Interplay Between TVWS and DSRC: Optimal Strategy for Safety Message Dissemination in VANET

Jae-Han Lim, Wooseong Kim, Katsuhiro Naito, Ji-Hoon Yun, Danijela Cabric, and Mario Gerla

Abstract—In vehicular safety systems, two types of safety messages are required: Emergency Safety Message (ESM) and Periodic Beacon Message (PBM). The ESM has to be disseminated within a specified area with stringent delay and delivery ratio requirements, while the PBM does not need to meet these requirements. For exchanging the safety messages in Vehicular Ad-hoc NETwork (VANET), Inter-Vehicle Communication (IVC) is necessary whose de facto standard is Dedicated Short-Range Communications (DSRC). However, the effective transmission range in the DSRC-based IVC is short since a signal can be attenuated due to blocking by obstacles. In order to cover a large dissemination area in the DSRC-based IVC, multi-hop dissemination is required, which however causes channel collision and network congestion. Moreover, the coexistence with PBMs aggravates the collision and the congestion, which make it hard to satisfy the requirements of the ESM dissemination. To overcome the limitation of the DSRC, we utilize an extra TV White Space (TVWS) band that has a large communication range for ESM disseminations, and exploit a DSRC band for 1) the exchange of control data and 2) the compensation of ESM reception errors. In this paper, we propose and analyze a distributed channel usage framework that exploits advantages of DSRC and TVWS bands for ESM dissemination under the existence of PBMs. Our scheme employs TVWS Channel Rendezvous Algorithm (TCRA), ensuring that vehicles within a dissemination area select the same channel with the ESM sender. To compensate ESM reception failures in a TVWS band, our scheme adopts Two-Way Recovery Algorithm (TWRA) that uses DSRC and TVWS bands for ESM retransmission. Further, we establish an analytical delivery ratio model that considers a delay bound of an ESM for optimal parameter selections. To the best of our knowledge, this is the first attempt to propose a distributed channel usage scheme that leverages the strengths of TVWS and DSRC bands for safety message dissemination. Through an in-depth simulation study, we show that the proposed scheme satisfies ESM requirements for latency and packet delivery ratio, and outperforms previous approaches in various vehicular scenarios.

Index Terms—Interplay, DSRC, TVWS, emergency safety message, dissemination

I. INTRODUCTION

A S VEHICLE accidents increase, developing new technologies for preventing vehicle accidents becomes a top priority for the U.S. Department of Transportation (DOT) [1]. In an attempt to reduce vehicle accidents, many automotive companies and academic institutes make efforts to implement “active safety systems”. In the active safety systems, Emergency Safety Message (ESM) dissemination is one of the key mechanisms for exchanging time-critical safety messages among vehicles in Vehicular Ad-hoc NETworks (VANET). ESMs have to be delivered to vehicles within a service area only when an emergency situation happens, and meet short latency and high delivery ratio requirements. One example of the ESM is “wrong-way driver warning”, which should be disseminated within 500m range in a real-time manner (≤100ms) [4]. The other type of a message in VANET, Periodic Beacon Message (PBM) is transmitted to advertise vehicle’s status information, e.g. position, speed, and direction.

For exchanging the safety messages in VANET, Inter-Vehicle Communication (IVC) is normally used and the dominant standard for IVC is Dedicated Short-Range Communications (DSRC) [2], which uses a 5.9 GHz licensed band. In the DSRC-based IVC, multi-hop transmission is necessary to support various safety applications that require high communication reliability and low delay bound (100 ms) within a large dissemination range (500 ∼ 1000m) [4] [5] [6]. This is because a transmission range of a DSRC band is short due to operation in a high frequency band. Since a high frequency signal cannot penetrate large size obstacles, the signal can be attenuated severely when Line Of Sight (LOS) is not guaranteed. According to experiments in [3], additional path loss induced by obstructions (i.e., blocking by truck, bus, or trees) is 10 ∼ 20dB (i.e., comparable to range reduction by 3.16 ∼ 10 times), which frequently happens in IVC. The blocking occurs more often as the distance between a sender and a receiver is longer and the vehicle density increases.

