Design and Analysis of a Robust Broadcast Scheme for VANET Safety-Related Services
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Abstract — IEEE- and ASTM-adopted Dedicated Short Range Communications (DSRC) standard is a key enabling technology for the next generation of vehicular safety communications. 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 cross-layer scheme for the design of the control channel in DSRC with three levels of broadcast services that are critical to most of the potential vehicle safety-related applications. The new scheme to enhance broadcast reliability includes preemptive priority in safety services, dynamic receiver-oriented packet repetitions for one-hop emergency warning message dissemination, multi-frequency busy tone and mini-slot within DIFS in IEEE 802.11, and robust distance based relay selection for multi-hop broadcast of emergency notification messages. Compared with current draft of IEEE 802.11p and other schemes for the DSRC safety-related services, the scheme proposed in this paper is more robust and scalable, and easy to implement. Additionally, 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 hidden terminal problem, the fading channel conditions, varied message arrival intervals, and the backoff counter process on the reliability and performance.

Index Terms—IEEE 802.11p, Vehicular ad hoc networks, Safety-related service, Broadcast, Reliability, Performance.

I. INTRODUCTION
Transportation systems are designed to transport people from one place to the next as safely and efficiently as possible. Unfortunately, many accidents and fatalities do occur on the road every day. The recent development of the Intelligent Transportation System (ITS) [1] is an effort towards safe and smooth driving without delay. Wireless communications systems are expected to play a pivotal role in the ITS safety-related applications. Dedicated Short Range Communication (DSRC) radio technology with a 75 MHz bandwidth at the 5.9 GHz band [3], [6] is projected to support low-latency wireless data communications among vehicles and from vehicles to roadside units in North America. DSRC based communication devices are expected to be installed in future vehicles and to work with sensors in the vehicles to enhance road safety. The draft of the upcoming 802.11p standard, defining specifications of the physical layer and the medium access control (MAC) layer of the vehicular wireless communication networks based on DSRC, has been created and distributed for discussions. According to the updated version of the DSRC standard [3], 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). This is a random access scheme for all associated devices in a cluster based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In the 802.11 MAC protocols, the fundamental mechanism for medium access is the distributed coordination function (DCF), that is meant to support an ad hoc network without the need of any infrastructure element such as an access point. But, current IEEE 802.11p MAC is not able to provide predictable quality of service (QoS) for high priority safety services with the proposed EDCF. DSRC-based vehicular ad hoc networks (VANETs) technology has been identified as one of the key components of the ITS framework in the U.S.A. VANETs supporting vehicle-to-vehicle (V2V) communication enable the cooperation of vehicles by linking individual pieces of information distributed across multiple vehicles, to increase the drivers’ range of awareness to spots that both the driver and onboard sensors systems otherwise cannot see. Hence, V2V communications form a basis for decentralized active safety applications that is expected to reduce accidents and their severity. Generally, VANETs can support the following safety-related applications [28]: Cooperative forward collision warning, Pre-crash sensing/warning, and Hazardous location notification, etc. Most safety applications will likely work in a broadcast fashion since safety information can be beneficial to all vehicles around a sender. VANETs use one-hop or multi-hop broadcasting to disseminate real-time traffic information or safety-related messages [4], [5], [7]. Once an emergency situation occurs, it is critical to inform surrounding vehicles as soon as possible. Because the driver reaction time to traffic warning signals can be in the order of 700ms or longer, the update interval of safety messages should be less than 500ms (we refer to it as the lifetime of safety messages) [5]. Otherwise,
the safety system is useless to help the driver deal with emergency situations. Hence, it is required that the safety-related V2V communication must provide a service delivering safety messages within their lifetime with high reliability under the vehicular environment. According to the requirements in [5], the probability of message delivery failure in a vehicular network should be less than 0.01.

So, it is clear that efficient information dissemination in a decentralized VANET is a very challenging research problem. VANETs have some features that are different from those of the conventional wireless networks such as local area networks (LANs) and Mobile Ad hoc Networks (MANETs) [4]. Furthermore, main factors that cause unreliable message disseminations in VANET include erroneous channels, hidden terminals, highly dynamic topology due to mobility of vehicles, and concurrent message transmissions. Broadcast in IEEE 802.11 does not use virtual carrier sensing and thus only relies on physical carrier sensing to reduce collisions [2]. In the case of broadcast communication, the broadcast fashion of V2V safety communications makes them more sensitive to the hidden terminal problem. While the development of vehicular DSRC technology based on IEEE 802.11p has considerably progressed in the past years, the introduction and wide-scale deployment of such a system has not been agreed on. The major obstacle that hinders the successful deployment of the DSRC systems is the lack of reliable and scalable communication protocols for safety-related services. Because of the unique characteristic of the VANETs, the current draft of IEEE 802.11p MAC [3] [24], and most of other MAC protocols, cannot meet the strict reliability requirements for safety-related communication applications under adverse DSRC environments and traffic conditions.

In this paper, we first propose and justify an effective solution to the design of the control channel in DSRC with three levels of safety-related broadcast services that are critical to most of possible safety applications. Then, we construct an analytic model to evaluate the reliability and the performance of one-hop and multi-hop IEEE 802.11 based broadcast for the safety-related services under harsh wireless communication environments. Our proposed model accounts for the impact of the hidden terminal problem, erroneous channel, and message arrival intervals, on the reliability and the performance of the safety-related broadcast services.

The remainder of this paper is organized as follows. Section II briefly reviews the work related to the design and modeling of safety-related broadcast services in DSRC systems. Section III presents a robust and cross-layer scheme designing DSRC control channel for possible safety applications. Section IV builds analytic models for the broadcast of three levels of safety-related messages using the control channel in the highway scenario. Consequently, closed form expressions of performance and reliability indices are derived. In Section V, the proposed analytical model is validated by extensive software simulations. Some important observations and constructive enhancement suggestions are also given. The paper is concluded in Section VI.

