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

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Abstract—An analytical model for the reliability of the Dedicated Short Range Communication (DSRC) control channel 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 the 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 accurately derive the relationship between the average vehicle speed and density. Moreover, the model takes into consideration: 1) the impact of mobility on vehicles density 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; 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 the system reliability in terms of the probability of packet’s successful reception and delay of emergency messages in a harsh vehicular environment. The proposed model and the enhancement algorithm are validated by simulation using realistic vehicular traces.

Keywords
Vehicular Ad hoc Network (VANET), Medium Access Control, Dedicated Short Range Communication (DSRC), Markov Chain, Mobility, Connectivity, Reliability, IEEE 802.11p.

I. INTRODUCTION

The research and application development in vehicular ad hoc networks (VANETs) have been driven by the Dedicated Short Range Communication (DSRC) technology or IEEE 802.11p [1] designed to help drivers to travel more safely and to reduce the number of fatalities due to road accidents. The IEEE 802.11p MAC uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and some concepts from the Enhanced Distributed Channel Access (EDCA) [2]. In this technology, there are four access classes (ACs) with different Arbitration Inter Frame Space Numbers (AIFSN) to insure less waiting time for high priority packets as listed in Table I.

The DSRC is licensed at 5.9GHz with 75MHz spectrum which is divided into seven 10MHz channels and 5MHz guard band. The control channel (CCH) will be used for safety applications while the other six channels, called service channels, 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 service channels (SCH), hence safety related messages will not be missed or lost. The synchronization interval (SI) contains a control channel interval (CCI) followed by a service channel interval (SCI) [3]. Increasing the CCI will enhance the reliability of safety applications and challenge the coexistence of both safety and non-safety applications on the DSRC.

VANET is a self-organizing network that works on both Inter-Vehicle Communication (IVC) and Vehicle to Infrastructure communication. In this paper, IVC is taken into consideration where vehicles will be equipped with sensors and GPS 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 broadcasted periodically 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 and hence 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 problem 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 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 accurately derive 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’s reliability in terms of the probability of packet’s successful reception and time delay of emergency messages in a harsh vehicular environment.
of the transmitter and did not include vehicles mobility in their model. In [19] and [20], the authors study 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, stationary distribution without considering the impact of vehicle mobility on the system performance. In [21], an analytical model for delivering safety messages within inter-vehicle communication (IVC) is derived. They assume a perfect channel access and have not accounted for the hidden terminal problem, collision probability and vehicle mobility. The authors in [22] study 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], the authors analyze 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 channel. As the channel occupancy increases, they decrease the communication range to maintain an acceptable channel capacity. We will compare their algorithm and our proposed one 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 vehicles positions are known by either simulation or observation, the authors in [27] present an analytical model for VANET’s multi-hop connectivity. A mobility model has been derived in [28] considering the arrival of vehicles to a service area as a Poisson distribution. The authors in [29] derive 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’s 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 are introduced such as changing lanes, slowing down or even changing routes to allow a micro-mobility behavior control. In [31], the authors argued that coupling more than one simulator is an important step towards a realistic VANET’s mobility model. Therefore, we built our simulations by coupling the mobility model (MOVE) [32] with the micro-traffic simulator 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 non-saturation 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 accurately derive 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 has also the capacity to handle the sudden increase in vehicles’ density (from jam, accident, or other events) in order to keep safe distance between vehicles. The packet reception rate is derived, taking into account the inter distance between the transmitter and all potential receivers and their speeds. The proposed model uses a Markov chain approach, which includes the probability of 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 VANETs performance. Simulation results show that the proposed model is quite accurate and the proposed algorithm enhances the DSRC performance compared to other algorithms in the literature.

III. **System Model and Performance Parameters**

In VANETs’ safety applications, vehicles broadcast two types of messages: warning (event driven) and status messages. While warning messages usually contain safety related information, status messages are sent periodically 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 while status message will use AC0.

