A Robust Broadcast Scheme for VANET One-hop Emergency Services

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Abstract— IEEE- and ASTM-adopted Dedicated Short Range Communications (DSRC) vehicle safety-related communication services, which require reliable and fast message delivery, usually demand broadcast communications in vehicular ad hoc networks (VANETs). In this paper, we propose and justify a distributive robust scheme for DSRC one-hop safety-critical services. The new scheme enhances broadcast reliability using dynamic receiver-oriented packet repetitions and mini-slot within DIFS in IEEE 802.11 for one-hop emergency warning message dissemination. In addition, we investigate the reliability and performance of the proposed broadcast scheme for DSRC VANET safety-related services on highway analytically and by simulations. The analytic model accounts for the impact of the beacon message broadcast and the fading channel conditions on the reliability and performance.

Keywords—broadcast; medium access control; performance; reliability; wireless ad hoc networks.

I. INTRODUCTION

Dedicated Short Range Communication (DSRC) based communication devices are expected to be installed in future vehicles and to work with sensors in the vehicles to enhance road safety. According to the updated version of the DSRC standard [1], the DSRC physical layer follows the same frame structure, modulation scheme and training sequences specified by IEEE 802.11a physical layer. MAC layer of the DSRC is equivalent to the Enhanced Distribution Coordination Function (EDCF) 802.11e that has four different access classes (ACs). However, current IEEE 802.11p MAC with the proposed EDCF is not able to provide predictable quality of service (QoS) for safety-critical services.

One-hop broadcast is deployed for emergency warning messages [2]. Examples of this type of messages include the braking of a leading vehicle, vehicle crashes and other hazardous road conditions. This type of the safety messages will be transmitted to make all the vehicles in the area aware when an unsafe situation is detected, or to trigger an actuator on an active vehicular safety system. Efforts have been made to enhance the reliability of safety critical services in DSRC. Repetition of emergency message to improve reception reliability of one-hop broadcast is straightforward. There have been a few message repetition schemes proposed to improve broadcast reliability [2], [3]. Under adverse DSRC environments, multiple repetitions of messages provide redundancy of packet transmission, which can help enhance packet reception ratios. However, these sender-oriented transmission schemes only function if the factors causing failures of message transmissions are temporary or intermittent. If the factors stay for relatively long time, simple repetitions may lead to continuous transmission failures. For example, as a car on the road sends an emergency message, a big truck neighboring the sending car will attenuate the communication signal strength so that some vehicles within the sending car’s transmission range fail to receive the message. If the truck runs in the same direction as the car, this situation will last and hence redundant messages sent out by the car will not help.

In this paper, we first propose a new robust receiver-oriented repetition (ROR) scheme to enhance the reliability of one-hop broadcast, and also overcome the shortcoming of the sender-oriented repetitions. Section II presents the ROR scheme designing DSRC control channel for possible safety critical services. Section III builds analytic models to evaluate effectiveness of the proposed scheme. Consequently, expressions in the performance and reliability indices are derived. In Section IV, the numerical results are demonstrated to verify the effectiveness of ROR scheme, and validate the proposed analytical models. Conclusions are given in Section V.

II. RECEIVER-ORIENTED REPETITIONS (ROR) OF EMERGENCY WARNING MESSAGES

We consider a VANET that consists of DSRC equipped vehicles on the road. Control channel (ch 178) in DSRC [1] is used for the safety services. It is assumed that each vehicle has access to the information of its location, speed and moving direction through an installed Global Positioning System (GPS) or Inertial Navigation System. Through exchanging periodic beacon messages, each node in the network maintains a list and mobility information of all one-hop surrounding nodes, which includes identification number, position, speed and moving direction. In this way, the receiver will be able to easily calculate its distance to the sender. Moreover, each receiving node is able to distinguish copies of the broadcast packet from the newly generated packets through a 12-bit sequence number of the received packet.
message in the MAC header of IEEE 802.11 [5]. Emergency events take place occasionally. Once an emergency message is generated in a vehicle, the vehicle will sense and take control of the channel right after the last beacon message, if any, completes its transmission. Before sending out the first cycle emergency message, the vehicle utilizes busy tone signal to suppress transmissions of beacon messages and possible hidden terminals.

