS}} = \overline{R}$)
    else
      if $i \leq 7$ **then**
        $\rho_c \leftarrow 0.5$ (in medium density, $\overline{R} \leq L_{\text{CS}} \leq 2\overline{R}$)
      else
        $\rho_c \leftarrow 0.25$ (in low density, $L_{\text{CS}} \simeq 2\overline{R}$)
      end if
    end if
    if $T_{b_{\text{new}}} > (1+\psi) \cdot T_{b_{\text{old}}}$ **then**
      $W_{s_c} \leftarrow \min(W_{s_c} + 16, 127)$ (if the time delay increases, i.e., more contention, increase W_s)
    else
      if $T_{b_{\text{new}}} < (1-\psi) \cdot T_{b_{\text{old}}}$ **then**
        $W_{s_c} \leftarrow \max(W_{s_c} - 16, 15)$ (if the time delay decreases, i.e., less contention, decrease W_s)
      end if
    end if
  end if
end for

VI. Model Validation and Simulation

Here, the DSRC performance will be analyzed based on the probability of successful reception derived in (34). All vehicles send their status messages, except for one vehicle, which will send an emergency message. The time it takes for that emergency message to propagate to a certain distance (3000 m) is of interest. It is assumed that all vehicles are synchronized to the CCI all the time, and the generation time of each status packet is uniformly distributed over that interval.

To validate the model, we use ns2 [34] with realistic mobility models generated by MOVE [32], which is built on top of the microtraffic simulator SUMO [33] that has the most realistic mobility traces for VANETs [40]. The trace file realistically evaluates and generates the motion behavior of vehicles on the highway where vehicles could change lane and speed, and could take over other vehicles in front of them. The simulation setup is a one directional highway segment of 4000 m in length with four lanes. The vehicles' speed ranges from 80–120 km/h, which is typical for Ontario highways.

The Nakagami-m propagation model is used, which has two distance dependent parameters: the fading factor m and the average power Ω. Torrent-Moreno *et al.* [41] performed a maximum-likelihood estimation of m and Ω for a vehicular highway scenario. They found that Ω decreases as the distance to the receiver increases as expected from the average power in the deterministic models, i.e., by d^{-2}. On the other hand, fading parameter $m = 3$ is selected for short interdistance between the transmitter and the receiver $(d \leq 50)$ since the line-of-sight

TABLE III
VALUE OF PARAMETERS USED IN SIMULATION

Parameter	Value
Modulation and Data rate	BPSK , 3 Mbps
Message and Header sizes	512 , 64 Bytes
Status packets rate λ_s	10 packets/s
vehicle's speed	80-120Km/h
vehicle's arriving rate β	1 vehicle/s
Exponent factor α	2.00
Communication range $\overline{R}$	300 m
Transmission power $P_t(300m)$	20 mW
Emergency Min. Contention Window W_e	3
Status Min. Contention Window W_s	15
Received power threshold P_{th}	3.162e-13 W
Carrier sense power percentage ρ	0.5
Noise-floor	1.26e-14 W
T_{tx} & T_{rx} antennas heights	1.5 m
T_{tx} & T_{rx} antennas Gain $G_t = G_r$	1
DIFS	64 μ s
Slot time ϱ	13 μ s
Propagation delay δ	1 μ s
Percentage of drivers that follow safety rule ε	80%
CCI	100ms
T_{alg}	$10 \cdot CCI$ s
Number of lanes N_l	4

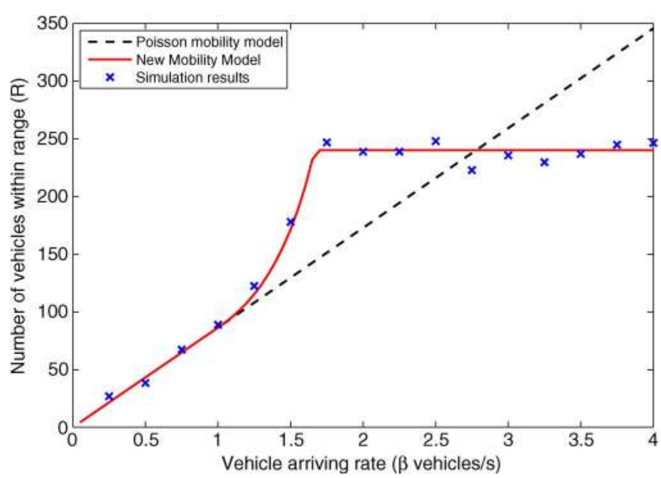

Fig. 5. Number of vehicles within the communication range of the transmitter.