II. RELATED WORK

There have been active researches on the design and analysis of real-time broadcast services in VANETs or MANETs. Two broadcast mechanisms for real-time services are investigated in these researches: one-hop direct messaging and multi-hop messaging for long range coverage. Some direct (or one-hop) broadcast solutions to safety-related message delivery have been suggested and investigated. Xu et al. [5] proposed several single-hop broadcast protocols to improve reception reliability and channel throughput. Torrent- Moreno et al. [4], [7] proposed a priority access scheme for IEEE 802.11 based vehicular ad hoc networks and showed that the broadcast reception probability can become very low under saturation conditions. Jiang et al. [26] raised channel congestion control issues for vehicular safety communications, and introduced feedback information to enhance system performance and reliability. Elbatt et al. [27] discussed the suitability of DSRC periodic broadcast messages for cooperative collision warning applications. Sibecas et al [8] analyzed and improved the performance and the reliability of IEEE 802.11a broadcast for safety-related vehicle-to-vehicle applications. Xing et al [9] dealt with the problem of reliable and fast broadcast of mission-critical data with rich content over ad hoc networks. Peng et al [10] proposed a distributed MAC scheme for emergency message dissemination in vehicular ad hoc networks. Yu et al [11] presented a self-configuring TDMA protocol for enhancing safety messages in DSRC vehicular communication systems. Palazzi et al [35] proposed inter-vehicular communication architecture for both safety and entertainment. Recently, Barradi et al [36] proposed an effective scheme to establish strict priorities among four access categories of the control channel in the current IEEE 802.11p using distinct ranges of backoff window sizes and AIFS. However, this scheme still cannot guarantee preemptive transmissions of the safety-critical message with the highest level of priority once the message is generated. Li et al [16] presented an analytical model predicting the optimal range for maximizing 1-hop broadcast coverage in two-dimensional ad-hoc wireless networks. Choi et al [17] provided an approximated throughput analysis of broadcast scheme in multi-channel wireless ad-hoc networks. Our previous research on analysis of VANET safety services revealed that current IEEE 802.11a based MAC layer failed to meet the strict requirements on reliability for guaranteed delivery of safety messages [24]. In summary, these existing techniques tried to improve the reliability of one-hop broadcast through the following strategies. 1) Acknowledgements: the source node collects acknowledgements from the receivers; 2) Continuous push: the source node repeatedly transmits the data; 3) Priority setting: the emergency messages are given higher priority to
access the channel through sending pulse signals or setting different MAC backoff windows. However, these schemes did not distinguish the designated safety-related services; acknowledgements to improve reliable delivery of the messages are also subject to interferences or unreliable delivery; repeatedly broadcasting messages from source node cannot always alleviate the situations that cause the failure of message transmissions; IEEE 802.11 e like priority schemes only support “statistical” priority for specific flows but not “strict” priority for individual packets.

To solve the multi-hop broadcast storm problem, a number of methods have been explored [12], [13], [14]. Most existing distributed network-wide broadcast protocols have been summarized and categorized in [15]. In addition to simple flooding, categories proposed in [15] include probability-based methods, area-based methods, and neighbor knowledge methods. All of these methods improve the simple flooding method by reducing the number of rebroadcast from nodes that receive the packet from the originating sender. For example, in the counter-based scheme, a receiving node makes its decision on the basis of the number of redundant packets it receives during a RAD (random assessing delay), which is a timer set to a random number of seconds in a given interval. In the distance-based scheme, only the receivers whose distance to the sender is greater than a threshold value are allowed to retransmit the received packet. Zhang et al [19] further studied the counter-based scheme and the distance-based scheme, finding out the qualitative relationship between performance metrics and protocol parameters. Fracchia et al [20] developed some analytical models for the study of warning delivery service in 1-D multi-hop vehicular ad hoc networks. All these aforementioned broadcast protocols aim to reduce the number of redundant messages without taking collisions, hidden terminal problem, and link reliability into account. Lou et al [29] proposed a broadcast algorithm called double covered broadcast that takes advantage of broadcast redundancy to improve the delivery ratio. But, the algorithm needs the knowledge of two-hop neighbors. Recently, Bi et al [30] addressed challenges in multi-hop Inter-vehicle communications by adopting a cross-layer approach considering the Physical layer, MAC and Network layers. However, if the key component (BRTS/BCTS handshake) is interfered in adverse vehicular environment, the proposed protocol will not work properly.

III. NEW BROADCAST SCHEME FOR DSRC SAFETY-RELATED SERVICES

We consider a VANET that consists of DSRC equipped vehicles on the road. Control channel (ch 178) in DSRC is used for the safety services. IEEE 802.11 based ad hoc network with broadcast distributed coordination function (DCF) is adopted for safety-related 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. The following safety-related services need to be delivered with required QoS: beacon messages that contain states of vehicles (e.g., position, speed, and direction), pre-crash warning messages, post-crash notification messages, and emergency information about environment and road hazards. Hence, a key research problem here is how to design a scalable information dissemination method that can efficiently work with high reliability and short delay under different network conditions. In this section, new cross-layer solutions are proposed to deal with these challenges. These solutions include 1) a priority scheme for three levels of safety services; 2) a dynamic receiver-oriented repetition method for reliable one-hop emergency message broadcast 3) a robust relay selection scheme for multi-hop propagation of emergency notification messages; 4) suppression of hidden terminals via long range multi-frequency busy tone. Consequently, a systematic protocol for VANET safety-related services is proposed.

A. Priority Establishment of Three Levels of Safety Services in the Control Channel

First, we classify the safety-related messages in a VANET into three categories and assign different priorities to these messages. Class-one messages are emergency warning messages. Examples of this type of message include the braking of a leading vehicle, vehicle crashes and other hazardous road conditions. This type of the safety message will be transmitted to make all the vehicles in the area aware when an emergency or a non-safe situation is detected, or to trigger an actuator on an active vehicular safety system. Class-two messages are long-range emergency notification messages. Typical examples of this type of messages are post-crash notification (e.g., call ambulance), and emergency information about environment and road hazards (e.g., scatter traffic jam). These event-driven emergency communications happen only occasionally, but must meet the requirement of quick and guaranteed delivery. Class-three messages include periodic beacon messages (or routine safety messages). An example of this type of messages is the periodic vehicle status reporting message. Vehicles periodically send their updated vehicle positions, speeds, travel time, and moving directions to surrounding vehicles. The beacon messages that are essential for many safety applications (e.g., collision avoidance) are required to be sent out at an updating rate as high as 10 messages per second. Among these safety-related messages, class-one messages are the most critical for safety of people on the road. Here, we design the DSRC control channel to accommodate these three types of safety messages with distinct priority levels.

