Abstract—IEEE- and ASTM-adopted dedicated short range communications (DSRC) standard towards 802.11p is a key enabling technology for the next generation of vehicular safety communication. Broadcasting of safety messages is one of the fundamental services in DSRC. In this paper, requirements and channel design of vehicular ad hoc networks for safety applications are addressed. Performance of vehicle-to-vehicle (v2v) safety related services in DSRC system on highway is investigated analytically and by simulation. Under some reasonable assumptions, analysis is conducted to characterize IEEE 802.11a-based channel for safety message broadcast under harsh DSRC highway environment with high vehicle mobility, dynamic self-organized network topology, and adverse multi-path fading channel. Based on solutions to the proposed analytic model, transmission delay and packet reception rates are derived. The proposed analytic model accounts for impact of priority access, message arrival interval, hidden terminal problem, fading transmission channel, and highly mobile vehicles on performance indices for DSRC safety related communication. From the obtained numerical results under various offered traffic and network parameters, new observations and effective enhancement suggestions are given.

Keywords--vehicle-to-vehicle communication, DSRC, wireless ad hoc networks, medium access control, broadcast.

I. INTRODUCTION

Transportation safety is one of the most important applications of vehicular ad hoc networks. Recently, the developments of Intelligent Transportation System (ITS) have been going on towards safe and comfort driving. Vehicle-to-vehicle (v2v) communication is a vital part of ITS. The DSRC standard with 75 MHz at 5.9 GHz band was projected and licensed to support low-latency wireless data communications between vehicles and from vehicles to roadside units in USA. Safety applications usually demand direct v2v ad hoc communication networks due to highly dynamic topology of the networks and the stringent delay requirements. They will likely work in a broadcast fashion since safety information can be beneficial to all vehicles around a sender. Recently, ASTM Committee E17.51 endorsed a variant of the IEEE 802.11a Roadside Applications (R/A), as the platform for the DSRC link and data link layer. Therefore, channel congestion control and broadcast performance improvement are of particular concern and need to be addressed in the overall protocol design. Safety related communication in DSRC system is studied in [6] [7] [9] [13]. So far, all analysis and observations are mainly based on simulations. Factors that affect system performance and reliability such as IEEE 802.11 backoff counter process, hidden terminals, channel access priority, message generation interval, and high mobility on the road, etc. have not been analytically addressed yet for the analysis of the DSRC safety broadcast communications.

In this paper, we construct analytic model to evaluate delay and packet reception rates of a typical network solution for DSRC-based safety related communication under harsh wireless communication environment with high vehicle mobility, dynamic self-organized network topology, and adverse multi-path fading channel. We apply our proposed model to evaluate the impact of message arrival interval, channel access priority scheme, hidden terminal problem, fading transmission channel, and highly mobile vehicles on transmission delay and packet reception rates. Based on observations of performance under typical DSRC environment, some enhancement schemes are suggested accordingly.

II. DSRC SYSTEM DESCRIPTIONS AND ENVIRONMENT

The DSRC spectrum is divided into seven 10 MHz wide channels. Channel 178 is the control channel, which is generally restricted to safety communications only [3] [4]. There are two types of safety related life messages that will likely be transmitted over the control channel [12] [13]: event driven (or emergent) safety messages and routine safety messages. Event driven messages will contain information about environment hazards, and will be transmitted when an emergency or non-safe situation is detected to make all the vehicles in the area aware or activate an actuator of an active safety system. Event driven communications happen only occasionally, but must meet a requirement of fast and
guaranteed delivery. Routine messages will contain state of vehicles (e.g., position, speed, direction), and will be broadcast by all vehicles at a frequency between 10-20 times per second for each vehicle.