conditions is expected, and then, decrease it to $m = 1.5$ for medium distances ($50 < d \leq 100$), and make it as Rayleigh distributed, i.e., $m = 1$ for longer distances. Ω is set in each interval to be the average power calculated from a free-space propagation model; hence, receivers located within 100 m of the transmitter will receive the signal with Rician distribution, whereas others will have Rayleigh distribution. Since the receiver in ns2 will receive the signal if its power is higher than the threshold P_{th}, the transmitting power is set such that the receiving power at the communication range $\overline{R}$ is the threshold P_{th} as per (6), and the carrier sense range $E[L_{\mathrm{CS}}]$ is as in (7). Each simulation is performed for a period of 300 s of real time. Table III lists the simulation parameters used, unless a change is mentioned explicitly.

To compare the accuracy of the proposed mobility model with mobility models based on Poisson distribution, the average number of vehicles within the transmitter's range is plotted in Fig. 5 as a function of the vehicles' arrival rate. Note that the Poisson models do not take into account the follow-on safety rule, the increase in vehicles arrival rate, or the maximum road capacity. From the numerical results in Fig. 5, it is shown that the proposed model is more accurate in predicting the number of vehicles around the transmitter than other models that use only one Poisson distribution. It can be seen that, as the number of vehicles arriving at the reference point increases, the number of vehicles will start to deviate from the old model assumption until it reaches a point where it stays constant. This is the jam scenario case where vehicles start to backlog on the road, decreasing the interdistance between them as a result of decreasing their speed. This is also obvious in Fig. 6, which shows how vehicles' average speed and density are affected by the increase in their arrival rate.

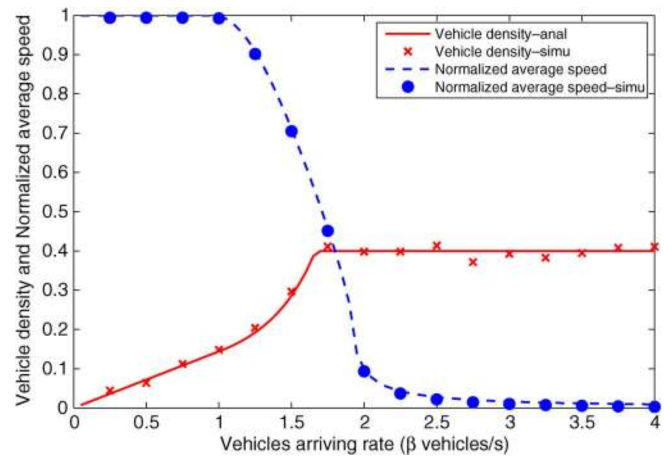

Fig. 6. Vehicle density and their normalized average speed versus vehicle arrival rate.

The following four metrics are defined to evaluate the accuracy of the proposed model and reliability of the DSRC protocol in VANETs: 1) the effective communication range, which is the range at which most vehicles (95%) that are located around the transmitter will receive the transmitted message successfully and compare it with the communication range derived from (6); 2) the success rate, which is the number of vehicles that receives the transmitted packet successfully divided by the total number of vehicles that is within the range of the transmitter and compare it with (34); 3) the average delay for a vehicle to send its status message and compare it with the delay derived in (32); and 4) the system reliability, which is the percentage of vehicles that managed to send their status messages successfully within any SI.

