Abstract— In this paper, a new analytic model is built to derive MAC and application-level reliability metrics of IEEE 802.11 based one-dimensional (1-D) vehicular ad-hoc networks (VANETs) in highways, which include Packet Reception Probability, Packet Reception Ratio, T-window Reliability, and Awareness Probability. The metrics derivation starts with the evaluation of point-to-point reception probability through coverage area computation for the impact of hidden terminal problem and concurrent transmissions. The proposed approach facilitates impact analysis of distance dependent DSRC fading channel and application-level analysis. The analytical model takes IEEE 802.11 MAC, 1-D highway geometry, non-saturated message arrival interval, and Nakagami fading channel with path loss into account. The proposed model is validated/verified by extensive simulations. From the obtained numerical results under various network parameters, new important observations are given.

Keywords- vehicular ad hoc networks, broadcast, reliability, channel fading, application-level reliability.

I. INTRODUCTION

Vehicular ad hoc network (VANET) is one of the key enabling components in Intelligent Transportation System (ITS) [1]. A VANET consists of a large number of vehicles that are capable of wireless communication in an ad hoc manner without central control. Dedicated Short Range Communication (DSRC) radio technology, being standardized as IEEE 802.11p [2], is projected to support low-latency wireless data communications between vehicles and from vehicles to roadside units. The DSRC physical layer follows the same frame structure, modulation scheme and training sequences specified by IEEE 802.11a physical layer except that IEEE 802.11p PHY uses 10 MHz bandwidth instead of the 20 MHz used by IEEE 802.11a [3]. MAC layer of the DSRC is equivalent to the Enhanced Distribution Coordination Access (EDCA) 802.11e that has four different access classes (ACs) [4]. VANETs can support many safety-related applications [5] using one-hop or multi-hop broadcasting to disseminate real-time traffic information or safety-related messages [6][7][8]. High reliability and short delay are required for dissemination of these safety-related messages under adverse environments.

The MAC-level (or network layer) performance of the broadcast message dissemination in DSRC system has been studied. Several important reliability metrics such as Packet Reception Probability (PRP), Packet Reception Ratio (PRR) and Packet Delivery Ratio (PDR), etc. are defined and evaluated [6-13]. Normally, PRP and PRR were evaluated by simulations [6][13]. In [9][10], analytical models were proposed to obtain PRR expressions in one-dimensional (1-D) IEEE 802.11 based broadcast MANETs with hidden terminals. However, impact analysis of fading channel model, if any, was approximated by a constant bit error rate (BER). Assuming Poisson distributed nodes, and saturation packet generation, PRR of beacon message broadcast in 1-D DSRC VANETs was investigated in [11] taking the impact of Rayleigh fading into account. However, hidden terminal problem was neglected in the paper.

Even though the MAC-level performance metrics play an important role for understanding the packet transmission behavior and evaluating the efficiency of a protocol, the application-level metrics constitute the driving force for protocol development [15]. Efforts have been made in previous work [15][16][17] to characterize the application-level performance metrics for specifying the application performance requirements. Bai et al. [15] introduced the application-level latency and T-window reliability (TWR) (i.e., the probability to successfully receive at least one packet during tolerance time window T) to guide performance requirements in terms of application-level metrics. An et al. [17] proposed that the application requirements can be specified as awareness range and awareness probability. However, these application-level metrics were not well studied analytically under realistic DSRC environment.

In this paper, we propose a new analytical model to investigate the impact of various realistic factors in DSRC environment on MAC-level and Application-level reliability metrics. Compared with the existing models for reliability analysis of broadcast in VANETs, the main contributions of the proposed analytic model in this paper are: 1) the proposed model is more general to account for impact of DSRC environment factors such as IEEE 802.11 CSMA, non-saturated packet generation, hidden terminal problem, and DSRC fading channel with path loss; 2) the new approach facilitates derivation of both MAC-level and Application-level reliability as well as the impact analysis of distance dependent Nakagami fading; 3) A more accurate approach is introduced for the analysis of hidden terminal that is one of major factors for degradation of the reliability. This paper is organized as follows. Section II presents brief description of IEEE 802.11 broadcast MAC, broadcast hidden terminal problem, and channel fading and path loss in the VANET environment. Section III presents the analytic model for the analysis of MAC level and Application-level
reliability metrics in 1-D IEEE 802.11 broadcast VANETs with hidden terminals and channel fading. Section IV applies the proposed model to an analysis of a typical broadcast system for VANET safety applications, and demonstrates and discusses the numerical results and statistical evaluations of the analytical model and the simulation. The paper is concluded in Section V.