In our model, vehicles generate their status messages at a rate of $\lambda_s$, which implies that the length of the synchronization interval is $SI = 1/\lambda_s$ [8]. We assume that all packets have the same length 1 $\text{bits}$ and the whole $SI$ interval is dedicated to safety applications, that is $CCI = SI$. Each vehicle will randomly choose a slot within the $SI$ interval to transmit its status packet, while emergency packets are sent only during emergency situations such as an accident or warning from hazardous 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 on these assumptions, we analyze the DSRC protocol to find the smallest channel interval that maximizes the reliability. The performance parameters of these assumptions are then derived.

It is assumed that all vehicles have the same transmitting power ($P_t$) and each vehicle receives the signal successfully if the received power is higher than a certain threshold $P_{th}$. Since fading is a major characteristic of VANET channel, the received signal power is random and 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 next subsections. Table II lists all notation 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 which 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 transmitters and receivers speed, the contention window and the carrier sense range on the packet successful reception rate 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 researches have paid more attention to the vehicle-to-vehicle (V2V) 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

$$P_{X}(x) = \left(\frac{m}{P_r}\right)^m x^{m-1} e^{-\frac{m}{P_r}x}, \text{ for } x \geq 0,$$

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, $\alpha$ is the path loss exponent, $K = G_t G_r (C/(4\pi f_c))^2$, $C$ is the speed

<table>
<thead>
<tr>
<th>Notation</th>
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<tr>
<td>CCH</td>
<td>Control Channel</td>
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<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>CCI</td>
<td>Control Channel Interval</td>
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<tr>
<td>SCI</td>
<td>Service Channel Interval</td>
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<tr>
<td>SI</td>
<td>Synchronization Interval</td>
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<td>AC</td>
<td>Access Class</td>
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<tr>
<td>$\lambda_s$</td>
<td>Status message generation rate</td>
</tr>
<tr>
<td>$L$</td>
<td>status packet length in bits</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Transmission power</td>
</tr>
<tr>
<td>$P_{th}$</td>
<td>received power threshold at the communication range</td>
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<td>$E[R]$</td>
<td>Average communication range</td>
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<tr>
<td>$E[L_{CS}]$</td>
<td>Average carrier sense range</td>
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<tr>
<td>$P_{CS}$</td>
<td>received power threshold at the carrier sense range</td>
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<tr>
<td>$\rho \in [0, 1]$</td>
<td>$P_{CS} = \rho P_{th}$</td>
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<tr>
<td>$\mu$</td>
<td>Average vehicle speed</td>
</tr>
<tr>
<td>$V_{min}$</td>
<td>minimum vehicle speed</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>maximum vehicle speed</td>
</tr>
<tr>
<td>$N_c$</td>
<td>Number of vehicles within the communication range</td>
</tr>
<tr>
<td>$N_{th}$</td>
<td>Number of hidden terminals</td>
</tr>
<tr>
<td>$N_l$</td>
<td>Number of lanes</td>
</tr>
<tr>
<td>$d_{th}$</td>
<td>Safety distance between two vehicles</td>
</tr>
<tr>
<td>$\beta_i$</td>
<td>Vehicles arriving rate in the $i^{th}$ lane</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Total vehicles arriving rate</td>
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<tr>
<td>$\epsilon \in [0, 1]$</td>
<td>fraction of vehicles that follow the following distance safety rule</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Safety time needed to cross the safety distance</td>
</tr>
<tr>
<td>$\theta$</td>
<td>slot time</td>
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<td>$AIFS$</td>
<td>Arbitration Inter frame space</td>
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<tr>
<td>$W_s$</td>
<td>Minimum contention window for status message</td>
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</tbody>
</table>
of light, $f_r = 5.9GHz$ is the carrier frequency, $G_t$ 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, 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 none line-of-sight.