The results shown in Figs. 7–10 are based on the vehicle density and average speed corresponding to the density extracted in Fig. 6. Specifically, Figs. 7–10 show, respectively, the effective communication range, the success rate, status packet delay, and the reliability versus the vehicle density for different generation rates of status packets. It is obvious that, as the vehicle density increases, the effective range and success rate will decrease. At the same time, the status packet delay will increase, resulting in decreasing the system reliability since the number of vehicles that have the chance to send their status messages will decrease. This means that not all vehicles get the chance to access the channel and send their status packets. To improve system reliability, the status packet generation rate is

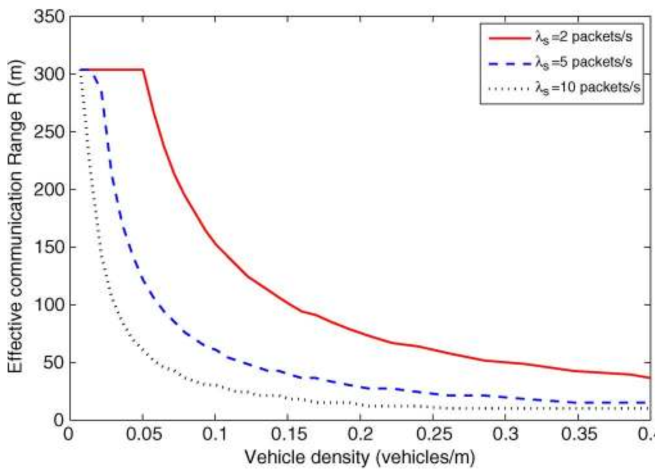

Fig. 7. Effective communication range versus vehicle density when the success rate is set at 95% for different status packet-sending rates.

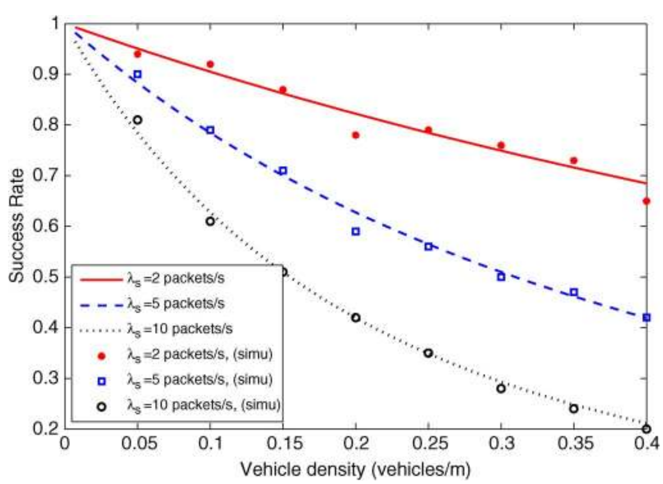

Fig. 8. Successful rate versus vehicle density for different status packet-sending rates.

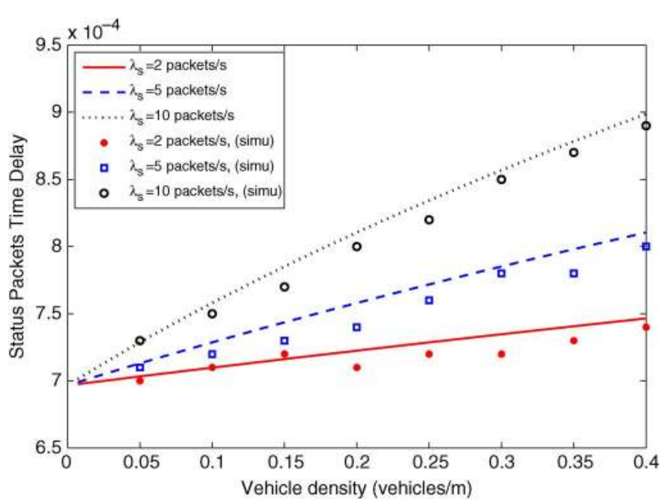

Fig. 9. Status packets delay versus vehicle density for different status packet-sending rates.

reduced from 10 to 5 and then to 2 packets/s. This improves the system reliability and success rate, but it is still below the threshold of 95%, particularly when the vehicle density is high.