II. DSRC VANET BROADCAST AND ENVIRONMENT

A. Distributed Coordination Function (DCF) for IEEE 802.11 Broadcast Service

Without loss of generality, only a single safety related service in DSRC control channel is considered in this paper. The results can be easily extended to that for multiple services. MAC layer of IEEE 802.11 deploys a carrier sense multiple access with collision avoidance (CSMA/CA). The basic mechanism for the 802.11 based MAC protocols is the distributed coordination function (DCF). Broadcast procedure of 802.11p MAC follows the basic medium access protocol of DCF. Broadcast of IEEE 802.11p based MAC starts to work when a broadcast packet arrives at VANET MAC layer of a mobile node from upper layer and the MAC senses the channel status first and stores the status. Once an idle period of DIFS/EIFS is observed, the mobile node takes the next action based on the observed channel status and the current value of its backoff counter. If the current value of the backoff counter is not zero, the mobile node begins the backoff countdown process. Otherwise, if the current value is zero and the observed status of the channel is busy, the mobile node generates a random backoff time and starts backoff process. If the backoff counter is decremented to zero and the channel is still available, MAC begins data packet transmission immediately. During the backoff process, carrier-sense persists to work. If the channel becomes busy again, MAC of the mobile node goes back to the DIFS/EIFS observation process. It is noticed that, during or after a broadcast transmission, MAC of the mobile node is not able to monitor the success or failure of the transmission. Once current transmission is done, the node simply releases the medium and does not compete for a channel until a new packet is coming and ready to be transmitted.

B. Radio Channel Fading & Path Loss in VANETs

VANET environments present scenarios with unfavorable characteristics to develop wireless communications. First, multiple reflecting objects may degrade the strength and quality of the received signal. Second, fading effects could be resulted from the mobility of the surrounding objects, the senders, and/or receivers. DSRC channel modeling has to consider impact of two important issues: large scale distance dependent path loss and small scale channel fading. The large scale distance dependent path loss model is adopted to determine the average received signal power at a certain distance from the transmitting node, whereas small scale channel fading model generally involves the detailed modeling of multi-path fading statistics, power delay profile, and Doppler spectrum. The Nakagami distribution is believed to fit the amplitude envelope of signal transmitting on DSRC channel well [6]. The probability density function of a signal amplitude \( y \) in Nakagami fading can be expressed as:

\[
f(y, \omega, m) = \frac{2m^m}{\Gamma(m)} y^{2m-1} \exp\left(\frac{-my^2}{\omega}\right), \quad y \geq 0, \omega > 0, m \geq 1/2
\]

where \( m \) is the fading parameter, and \( \omega \) is the average received power. The values of the two parameters are functions of distance to the sender. From empirical data obtained for vehicular environment in [8], the fading parameter \( m \) is approximated as 3 for low values of \( d \) (\( d < 50 \text{m} \)) expecting line of sight conditions, 1.5 for middle range distances (50m\( \leq d \leq 150 \text{m} \)), and 1 (Rayleigh distribution) for distance higher than 150m.

The path loss model is represented by the following equation:

\[
\frac{\omega(d_o)}{\omega(d)} = \left(\frac{d}{d_o}\right)^{\beta}
\]

where \( \omega(d_o) \) and \( \omega(d) \) are the mean received power with distance to the sender \( d_o \) and \( d \), respectively, and \( \gamma \) is the path loss exponent, and is usually empirically determined by field measurement. \( \gamma \) can be 2 for free space environment, 1.6–1.8 for line of sight, and 2.7–3 for obstructed area or shadowed urban area.