It is well known that multi-hop dissemination causes serious contention and collision, which become more serious when many messages are generated by multiple sources. In VANET, unfortunately, all vehicles generate PBMs periodically. Hence, in the DSRC band, it is hard to satisfy the delay and delivery ratio requirements of ESM dissemination in congested traffic situations (e.g. traffic jams on highways) [8] [9], which will be shown in Fig.13.

1Emergency events can happen under high vehicle density such as appearance of fire engine and malfunctioning of brake system.
There have been previous approaches for mitigating network congestion of VANET in a DSRC band [10] [11]. [10] proposed a multi-hop dissemination scheme for reducing redundant rebroadcasts. However, [10] did not employ a mechanism for supporting high delivery ratio of safety message. [11] addressed this issue by proposing an acknowledgement-based broadcast mechanism. However, [11] did not consider a low delay requirement; simulation results showed that latency could be 100 second in high vehicle density.

In order to overcome the limitation of a DSRC band, we propose to adopt a protocol with a large transmission range. For instance, Wi-Fi using a TV white space (TVWS) band has good propagation characteristics (e.g., low path loss, low penetration loss, high permeability), which enables the ESM to reach the large service area by one hop transmission [12]. This is because the operation frequency of a TVWS band is much lower than a DSRC band [13] [14]. Recently, the Federal Communications Commission (FCC) allowed unlicensed users to access the TVWS band provided that they do not disturb the services of licensed users [8]. Thus, vehicles can use the TVWS band opportunistically based on spectrum availability data on each geo location, which was measured in advance [15].

However, using only a TVWS band is not enough to satisfy stringent requirements of an ESM due to two reasons. First, vehicles might not have enough TV channels for recovering ESM reception failure. To be specific, retransmission at the same TVWS channel is inefficient because of relatively long coherence time, thus vehicles need additional TVWS channels for retransmitting the ESM. However, vehicles may not have additional available TVWS channels. Second, as a TVWS band is not always available to vehicles, it cannot serve as common control channel, which is necessary for optimal configurations. Hence, to further improve delivery ratio and latency of ESM, we should exploit an additional band that is always available and has short coherence time, like a DSRC band.

Recently, researchers proposed schemes that exploited DSRC and TVWS bands with two interfaces for supporting QoS in VANET [16] [17]. [16] proposed to use additional TVWS band when estimated contention delay in a DSRC band is larger than a pre-defined threshold. However, in [16], Road Side Unit (RSU) is necessary for making decision on accessing a TVWS band. [17] proposed a cognitive network system that had two network interfaces, one for an exclusive usage band such as a DSRC band and the other for a cognitive usage band like a TVWS band. However, [17] is based on a clustering mechanism, which induces large overhead when topology changes frequently like in VANET. Given all of the above, [16] [17] depended on centralized devices (e.g. cluster head or RSU). Moreover, they employed TVWS and DSRC bands without considering characteristics of each band.

To address these issues, in this paper, we propose and analyze a distributed scheme that fully exploits the advantages of TVWS and DSRC bands for an ESM dissemination with two radio interfaces. To leverage the advantages of two bands, we investigate characteristics of both bands and then determine how to use each band efficiently. Moreover, the proposed scheme does not depend on centralized devices.

When a vehicle generates an ESM, the vehicle checks available TVWS channels using a TVWS channel database, and then disseminates the ESM in one TVWS channel. However, due to heterogeneity of available TVWS channels over location and time, vehicles cannot expect the TVWS channel and the time that the ESM is transmitted. To overcome this challenge, our scheme employs TVWS Channel Rendezvous Algorithm (TCRA) that a sender transmits a harbinger signal before sending an ESM and receivers continuously scan TVWS channels to hear the signal.

Sometimes, vehicles do not successfully receive an ESM in a TVWS band. To compensate the reception error, our scheme adopts Two-Way Recovery Algorithm (TWRA) that 1) an ESM sender retransmits the ESM in a different TVWS channel and 2) other vehicles further transmit the ESM using a DSRC band only after listening to recovery requests.