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

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

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

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

By using

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

the CDF can be written as

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

The average value of the communication range $E[R]$ (or $R$) can be derived as:

$$E[R] = \int_{0}^{\infty} (1-F_R(r))dr. \tag{5}$$

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

$$E[R] = \frac{1}{\alpha \Gamma(m)} \sum_{i=0}^{m-1} \frac{(m-1)!}{(m-1-i)!} \left(\frac{mP_{th}}{P_r}\right)^{m-1-i} e^{-\frac{mP_{th}}{P_r}} \tag{6}.$$  

To derive the average carrier sense range $(E[L_{CS}])$ 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 $(P_{CS})$, which will be defined as a percentage of the threshold $P_{th}$ as $P_{CS} = \rho P_{th}$, where $\rho \in (0, 1]$. Therefore, the expected carrier sense range will be:

$$E[L_{CS}] = \frac{E[R]}{\sqrt{\rho}}. \tag{7}$$

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

The proposed VANET mobility model is built based on one way multiline 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 one dimensional 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 $(N_s)$ 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, and 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 $\beta_i$ vehicles/s for the $i$th 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 move independently 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 $\tau_d$ 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 ($t_s$ seconds rule). This means that the following vehicle traveling with speed $V_j$ has to keep a safe distance $(d_{th})$ from the in front vehicle such that $d_{th} > V_j t_s$ to avoid an accident if the front vehicle stops suddenly. This minimum distance is a random variable and depends on the following vehicle’s speed $V_j$ if a 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 inter arrival time $(\tau_d = 1/\beta_i)$ between vehicles in the $i$th lane is larger than $t_s$. In this case the probability of having $N_{ci} = k$ vehicles within the communication range of the tagged vehicle (i.e. within a
which the vehicle traveled equals distance), the new vehicle would wait in the queue for time i.e. served (Fig. 2). A vehicle is immediately served if the server is empty is modeled as a single server Poisson arrival queue as shown in Fig. 2. Single server queue model.

The distance of \(2\overline{R}\) in the \(i\)th lane is Poisson distributed \([36]\) as

\[
P_{i\overline{R}}(N_{e_i} = k) = \frac{(2\overline{R})^k}{k!} e^{-2\overline{R}}, \tag{8}
\]

and the average number of vehicles around the tagged vehicle in the \(i\)th lane is

\[
\overline{N}_{e_i} = \frac{2\overline{R}}{\mu}. \tag{9}
\]

The probability of having \(N_{b_i} = k\) vehicles within the carrier sense range of the tagged vehicle is

\[
P_{i\overline{BCS}}(N_{b_i} = k) = \frac{(\frac{2\overline{R}}{\mu})^k}{k!} e^{-\frac{2\overline{R}}{\mu}}. \tag{10}
\]

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

\[
d_i = V_f t_d < V_f t_s, \tag{11}
\]

where \(V_f\) and \(V_f\) are the in front and following vehicles' speeds in the \(i\)th lane, respectively. In this case, the following vehicle has to reduce its speed in order 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 \((S + 1/\beta_i)\cdot V_f = V_f t_s\) and therefore

\[
S = \frac{V_f}{V_f} t_s - \frac{1}{\beta_i}. \tag{12}
\]

On the other hand, if a vehicle finds 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. That is the distance which the vehicle traveled equals \(d_{th}\). If another vehicle arrives during the time \((S)\), it will wait in the queue until all vehicles in front of it have been served, that is, 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 inter distances between vehicles. Since the arrival time is Poisson with rate \(\beta_i\), 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

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

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

\[
f_Z(\alpha) = \begin{cases} \frac{1}{2(V_{max} - V_{min})} & \frac{V_{max}^2 - V_{min}^2}{2V_{max}} - \frac{V_{min}^2}{2V_{max}}, \quad 1 \leq \alpha < \frac{V_{max}}{V_{min}} \\ 0, & \text{otherwise} \end{cases} \tag{16}
\]

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

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

Equation (19) represents the average time that a vehicle will wait in the queue such that the inter distance 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 reduce their speed proportionally with \(E[B]\) which is normalized by the number of lanes, the maximum and the current average speeds as \(\mu_v = (N_l \mu) / \mu_{new}\). Initially \(\mu_{new} = \mu\) 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 keep the same speed. At the same time, decreasing the vehicles speed compared to the initial average speed will increase the inter arrival time between vehicles resulting in decreasing 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 in a speed close to zero. Therefore, it is assumed that each vehicle occupies a space of 10 meters on average and this is the maximum vehicle density a road lane can handle.