C. Hidden Terminal Problem in Broadcast

Hidden terminals are defined as the terminal(s) that, although they are outside the carrier sensing range of a transmitting node, share a set of receiving terminals that are within the transmission range of both the terminal(s) and the transmitting node. The hidden terminal problem is a critical issue affecting the performance and reliability of mobile ad hoc networks. Although support for reliable unicast using RTS/CTS has existed traditionally in IEEE 802.11 [3], there has not been any MAC-level recovery or retransmission on frames for reliable broadcasting. Since IEEE 802.11 broadcast only relies on physical carrier sensing to reduce collisions, the potential hidden terminal area of a sending node includes the interference range of all the nodes within transmission range of the sender. Thus, the hidden terminal problem in IEEE 802.11 broadcast can be significantly worse than that of IEEE 802.11 unicast.

III. ANALYTIC MODEL FOR RELIABILITY ANALYSIS

A. Assumptions for Analysis of VANET Safety Message Broadcast

The following assumptions are made for our analytical model.

1) We consider a one-dimensional broadcast VANET which consists of a collection of mobile vehicles randomly placed on a line according to a Poisson point process with network density \( \beta \) (in vehicles per meter); i.e., the probability \( P_r(j, l) \) of finding \( j \) vehicles in length of \( L \) is given by

\[
P_r(j, L) = (\beta L)^j e^{-\beta L} \frac{L!}{j!}
\]

The expected number of vehicles with the transmission range of a transmitting vehicle or tagged node on the line is \( 2\beta R \).
2) All vehicles in the VANET have identical transmission, receiving range, and carrier sensing range, which is denoted as \( R \).
3) At each vehicle, packet arrivals follow Poisson point process with rate \( \lambda \) (in packets per second). The queue length of packets at each vehicle is unlimited. In addition to its tractability, the Poisson arrival process is a good approximation of message arrivals in packet-data networks [10];
4) Nakagami fading with path loss model from (2) is assumed for impact analysis of DSRC channel fading [13];
5) Impacts of vehicle mobility on the reliability are neglected in this paper.

B. Packet Transmission Probability and Channel Busy Probability of VANET Broadcast

As described in [3], the IEEE 802.11 broadcast backoff counter in each vehicle can be characterized by a one-dimensional random process. Denote \( \tau \) as the packet transmission probability that a mobile vehicle transmits in a slot. Following the backoff model and procedure in [10], we have

\[
\tau = \frac{2p_0}{W_0 + 1}
\]

(4)

where \( p_0 \) is the probability that there is at least one packet ready to transmit at the MAC layer in each vehicle, which will be iteratively calculated later in subsection C. When detecting an ongoing transmission, the backoff timer will be suspended and deferred a time period of \( T \) which is expressed as

\[
T = (L_{tt} + E[PL]) / R_d + DIFS + \delta
\]

(5)

where \( R_d \) is system transmission data rate. \( PL \) is a packet holds size with average packet length \( E[PL] \). The packet header includes physical layer header plus MAC layer header: \( L_{tt}=PHY_{hda}+MAC_{hda}, \delta \) is the propagation delay, and \( DIFS \) is the time period for a DCF inter-frame space.

In the broadcast VANET, each vehicle can send out a packet if there is no transmission sensed within the carrier sensing range of the node. To facilitate modeling of such network, here a transmission channel is defined with respect to any vehicle sending out packet (called the tagged node or tagged vehicle). Denote \( p_h \) as the probability that the channel is sensed busy by the tagged vehicle, since the channel is sensed busy if there is at least one vehicle transmitting in the sensing range of the tagged vehicle, \( p_h \) is calculated as

\[
p_h = 1 - \sum_{r=0}^{\infty} (1 - r \lambda / \mu) e^{-r \lambda / \mu}
\]

(6)

C. Queue Model for Each Mobile Vehicle

According to assumption 3) in Section II-A, each mobile vehicle is modeled as an M/G/1 queuing system. The M/G/1 queue can be analyzed by the message arrival process and the channel service time distribution. The channel service time is defined as the time duration from the instant that a packet becomes a head of the queue and competes in the channel for transmission, to the instant that the packet is successfully received. It is evident that the distribution of the service time is discrete with time unit \( \sigma \) (a time slot) [10]. Here, we adopt probability generating function (PGF) to approach service time distribution.