Once a vehicle sends out a first cycle emergency packet, one or more neighboring nodes that have successfully received the packet will be selected to repeat the message. Observed that the farther a node is from the originating sender, the more likely it is in the broadcast message that the node receives to be distorted. Therefore, we design a distributive method to select nodes for the repetitions of the broadcast message such that wider area where the nodes missed the broadcast message will be potentially covered. Specifically, an Assessing Delay (AD) timer is set up according to the following formula:

\[ t_{AD} = T_{max} \left(1 - \frac{d}{R}\right) \]  

(1)

where \( t_{AD} \) is the AD timer value; \( d \) is the distance between the current node and the originating sender; \( R \) is the communication range of the sender; \( T_{max} \) is the maximum AD time duration allowed. Normally, \( T_{max} \) is less than life time of the message. According to this formula, \( t_{AD}=0 \), when \( d=R \); \( t_{AD} \rightarrow T_{max} \) when \( d=0 \). Hence, the formula ensures that the node with the longer distance to the originating sender has the smaller AD timer value. All vehicles that have successfully received the message in the first broadcast cycle will trigger the AD timer as in Eq. (1).

In the event that both emergency message and beacon message are ready to transmit due to their same zero backoff counter value, a preemptive priority is given to the emergency message transmission by setting up mini-slots in DIFS. Applying the concept of mini-slot in [6], we divide a cycle emergency message, the vehicle utilizes busy tone signal to suppress transmissions of beacon messages and possible hidden terminals.

The one whose timer is due first sends a copy of the message after a short waiting time \( t_m \), \( t_m \leq t_{switch} \). The short waiting time \( t_m \) is randomly selected within DIFS, which is designed for avoiding possible collisions caused by concurrent transmissions from two or more nodes with the same \( t_{AD} \) (or same distance to the sender). This process continues until the specified number of repetitions (say \( N_{rc} \)) has been issued in one-hop range. Meanwhile, the originating sender vehicle will wait until a specified time \( T_{max} \) has passed. If the sender vehicle has received the specified number of repetition messages within the specified time duration, the vehicle returns to serving the periodic beacon messages. Otherwise, the sender vehicle will issue one more round of emergency message broadcast if the life time of the message has not expired yet. Due to erroneous channel condition, some nodes within sender’s transmission range may fail to receive the broadcast packet from the sender. The source node or the sending nodes are informed if the previous broadcasts are successful or not via repetitions of the message by the receivers. Each copy of the emergency message will be assigned an identification number and a sequence number by the sender. Even though some copies may fail to reach a few receivers, the number of copies issued in the hop can be detected by the receiver through checking sequence number of the message or SNR scale of the channel in physical layer. When the specified number of copies has been received or detected by the originating sender and all the receivers, the vehicles stop running emergency service module. If the sender fails to receive the required number of repetitions of the emergency message during a specified time \( T_{max} \), it will resend the emergency message.

This receiver-oriented repetition scheme avoids the situation that results in possible continuous failures of message broadcast, and hence further enhances the broadcast reliability. Through working with ROR scheme in a distributive way, vehicles can receive multiple copies from different directions or angles, thus increasing likelihood of the message being reliably delivered to all associated vehicles.

III. SYSTEM ASSUMPTIONS AND PERFORMANCE

A. Assumptions For IEEE 802.11 Based Broadcast VANET

Real world radio networks are influenced by many factors. In our study we make some assumptions to give a tractable yet reasonable model to characterize the performance of the proposed schemes. In our model, we assume that IEEE 802.11 based broadcast VANETs built along a highway are simplified as one-dimensional (1-D) mobile ad hoc networks, as shown in Fig. 1, which consist of a collection of statistically identical mobile stations randomly located on a line. The 1-D network model is a good approximation of ad hoc networks on a highway. We assume:

A.1. Nodes are placed on the line according to a Poisson point process with network density \( \beta \) (in nodes per meter); i.e., the probability \( P(i,l) \) of finding \( i \) nodes in length of \( l \) is:

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

(4)

A.2. All nodes have the same transmission range and carrier sensing range, denoted as \( R \). Hence, the average number of nodes on the line in transmission range of a tagged node (the node sending message) is \( N_{av} = 2\beta R \);

A.3. Vehicular communications present scenarios with unfavorable characteristics of channel fading in DSRC. The
channel fading is reflected by simply introducing packet error probability \( p_{e} = 1 - (1 - p_{o})^{F/2} \), where \( P \) is the length of the packet, \( L_{host} \) is the length of packet header, and \( p_{o} \) is the fixed bit error rate (BER) probability. \( p_{e} \) can be numerically evaluated for a Rician fading channel [7]. When data bits are transmitted over Nakagami-\( m \) fading links, \( p_{e} \) can be easily obtained using the closed form expressions given in [8]. Capture effect is not considered in this paper;

A.4. At each node, beacon packet arrivals follow a Poisson process with a rate \( \lambda \) (in packets per second). Emergency message arrival is bursty;

A.5. Impacts of node mobility on reliability and performance are not considered in the model. In fact, it has been proven in [4] that high mobility of vehicles (up to 120mph) has very minor impact on the performance of the direct message broadcast network with high data rate (e.g. \( \geq 12 \text{Mbps} \)).