The new speeds and their mean are given respectively as

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

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

\[
\mu_{new} = \frac{V_{max}[\text{new}] + V_{min}[\text{new}]}{2}. \tag{22}
\]
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 drivers 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 substitute it in Equation (19) to calculate a new value of $E[B]$ as $E[B]_{\text{new}}$. The new distribution of vehicles will be a new Poisson with different mean $(2R\beta_i)/\mu_\text{new}$ if the condition $\beta_iE[S]_{\text{new}} < 1$ is satisfied. Otherwise, the road reaches the jam state. Therefore, the average number of vehicles ($N_{ci}$) within the communication range of any tagged vehicle in the $i$th lane will be

$$
N_{ci} = \begin{cases} 
\frac{2R\beta_i}{\mu_\text{new}}, & E[S] = 0 \\
\frac{2R\beta_i}{\mu_\text{new}} - \frac{\beta_iE[S]_{\text{new}}}{1}, & E[S] \neq 0, \beta_iE[S]_{\text{new}} < 1 \\
\frac{2R}{10}N_i, & E[S] \neq 0, \beta_iE[S]_{\text{new}} \geq 1.
\end{cases}
$$

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

The vehicles arriving rate and average speed could vary from lane to lane. The left most lane could have higher average speed and arriving rate than the right most 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 $N_{ci}$ in each lane and sum them all such that $N_c = \sum_{i=1}^{N_l} N_{ci}$. Without loss of generality, assuming that all lanes have the same arriving rate and average speed, then the total number of vehicles that are located within the range of the transmitter is

$$
N_c = \begin{cases} 
\frac{2R\beta_i}{\mu_\text{new}}, & E[S] = 0 \\
\frac{2R\beta_i}{\mu_\text{new}} - \frac{\beta_iE[S]_{\text{new}}}{1}, & E[S] \neq 0, \beta_iE[S]_{\text{new}} < 1 \\
\frac{2R}{10}N_i, & E[S] \neq 0, \beta_iE[S]_{\text{new}} \geq 1.
\end{cases}
$$

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 $R$. 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, that is moving in the same direction of the sender as shown in Fig. 1. Then the probability density function of this distance is $f_{d_1}(x) = 1/2R$. Since the status packet transmission time $T_i$ 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 $d_n = d_1 + (v_x - v_t)T_i$, 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 receive the packet successfully is when its $d_n$ is still within the transmitter’s range as

$$
P_l = P \left( -R \leq d_1 + (v_x - v_t)T_i \leq R \right).
$$

From (25), if the receiver’s speed $v_x \geq v_t$, then 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 receive the packet successfully is given by

$$
P_{l1}(v_t) = P \left( -R \leq d_1 \leq R - (v_x - v_t)T_i \right) = \int_{v_t}^{v_{max}} \int_{-R}^{R-(v_x-v_t)T_i} \frac{1}{2R} \frac{1}{v_{max} - v_x} \, dx \, dv_x
$$

$$
= 1 - \frac{v_{max} - v_t}{4R} T_i.
$$

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

$$
P_{l2}(v_t) = P \left( -R + (v_x - v_t)T_i \leq d_1 \leq R \right) = \int_{v_{min}}^{v_t} \int_{R-(v_x-v_t)T_i}^{R} \frac{1}{2R} \frac{1}{v_{max} - v_x} \, dx \, dv_x
$$

$$
= 1 - \frac{v_{max} - v_t}{4R} T_i.
$$

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 $P_{l3}(v_t)$ that a vehicle traveling in the same direction as the transmitting vehicle will receive the packet successfully is given by

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

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

$$
P_l = 1 - \frac{v_{max} - v_{min}}{8R} T_i.
$$

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 wait initially for a period of $\text{AIFS} = \text{AIFS}_0 \cdot o$ before it can broadcast the packet, where $\text{AIFS}$ is the Arbitration Inter Frame Space for status packet’s access class (chosen here $\text{AC}_0$), $\text{AIFS}_0$ is the Arbitration Inter Frame Space number associated with this class as listed in Table I and $o = 13\mu s$ is the length of the time slot [1]. If the channel is sensed busy (with probability $p$) during the $\text{AIFS}$ time, the access class $\text{AC}$ will choose a contention window ($W_c$) uniformly and randomly from [0, ..., $W_c$] as a back-off counter, where $W_c$ is the minimum contention window associated with this class ($\text{AC}_0$). At any time slot during the back-off process with probability $(1-p)$, the $\text{AC}$ 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 ($T_i = L/T_4 + \text{AIFS} \cdot o + \delta$) 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, $\delta$ 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 is collided and hence the packet is lost.