For a tagged node in broadcast VANET, the transition for backoff counter decremented by one can be derived by the following PGF,

\[
G_d(z) = (1 - p_0)z + p_0 [z^2]
\]

(7)

Define \( q_i \) as the steady state probability that the packet service time is \( i \sigma \). Let \( Q(z) \) be the PGF of \( q_i \), which is [10] [12]

\[
Q(z) = \sum_i q_i z^i = z^2 / (1 - p_0) z^2 / W_0 \sum_i G_i(z)
\]

(8)

Then, an iterative algorithm is introduced to calculate \( p_0 \). The iterative steps are outlined as follows.

Step 1: Initialize \( p_0 = 1 \).
Step 2: With updated \( p_0 \), calculate \( p_h \) from (4) and (6).
Step 3: Calculate \( Q(z) \) through PGF.
Step 4: Service rate \( \mu = 1 / Q'(1) \).
Step 5: If \( \lambda < \mu \), \( p_0 = 1 - \lambda / \mu \); otherwise, \( p_0 = 0 \);
Step 6: If \( p_0 \) converges with the previous value, then stop the algorithm; otherwise, go to step 2 with updated \( p_0 \).

D. Evaluation of MAC Reliability

Derivation of MAC and application-level reliability starts with the evaluation of point-to-point packet reception probability through coverage area computation. The transmission scenario is shown in Fig. 1. Given a transmitting node \( O \) placed at the origin, \( U \) is one of the receivers within transmission range \( R \) of node \( O \). \( U \) is placed on x-axis with certain distance to \( O \), which is denoted as \( x \) (0<x<R). There are three factors affecting the reliability of safety message broadcast: hidden terminal problems, concurrent transmission collisions, and packet errors as a result of fading channel with distance dependent path loss.

Impact of Hidden Terminals

It is observed that two necessary conditions must be satisfied so that collisions between packets from hidden terminal vehicles and the packet from the tagged vehicle can be avoided. First, when the tagged node starts its transmission, none of the hidden terminal vehicles can be in the transmitting state, which is denoted as event \( HE_1 \). Second, after the tagged node starts its transmission given that event \( HE_1 \) event is true, none of the hidden terminal vehicles should start transmitting until after the packet broadcast from the tagged node is completed, which is denoted as event \( HE_2 \).

For event \( HE_1 \), all the happening packet transmissions from the vehicles in the potential hidden terminal area should take \( xB/4 \) time duration per second. Because of direct
concurrent transmission collisions among hidden terminal vehicles, some packet transmissions may overlap. The direct transmission collision probability among the vehicles within transmission range of the tagged node is

\[ P_{dc} = 1 - e^{-\beta \lambda t} \]

With the direct collision probability, we have \( x \beta \lambda T_{dc} \) such overlapping packets. Considering that the chance of direct collision involving three or more packets is very small, the transmission time to send the concurrently collided packets would be \( x \beta \lambda T_{dc}/2 \) [14]. Considering that HE1 is the complement of the event of finding at least one hidden terminal in the transmitting state, we have the probability that no hidden terminal is in the transmitting state:

\[ P_{he2}(x) = 1 - x \beta \lambda T(1 - P_{dc}) \] (9)