To support safety applications in the DSRC system with high reliability and low delay, the basic link-layer behavior and the environment of safety communications in the control channel can be defined as follows [7] [9] [12]. 1) Two types of the safety messages are broadcast in the control channel; 2) Most of the identified safety applications are based on direct or single-hop communication among vehicles within range of one another; 3) Transmission power in each vehicle for safety related communication should be strong enough to reach all potentially affected vehicles; 4) Each safety message is usually very short (100~300 bytes); 5) A real-time priority scheme similar to IEEE 802.11e is adopted to differentiate two safety services by using different distributed coordination function (DCF) backoff window sizes: the higher priority class uses the window \([0, W_0-1]\) and the lower priority class uses the window \([W_0, W_m-1]\); 6) The broadcast fashion of v2v safety communications makes them very sensitive to hidden terminal problems; 7) High mobility of vehicles on the road may cause adverse effects on performance of message sending and receiving; 8) V2v communications present scenarios with unfavorable characteristics of channel fading in DSRC. The channel fading is considered by introducing packet error probability \(p_e = 1 - (1 - p_{ber})^{W_{th}}\), where \(P\) is the length of the packet, \(T_{th}\) is the length of packet header, and \(p_{ber}\) is the bit error rate (BER) probability.

Requirements for performance in emergency situations: the update interval of safety message should be less than 500ms so that drivers or automatic mechanism in vehicles have enough time to react [5] [13]; the probability of message delivery failure should be less than 0.01 [13]. In other words, the probability of packet reception should be bigger than 0.99.

A. Impact of Hidden terminal Problem

Hidden terminals are two terminals that, although they are outside the interference range of one another, share a set of terminals that are within the transmission range of both. The problem of hidden terminals is a critical issue in the performance of ad hoc networks. Broadcast in IEEE 802.11 does not use virtual carrier sensing and thus only relies on physical carrier sensing to reduce collision [1]. In case of broadcast communication, the potential hidden terminal area needs to include the receiving range of all the terminals within transmission range of the senders. Thus, the potential hidden terminal area in broadcast can be dramatically larger than that of unicast. In other words, the broadcast fashion of v2v safety communications makes them very sensitive to hidden terminals.

B. Impact of High Mobility

Under v2v communication environment, the vehicles are highly mobile and the network topology changes very frequently. These changes are due to the high relative speed of vehicles, even when they are moving in the same direction. Two vehicles can directly communicate only when they are within their radio range.

For safety communication in DSRC, high mobility of vehicles on the road may cause two adverse effects on performance of message sending and receiving. On one hand, during transmission of safety-related message, some of receivers may move out of transmission range of the sender, resulting in failure of receiving the message. On the other hand, high mobility makes worse Doppler spread on orthogonal frequency division multiplex (OFDM), which leads to higher packet error rates and consequently lower channel capacity.

C. Radio Channel Fading in DSRC

V2v communications present scenarios with unfavorable characteristics to deploy wireless communications, i.e., multiple reflecting objects able to degrade the strength and quality of the received signal. Additionally, due to the mobility of the surrounding objects and/or the sender and receivers themselves, fading effects have to be taken into account. While there are many factors that can affect the bit error rate (BER) on a multi-hop communication environment, mobility of nodes is one of the most important factors that can cause packet errors.

III. SYSTEM MODEL AND PERFORMANCE ANALYSIS

A. Assumptions For IEEE 802.11 Broadcast in DSRC

In this paper, we focus on performance analysis of the control channel with two levels of safety services. Real world radio networks are influenced by many factors. In our model, we assume that IEEE 802.11 broadcast DCF works under following scenarios.

1) We consider a highway environment where vehicles are exponentially distributed with density \(\beta\) and they travel in free-flow conditions. As seen in Fig. 1, the vehicular v2v network built along a highway is simplified as a one-dimensional (1-D) mobile ad hoc networks which consists of a collection of statistical identical mobile stations randomly located on a line;

2) All vehicles have same transmission and receiving range, which is denoted as \(R\). The average number of vehicles in transmission range of a vehicle on the road is \(N_c = 2\beta R\);

3) Vehicles are placed on the road according to a Poisson point process with network density \(\beta\) (in vehicles per meter);

Fig. 1 Highway one-dimensional vehicular ad hoc network model
i.e. the probability \( P(i,l) \) of finding \( i \) vehicles in length of \( l \) is given by

\[
P(i,l) = \frac{(\beta l)^i e^{-\beta l}}{i!} ;
\]

4) Given the tagged vehicle (the vehicle sending message) placed in origin, all vehicles have same carrier sensing range \( l_s \) which is assumed to vary between the range \([R, 2R]\). The average number of vehicles in carrier sensing range of the tagged vehicle on the road is \( N_{cs} = 2\beta l_s \). 