B. Performance and Reliability of Emergency Message Broadcast

In the proposed scheme, an emergency message is sent through one-hop multi-cycle broadcast. This one-hop message broadcast serves to alert or warn all surrounding vehicles to avoid further damages or accidents. Several important metrics will be defined and derived analytically for evaluation and comparison of performance and reliability of these broadcast services.

Performance For One-hop One-cycle Broadcast

Once an emergency message is generated, it will be sent out right away if the channel is sensed idle or right after the current beacon transmission is completed if the channel is sensed busy. According to the proposed scheme for the emergency broadcast, the back-off window size for the emergency message is zero. It is possible that the channel is occupied by the beacon message transmission. After the channel is sensed idle, mini-slots are deferred before the message is sent out. Therefore, the average packet transmission delay for the emergency message is caused by average channel sensing time, mini-slots waiting time, plus the message transmission time, which can be calculated as:

\[
E[D_i] = p_{o}T + 2 + DIFS + 2 + (E[P_i] + L_{host}) / R_i
\]

where \( E[P_i] \) is the average length of emergency messages; \( R_i \) is emergency message transmission data rate; Beacon Packet duration \( T = (E[P_i] + L_{host}) / R_i \); \( E[P_i] \) is the average length of beacon messages; \( R_i \) is beacon message transmission data rate. \( p_{o} \) is the probability that the channel is sensed busy by the sending node when an emergency message is generated in the node, which is expressed as

\[
p_{o} = 2\beta R\lambda (E[P_i] + L_{host}) / R_i
\]

On the other hand, transmission of the emergency message with two-hop busy tone will block all nodes within the sender’s two-hop transmission range from attempting to send beacon messages afterwards. Therefore, both concurrent beacon transmissions and the hidden terminals cannot interfere with one-hop nodes receiving the emergency message. However, as an emergency situation takes place, it is possible that multiple vehicles (say \( N_{i} \)) send out their messages for the same event leading to concurrent transmissions. The concurrent transmissions can be alleviated by the proposed mini-slot access method. By adopting \( w_{m} \) mini-slots within DIFS, a collision only occurs as two or more terminals out of \( N_{i} \) terminals happen to choose the same mini-slot for the transmissions. As a result, one-hop one-cycle emergency packet reception ratio is the percentage of receivers that are free from channel transmission errors and possible concurrent transmissions. Thus, we have

\[
P_{RR_{i}} = (1 - \frac{1}{w_{m}})^{N_{i} - 1}(1 - p_{e}) \quad (6)
\]

Analysis of One-hop Multi-cycle Broadcast

Based on the proposed scheme for class-one message, multiple receiver-oriented repetitions are distributively performed through distance-based AD timer in each one-hop receivers. The farthest node in the hop has the highest priority to repeat the message first. Next, given a node distribution, we will investigate the performance and reliability of the broadcast schemes.

Let \( m \) be the average number of nodes within the transmission range of the sender (the tagged node) and \( d_i \) be the distance of the \( i \)-th node to the sender. Knowing that the distance between two successive nodes is exponentially distributed with density \( \beta \). We have \( m = \beta R \). Hence, it is easy to find that the average distance between two consecutive nodes is \( 1/\beta \). Furthermore, let \( d_0 \) be the distance of the node that is the most distant from the originating sender among all nodes within the sender’s transmission range. Given exponential distribution of the distance between nodes, the cumulative distribution function of \( d_0 \) can be calculated as:

\[
F_{d_{0}}(\tau) = P(d_{0} < \tau) = e^{-\beta \tau} \quad (7)
\]

Define distances of the other nodes from the sender to be \( d_{m_{1}}, d_{m_{2}}, ..., d_{m_{i}}, \ldots, d_{0} \). Similarly, the density functions of \( d_{m_{1}}, d_{m_{2}}, ..., d_{m_{i}}, \ldots, d_{0} \) can be calculated from density function of \( d_{0} \).

\[
f_{d_{m_{i}}}(\tau) = \frac{\beta e^{-\beta \tau} \tau^{i-1}}{i!}, 0 \leq \tau \leq R \quad (8)
\]