1) The highest priority is given to emergency warning messages (class-one messages), followed by long-range emergency notification messages (class-two messages), then beacon (class-three messages). One-hop multi-cycle broadcast is assigned for the emergency warning (or class-one) messages; Multi-hop one-cycle broadcast is assigned for the long-range emergency notification (or
class-two) messages; One-hop one-cycle broadcast is assigned for beacon (or class-three) messages. Here, “n-cycle” is defined as n rounds of message repetitions.

2) Instead of adopting distinct ranges of backoff window sizes and AIFS duration in [3] and [36], we propose a new preemptive priority setting scheme to distinguish different classes of the safety-related services. Non-zero IEEE 802.11 MAC backoff window sizes are given to the periodic beacon (class-three) service; Zero window size is given to the emergency message transmissions. 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 [33], we divide a DIFS interval into a number of mini-slots. The length of mini-slot \( l_m \) and the number of mini-slots \( w_m \) can be calculated as:

\[
l_m = 2\delta + t_{\text{switch}}
\]

\[
w_m = \left\lfloor \frac{DIFS}{l_m} \right\rfloor
\]

where \( \delta \) is the maximum channel propagation delay within the transmission range \( R \), and \( t_{\text{switch}} \) is the time duration that a transceiver switches between the receiving mode and transmitting mode. In order to give preemptive channel access priority to a node with class-one emergency message, a small waiting time \( t_{\text{ws}} \), \( l_m \leq t_{\text{ws}} < DIFS \) is assigned to the node in addition to zero backoff window size so that the node will immediately get the channel once the message is ready to transmit. The mechanism assures that the nodes with emergency message can get the channel before the nodes with beacon messages even though they are ready to transmit at same time because the node with beacon message has to wait for a DIFS before transmission. On the other hand, the mechanism adopting mini-slot within DIFS reduces possible collisions caused by simultaneous transmissions of the emergency messages. It is noteworthy to mention that the proposed “mini-slots” technique can coexist with the AIFS in the current IEEE 802.11p. It is observed that \( t_{\text{ws}} \leq DIFS < AIFS[AC] \) given \( DIFS = SIFS + 2 \times \text{slot time} \), and \( AIFS[AC] = SIFS + AIFS[AC] \times \text{slot time} \). Therefore, the preemptive priority of the emergency warning message within DIFS reduces the backoff window size and \( t_{\text{ws}} \) delay over the Enhance Distributed Channel Access (EDCA) driven services in the channel is guaranteed.

3) All nodes receiving the emergency messages will stop their own attempts to send out messages with lower (or same) level priority for at least specified number of copies of such messages.

4) Once a node with an emergency (class-one or class-two) message gets access the channel, it sends the emergency broadcast packet along with a long range (two-hop distance) busy tone. This busy tone is a two-frequency (one frequency corresponds class-one messages, the other corresponds class-two messages) un-modulated sinusoidal carrier wave outside the data band, which can reach all two-hop nodes informing the advent of the high priority message. Tones are not subject to collisions in the same way as packets. As tones are out of band, they cannot collide or interfere with data communications. The nodes hearing the busy tone inhibit all their transmission attempts of beacon messages or other lower priority messages until the specified number of copies of such message has been received. The reason that the two-hop transmission range is designed for the busy tone signals is because the nodes staying between carrier sensing range (normally greater than the transmission range) and two-hop transmission range of the originating sender are potential hidden terminals. In this way, all the hidden terminals are suppressed when the emergency message is in transmission. Type of the messages (or priority level of emergency message) is identified by frequency of the busy tone signal.

B. Receiver-oriented Repetitions of Emergency Warning (Class-one) Messages

Under adverse DSRC environments, multiple repetitions of messages provide redundancy of packet transmission, which can help enhance packet reception ratios. There have been a few message repetition schemes proposed to improve broadcast reliability [5], [26]. However, these 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 get the message. If the truck runs in the same direction as the car, this situation will last for a while although redundant messages are sent out by the car.

To overcome the shortcoming of the sender-oriented repetitions, we propose a new receiver-oriented repetition scheme. 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. As described in Section III-A, through exchanging 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. Also, 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 message in the MAC header of IEEE 802.11 [2]. It is

Fig. 1 Example of receiver-oriented repetitions of class-two message
observed that the farther a node is away from the originating sender, the more likely the broadcast message that the node receives is distorted. So, we design a distributive method to select nodes for 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:

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

where \( t_{AD} \) is the AD timer value; \( d \) is the distance between this node and the sender; \( R \) is the communication range of the sender; \( T_{\text{max}} \) is the maximum AD time duration allowed. Normally, \( T_{\text{max}} \) is less than the lifetime of the message. According to this formula, \( t_{AD} = 0 \), when \( d = R \); and \( t_{AD} \rightarrow T_{\text{max}} \), 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 first broadcast cycle will trigger the AD timer in terms of (3). The one whose timer is due first sends a copy of the message after a short waiting time \( t_{m} \), \( t_{m} \leq t_{a} \leq DIFS \). The short waiting time \( t_{a} \) is randomly selected within DIFS, which is designed for avoiding possible collisions caused by concurrent transmissions from two or more nodes with same \( t_{AD} \) (or same distance to the sender). This process is going on (each triggered AD timer keeps counting) until the specified number of repetitions (say \( N_{c} \)) has been issued in one-hop range. Meanwhile, the originating sender vehicle will wait until a specified time \( T_{\text{max}} \) 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 emergency message broadcast if the life time of the message has not expired yet. Due to erroneous channel and/or collisions caused by the hidden terminal problem, 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.

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

C. Robust Relay Selection for Multi-hop Broadcast of Class-two Emergency Message

Once a class-two emergency message is generated, its header contains the information about the originating source node, the type of message, the sequence number of the emergency message, and the message propagation direction. With this information, a robust and efficient multi-hop broadcast scheme for the emergency notification service is shaped.