5) As shown in Fig. 1, when the vehicular v2v network we consider is simplified as a one-dimensional network, the potential hidden terminal area of the tagged vehicle in broadcast communication drops in the range of \([\text{max}(R, l_s), 2R] \) and \([-2R, -\text{min}(R, l_s)]\). The average number of the potential hidden vehicles of the tagged vehicle on the road is \( N_{pb} = 4BR - N_{cs} \). 

6) At each vehicle, routine packets and emergent packets have same average length \( E[P] \); both arrivals are Poisson processes with rates \( \lambda_r \) and \( \lambda_e \) (in packets per second), respectively.

7) There are two queues in each vehicle. One for routine message, the other for emergency message. They sense and access the channel independently. If two services conflict with each other in a vehicle, the emergency packet will be served first. The queue length of packets each vehicle can store at the MAC layer is unlimited. So, each vehicle can be modeled as two independent discrete time M/G/1 queues. Two broadcast services share the common control channel.

8) The average relative velocity of vehicles in the network is assumed to be a constant value \( \bar{v} \).

B. Backoff Process in IEEE 802.11 Broadcast

Now, we construct a model to characterize backoff counter process of each vehicle in IEEE 802.11 broadcast network. We know that the stochastic process indexed by backoff counter values of a broadcast vehicle is a one-dimensional discrete-time Markov chain [14]. Fig. 2 shows the Markov chains for two safety services. Let \( \tau_r \) and \( \tau_e \) be the probability that a vehicle transmits emergent packet and routine packet, respectively. From solutions to the one-dimensional Markov chain, we have

\[
\tau_e = \frac{2(1 - p_e^*)}{W_e + 1} ; \quad \tau_r = \frac{2(1 - p_r^*)}{W_r + W_e + 1} 
\]

where \( p_e^* \) (\( p_r^* \)) is the probability that there are no emergent (routine) packets ready to transmit at the MAC layer in each vehicle, which can be derived later in this paper. In the backoff process, if the medium is idle, the backoff timer will decrease by one for every idle slot detected. When detecting an ongoing successful transmission, the backoff timer will be suspended and deferred a time period of \( T \) which is expressed as

\[
T = T_e = T_r = \left( T_{\text{ifu}} + E[P] \right) / R_d + \text{DIFS} + \delta
\]

where \( T_e \) is the average time the channel is sensed busy because of a successful transmission, \( T_r \) is the average time the channel is sensed busy by each station during a collision, \( R_d \) is system transmission data rate, and \( \delta \) is the slot time duration. It is assumed that a packet holds size \( P \) with average packet length \( E[P] \), and packet header includes physical layer header plus MAC layer header: \( T_s = \text{PHYhdr} + \text{MAChdr} \). Let \( \beta \) be the propagation delay, and \( \text{DIFS} \) be the time period for a DCF inter-frame space.

C. Performance of Channel for Tagged Vehicle

We consider a vehicular wireless ad hoc broadcast network with dynamic topology where each vehicle can send out a packet if there is no transmission sensed within the carrier sensing range of the vehicle. So, here a channel is defined with respect to any vehicle sending out packet (referred as the tagged vehicle).

Now, we calculate channel performance from the tagged vehicles’ point of view. Define \( p_b \) as the probability that the channel for the tagged vehicle is busy. Knowing that the channel is busy if there is at least one vehicle transmitting any type of services in the transmission range of the tagged vehicle, we have

\[
p_b = 1 - \sum_{i=0}^{\infty} (1 - \tau_r) \left(2BR\right)^i / i! \sum_{j=0}^{\infty} (1 - \tau_e) \left(2BR\right)^j / j! = 1 - e^{-2(BR)}(\tau_r + \tau_e)
\]

D. Service Time

The MAC layer service time is the time interval from the time instant when a packet becomes the head of the queue and starts to contend for transmission, to the time instant when the packet is received. This time is important when we examine the performance of higher protocol layers.