The expectation of \( d_{m_{i}} \) can be derived as:

\[
E[d_{m_{i}}] = \int_{0}^{R} f_{d_{m_{i}}}(\tau) d\tau = \frac{R}{1 - e^{-\beta R}} - \frac{1}{\beta} \quad (9)
\]

Given the average distance between nodes \( 1/\beta \), the expectations of these distances \( d_{m_{1}}, d_{m_{2}}, d_{m_{3}},...,d_{m_{i}},...,d_{0} \) are

\[
E[d_{m_{i}}] = E[d_{m_{i+1}}] - \frac{i+1}{\beta} = \frac{R}{1 - e^{-\beta R}} - \frac{i+1}{\beta}, i = 1, 2, ..., m \quad (9)
\]

Every packet repetition will experience an AD timer delay \( t_{AD} \) before it is retransmitted. The expectation of \( t_{AD} \) can be calculated as

\[
E[t_{AD}^{m_{i}}] = T_{min}(1 - \frac{E[d_{m_{i}}]}{R}), i = 1, 2, ..., m \quad (10)
\]

According to the proposed new scheme, all nodes within two-hop range of the tagged node are informed transmissions of the emergency message before the first repetition starts.
Therefore, the packet reception ratio in the first cycle is equal to $P_{RR}$, expressed in Equation (6); while the packet reception ratio after the first cycle is evaluated as

$$P_{RR} = 1 - p_j$$

Then, the one-hop $N_c$-cycle $P_{RR}$ should be

$$P_{RR}^{N_c} = 1 - (1 - P_{RR}) (1 - P_{RR})^{N_c - 1}$$

(11)

As described in the proposed schemes, an emergency message may be repeated by different receivers within one-hop range of the sender for multiple times. Thus, transmission delays of the broadcast message will be different for respective receiving nodes. The one-hop $N_c$-cycle transmission delay $D_{Nc}^{-1}$ is defined as the time period between the time instant on which the message is sent out by the originating sender and the earliest time instant on which a correct copy is received by each node within one-hop range of the sender. In order to calculate closed form average of $D_{Nc}^{-1}$, we first define and derive the probability $P_{pp}(j,m-i)$ that the $(m-i)$th node repeats the message in the jth cycle of the repetitions. On the description of receiver-oriented repetitions in Section III-B, the farther node that has received the current-first cycle message successfully has higher priority to repeat the message if the current number of repetitions is less than $N_c$. Hence, we have

$$P_{pp}(j,m-i) = \begin{cases} 0; & j > i + 2; j \leq N_c; 0 \leq i \leq m - 1 \\ \left(1 - p_j\right); & j < i + 2; j \leq N_c; 0 \leq i \leq m - 1 \\ \left(1 - p_j\right)^{i}; & j = i + 2; j \leq N_c; 0 \leq i \leq m - 1 \end{cases}$$

(12)

where three cases are considered separately: 1) the probability is 0 when the number of repetition cycles is greater than the order number counting downward from $m$; 2) the probability is the number of cycles that the previous nodes with higher priority have gone through is exactly equal to the current cycle order number minus one; 3) the probability that the current node is the first candidate for the current cycle of the repetitions.

Given the probability $P_{pp}(j,m-i)$, the average AD timer delay for a specific cycle can be derived as

$$E[D_{AD}(j)] = \sum_{j=1}^{N} E[D_{AD}^{i}] (1 - P_{pp})^{i} \sum_{j=1}^{N} (1 - P_{pp})^{i-j}$$

(13)

Since the percentage of one-hop nodes that have received the message in a specific cycle depends on underlying packet reception ratio, then, the average $D_{AD}^{i}$ can be estimated as Equation 14 (see bottom of this page).

IV. NUMERICAL RESULTS AND DISCUSSIONS: AN EXAMPLE

In this section, the proposed analytical model is applied to a specific DSRC environment [1] for the evaluation of performance and reliability of the proposed protocol for VANET safety-related services. We consider a 5000m long freeway where all vehicles are exponentially distributed. Each vehicle on the road is equipped with the DSRC wireless capability with communication parameters shown in Table I. The control channel in DSRC is exclusively used for safety-related broadcast communication. In order to validate the proposed analytic model, we conduct simulations using both the ns2 simulation tool and Matlab.