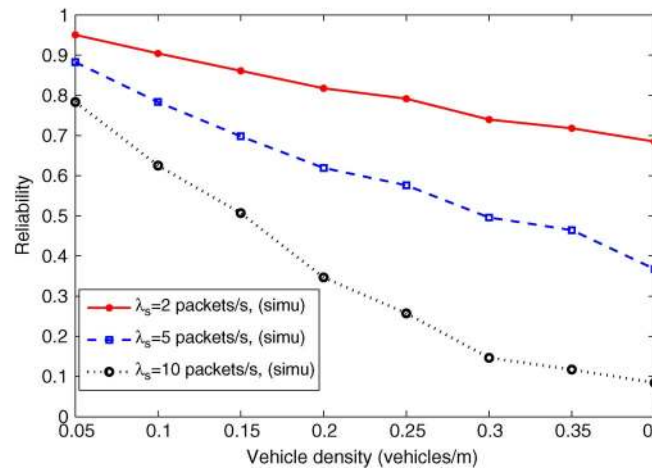

Fig. 10. System reliability versus vehicle density for different status packet-sending rates.

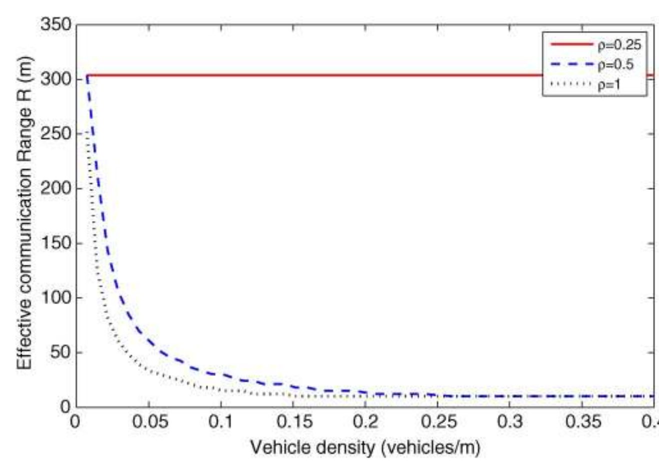

Fig. 11. Effective communication range versus vehicle density when the success rate is set 95% for different carrier sense ranges.

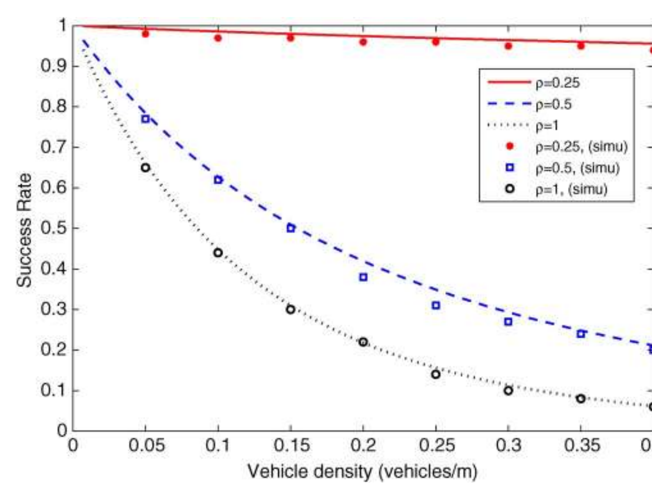

Fig. 12. Successful rate versus vehicle density for different carrier sense ranges.

To meet this threshold for any vehicle density, vehicles have to reduce their communication range based on Fig. 7.

Figs. 11–14 show, respectively, the effective communication range, the success rate, status packet delay, and the reliability

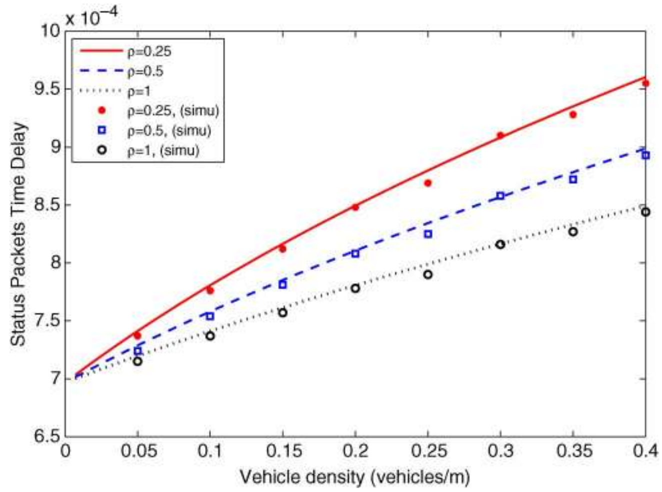

Fig. 13. Status packets delay versus vehicle density for different carrier sense ranges.