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

$$P_s = 1 - \sum_{k=0}^{\infty} (1 - \tau_s)^k P_{2L_{CS}}(k) = 1 - e^{-\frac{2\varrho L_{CS}}{pW_s} \tau_s},$$  \hspace{1cm} (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 $E[T_{ss}]$ 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

$$E[T_{ss}] = \sum_{i=0}^{W_s-1} \frac{p}{W_s} \sum_{k=0}^{i} (pT_i) + T_i = \frac{p^2 T_s(W_s-1)}{2} + T_i. \hspace{1cm} (32)$$

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 $R$, it is imperative that no vehicle within its carrier sense range $(2E[L_{CS}])$ or within the maximum $4R$ if $E[L_{CS}] > 2R$ will transmit in the same time slot in which the tagged vehicle is transmitting. At the same time, vehicles within the interfering areas, which is at maximum equal to $2(2R - E[L_{CS}])$ if $E[L_{CS}] < 2R$, should not transmit during the vulnerable interval of un-slotted ALOHA, which equals two transmission periods weighted by the time slot $T_v = 2T_i/\varrho$. The transmitted packet has also to be error free and the received signal strength has to be higher than the threshold $P_{th}$ which 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 receive the status packet successfully can be written as

$$P_s = P_{\tau} \cdot \left( \sum_{k=0}^{\infty} (1 - \tau_s)^k P_{d_s}(k) \right) \cdot \left( \sum_{k=0}^{\infty} (1 - \tau_s)^k P_{d_h}(k) \right), \hspace{1cm} (33)$$

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

$$P_s = \left\{ \begin{array}{ll} P_{\tau} \cdot e^{-(1 + 5R - 2RT_s)/\varrho}, & \rho > 0.5^\circ \\ P_{\tau} \cdot e^{-2RT_s/\varrho}, & \rho \leq 0.5^\circ \end{array} \right. \hspace{1cm} (34)$$

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

IV. EMERGENCY TIME DELAY

In this section, 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 access class (AC3) to send the emergency message after sensing an idle channel for an $AIFS_N \cdot \varrho$ seconds, where $AIFS_N = 2$ for this class as listed in Table I. If the channel is sensed busy, the access class selects a contention window from the range $[0, W_c]$ where $W_c = 3$ in this case and starts decrementing this counter as in the Markov chain in Fig. 3. Therefore, the probability $\tau_c$ that the emergency message will be sent can be derived by analyzing the Markov chain as in (30) except changing $W_s$ by $W_c$ as

$$\tau_c = \frac{2(1 - p)^2}{2 + pW_c - 3p}. \hspace{1cm} (35)$$

The average delay $E[T_{ss}]$ 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

$$E[T_{ss}] = \sum_{i=0}^{W_c-1} \frac{p}{W_c} \sum_{k=0}^{i} (pT_i) + T_i = \frac{p^2 T_s(W_c-1)}{2} + T_i. \hspace{1cm} (36)$$

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 NTTP 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

$$P_{tr}(d) = \frac{1}{2} \left( \frac{d}{R} \right) + \left( 1 - \frac{\beta}{\mu} \frac{1}{N_t/10} \right), \quad \text{(37)}$$

$$T_w(d) = \left( 1 - \frac{d}{R} \right) \left( \frac{\beta}{\mu} \frac{1}{N_t/10} \right) (2T_c + \delta), \quad \text{(38)}$$

where $d$ is the inter distance between the transmitter and the potential relay vehicle, $\beta/\mu$ is the current vehicle density and $N_t/10$ is the maximum vehicle density, that is, jam scenario. For more information on deriving (37) and (38), we refer the reader to [39].