The simulation covers main physical and MAC behavior of IEEE 802.11 broadcast with DSRC parameters, which includes transmission data rates, PHY preamble length and Physical Layer Convergence Protocol (PLCP) length, IEEE 802.11 Carrier Sense Multiple Access (CSMA) protocol with DIFS, SIFS, backoff counter behavior, and a message queue at each node in the network. With distributed asynchronous channel access and limited transmission range and carrier sensing range, asynchronous time scale and the hidden terminal problem are naturally reflected in the simulation process. The time resolution of the simulation program is exactly the minimum time unit (1μs) specified in IEEE 802.11 standard. To embody the design of the proposed schemes for three levels of safety-related services, the following parameter setting is adopted: $w_{min}=DIFS/(2\delta+T_{on/off})=21$, data rate $R_d=24$ Mbps. Transmission range $R_c=500m$, carrier sensing range=500–1000m.

Fig. 2 and Fig. 3 demonstrate the performance and the reliability of the class-one emergency service under our proposed schemes. From Fig. 2, we can see that one-hop five-cycle $P_{RR}$s can reach almost 100% under all traffic loads although one-hop one-cycle $P_{RR}$s failed to meet the one-hop reliability requirement for the emergency service ($PRR>0.99$) as the traffic on the road becomes heavier. This demonstrates the effectiveness of the proposed strict priority setting, receiver-oriented repetitions, multi-frequency busy tone, and mini-slot within DIFS. From Fig. 8, we notice that the improvement of the $P_{RR}$s causes significant increment of transmission delays. However, Due to the high data rate and the proposed priority setting, the maximum transmission delay (<1.4ms) is much smaller than the required one-hop delay for delivery of emergency message (<500ms). Incrementing the number of message repetitions under certain channel condition can significantly improve the reliability of the message broadcast, but prolong the transmission delay. The other interesting observation from Fig. 2 is that $P_{RR}$s are independent of traffic because the network for the emergency message broadcasting is free of hidden terminals and concurrent transmissions. However, even the transmission delay in the worst case (all of one-hop receivers are involved in rebroadcast) is less than 100ms.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Coding Rates</td>
<td>1/2, 2/3, 3/4</td>
</tr>
<tr>
<td>OFDM Symbol Duration</td>
<td>8 µs</td>
</tr>
<tr>
<td>Signal Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Channel Data rate</td>
<td>6, 9, 12, 36, 54 Mbit/s</td>
</tr>
<tr>
<td>DIFS for 802.11a</td>
<td>64 µs</td>
</tr>
<tr>
<td>Slot time, $\alpha$</td>
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<tr>
<td>SIFS for 802.11a</td>
<td>32 µs</td>
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<tr>
<td>Propagation delay, $\delta$</td>
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</tr>
<tr>
<td>PLCP Physical Length</td>
<td>40 µs</td>
</tr>
<tr>
<td>PLCP header Length</td>
<td>8 µs</td>
</tr>
</tbody>
</table>

TABLE I

PARAMETERS FOR COMMUNICATIONS IN DSRC

$$E[D_{AD}(j)] = \frac{\sum_{i=1}^{N} (1 - P_{pp})^{i} \sum_{j=1}^{N} (1 - P_{pp})^{i-j} P_{pp}^{i}(1+L_{on})/R_d + DIFS/2 + E[D_{AD}(j)])}{P_{RR}}$$

(14)
Fig. 2 Packet reception ratio of emergency service ($R=500\,\text{m}$, $R_e=24\,\text{Mbps}$, $E[P]=200\,\text{Bytes}$, $\text{SNR}=78\,\text{dB}$)

Fig. 3 Packet transmission delay of emergency service ($R=500\,\text{m}$, $R_e=24\,\text{Mbps}$, $E[P]=200\,\text{Bytes}$, $\text{SNR}=78\,\text{dB}$)

V. CONCLUSIONS

In this paper, a novel receiver-oriented (ROR) scheme for reliable delivery of safety-critical messages using the control channel for DSRC VANET is proposed and investigated. ROR scheme enhances the reliability of the safety message broadcast, and allows the control channel to deliver the emergency messages with required quality of service, and is easy to implement. Also, analytic models as well as simulations are constructed to analyze the performance and reliability of the proposed scheme. The models account for the impact of the fading channel conditions on the performance and the reliability. Our analysis reveals that (1) the analytic results from the developed models show close agreement with those from the computer simulations; (2) the proposed ROR scheme is effective to improve the reliability of the safety services so that the requirements for safety-related applications can be met; (3) comparing with the existing schemes for the VANET safety services, the proposed schemes are more robust to varied vehicular environments, and more scalable to the density of vehicles on the road.

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