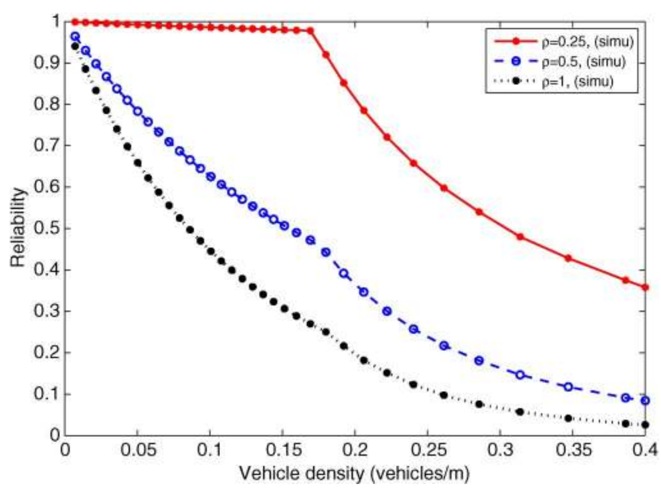

Fig. 14. System reliability versus vehicle density for different carrier sense ranges.

versus the vehicle density for different carrier sense ranges. The carrier sense range is increased by decreasing the carrier sense power or the parameter ρ. By decreasing ρ from 1 to 0.25, the carrier sense range doubles that of the communication range. It is evident that increasing the carrier sense range will increase the contention region and decrease the hidden terminal region. Therefore, increasing the carrier sense range will increase the success rate and the system reliability for fixed vehicle density, as shown in Figs. 12 and 14, respectively. As a consequence, the effective communication range will increase, as shown in Fig. 11. At the same time, vehicles will take longer time to access the channel, as shown in Fig. 13, due to the increase in the number of vehicles contending for the channel. As a result, the number of vehicles that has the chance to send their status messages will decrease and can be observed from the difference between Figs. 12 and 14.

To find the impact of the minimum contention window size W_s on VANETs, W_s is increased from 15 to 1023 and the success rate, status packet delay, and the reliability for different vehicle densities are plotted in Figs. 15–17, respectively. It is shown that increasing the minimum contention window will

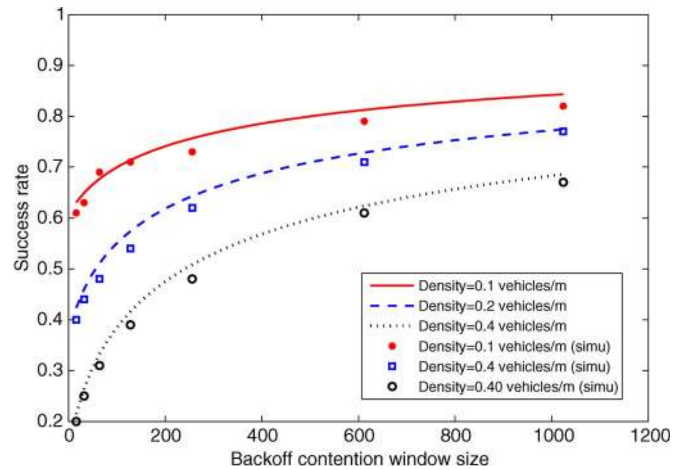

Fig. 15. Successful rate versus contention window size for different vehicle densities.

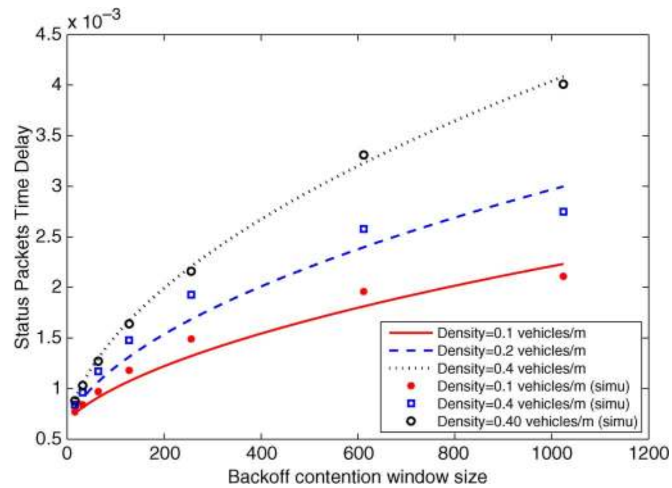

Fig. 16. Delay of status packets versus contention window size for different vehicle densities.