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 receives the message successfully. 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 receive the message successfully (assuming that the message is transmitted with probability $\tau_c$), can be derived in two cases: First when $0 \leq d \leq L_{cs} - R$, in this case the relay vehicle would receive the message successfully when all vehicles within the range $[d - L_{cs}, d + R]$ do not use the channel in the same time slot as the transmitter. The second case is when $L_{cs} - R < d \leq R$, in this case the vehicles within the range of $[d - L_{cs}, L_{cs}]$ should not use the channel in the same time slot as the transmitter and the vehicles within the range $[L_{cs}, d + R]$ should not use the channel for the vulnerable period $T_v$. Therefore, the $P_{rec}$ can be derived in the same way as in (34) as

$$P_{rec}(d) = \begin{cases} P_t \cdot \tau_c \cdot e^{-\frac{d}{\mu} (1 + \frac{\beta}{\mu}) T_v}, & 0 < d \leq L_{cs} - R \\ P_t \cdot \tau_c \cdot e^{-\frac{d}{\mu} (1 + \frac{\beta}{\mu}) (d + (d + \frac{R}{\mu} - \frac{\beta}{\mu}) T_v)}, & L_{cs} - R < d \leq R. \end{cases} \quad \text{(39)}$$

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. But as $d$ increases, the relay vehicle is more vulnerable to the hidden terminal problem especially in high density scenarios. Therefore, a condition of receiving the emergency message with probability $P_{rec}(d) \geq 90\%$ is applied to find the average inter distance $d$ of the relay vehicle from the transmitter. Since this relay vehicle has a retransmission probability of $P_{tr}(d)$, its average waiting time till it transmits the emergency message is $T_w(d)/P_{tr}(d)$. The average number of hops the emergency message will travel to reach its intended distance $D$ is $[D/d]$. Therefore, the average emergency message travel time to reach a distance $D$ is

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

**V. Adaptive and Mobility Based Algorithm (AMBA) for Enhancing VANETs’ Performance**

From the analysis above, 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, especially 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 ($\lambda_s$), communication range ($R$) or (transmission power), carrier sense range ($L_{CS}$) and/or their minimum contention window size ($W_s$) based on the situation on the road in order to increase the success rate and VANETs’ reliability.

Therefore, a new adaptive and mobility based algorithm (AMBA) in which vehicles change their parameters according to their density and average speed on the road, pertaining to the following assumptions, is proposed:

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 ($\rho$) 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 as $V_c, R_c, \rho_c, \lambda_s, W_s$, respectively.

Vehicles will execute the AMBA algorithm every $T_{alg}$ seconds, 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 below. 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, 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 $W_{s}$. On the other hand, if $T_{b}$ is smaller than its previous value by $\psi = 10\%$, it will decrease its $W_{s}$. Otherwise it will keep 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 $30\%V_{\text{max}}$), the carrier sense range is decreased in order 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 synchronization interval with high successful reception rate.

### Algorithm 1: Adaptive and Mobile Based Algorithm (AMBA)

To set VANETs parameters according to the vehicles density on the road,

**Initial setup**

- $R_{c} \leftarrow R_{\text{max}}$
- $\rho_{c} \leftarrow 0.25$
- $\lambda_{s} \leftarrow 10$
- $W_{s} \leftarrow 15$

**for** Every $T_{\text{alg}} = 10 \cdot CCI$ seconds **do**

- if $V_{c} < V_{\text{max}}$ then
  - $i \leftarrow \lfloor \frac{V_{c}}{V_{\text{max}} \cdot 10} \rfloor$ \{i represents a step from 1 to 10 in which the current speed falls in compared to the max. speed\}
  - $R_{c} \leftarrow R_{\text{min}} + i \cdot \frac{R_{\text{max}} - R_{\text{min}}}{10}$ \{use a new range based on the step $i$\}
  - $\lambda_{s} \leftarrow \max(i, 1)$ \{use a new sending rate based on the step $i$\}
- if $i \leq 3$ then
  - $\rho_{c} \leftarrow 1$ \{in high density, $L_{CS} = \bar{R}$\}
- else
  - if $i \leq 7$ then
    - $\rho_{c} \leftarrow 0.5$ \{in medium density, $\bar{R} \leq L_{CS} \leq 2\bar{R}$\}
  - else
    - $\rho_{c} \leftarrow 0.25$ \{in low density, $L_{CS} \simeq 2\bar{R}$\}