The scheme provides a reliable way to select a routing node to rebroadcast the emergency message. A node will be selected under the following conditions: 1) the node has successfully received the message; 2) the channel is available, i.e., no any other node is transmitting the message on the channel; 3) the node’s directional distance to the source node is the farthest among all one-hop nodes that have received the message successfully. The node’s directional distance is defined as projection of Euclidean distance between the node and the source node along the source node’s moving direction. Given the position \((x, y)\) and velocity \((v_x, v_y)\) of each eligible rebroadcasting node, as well as the position \((x_s, y_s)\) and velocity \((v_{xs}, v_{ys})\) of the source node, then the directional distance, as seen from Fig. 2, can be calculated as

\[ d_d = d_e \cos \theta , \]  

where

\[ d_e = \sqrt{(x - x_s)^2 + (y - y_s)^2} , \]

and

\[ \theta = \arctan \left( \frac{y - y_{s}}{x - x_{s}} \right) . \]

Then, a deterministic timer as a function of the directional distance of the node to the sender is set as follows

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

All vehicles that have received the message successfully will trigger the AD timer in terms of (5). A candidate node with longer directional distance to the sender is more preferable for relaying the emergency message. Similar to Section III-B, rebroadcasting the emergency message by the one whose AD timer is due first is deferred for a randomly selected time \( t_{m} \), \( t_{a} \leq t_{d} \leq t_{a} \leq DIFS \). If the message rebroadcast is successfully received by some nodes in the hop, the nodes cancel their AD timers and stop their attempts to relay the emergency message. In case that the farthest node fails to receive the emergency message or the rebroadcast message from the selected node fails to reach some nodes in the hop due to message collisions or erroneous channel condition, all candidate nodes keep counting their AD timers until one of the candidates is
selected as a new relaying node. This process will continue until at least one rebroadcast is successful in the hop.

The main objective of the proposed scheme is to deliver the emergency notification message (or class-two message) to other vehicles as fast and reliable as possible. Introduction of the new directional distance in the AD timer assures that the farthest node in the moving direction of the source node has the highest priority to be selected as the relaying node so that the multi-hop coverage will be extended to its maximum in the direction of vehicle flow. In order to guarantee reliable rebroadcast of the emergency message, redundant relaying nodes are set through the distance based counters in a distributive way to deal with possible failures of multi-hop message delivery. Furthermore, a small mini-slot waiting time within DIFS is designed to avoid possible collisions caused by concurrent transmissions from two or more nodes with same $\tau_{IDS}$.

**D. Integration of Broadcast Schemes and Its Implementation Issues**

Based on the above schemes raised for the safety-related services, a systematic protocol can be shaped. Two modules will be installed on each vehicle: routine service module and emergency service module. Flow diagrams of these two modules are shown in Fig. 3 (a) and Fig. 3 (b), respectively. Normally, each vehicle with a GPS receiver and ad hoc wireless communication capabilities runs routine service module to exchange beacon messages or traffic information. Communication mode mainly adopts IEEE 802.11 Physical and MAC layer operations for broadcast. Beacon messages are generated and updated periodically in each vehicle on the road. Once a beacon message is ready, the vehicle will sense the channel. When the channel is available, the message is sent out after delaying for a specified backoff window time plus a DIFS. Each vehicle sets up and dynamically updates a database that contains identification and mobility information of all one-hop surrounding vehicles. Once an emergency situation takes place, the involved vehicles will trigger the emergency service modules. If a header of an emergency message (or tone signal) is detected, ongoing beacon message transmission attempt and backoff window updating will stop. All vehicles will keep receiving, sensing the channel, and waiting until the specified numbers of the emergency message copies are received. Both class-one service and class-two service go through the same procedures: emergency message generation, sensing the channel, AD timer delay, sending out the message after a short time delay $\tau_e$. On the other hand, AD timer delay is used for both repetitions of class-one messages and rebroadcast node selection of class-two messages. But, the differences are twofold. First, Euclidean distance is used for selection of the nodes for class-one message repetitions, while the directional distance is used for class-two routing node selections. Second, the number of message copies that leads to termination of the AD timer in a candidate vehicle is $m_{Nc}$ for class-one service ($m$ is defined as the number of receivers within one-hop transmission range of the source node), but $N_c=2$ for class-two service. When the specified number of copies has been received or detected by the sender and all receivers, the vehicles stop running emergency service module and return to the routine 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. As shown in Fig. 3 (b), both source node and the routing nodes go through same procedure to send (or rebroadcast) an emergency message except the AD timer value for the source node is equal to 0.

Since the entire protocol works in a distributive way without any central control, it does not add significant hardware burden to the DSRC systems except a busy tone transceiver for each vehicle is installed. The busy tones are implemented as transmission of low-frequency un-modulated carrier waves. Thus, the required bandwidth is very small. In addition, all proposed schemes are simple and easy to implement.

**IV. Modeling and Analysis**

In order to verify the effectiveness of the proposed schemes, we study and compare the performance of the selected VANET broadcast schemes for the safety-related services in a highway environment. We examine analytically how a new packet from a node is transmitted and propagated in the network under the proposed broadcast schemes.

**A. Assumptions for IEEE 802.11 1-D 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. 4, 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 in highway. Also, the analysis of the 1-D network model provides insight into more complex two-dimensional networks. The VANETs work under the following scenarios:

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 lane of length $l$ is given by

$$P(i,l) = \frac{(\beta l)^i e^{-\beta l}}{i!} \quad (6)$$

A.2. All nodes have same transmission/receiving range, which is denoted as $R$. So, the average number of nodes on the line in transmission range of a tagged node (the node sending message) is $N_i = 2\beta R$;

A.3. All nodes have same carrier sensing range $L_{cs}, R \leq L_{cs} \leq 2R$. It is also assumed that a transmission from one node cannot interfere with other nodes receiving other broadcast messages as long as they are more than $R$ away from the transmitting node. Therefore, given the tagged node placed in origin, as shown in Fig. 4, as long as the tagged node hears a transmission from any node within its carrier sensing range $\{x | x \in [-L_{cs}, L_{cs}]\}$, the tagged node will not initiate any transmission at the moment. On the other hand, the potential hidden terminal area of the tagged node in broadcast communication drops in the range of $\{x | x \in [L_{cs}, 2R]\}$ and $\{x | x \in [-L_{cs}, -2R]\}$ where nodes’ transmissions cannot be sensed by the tagged node, but can interfere with the nodes in $\{x | x \in [-R, R]\}$ receiving the packets from the tagged node. The average number of nodes in carrier sensing range of one tagged node on the line is $N_{cs} = 2\beta L_{cs}$. The average potential hidden nodes of the tagged node on the line is $N_{ph} = 2\beta (2R-L_{cs})$;

A.4. At each node, beacon packet arrivals form a Poisson process with rate $\lambda$ (in packets per second);

A.5. V2V communications present scenarios with unfavorable characteristics of channel fading in DSRC. The channel fading is reflected by simply introducing packet error probability $p_e = 1 - (1-p_{ber})^{L_{bf}+L_{ph}}$, where $P$ is the length of the packet, $L_{bf}$ is the length of packet header, and $p_{ber}$ is the fixed bit error rate (BER) probability. $p_{ber}$ can be numerically evaluated for a Rician fading channel [31] or Nakagami-m fading channel [32]. Capture effect is not considered in this paper;

A.6. The queue length of packets each node can store at the MAC layer is unlimited;

A.7. Impacts of node mobility on reliability and performance are not considered in the model. In fact, it has been proved in [7], [24] 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. $\geq 12$Mbps).