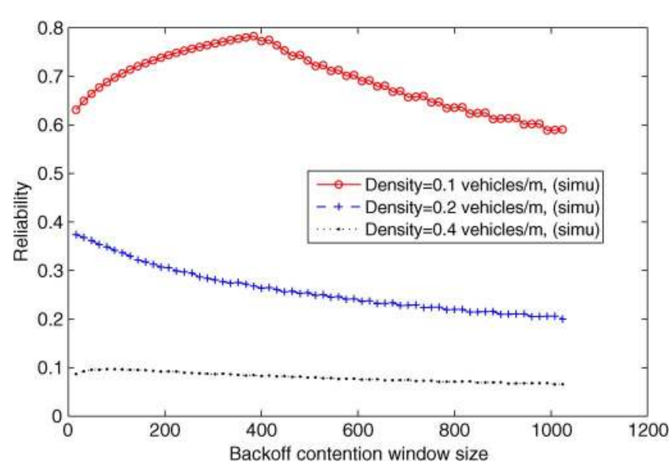

Fig. 17. System reliability versus contention window size for different vehicle densities.

decrease the probability of packet collisions between vehicles, which is obvious in Fig 15, since the successful rate increases by the increase in W_s. It is also shown that there is an optimal value of W_s, which gives the maximum success rate since

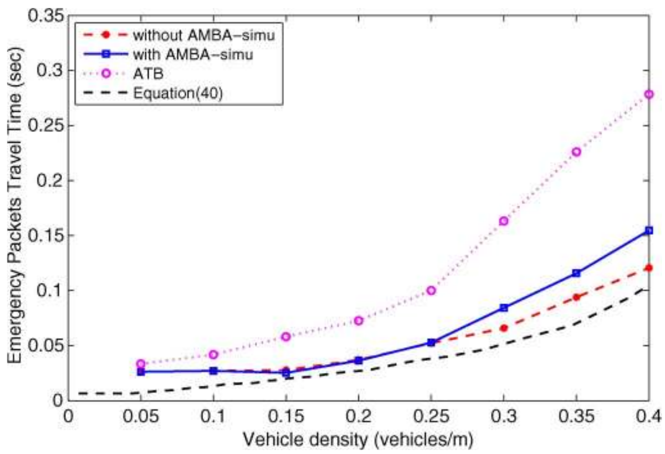

Fig. 18. Emergency-packet travel time versus vehicle's density.

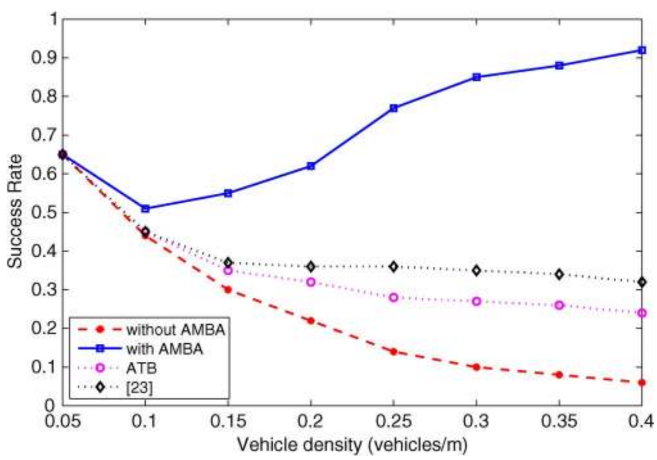

Fig. 19. Percentage of vehicles within the distance (3000 m) that received the emergency message successfully.

increasing it would not further result in much of an increase in the success rate. At the same time, the status packet delay will increase dramatically by increasing W_s, particularly when the vehicle density is high. This may result in decreasing the system reliability since not many vehicles might have the chance to send their status messages, as shown in Fig. 17.