For event HE2, since generated packets arrive in each vehicle’s buffer according to a Poisson process, the combined arrival of all the hidden terminal vehicles is also Poisson with rate \( x \beta \lambda \) (packets/sec). Therefore, the condition HE2 is satisfied if no packet is generated at any of the hidden terminal vehicles during the transmission excluding DIFS from the tagged vehicle. Given that HE3 is true, the probability that a packet is generated by any hidden vehicle after the tagged node starts its transmission and eventually collides with the transmission of the tagged vehicle is expressed as

\[ P_{he3}(x) = \frac{(\beta \lambda T)^{x} e^{-\beta \lambda T(1 - P_{dc})}}{x!} = e^{-\beta \lambda t} (\beta \lambda T)^{x} e^{-\beta \lambda T(1 - P_{dc})} \] (10)

Impact of Concurrent Transmission Collisions

Apart from collisions caused by the hidden nodes, transmissions from nodes within the carrier sensing range of the tagged node in the meantime at which the tagged node transmits may also cause collisions. When the tagged vehicle transmits in a slot time, the concurrent transmission collisions will occur if any vehicle within the carrier sensing range of the tagged vehicle transmits in same slot.

Given that both \( O \) and \( U \) sense the channel idle, \( O \) will transmit within the duration of a slot. It should be noted that the slots of \( O \) and \( U \) are not necessarily synchronized. In order to prevent interference due to concurrent collisions to \( U \)'s receiving the broadcast message sent by \( O \), no transmission in \([-R, x] \) is required. The average number of nodes transmitting in the concurrent slot in area \([0, R]\) is \( \beta R x \). Suppose node \( V \) is \( z \) away from \( O \), \( - (R-x < z < 0) \), the probability that the node \( V \) starts transmitting during the slot is the probability that node \( V \) intends to transmit and all nodes within \([-R, -R] \) are not transmitting state, which is expressed as

\[ P^*(x, z) = \tau (1 - \beta \lambda t (1 - P_{dc}/2)) \] (11)

Then, the average number of nodes that start transmission during the slot that collides with the transmission from \( O \) is

\[ \bar{n}_{1} = \int_{0}^{\beta R x} P^*(x, z) dz = \beta R \int_{0}^{\beta R x} (1 - \beta \lambda t (1 - P_{dc}/2)) dz \]

\[ = \beta x (R - x) - \frac{1}{2} \beta^{2} \int_{0}^{\beta R x} z^{2} T (R - x)^{2} (1 - P_{dc}/2) dz \] (12)

Then

\[ \bar{n}_{2} = \bar{n}_{1} + \beta R \tau \]

Therefore, given Poisson node distribution, the probability that no nodes within the reception range of \( U \) start transmission during the slot that collides with the transmission from \( O \) is

\[ P_{con}(x) = \frac{(\beta R x)^{y} e^{-\beta R x}}{y!} = e^{-\beta R x} \] (13)

Impact of Channel Fading with Path Loss

For the Nakagami distribution with a positive integer value for fading parameter \( m \), we obtain the corresponding cumulative distribution function \( cdf \) for a signal to be received with power \( y \) for a given average power strength \( \omega \),

\[ F_{w}(y; m, \omega) = \frac{m^{m} \Gamma(m) \omega^{m-y}}{\Gamma(m-m-y) \omega^{m}} \int_{y}^{1} z^{m-1} e^{-(m)/(z \omega)} dz \] (14)

From (14), the probability that a packet is successfully received in the absence of interferers can be equal to the probability that the packet’s signal is stronger than the reception threshold \( TR_{r} \),

\[ P_{r}(y > TR_{r}) = 1 - F_{w}(TR_{r}, m, \omega) = 1 - \frac{m^{m} \Gamma(m) \omega^{m-y}}{\Gamma(m-m-y) \omega^{m}} \int_{y}^{1} z^{m-1} e^{-(m)/(z \omega)} dz \] (15)

On the average, \( TR_{r} \) can be detected in a distance equal to the “intended” communication range \( R \) from the transmitter. Considering a quadratic path loss according to the Friis model [13] we get the relationship

\[ TR_{r} = \frac{T_{p}}{R} G \] (16)

where \( T_{p} \) denotes the transmission power to be selected. \( G \) is a constant value defined as

\[ G = \frac{G_{t} G_{r} \lambda_{w}}{(4 \pi)^{2} L} \] (17)

where \( G_{t} \) and \( G_{r} \) denote the antenna gains of transmitter and receiver, respectively, \( \lambda_{w} \) is the wavelength of the transmission, and \( L \) is the path loss factor, usually set to 1. We again apply the Friis model to determine the average reception power \( Q(x) \) at the distance \( x \), that is,

\[ Q(x) = \frac{T_{p} G}{x^{2}} \] (18)