B. Performance Analysis of One-hop One-Cycle Broadcast for Class-three Beacon Service

As designed in Section III-A, class-three beacon messages are periodically broadcast by each vehicle when no emergency situation is detected. Approximating beacon arrivals form a Poisson process with certain rate, performance analysis of the beacon service can be carried out in the same way as that in [22]. Here, we model the characteristics of each node in the network as an M/G/1 queuing system with exponentially distributed inter-arrival times and an arbitrary distribution for service times. Backoff Process and Channel Performance in IEEE 802.11 Broadcast

Knowing current backoff window size $W_0$ is always a constant for broadcast, the backoff counter in each node can be characterized by a 1-D random process [21]. Denote $\tau$ as the packet transmission probability that a node transmits in a generic slot under unsaturated condition. Following a similar procedure in [22],

$$\tau = \frac{2(1-p_0)}{W_0+1} \quad (7)$$

where $p_0$ is the probability that there are no packets ready to transmit at the MAC layer in each node, which will be derived later in the paper. Denote $R_s$ as system transmission data rate, and $\sigma$ as the slot time duration. Given that a packet holds size $P$ with average packet length $E[P]$, packet header $L_{bh}$ including physical layer header PHY_{adh} plus MAC layer header MAC_{adh}, the propagation delay $\delta$, and the time period for a DCF (distributed coordination function) inter-frame space denoted as $DIFS$, when detecting an ongoing transmission, the backoff timer will be suspended and deferred a time period of $T$ which is expressed as

$$T = (L_{bh} + E[P]) / R_s + DIFS + \sigma + \delta \quad (8)$$

Now, we calculate channel performance from the tagged transmitting node point of view. Define $p_b$ as the probability that the channel sensed by the tagged node is busy. Knowing that the channel is determined as busy if there is at least one node transmitting in the carrier sensing range of the tagged node, with assumption that nodes are exponentially distributed on the line, we have

$$p_b = 1 - \sum_{i=0}^{\infty} (1-\tau)^i (\frac{2\beta L_{cs}}{\tau})^i e^{-\frac{2\beta L_{cs}}{\tau}} = 1 - e^{-\frac{2\beta L_{cs}}{\tau}} \quad (9)$$

Service Time and Delay: Each node with a queue in the VANET can be characterized by the arrival process and the service time distribution. The MAC layer service time is the time interval from the time instant that a packet becomes the head of the queue and starts to contend for transmission, to the time instant that the packet is received. 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 $\sigma$. In this paper, we approach
service time distribution through probability generating function (PGF) [23].

We understand that the backoff counter in each node 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 [2]. For a tagged node in broadcast communication, the transition for backoff counter can be expressed by the following PGF in z transformation domain [22], [23],

\[ H_d(z) = (1 - p_o)z + p_o z^{-1} \]  \tag{10}

where \( j \) is a function to round floating numbers to integers; and \( T \) is the time duration during which the channel is sensed busy by the tagged node (see Eq. 8). Denote \( q_i \) as the steady state probability that the packet service time is \( i \sigma \). Let \( Q(z) \) be the PGF of \( q_i \), which characterizes the process that a node will go through before it transmits a packet out

\[ Q(z) = \sum q_{i-1}' z^i \frac{z^{i-1}}{W_o} \sum H_d(z) \]  \tag{11}

Based on (11), we can obtain the arbitrary nth moment of service time by differentiation. Therefore, the average service time can be obtained by

\[ T_{av} = \sum q_i (i \sigma) = Q(z) \]  \tag{12}

In order to derive the average service time distribution, the probability \( p_0 \) must be determined, while \( p_0 \) calculation depends on duration of service time. The iterative algorithm in [22] is used to calculate \( p_0 \).

Packet transmission delay \( E[D_e] \) 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. For the case of unsaturated condition \( \lambda/\mu \leq 1 \), the expected virtual queuing delay can be obtained by the Pollaczek-Khinchine mean value formula [23] for M/G/1 queues

\[ E[D_q] = \frac{\lambda (Q''(1) + Q'(1))}{2(1 - \rho)} \mu \leq 1 \]  \tag{12}

The average packet transmission delay can be calculated as

\[ E[D_t] = E[D_q] + T_{ave} + DIFS + \delta \]  \tag{13}

For the case of saturated condition \( \lambda/\mu > 1 \), Queuing process in each node is unstable.

Beacon Message 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 [7]. Following PRR calculation in [24], the percentage of receivers that are free from collisions caused by the hidden terminal problem is evaluated as

\[ PRR_i = \frac{2BR - 2NF_c}{2BR} \frac{L_{av}}{R} - \frac{C}{RC} (1 - e^{-CL_{av}/R}) \]  \tag{14}

where \( C=\beta T_{idle}/\tau \), and \( T_{idle} = (1-p_o)T + T(t) \) (the average time duration of a virtual slot [24]); \( T_{idle} = 2(1-p_b)T \) is the vulnerable period (normalized to the time slot) during which the tagged node’s transmission is vulnerable to the hidden terminal problem. In addition to collisions caused by the hidden nodes, transmissions from nodes within \( R \) from the tagged node in the meantime at which the tagged node transmits may also cause collisions (referred to as concurrent collisions). Ratio of successful receiving nodes in the range \( L_t = \{x \in [0, L_{av}] \} \) and \( L_d = \{x \in [-R, 0] \} \) that are free from collisions caused by concurrent transmissions can be expressed as [24]

\[ PRR_i = \frac{e^{-\beta R(L_{av} - 1)c}}{\beta R c} - (1 - e^{-\beta c R t}) \]  \tag{15}

Taking hidden terminals, possible packet collisions caused by concurrent transmissions, and channel transmission errors into account, we derive PRR for class-three message transmission as

\[ PRR_i = PRR_1 \cdot PRR_2 \]

\[ = \frac{e^{-\beta R L_{av}}}{\beta R C} - (1 - e^{-\beta R L_{av}})(1 - e^{-\beta R t})(1 - p_b) \]  \tag{16}

C. Performance and Reliability of Class-one Emergency Message Broadcast

In the proposed scheme, a class-one emergency message is sent through one-hop multi-cycle receiver-oriented broadcast.