To evaluate the effect of the AMBA algorithm on the reliability of VANETs, the main simulation parameters, as in Table III, are applied, and let one vehicle send an emergency packet, which should propagate for a distance of 3000 m behind the transmitter. This emergency message will be rebroadcasted in every hop based on the NTPP algorithm described in [39]. Figs. 18 and 19 show, respectively, the delay until the emergency message reaches the intended distance and the percentage of vehicles that received it successfully with and without using the AMBA algorithm. We compare the proposed AMBA algorithm with the adaptive traffic beacon (ATB) in [42] and the algorithm in [23]. It is clear that the proposed AMBA outperforms the other algorithms since AMBA adapts not only the beaconing interval, as in ATB, but the communication and carrier sense ranges based on the average vehicle density as well. It can be seen that the time needed for the emergency message to reach the intended distance increases as the vehicle density increases due to the increase in channel contention and

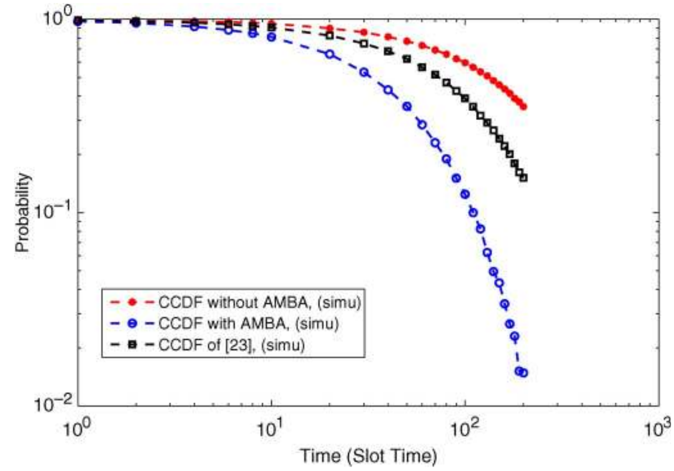

Fig. 20. CCDF of the interarrival time of status messages versus the number of time slots.

collisions. Adapting the AMBA algorithm results in increasing the emergency delay even more because the vehicles would decrease their communication range as the vehicle density increases. It is also clear that the simulated delay is close to the theoretical value derived from (40). On the other hand, adapting the new algorithm increases the system reliability dramatically, particularly in a high-density scenario, as shown in Fig. 19. This means that more vehicles will be informed of the emergency on the road ahead, although it arrives late but within tolerable delay, as defined in [43]. This is also clear in Fig. 20, which shows the complementary cdf (ccdf) of the interarrival time of status messages versus the number of time slots with and without the use of the AMBA algorithm and compare it with the algorithm proposed in [23]. By using the AMBA algorithm, the interarrival time between status messages decreases; therefore, more vehicles will have the chance to send their status messages during the CCI. It is obvious that the AMBA algorithm outperforms the one proposed by [23] since the AMBA algorithm not only adapts the communication range as in [23] but changes the carrier sense range and the sending rate of status messages as well, based on the network density. Therefore, the AMBA algorithm mitigates the effect of the hidden terminal problem and the network congestion in a distributed manner more properly than the algorithm in [23].

VII. Conclusion

In this paper, an analytical model has been presented to analyze the reliability of the IEEE 802.11p in VANETs' safety and warning applications. The analysis is based on a new mobility model in which the relationship among vehicle density, speed, and the follow-on distance rule is derived. In the analysis, several factors have been considered, such as the impact of mobility on the link availability between the transmitter and the receiver, the distribution of vehicles on the road, and the average number of vehicles within the range of the transmitter. The proposed model is built on the fact that vehicles are broadcasting their status messages within the SI and model each vehicle as a 1-D Markov chain, including the channel busy probability in every state. The effective maximum communication range that can be used in certain conditions to achieve a certain successful rate is shown analytically and by simulation. It is shown from the analytical and simulation results that the current DSRC specifications may lead to undesirable performance under harsh vehicular environments. Therefore, a new adaptive algorithm, AMBA, is introduced to enhance VANET's reliability. By using the AMBA algorithm, vehicles are able to estimate the vehicle density and change their transmission parameters accordingly based on their current average speed to enhance VANETs' performance. The simulation results, which coincide with the analytical results, show that the proposed model is quite accurate in calculating the system reliability, and the proposed AMBA algorithm has high performance compared with other algorithms.