By applying \( TR_{r} \) in (16) and \( Q(x) \) in (18) to (15), with a certain mathematical manipulation, we obtain the expected probability of successfully receiving a message at distance \( x \):

\[ P_{r}(x) = 1 - \frac{(x m)^{m} e^{-x m}}{\Gamma(m)} \int_{y}^{1} z^{m-1} e^{-(m)/(z \omega)} dz \] (19)

Notice that \( m \) value in above equation for vehicular environment is a function of \( x \) [8]:

\[ m(x) = \begin{cases} 3, & x < 50m \\ 1.5, & 50m \leq x < 150m \\ 1, & x \geq 150m \end{cases} \] (20)

Taking hidden terminal, possible packet collisions, and channel fading and path loss into account, the probability (or node reception probability) that the node \( U \) receives the broadcast message from the tagged node \( O \) is

\[ P_{r}(x) = P_{n1}(x) P_{n2}(x) P_{con}(x) P_{r}(x) \] (21)

MAC-Level Packet Reception Ratio (PRR) PRR is defined as a percentage of nodes that successfully receive a packet from the tagged node among the receivers that are within transmission range of the sender at the moment that the packet is sent out [9].

Assuming Poisson distribution of nodes along a 1-D line, the average number of nodes within an incremental distance
dx should be βdx. Given the reception probability \( P_r(x) \) of each receiver in Eq. (21), the average number of nodes in \( dx \) that successfully receive the broadcast message from the tagged node is \( P_r(x)dx \). For a coverage distance with range \( R \) from node \( O \), \( PRR \) over a coverage range with distance \( x \) \((0<x\leq R)\) found by integrating the probabilities that nodes with distance \( x \) to the source node \( O \) within an incremental range \( dx \) successfully receives the broadcast message from \( O \). Therefore,

\[
PRR(x) = \frac{\beta P_r(x)dt}{dx} = \frac{1}{x} \int_0^x P_r(t)dt ; x \leq R \tag{22}
\]

E. Evaluation of Application-Level Reliability

Having derived point-to-point packet reception probability, two application-level reliability metrics for DSRC safety applications will be subsequently evaluated. Since these application-level reliability metrics are functions of distance and time, they may be used to judge if current DSRC protocol meets the requirements of specific safety applications such as lane change warning, stationary vehicle warning, and post-crash notification, etc.

**T-window Reliability** Application-level T-window reliability is defined in [15] as the probability of successfully receiving at least one packet out of multiple packets from a broadcast vehicle at distance \( x \), within a given time \( T_a \) (referred to as application tolerance window):

\[
P_{app}(x, T_a) = 1 - \left(1 - P_r(x)\right)^{\frac{T_a}{\Delta t}} \tag{23}
\]

where \( t \) is the broadcast message generation interval and \( P_r(x) \) is the node reception probability given in (21). T-window reliability can be applied to evaluate DSRC VANET for emergency vehicle warning application [18] which requires the probability that a vehicle within 500 meters from the sender successfully receives at least 1 packet in the tolerance time window \( T_w=1s \) is larger than 99.9%.  