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 class-one 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. So, 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

\[ E[D_e] = p_{bt} T / 2 + DIFS / 2 + (L_{bt} + E[P_e]) / R_d \]  \tag{17}

where \( E[P_e] \) is average length of emergency messages, \( R_d \) is emergency message transmission data rate. \( p_{bt} \) 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

\[ p_{bt} \approx 2BR \lambda (L_{bt} + E[P_e]) / R_d \]

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 \( N_v \)) 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 \( w_o \) mini-slots within DIFS, a collision only occurs as two or more terminals out of \( N_v \) terminals happen to choose 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

\[ PRR_e = (1 - \frac{1}{w_m})^{N_e-1}(1 - p_e) \]  

(18)

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 how the performance and reliability of the broadcast schemes are affected by hidden terminals, and channel transmission errors.

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 distance between two successive nodes is exponentially distributed with density \( \beta \). We have \( m = \beta R \). So, it is easy to find the average distance between two consecutive nodes is \( 1/\beta \). Also, 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 the average distance between nodes \( 1/\beta \), the expectations of these distances \( d_0 \), \( d_{m,1} \), \( d_{m,2} \), \( d_{m,3} \), …, \( d_{m,i} \), …, \( d_0 \) are

\[ E[d_{m,i}] = \frac{R}{1 - e^{-\beta d}} \cdot i + 1, \quad i = 0, 1, 2, \ldots, m \]  

(19)

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

\[ E[t_{AD}^m] = T_{max} \cdot (1 - E[d_{m,i}]/R), \quad i = 1, 2, \ldots, m. \]  

(20)

According to the proposed new scheme, all nodes within two-hop range of the tagged node are informed transmission of the emergency message before the first repetition starts. So, the packet reception ratio in the first cycle is equal to \( PRR_e \) expressed in (18); while the packet reception ratio after the first cycle is evaluated as

\[ PRR_p = 1 - p_e \]

Then, the one-hop \( N_e \)-cycle \( PRR \) should be

\[ PRR_{\text{one-hop}}^{N_e} = 1 - (1 - PRR_e)(1 - PRR_p)^{N_e-1} \]  

(21)

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 \( N_e \)-cycle transmission delay \( D_{\text{one-hop}}^{N_e} \) is defined as the time period between the time instant on which the emergency 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. Two cases are considered in the derivation of \( D_{\text{one-hop}}^{N_e} \):

Case 1: No emergency concurrent transmissions in the first cycle, with probability \( P_{\text{noc}} = (1-1/w_m)^{N_e-1} \), Case 2: Concurrent transmission in the first cycle, with probability \( P_{\text{cs}} = 1 - P_{\text{noc}} = 1 - (1-1/w_m)^{N_e-1} \). Then, the average \( D_{\text{one-hop}}^{N_e} \) can be estimated as

\[ E[D_{\text{one-hop}}^{N_e}] = A \cdot (1 - \frac{1}{w_m})^{N_e-1} + B \cdot [1 - (1 - \frac{1}{w_m})^{N_e-1}] \]  

(22)

where derivation of A and B can be seen in Appendix B.

D. Performance of Multi-hop Class-two Emergency Message Broadcast

In 1-D highway environment, the proposed robust relay selection method for class-two emergency message based on directional distance is also reduced to the selection of the farthest node based on straight distance. Hence, if the farthest node \( m \) fails to receive the broadcast message due to channel transmission errors, node \( m-1 \) will take charge of re-broadcasting the message under the condition that it receives the message successfully. The selection process will continue until a node is selected to rebroadcast the message. So, the analysis of the rebroadcast process is similar to that of the class-two message repetitions except the number of repetitions is 2 for this service.

We observe that a node meeting the following conditions will be selected to rebroadcast: 1) the node has successfully received the broadcast packet; 2) all nodes farther than the node within the tagged node’s transmission range fail to receive the broadcast packet due to channel errors; 3) the AD timer of this node is due. So, the rebroadcast probability for the nodes with different distances \( d_i \) is

\[ P_{\text{rb}}(d_i) = (1 - p_e) \prod_{j=1}^{m} (1 - p_e) = p_e^{m-i} \cdot (1 - p_e), \quad i = m-1, \ldots, 1 \]  

(24)

Then, assuming that there is at least one node selected to rebroadcast, the average distance of the rebroadcast node can be estimated as

\[ E[d] = \sum_{i=1}^{m} P_{\text{rb}}(d_i) E[d_i] \]  

(25)

Let \( K_\text{ns} \) be the number of retransmissions before the broadcast packet reaches all the nodes within a span of \( L_D \), then

\[ E[K_\text{ns}] = \frac{L_D}{E[d]} \]  

(26)

Also, the average AD time delay can be evaluated as

\[ E[t_{AD}] = \sum_{i=1}^{m} P_{\text{rb}}(d_i) E[t_{AD}^{i-1}] \]  

(27)

It is assumed that class-two message is independent of class-one message. So, the average one-hop packet transmission delay for the emergency message is caused by average channel sensing time, \( DIFS \), and the message transmission time, which can be calculated as

\[ E[D_{\text{two-hop}}] = p_{\text{rb}} T + DIFS + [E[P_{\text{cs}}] + L_H]/R_f, \]  