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Khalid Abdel Hafeez (S'07) received the B.Sc. degree in electrical and computer engineering from Jordan University of Science and Technology, Ar Ramtha, Jordan, in 1988 and the M.A.Sc. degree in computer networks and the Ph.D. degree in wireless communications and vehicular ad hoc networks from Ryerson University, Toronto, ON, Canada, in 2008 and 2012, respectively.

He is currently working as an Instructor with Ryerson University and the University of Ontario Institute of Technology, Oshawa, ON. His current research interests include computer networks, wireless communications, network security, and cryptography.

Lian Zhao (S'99–M'03–SM'06) received the B.S. degree in electrical engineering from the Civil Aviation University of China, Tianjin, China, in 1990; the M.S. degree in radio propagation from Wuhan University, Wuhan, China, in 1993; and the Ph.D. degree in wireless communications from the University of Waterloo, Waterloo, ON, Canada, in 2002.

Since 2003, she has been with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON, where she is currently an Associate Professor. In 2004, she co-founded the Optic Fiber Sensing Wireless Network Laboratory. Her research interests include wireless communications, radio resource management, power control, cognitive radio and cooperative communications, and the design and applications of energy-efficient wireless sensor networks.

Dr. Zhao is a Licensed Professional Engineer in Ontario and a member of the IEEE Communications Society.

Bobby Ma (SM'06) received the B.A.Sc., M.A.Sc., and Ph.D. degrees from the University of Waterloo, Waterloo, ON, Canada, in 1982, 1984, and 1988, respectively, all in electrical engineering.

Since 1988, he has been with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON, Canada, where he is currently a Professor and a Director of the Computer Networks Master of Engineering Program. His current research interests include network security, wireless networks, and peer-to-peer networks.

Dr. Ma is a member of the Professional Engineer in the Province Ontario.

Jon W. Mark (M'62–SM'80–F'88–LF'03) received the B.A.Sc. degree from the University of Toronto, Toronto, ON, Canada, in 1962 and the M.Eng. and Ph.D. degrees from McMaster University, Hamilton, ON, in 1968 and 1970, respectively, all in electrical engineering.

From 1962 to 1970, he was an Engineer and then a Senior Engineer with Canadian Westinghouse Company, Ltd., Hamilton. From October 1968 to August 1970, he was on leave of absence from Canadian Westinghouse to pursue the Ph.D. degree with McMaster University under the auspices of a National Research Council Post Industrial Experience fellowship. Since September 1970, he has been the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, where he is currently a Distinguished Professor Emeritus. He served as the Department Chair from July 1984 to June 1990. In 1996, he established the Centre for Wireless Communications, University of Waterloo, where he is currently serving as its Founding Director. From 1976 to 1977, he was on sabbatical leave with the IBM Thomas Watson Research Center, Yorktown Heights, NY, USA, as a Visiting Research Scientist; from 1982 to 1983, at AT&T Bell Laboratories, Murray Hill, NJ, USA, as a Resident Consultant; from 1990 at 1991, at the Laboratoire MASI, Université Pierre et Marie Curie, Paris, France, as an Invited Professor; and from 1994 to 1995, with the Department of Electrical Engineering, National University of Singapore, Singapore, as a Visiting Professor. He has worked in the areas of adaptive equalization, spread-spectrum communications, antijamming secure communications over satellites, and asynchronous transfer mode networks. His current research interests include broadband and wireless communications and networks, including power control, resource allocation, mobility management, and end-to-end quality-of-service provisioning in hybrid wireless/wireline networks.

Dr. Mark was an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS from 1983 to 1989. He served as the Technical Program Chair of the Eighth Annual Joint Conference of the IEEE Computer and Communications Societies in 1989. He was a member of the Intersociety Steering Committee of the IEEE/ACM TRANSACTIONS ON NETWORKING from 1992 to 2003, an Editor for the *ACM/Baltzer Wireless Networks Journal* from 1997 to 2004, and an Associate Editor for *Telecommunication Systems* from 1996 to 2004.