![Fig. 2 Markov chain model for backoff process in broadcast. (a) emergent service; (b) routine service.](image)

![Fig. 3 Generalized state transition diagram for broadcast. (a) emergent service; (b) routine service.](image)
Apparently, the distribution of the MAC layer service time is a discrete probability distribution when the smallest time unit of the backoff timer is a time slot $\sigma$. Here, we model the characteristics of each vehicle in the network as two M/G/1 queues and approach service time distributions through probability generating function (PGF).

We understand that the backoff counter in each vehicle will be decremented by a slot once an idle channel is sensed, and will wait for a transmission time once a busy channel is sensed. For a tagged vehicle in broadcast communication, the transition for backoff counter decremented by one can be expressed by the following PGF,

$$H_q(z) = (1 - p_n)z + p_nz^\tau$$  \hspace{1cm} (4)

Denote $q_s$ as the steady state probability that the packet service time is $s$. Let $Q(z)$ be the PGF of $q_s$, which is $Q(z) = \sum q_s z^s$.

Now, it is possible to draw the generalized state transition diagram for both the emergent packet broadcast transmission and routine packet broadcast transmission, as shown in Fig. 3. Knowing that successful transmission and transmission with collision take same amount of time in broadcast, we have $SC_1(z) = SC_2(z) = \frac{p_{rws}z^{W_0}}{W_0} \sum_{i=0}^{W_0-1} H_q^i(z)$. From Fig. 3, we can derive the transfer functions of the linear systems or distributions of the emergent service time, and routine service time, respectively.

$$Q_e(z) = \sum q_s z^s = \frac{p_{rws}z^{W_0}}{W_0} \sum_{i=0}^{W_0-1} H_q^i(z)$$ \hspace{1cm} (5)

$$Q_r(z) = \sum q_s z^s = \frac{1}{W_0 - W_0} \sum_{i=W_0}^{W_0-W_0} H_q^i(z)$$ \hspace{1cm} (6)

Based on (5) and (6), we can obtain the arbitrary $n$th moment of service time by differentiation. Therefore, the average service times or service rates can be obtained by

$$T_{av, e} = 1/\mu_e = \sum q_s^{(i\sigma)} = Q_e'(z)|_{z=1};$$  \hspace{1cm} (7)

$$T_{av, r} = 1/\mu_r = \sum q_s^{(i\sigma)} = Q_r'(z)|_{z=1}.$$  \hspace{1cm} (8)

In order to derive the average service time distributions, the probability $p_{0e}^\prime (p_{0r}^\prime)$ must be determined, while $p_{0e}^\prime (p_{0r}^\prime)$ calculation depends on duration of service time. In this paper, we apply an iterative algorithm to calculate $p_{0e}^\prime (p_{0r}^\prime)$.

The iterative steps are outlined as follows.

Step 1: Initialize $p_{0e} = p_{0r} = 0$, which is the saturated condition.

Step 2: With $p_{0e}^\prime (p_{0r}^\prime)$, calculate $p_{0e}$ according to (10).

Step 3: Calculate service time distributions through PGF.

Step 4: Calculate service rates $\mu_e = 1/Q_e(1); \mu_r = 1/Q_r(1)$.

Step 5: if $(\lambda_e + \lambda_r)/(\mu_e + \mu_r) \leq 1$, $p_{0e} = 1 - \lambda_r/(\mu_e + \mu_r)$; $p_{0r} = 1 - \lambda_e/(\mu_e + \mu_r)$, otherwise, $p_{0e} = p_{0r} = 0$.

Step 6: If both $p_{0e}^\prime$ and $p_{0r}^\prime$ converge with the previous values, then stop the algorithm; otherwise, go to step 2 with the updated $p_{0e}^\prime (p_{0r}^\prime)$.