Our scheme employs an optimal parameter selection for maximizing the reachability of an ESM. Here, reachability is defined as the ratio of the number of vehicles that successfully received ESM to the number of target vehicles (i.e., vehicles within a service area of the ESM) [7]. To this end, we propose a mathematical model on ESM reachability. The proposed model considers delay bound of a safety message that previous works did not consider [6] [21].

Intensive simulation studies show that our scheme outperforms legacy DSRC systems with two interfaces by 64 (86)% and [17] by 17 (56)% in highway (2X2 Manhattan grid) situation. Further, our system supports high reachability of ESM with delay bound constraints under various scenarios. In summary, the contributions of this paper are as follows:

- Propose a novel interplay strategy between TVWS and DSRC bands, which leverages the advantage of each band for an ESM dissemination.

- The interplay strategy is robust to dynamic vehicular topology changes.

- Establish a new analytical model that captures delay bound of an ESM.

The remainder of this paper is organized as follows. In section II, we propose our scheme that uses DSRC and TVWS bands for an ESM dissemination. In section III, we establish an analytical model on the reachability of ESM. In section IV, we formulate an optimization problem for maximizing the reachability. In section V, we evaluate the proposed scheme. This paper is concluded in section VI.

II. INTERPLAY BETWEEN TVWS BAND AND DSRC BAND

A. System Model

Similar to previous works [17] [18], we assume that every vehicle uses two radio interfaces. One interface is used for accessing a DSRC channel (“DSRC interface”) and the other is used to access one of the TVWS channels (“TVWS interface”). We use IEEE 802.11p with 10MHz option [2] on a DSRC interface and IEEE 802.11 with 5MHz option [19] on
a TVWS interface. Hence, the transmission rate of a TVWS interface is half of the DSRC interface. In a TVWS band, we define that TV broadcasting towers are Primary Users (PUs) and vehicles are Secondary Users (SUs). We do not consider typical secondary users, e.g. IEEE 802.22 Base Station (BS) or Customer Premises Equipment (CPE).

In the proposed system, two types of messages: periodic beacon message (PBM) and emergency safety message (ESM), are considered. We utilize PBM to exchange control data (e.g. system configuration parameters and measurement results) among vehicles. For this purpose, the control data are piggybacked onto existing PBM frame [20]. On the other hand, the ESM has higher priority than the PBM and is generated infrequently since the emergency event does not occur frequently in normal road situations. Thus, a collision rarely happens at a TVWS channel for dissemination of the ESM in the network [21].

### B. Characteristics of DSRC and TVWS bands

In IVC, the transmission range of a DSRC band is short due to operation in a high frequency band. In the DSRC band, a signal cannot pass through large-size obstacles (e.g. trucks, buses, or trees), which induces signal distortion at receivers in NLOS conditions. For example, an experimental study in [22] shows that 80% PER occurs when a pair of vehicles are apart by 50m with typical 802.11 transmit power (20dBm), and 85% PER occurs when separated by 180m with maximum allowable transmit power (33dBm).

On the other hand, a transmission range of a TVWS band is large due to operation in a low frequency band. This is because path loss and penetration loss is relatively small in a low frequency band. For example, the Wi-Fi in a TVWS band has a larger transmission range than IEEE 802.11 in 2.4GHz by 3 times [12]. Thus, a large transmission range of a TVWS band makes it possible to cover a dissemination area of most safety applications [4] [5] [12].

A TVWS band is not always available to vehicles. This is because vehicles are secondary users that can opportunistically access the TVWS band only when there is no activity of TV broadcasting towers. When we search available TVWS channels for portable devices in [23], we can find at least 1~2 available channels with transmission power 40mW (16dBm) in Los Angeles, which is the most densely populated city in America. However, available channels to vehicles are different according to location. This is because TV broadcasting towers that are located in different locations may have different active TV channels and operation hours. Therefore, we have to make channel rendezvous algorithm in a TVWS band.

On the other hand, a DSRC band is always available to vehicles since it is dedicated to vehicular communication. In multiple-channel protocols, control data is usually exchanged among vehicles via a channel that is always accessible by all vehicles. Hence, the DSRC band can be used for a common control channel, where network configuration parameter and network status information can be exchanged.