(28)

where \( E[P_{\text{cs}}] \) is the average length of class-two emergency messages, \( R_f \) is the emergency message transmission data rate. Consequently, \( i \)-hop average broadcast delay is defined as the average time needed for completion of \( i \)-hop broadcast, which is expressed as
$$E[D] = E[D_z] + (i-1)(E[I_w] + E[P_z] + L_{th})/R_p^i$$  \hspace{1cm} (29)$$
Considering that with the proposed rebroadcast schemes, each node in the network at least receives the same broadcast packet twice. Similar to PRR evaluation of class-one message broadcast, the one-hop PRR should be

$$PRR_2^2 = 1 - (1 - PRR_{1b})(1 - PRR_{1p})$$  \hspace{1cm} (30)$$
Then, since each rebroadcast is independent of each other, \(i\)-hop average PRR should be

$$PRR_i = PRR_2^i$$  \hspace{1cm} (31)$$

V. NUMERICAL RESULTS AND COMPARISONS: AN EXAMPLE

In this section, the proposed analytical model is applied to a specific DSRC environment [3] for the evaluation of performance and reliability of the proposed protocol for VANET safety-related services. We consider a 5000m long freeway where positions of vehicles spatially form a Poisson process. Each vehicle on the road is equipped with the DSRC wireless capability with communication parameters shown in Table I [3]. 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. For routine periodic service: packet arrival rate=1-10 packets/second, backoff window size=15-128, data rate \(R_p=12\text{ Mbps}\). For emergency service: \(w_m=21\), data rate \(R_p=24\text{ Mbps}\). Transmission range \(R=500\text{m}\), carrier sensing range=500-1000m.

Figs. 5-8 depict the packet transmission delays and packet reception ratios, respectively, of three levels of broadcast services over the density of vehicles on the road with varied data rates and packet arrival rates. As seen from these figures, analytical results (lines) practically coincide with the simulation results (symbols), which validate the proposed analytical model.

Fig. 5 and Fig. 6 show the performance of the routine service. From these two figures, we have the following interesting observations: 1) PRRs are getting worse as traffic on the road becomes heavier (from 0.02 vehicles/m to 0.2 vehicles/m); 2) One-hop transmission delays increase as the density of traffic goes higher. But the average delays (<1ms) are still small, and acceptable for the routine services; 3) Increasing message generation rates worsens both PRRs and the delays; 4) Due to the impact of hidden terminal, adverse channel condition, and possible concurrent transmissions, the gained PRRs are less than 0.8.

Fig. 7 and Fig. 8 demonstrate the performance and the reliability of the class-one emergency service under our proposed schemes. From Fig. 7, we can see that one-hop five-cycle PRRs can reach almost 100% under all traffic loads although one-hop one-cycle PRRs 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 PRRs causes significant increment of transmission delays. However, Due to the high data rate and the proposed priority setting, the maximum transmission delay (<1.4 ms) is much smaller than the required one-hop delay for delivery of emergency message (<500ms).

![Fig. 5 Packet reception ratio of routine service (R=500m, W=15, E[P]=200 Bytes, SNR=78dB).](image-url)
Fig. 6 Packet transmission delay of routine service ($R=500\text{m}$, $W=15$, $E[P]=200\text{Bytes}$, $SNR=78\text{dB}$).

Fig. 7 Packet reception ratio of emergency service ($R=500\text{m}$, $R_e=24\text{ Mbps}$, $E[P]=200\text{Bytes}$, $SNR=78\text{dB}$).

Fig. 8 Packet transmission delay of emergency service ($R=500\text{m}$, $R_e=24\text{ Mbps}$, $E[P]=200\text{Bytes}$, $SNR=78\text{dB}$).

Fig. 9 Packet reception ratio of emergency service ($R=500\text{m}$, $R_e=24\text{ Mbps}$, $E[P]=200\text{Bytes}$).

Fig. 10 Packet transmission delay of emergency service ($R=500\text{m}$, $R_e=24\text{ Mbps}$, $E[P]=200\text{Bytes}$).

Fig. 11 Packet reception ratio of multi-hop emergency broadcast ($R=500\text{m}$, $R_e=24\text{ Mbps}$, $E[P]=200\text{Bytes}$, $SNR=78\text{dB}$).
Fig. 12 Packet transmission delay of multi-hop emergency broadcast (R=500m, R_c=24Mbps, E[P]=200Bytes, SNR=78dB)

Fig. 9 and Fig. 10 demonstrate the impact of the proposed schemes on the performance of class-one emergency message broadcast, and comparisons of the proposed scheme with other similar protocols. Increasing the number of receiver-oriented repetitions under certain channel condition can significantly improve the reliability of the message broadcast, but prolong the transmission delay. However, even the transmission delay in the worst case (all of one-hop receivers are involved in rebroadcast) is less than 100ms. The other interesting observation from Fig. 9 is that PRRs are independent of traffic because the network for class-one message broadcasting is free of hidden terminals and concurrent transmissions. Given N_s=5, p_0=10^{-4}, if the number of mini-slots is decreased (from w_m=21 to w_m=5), PRRs are reduced from 0.75 to 0.2 due to concurrent initial transmissions from multiple vehicles. If IEEE 802.11a like broadcast without priority setting is used for emergency message transmissions, PRRs are remarkably degraded as density of vehicles goes up. Also, from Fig. 9 and Fig. 10 we observe that PPRs of the proposed scheme (0.77 as N_s=1, 0.999 as N_s=5) are larger than that of IEEE 802.11e like MAC with two levels of priority [24] (one for emergency messages, the other for beacon messages) (0.77–0.72) and that of the 802.11a like MAC (0.72–0.52), although the 802.11e like MAC leads to lower delay when the density of vehicles is relatively low.

Fig. 11 and Fig. 12 compare the performance and the reliability of the new multi-hop emergency message broadcast scheme with the conventional random accessing delay (RAD) broadcast scheme [18], [19]. From Fig. 11, we can see that the average PRRs of the multi-hop emergency broadcast under our proposed protocol stay stably between 0.98 and 1, while PRRs of the RAD scheme fluctuate between 0.88 and 0.97. As shown in Fig. 12, due to the proposed scheme, the end to end delays on the 5000m long freeway of our proposed scheme is much smaller than that of the RAD scheme. The reason for the observation is that the average rebroadcast distance of our proposed scheme is much longer than that of the RAD scheme, which indicates that the proposed scheme has higher multi-hop broadcast efficiency.

VI. CONCLUSIONS

In this paper, a novel protocol for reliable and fast delivery of safety-related messages using the control channel for DSRC VANET is introduced and investigated. Several core strategies are combined as an integral scheme to enhance the performance and the reliability of the safety message broadcast, which include cross-layer message priority setting, dynamic receiver-oriented packet repetitions, farthest relay with distance based AD timer for multi-hop broadcast, etc. The shaped protocol allows the control channel to deliver three classes of safety related messages with required quality of service, and is easy to implement. Also, analytic models as well as simulation models are constructed to analyze the performance and reliability of the proposed protocol. The models account for the impact of the hidden terminal problem, the fading channel conditions, the message arrival intervals, and the backoff counter process 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 message priority setting is effective to improve the reliability and the performance of the 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.