E. Delay

Packet transmission delay $E[D]$ is the average delay a packet experiences between the time at which the packet is generated and the time at which the packet is successfully received. It includes the medium service time (due to backoff, busy channel, inter-frame spaces, transmission delay, and propagation delay, etc.), and queueing delay.

For the case of unsaturated condition $(\lambda_e + \lambda_r)/(\mu_e + \mu_r) \leq 1$, the expected virtual queue delay can be obtained by the Pollaczek-Khinchine mean value formula [15] for M/G/1 queues

$$E[D_e^r] = \frac{\lambda_e(Q_e''(1) + Q_e'(1))}{2(1 - \lambda_e/(\mu_e + \mu_r))},$$  \hspace{1cm} (9)

$$E[D_r^r] = \frac{\lambda_r(Q_r''(1) + Q_r'(1))}{2(1 - \lambda_r/(\mu_e + \mu_r))}.$$  \hspace{1cm} (10)

The average packet transmission delays for two services can be calculated as

$$E[D_e^r] = E[D_e^r] + T_{av, e} + DIFS + \sigma + \delta,$$  \hspace{1cm} (11)

$$E[D_r^r] = E[D_r^r] + T_{av, e} + DIFS + \sigma + \delta.$$  \hspace{1cm} (12)

F. Link Breaking Probability

Define $X$ to be distance from position of any vehicle at instant when tagged vehicle is requesting channel for packet transmission, to boundary of the tagged vehicle transmission range.

From the assumption that all vehicles in the network are one-dimensional Poisson distributed with density $\beta$, the PDF of $X$ of a vehicle is

$$f_X(x) = \beta e^{-\beta|x|}, -R \leq x \leq R,$$  \hspace{1cm} (13)

The time period which a mobile vehicle spends within radio transmission range of the tagged vehicle is defined as the radio dwell time $T_{dwell}$, which follows

$$T_{dwell} = \frac{X}{V}$$  \hspace{1cm} (14)

where $X$ and $V$ are assumed to be independent. Consequently, if the relative velocity is a constant $\tau$, we have

$$f_{T_{dwell}}(t) = \frac{\tau V}{e^{-\beta\tau t}}, E[T_{dwell}] = \frac{1}{\beta\tau}$$  \hspace{1cm} (15)

When the tagged vehicle is transmitting, that some of receivers are moving out of it radio transmission range makes the link break. The link breaking probability $p_{lb}$ of a communication pair is the probability that the packet transmission time exceeds the radio range dwell time. Thus, we have

$$p_{lb} = Pr(T_{dwell} < T) = \int_0^T f_X(t) f_{T_{dwell}}(t) dt$$  \hspace{1cm} (16)

Knowing that $T$ is a constant, we have

$$p_{lb} = \int_0^T f_X(t) dt = 1 - e^{-\beta\tau T}$$  \hspace{1cm} (17)

G. Packet Reception Rate

Packet reception rate (PRR) is defined as the ratio of the number of packets successfully received by all vehicles within the range of the tagged vehicle to the number of packets transmitted. So, $PRR$ can be interpreted as the
probability that all vehicles within transmission range of the tagged vehicle receive the broadcast message successfully in a virtual slot. Taking packet arrival rate, hidden terminal, transmission errors, and vehicle mobility into account, we have PRR for single packet transmission or first packet in multiple packet transmissions.

\[
P_{\text{pr}} = (1 - p_v) \sum_{i=0}^{\infty} (1 - \tau_v) \left( \frac{N_m \cdot (N_m - 1)^i}{i!} \right) \left( e^{-\lambda_p} \right) \left( 1 - p_a \right)^{N_m - 1} \tau_v \left( 1 - p_v \right)^{N_m - 1} \end{equation}