### C. Overview of the Proposed System

Fig.1 depicts an overall operation of the proposed scheme. In normal situations (Fig.1(a)), vehicles periodically exchange PBMs with each other using a DSRC interface. When detecting an emergency event (Fig.1(b)), a vehicle generates and disseminates an ESM to the vehicles within a service area using a TVWS interface. However, since there are multiple channels in a TVWS band, rendezvous at the same TVWS channel is necessary among vehicles within a service area. Moreover, to compensate the ESM reception failure in a TVWS band, our system employs a recovery algorithm for the reception failures.

The proposed system exploits a DSRC band for exchanging PBMs among vehicles. In the proposed system, a PBM includes control data, which is generally transmitted using a channel that is always accessible by all vehicles. Hence, vehicles transmit PBMs using a DSRC interface.

On the other hand, we utilize a TVWS band for an ESM dissemination. An ESM has to be disseminated within a large service area and comply with strict delay and reliability requirements. However, if a DSRC band is used for an ESM dissemination, it is difficult to satisfy the requirements of an ESM due to high network congestion, which is induced by multi-hop dissemination and large background traffic (e.g. periodic PBM transmissions by all vehicles). Hence, for ESM dissemination, our system adopts a TVWS band that has a large transmission range. However, the usage of a TVWS band for ESM dissemination poses three technical challenges: 1) finding available TVWS channels to vehicles, 2) rendezvous among vehicles within a service area, and 3) recovery of ESM reception errors.

Many government authorities (FCC in U.S. and IDA in Singapore) declared that the secondary users are required to rely on “TVWS channel database” for accessing to TVWS channels, and the authorities eliminate the requirements of a physical sensing [37] [38]. The database specifies available TVWS channels and maximum transmission power for the secondary user according to position. Fortunately, a long updating interval of available channels in a TVWS channel database (e.g., FCC requirements - one day, IDA requirements: 6~12 hours [37] [38]) enables vehicles to obtain available TV channels without real-time update. Thus, in our scheme, a vehicle pre-computes a spectrum map indexed by positions of a driving route, and obtains available channels by a table look-up, using its position as an index at run-time [34].

In the spectrum map, a vehicle includes available channels on every position of its driving route.

---

3 A TVWS interface adopts communication system with 802.11a/g such as OFDM, en/decoding module. Only RF frontend is modified by setting its frequency to TVWS channel.

4 Even if typical secondary users exist, a vehicle can avoid interference from the typical secondary users. For example, a vehicle avoids the TVWS channel before accessing the channel if the vehicle detects typical users in the channel. We can differentiate between ESM and typical user signals via preamble detection. We will handle details on this issue in our future work.

5 In certain safety systems, multiple vehicles generate ESMs for the same emergency event. For this case, a CSMA/CA with a random backoff and suppression mechanism are integrated to reduce congestion in a TVWS band. Here, an ESM suppression mechanism is that vehicles cancel transmission attempts if the vehicles already received the same ESM. Suppression is necessary since only one ESM among several ESMs for the same emergency event need to be delivered. Since vehicles that see the same emergency event are located in a similar area, the vehicles can receive an ESM signal with high SNR. So, many vehicles can suppress their ESM transmission attempts.

6 In the spectrum map, a vehicle includes available channels on every position of its driving route.
However, a channel rendezvous algorithm in a TVWS band is necessary since available TV channels are different according to the position of a vehicle. Thus, we propose TVWS Channel Rendezvous Algorithm (TCRA) to remedy this problem. In TCRA, when a vehicle generates an ESM, the vehicle selects its TVWS channel for ESM dissemination and other vehicles within a service area tune their TVWS interfaces to the selected transmission channel. When determining a transmission channel, a vehicle selects one of its available channels that is available to the largest number of vehicles within a service area. To get information on the largest number of vehicles with a common available channel, the vehicle follows a three-step procedure. In the first step, the vehicle obtains the available channel set of its neighbors within a service area by looking up its pre-computed spectrum map with a neighbor’s position. In the second step, the vehicle accumulates the count for each available channel in all the sets of the first step. In the third step, the vehicle selects a channel with the maximum count.