The proposed broadcast scheme is a combination of several cross-layer core strategies. Although some ideas such as busy tone, mini-slots, and distance based relay have been previously known in the literature for enhancing the reliability and performance of ad hoc networks, the proposed solutions in this paper are different from those known ideas in the way of being incorporated into the scheme for safety-related applications. For example, the source node packet repetition strategy was used earlier to help improve the reliability, but the idea of receiver-oriented packet repetition is original. Besides, the busy tone signal strategy in this paper is adopted for performing two functions: suppression of hidden terminals as well as setting up preemptive priority for one-hop emergency message transmissions. The other difference of the proposed busy tone strategy from previous busy tone concept is that the busy tone signal is a long-range two-frequency carried wave for two classes of the emergency services. Mini-slots strategy in this paper is designed for not only avoidance of collisions due to concurrent emergency message transmissions but also working together with the busy tone to provide the emergency message transmissions with preemptive priority over other possible non-emergency message transmissions. The distance based node selection algorithm in this paper is different from the existing distance (or time) based selection.
algorithms, and is designed for both one-hop message repetitions and multi-hop broadcast relay. Therefore, the proposed scheme is not a simple sum of the isolated strategies, but a systematic integration of the strategies that interact with each other.

Based on the current work, our future research will focus on the development and the analysis of new adaptive IEEE 802.11p compatible protocol that is able to adjust the network parameters in terms of current traffic load and network conditions for optimized performance and reliability. We will also work on analysis of the protocols for the DSRC safety-related services through building more general models such as 2-D mobility model, impact of channel shadowing or fading, etc.

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APPENDIX

A. Derivation of Expected Vehicle Distance

Given exponential distribution of distance between nodes, the cumulative distribution function of $d_m$ can be calculated as

$$F_m(\tau) = P(d_m < \tau) = \frac{e^{-R\beta \tau}(e^{R\beta} - 1)}{1 - e^{-R\beta}}$$

and the density function of $d_m$ is

$$f_m(\tau) = \frac{\beta e^{-R\beta \tau}}{1 - e^{-R\beta}} , 0 \leq \tau \leq R$$

Define distances of the other nodes from the sender to be $d_{m-1}, d_{m-2}, \ldots, d_{m-i}, \ldots, d_0$. Similarly, the density functions of $d_{m-1}, d_{m-2}, \ldots, d_{m-i}$ can be calculated from density function of $d_m$

$$f_{m-k}(\tau) = \frac{\beta^k e^{-R\beta \tau}}{l_k(1 - e^{-R\beta})} , 0 \leq \tau \leq R$$

The expectation of $d_m$ can be derived as

$$E[d_m] = \int_0^R f_m(\tau) d\tau = \frac{R}{1 - e^{-R\beta}} - 1$$

Given the average distance between nodes $1/\beta$, the expectations of these distances $d_{m-1}, d_{m-2}, d_{m-3}, \ldots, d_0$ are

$$E[d_{m-i}] = \frac{i}{\beta} = \frac{R}{1 - e^{-R\beta}} - i + \frac{1}{\beta} , i = 1, 2, \ldots, m$$

B. Derivation of one-hop $N_c$-cycle Transmission Delay

Case 1: No emergency concurrent transmissions in the first cycle

In order to calculate closed form average of $D_{Nc}$, we first define and derive the probability $P_{m,j,m-i}$ that the $(m,i)$-th node repeats the message in the $j$-th cycle of the repetitions. Based on the description of receiver-oriented repetitions in Section III-B, the farther node that has received the 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

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

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 probability that the number of cycles that the previous nodes with higher priority have gone through is exactly equal to the current cycle number minus one; 3) the probability that the current node is the first candidate for the current cycle of the repetitions.

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

$$E[t_{AD}(j)] = \sum_{i=0}^{N_c} E[d_{m-i}] P_{m,j,m-i}^{(i)} / N_c$$

Since the percentage of one-hop nodes that have received the message in a specific cycle depends on undergoing packet reception ratio, then, the average $D_{Nc}$ in case 1 can be expressed as (37) at the bottom of this page.

Case 2: Concurrent transmission in the first cycle

If there is emergency concurrent transmission in the first cycle, all receivers cannot receive the message in the first cycle and nobody can rebroadcast the message in the second cycle. Hence, the original sender will wait $T_{max}$ time before it resends the message in the second cycle. In this case, the original sender resends the message in the second cycle, and there will be no more concurrent transmission in this and later cycles. Thus, the average $D_{Nc}$ in case 2 can be expressed as (38) at the bottom of this page. Then, we have

$$P_{m,j,m-i}^{(i)}(n) = \begin{cases} 0; & j > i + 3; j \leq N_c; 0 \leq i \leq m - 1 \\ \sum_{i'} \left(1 - p_i\right)^{i'-j} p_i^{i'-i}; & j < i + 3; j \leq N_c; 0 \leq i \leq m - 1 \\ \left(1 - p_i\right)^{i'-i}; & j = i + 3; j \leq N_c; 0 \leq i \leq m - 1 \end{cases}$$

The equations for the average delay are then

$$E[D_{Nc}] = E[D_m] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$A = E[D_{Nc}] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$B = E[D_{Nc}] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$E[t_{AD}(j)] = \frac{E[D_m] - i}{\beta} = \frac{R}{1 - e^{-R\beta}} - i + 1, i = 1, 2, \ldots, m$$

Finally, the equations for the average delay are then

$$E[D_{Nc}] = E[D_m] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$A = E[D_{Nc}] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$B = E[D_{Nc}] = \frac{R}{1 - e^{-R\beta}} - 1$$

$$E[t_{AD}(j)] = \frac{E[D_m] - i}{\beta} = \frac{R}{1 - e^{-R\beta}} - i + 1, i = 1, 2, \ldots, m$$
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and communication systems, physical layer and MAC layer of vehicular ad hoc wireless networks, computational intelligence and its applications to coding, signal processing, and control, and Quality of service (QoS) and call admission control protocols in wireless networks.

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