From (18), we can see that the successful transmission takes place under following conditions: 1) no vehicles within transmission range of the tagged vehicle transmit at the time instant when the tagged vehicle starts to transmit; 2) no vehicles in the two potential hidden terminal areas (see Fig. 1) transmit during a vulnerable period \( T_{\text{vuln}} = 2\left( T_H + P_+ \right) / R_d \) (normalized to the time slot through dividing by length of a virtual slot). There are two pieces of potential hidden terminal area in Fig. 1 which are mutually independent. Each hidden terminal has chances to fail the target vehicle transmission: either by that the tagged vehicle starts sending while a hidden terminal is sending or by that one hidden terminal starts sending while the tagged vehicle is sending; 3) no transmission errors occur during the packet transmission; 4) no vehicles receiving the packet move out of the transmission range of the tagged vehicle throughout the packet transmission.

IV. MODEL VALIDATION AND NUMERICAL RESULTS

In this section, given a specific DSRC environment, performance of IEEE 802.11a for DSRC and performance of the proposed enhancement are derived and compared. We consider a two-lane high freeway system where all vehicles are exponentially distributed. Each vehicle moves on the road with average velocity 90mph in two directions. The average relative speed of two vehicles is 120mph. Each vehicle on the road is equipped with DSRC wireless ad hoc network capability with communication parameters shown in Table I. The control channel is exclusively used for safety related broadcast communication. Transmission range of each vehicle is 500m. Impact of hidden terminal, high mobility, message length and message arrival rate, variable date rate, and carrier sensing range in IEEE 802.11a is all embodied in the numerical computation and the simulation. Our simulation is conducted under a highway DSRC environment within length of road 5000m.

Fig. 4 and Fig. 5 depict the packet delivery delay, and packet reception rates, respectively, over the density of vehicles on the road with varied data rate and packet arrival rate. As we see from these figures, analytical results (lines) practically coincide with the simulation results (symbols). The analytic delay and PRRs match their simulation counterparts very well. We also observe that increasing data rate (from 24Mbps to 54Mbps) helps significantly improving delay and packet reception rate.

Comparing the obtained performance with requirements set for safety related ad hoc communication network, we can see that it is no problem for packet delivery delay (<2ms) to meet the requirement (500ms). However, the obtained packet reception rates fail to meet reliability requirement (1-0.01=0.99) for DSRC safety critical messaging.

Fig. 4 Packet delivery delay of DSRC broadcast with parameters \( R=500m, W_0=15, W_m=63, E[P]=200 \text{ bytes}, p_{\text{ber}}=10^{-4}, \lambda_e=1 \text{ pck/s}, \lambda_r=10 \text{ pck/s} \)

Fig. 5 Packet reception rates of DSRC broadcast with parameters \( R=500m, W_0=15, W_m=63, E[P]=200 \text{ bytes}, p_{\text{ber}}=10^{-4}, \lambda_e=1 \text{ pck/s}, \lambda_r=10 \text{ pck/s} \)
As seen in Fig. 6, transmission delay of emergent safety service is much shorter than that of routine safety service because different DCF backoff window sizes are adopted. Increasing message arrival rate may also increase the packet delivery delay. Fig. 7 shows how hidden terminal problem and mobility of vehicle affect PRRs of the DSRC broadcast communication. We observe that the hidden terminal problem degrades PRRs significantly, but high mobility of vehicles has minor impact on the performance.

V. CONCLUSIONS

In this paper, we investigate performance of DSRC safety related ad hoc v2v communication networks analytically and by simulation. Several important performance indices for broadcast such as packet reception rates and packet delivery delay are derived from the proposed analytical model taking IEEE 802.11 backoff counter process, fading channel, hidden terminal, non-saturation traffic, and mobility etc. into account.

Considering that reliability of safety message transmission is the most critical among other performance indices, we suggest several potential mechanisms to enhance the packet reception rates. 1) Increase backoff window sizes to reduce chances of packet collisions; 2) Increase carrier sensing range to withstand effect of hidden terminal; 3) Design proper repetitions of the emergent packet within the packet life time; 4) Give preemptive priority to the emergent message delivery. Design and analysis of the enhancement will be addressed in the future.

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