Sometimes, there is a case when a vehicle has more than two available channels with the maximum count. In this case, the vehicle selects the channel with a minimum background signal strength (i.e., the signal strength that a vehicle measures when a preamble of an ESM is not detected). Specifically, during a periodic scan process (see Fig. 2(a) and section II-D for detail), the vehicle measures and stores the background signal strength for each channel. Then, among the several available channels with the maximum count, the vehicle chooses the channel with the minimum background signal strength. This criteria comes from the belief that the background signal strength that a vehicle measures is small, a TV broadcasting tower tends to be far from the vehicle. Thus, vehicles within a service area will experience high SINR.

Even if rendezvous among vehicles is successful, the reception of an ESM cannot be guaranteed. This is because 1) vehicles may suffer from interference by TV towers; 2) a signal can be distorted from blocking and multi-path effect since line-of-sight (LOS) is not guaranteed between a sender and a receiver. To compensate reception failures of the ESM, we employ Two-Way Retransmission Algorithm (TWRA) that the ESM is retransmitted in both DSRC and TVWS bands.

In TWRA, a DSRC band is used as a basic channel for ESM retransmission for the following reasons. First, a DSRC band is always available to vehicles. Second, it is highly probable to guarantee LOS between a sender and a receiver if the ESM is retransmitted by close neighbor vehicles in a DSRC band. Hence, retransmissions in a DSRC band are efficient in compensating ESM reception failures. Third, a short transmission range of a DSRC band is beneficial since concurrent ESM retransmissions by multiple vehicles are possible owing to channel reusability.

To further improve the retransmission efficiency, TWRA resorts to a TVWS band as a supplementary channel for ESM retransmission. This is because retransmissions in a DSRC band can suffer from network congestion induced by multiple vehicle transmissions. However, since channel coherence time is comparable with a lifetime of ESM, the TVWS band is used only when a sender vehicle has available channels other than ESM transmission channel. For example, using Clarke’s model, we can estimate coherence time as 65 ~ 92 ms (512 ~ 698MHz) when the relative speed is 10km/h [25] [26].

Fig. 2(a) illustrates a flow chart for an overall operation of each vehicle. As an initial step, the vehicle exchanges a PBM via a DSRC interface and determines its scanning channel set, which we will elaborate on in the following subsection. Then, the vehicle checks whether an emergency event happens or not. As long as the event does not occur, the vehicle continues to conduct a normal operation: a periodic scan in a TVWS band and a PBM exchange in a DSRC band. However, when an emergency event happens, a vehicle starts a TCRA.

8The vehicle obtains neighbors’ position by exchanging a PBM, which includes sender’s position as well as neighbors’ positions.

8A vehicle might select a sub-optimal channel for its transmission. However, in our system, selecting the sub-optimal channel rarely degrades the system performance. This is because the other available channels will be also used for retransmitting the same ESM.

10Here, one may insist that neighbor vehicles can retransmit ESM via TVWS band. However, adoption of TVWS band by neighbor vehicles has several drawbacks. First, rendezvous overhead is necessary for retransmission and transmission rate of a TVWS band is half of that of a DSRC band. Second, vehicles cannot tune their TVWS interfaces to the channels that their close vehicles utilize, thereby suffering from low SINR or blocking. This is because several ESM holders may utilize different channels for their ESM transmissions.

11Since the vehicle moves by platoon, the relative speed is small.
procedure, which we will further explain in section II-D. In the final stage of TCRA, if there is an ESM that should be sent, the vehicle sends the ESM via a TVWS interface; otherwise the vehicle just receives the ESM. However, a failure of ESM reception might happen. To recover the reception failure, the vehicle retransmits the ESM using a TVWS interface if the vehicle is the ESM sender and has more than one available TVWS channels, which is called “Proactive TVWS Retransmission (PTRet)”. The vehicle also starts “On-demand DSRC Retransmission (ODRet)” procedure, with which the vehicle compensates the reception failure through an ESM retransmission in a DSRC band. The detailed explanation of ODRet and PTRet can be found in section II-E.