**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

In this section, 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 that will send an emergency message. The time it takes for that emergency message to propagate to a certain distance (3000 meters) is of interest. It is assumed that all vehicles are synchronized to the control channel interval 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 micro-traffic 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 lanes, speed and could take over other vehicles in front of them. The simulation setup is a one directional highway segment of 4000m in length with 4 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 $\Omega$. The authors in [41] performed a maximum likelihood estimation of $m$ and $\Omega$ for vehicular highway scenario. They found that $\Omega$ decreases as the distance to the receiver increases as expected from the average power in the deterministic models, that is by $d^{-2}$. On the other hand, fading parameter $m = 3$ is selected for short inter distance between the transmitter and the receiver ($d \leq 50$), since line of sight conditions is expected, 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. $\Omega$ is set in each interval to be the average power calculated from a free space propagation model; hence receivers located within 100m of the transmitter will receive the signal with Rician distribution, while 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 $\bar{R}$ is the threshold $P_{th}$ as per (6), and the carrier sense range $E[L_{CS}]$ is as in (7). Each simulation is performed for a period of 300 seconds 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’ arriving rate. Note that the Poisson models do not take into account the follow-on safety rule, the increase in vehicles arriving 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 inter distance between them as a result of decreasing their speed. This is also obvious from Fig. 6 which shows how vehicles average speed and density are affected by the increase of their arrival rate.

The following four metrics are defined to evaluate the accuracy of the proposed model and reliability of the DSRC protocol in VANETs. First: the effective communication range, which is the range in 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). Second: The success rate, which is the number of vehicles that receive the transmitted packet successfully divided by the total number of vehicles that are within the range of the transmitter and compare it with (34). Third: the average delay for a vehicle to send its status message and compare it with the delay derived in (32). Fourth: the system reliability, which is the percentage of vehicles that managed to send their status messages successfully within any synchronization interval (SI).

The results shown in Figs. 7-10 are based on the vehicle density and average speed corresponding to the density extracted from 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 status packets generation rates. 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 the system reliability, the status packet generation rate is reduced from 10 to 5 and then 2 packets/s. This improves the system reliability and success rate but it is still below the threshold of 95% especially when the vehicle density is high. In order to meet this threshold for any vehicle density, vehicles have to reduce their communication range based on Fig. 7.

Figs. 11, 12, 13 and 14 show respectively the effective communication range, the success rate, status packet delay and the reliability versus the vehicle density for different

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Table III

Value of parameters used in simulation

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

Fig. 6. Vehicle density and their normalized average speed vs vehicle arriving rate.

Fig. 7. Effective communication range versus vehicle density when the success rate is set at 95% for different status packet sending rates.
carrier sense ranges. The carrier sense range is increased by decreasing the carrier sense power or the parameter $\rho$. By decreasing $\rho$ 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 have 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, 16 and 17, respectively. It is shown that increasing the minimum contention window will decrease the probability of packet collisions between vehicles which is obvious from Fig 15 since the successful rate increases by the increase of $W_s$. It is also shown that there is an optimal value of $W_s$ which gives the maximum success rate since increasing it would not further result in much increase in the success rate. At the same time, the status packet delay will increase dramatically by increasing $W_s$ especially 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 VANETs reliability, 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 meters behind the transmitter. This emergency message will be rebroadcasted in every hop based on the NTTP 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. 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 collisions. Adapting the AMBA algorithm results in increasing the emergency delay even more and this is 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 especially in a high density scenario as shown in Fig. 19. This means that more vehicles will be
in which the relationship between vehicle density, speed and applications. The analysis is based on a new mobility model to enhance VANET’s performance. The proposed model is built on the fact that vehicles are broadcasting their status messages within the synchronization interval and model each vehicle as one-dimensional Markov chain including the channel busy probability in every state. It is shown analytically and by simulation that the effective maximum communication range that can be used in certain conditions to achieve certain successful rate. 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, Adaptive and Mobility Based 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 to other algorithms.

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