**The Awareness Probability** The awareness probability [16] is the probability of successfully receiving at least \( n \) packets in the tolerance time window \( T \):

\[
P_a(x, n) = \sum_{k=n}^{\infty} \frac{T^k}{k!} \left(1 - P_r(x)\right)^{\frac{T}{\Delta t}} \tag{24}
\]

It is noted that the awareness probability \( P_a(x, n) \) becomes the T-window Reliability \( P_{app}(x, T) \) as \( n \) is equal to 1. A typical safety application that the awareness probability can apply to is Rear-end collision warning application, which requires the probability that a vehicle within 50 meters from the sender successfully receives 4 out of 5 packet in the tolerance time window \( T_w=1s \) is larger than 99.9%.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In order to validate the proposed analytic model, we consider a specific Dedicated Short Range Communications (DSRC) VANET in highway for safety message dissemination. Each vehicle in the network is equipped with DSRC capability with following communication parameters [10]: \( E[PL]=200–400 \) bytes (average message length), \( L_d=272\times178 \) bits (MAC header+PHY header), \( R=500 \) m (carrier sensing range/transmission range of each node), \( \sigma=16\mu s \) (slot time), \( DIFS=64\mu s \), \( BW=10 MHz \) (channel bandwidth), \( SIFS=32\mu s \), \( \delta=1\mu s \) (propagation delay). Our simulation using both NS2 and MATLAB is conducted under a highway DSRC environment within length of road 5000 m. In the NS2 program, the communication nodes are connected through setting up transmission powers and receiving thresholds so that communication ranges are random variables in the simulation.

Fig. 2 depicts the packet reception rates (PRRs), over the density of vehicles with varied data rates. As we see from Fig. 2, analytical PRR results (lines) are practically consistent with the simulation results (symbols). In support of this position we perform analysis of standard deviation between the NS2 simulations and the theoretical model. The expectations used to evaluate the standard deviations were determined by the mathematical model. It is observed that the standard deviation is less than 1\% to a maximum of less than 4\% of the models data values.

We observe that Nakagami fading channel degrades PRRs significantly. Fig. 2 also shows that the PRRs are very small especially as the offered traffic is heavy, which do not meet reliability requirement for most of VANET safety applications from MAC-level perspective.

Fig. 3 shows the impact of evaluation distance, IEEE 802.11 DCF backoff window sizes, and packet lengths on PRRs. PRRs go up as the evaluation distance to the sender is reduced. The observation is due to the fact that the longer the receiver’s distance to the sender, the more likely the receiver is affected by hidden terminal problem and channel fading.

![Fig. 2 Packet reception ratios of DSRC broadcast](image)

![Fig. 3 Packet reception ratios of DSRC broadcast with different parameters](image)
Increasing backoff window sizes (from 15 to 1024) helps improve PRRs. In addition, the shorter the average length of transmitting packets is, the higher the PRRs become.

Fig. 4 depicts analytic results for the application-level reliability metrics under a given network parameter settings: Transmission range $R=500$m, Time window $T_0=1$s, Data rate $R_c=24$ Mbps, Packet length $PL=200$ bytes. Beacon message interval $t=1, \lambda=0.1$ s. Vehicle density $V=0.2$ vehicles/m. From Fig. 4, we can observe that all packet reception reliability metrics decrease with the distance from the sender. During the time window $T_0=1$s, there are 10 beacon packets sent out from the sender since the beacon message interval is 0.1 s. If the packet requirement is less than or equals to 2 packets, the T-window reliability and the awareness obtained are larger than 99% as transmission distance is less than 450 m, which can ensure the application works appropriate even though the PRR and PRR in the network layer are not high enough. Otherwise, if the packet requirement is larger than 2 among 10 packets transmitted within 1 second, the application layer awareness probability may be even lower than the PRR and PRR in the network layer as seen from Awareness Probability ($n=5$, $n=7$) cases. Hence, for some applications that require more than 2 packets within $T_0=1$s, the reliability requirement may not be met.

V. CONCLUSIONS

In this paper, we propose an analytical model to evaluate the reliability of IEEE 802.11 based broadcast VANETs in both the MAC and application level. The proposed approach using point-to-point integration facilitates application-level reliability metrics derivation and the accurate impact analysis of fading channel. The derived expressions of the reliability metrics take the impact of Nakagami fading and path loss, hidden terminal problem and DCF backoff process into account. Characteristics of the reliability for DSRC safety related services are analyzed and discussed. The analysis in this paper can be very useful for tuning network parameters in order to obtain satisfied QoS for many VANET safety applications.

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REFERENCES