D. Rendezvous Algorithm among multiple TVWS channels

Since our system is a distributed system, there is no coordination for TVWS channel rendezvous among vehicles. Hence, for rendezvous at the same TVWS channel, our TVWS Channel Rendezvous Algorithm (TCRA) must overcome challenges in two domains: 1) frequency domain challenge and 2) time domain challenge.

Frequency domain challenge is that vehicles must know which frequency channel is used for transmitting an ESM. In order to overcome this challenge, vehicles scan all the available TVWS channels within their service area (scanning channel list) periodically. Vehicles can find all the available TVWS channels within a service area by inquiring available TVWS channels of a TVWS database for each position. In a scanning phase, a vehicle advertises its attempt to transmit an ESM by sending a reference tone signal in its transmission channel. Here, the reference tone signal consists of a repetition of 802.11 preambles. Vehicles within a service range of transmitted ESM (target vehicles) can detect a reference signal since they scan all the available TVWS channels of ESM sending vehicle periodically. In an ESM transmission phase, the sending vehicle transmits an ESM using the same channel where a reference tone signal was sent. Meanwhile, in order to receive an ESM, target vehicles tune their TVWS interfaces to the TVWS channel in which they detect the reference tone signal.

Time domain challenge is that vehicles must know when an ESM is transmitted in a TVWS channel. To remedy this problem, we divide TVWS interface operation time into two phases: 1) scanning phase and 2) ESM transmission phase. In a scanning phase, a vehicle advertises its attempt to transmit an ESM by sending a reference tone signal in its transmission channel. Here, the reference tone signal consists of a repetition of 802.11 preambles. Vehicles within a service range of transmitted ESM (target vehicles) can detect a reference signal since they scan all the available TVWS channels of ESM sending vehicle periodically. In an ESM transmission phase, the sending vehicle transmits an ESM using the same channel where a reference tone signal was sent. Meanwhile, in order to receive an ESM, target vehicles tune their TVWS interfaces to the TVWS channel in which they detect the reference tone signal.

One may insist that a vehicle has to search all the positions within a service area for obtaining all available TVWS channels, and thus required time and computation resource might be too large to work in a real-time manner. In practical situation, however, as a transmission range of TV broadcasting tower is very long, vehicles located in close distance tend to share the available TV channels. Hence, in our system, vehicles inquire available TVWS channels of a TVWS database every 50m [24].
It is noted that the duration of a reference tone signal is very short even in the worst case. In detail, the duration of the reference tone signal must be larger than maximum scan period of vehicles within a dissemination area. The maximum scan period can be derived from the number of available channels multiplied by the scan duration of each channel. According to [24], the maximum number of available channels for portable devices is 30. The scan duration of each channel consists of channel switching time and the duration of preamble detection. The channel switching time in Maxim 2831 is only 9.5us [26] and the duration of preamble detection is 64us in TVWS band [19]. Therefore, the duration of reference tone signal is at most 2.205ms, which is much shorter than delay bound of an ESM (100ms).

We should note that a detected signal in a TVWS band can be either a reference tone signal by a vehicle or a signal by a TV broadcasting tower.\(^\text{13}\) To differentiate the two types of signals, vehicles can distinguish a reference tone signal from a TV broadcasting signal. Considering solutions for two-domain challenges, we propose TVWS Channel Rendezvous Algorithm (TCRA) and explain the TCRA behavior with a simple example in Fig.3.

**F. Recovery of ESM Reception Error in TVWS band**

We propose Two-Way Retransmission Algorithm (TWRA) to compensate the reception errors of an ESM. TWRA must compensate 1) a failure of ESM reception caused by ESM decoding error and 2) a failure of ESM reception induced by TVWS rendezvous error. For this purpose, TWRA employs two retransmission mechanisms: mandatory On-demand DSRC Retransmission (ODRet) and 2) optional Proactive TVWS Retransmission (PRTret), as depicted in Fig.4(a).

1) **On-demand DSRC Retransmission (ODRet):** Fig.4(b) illustrates the behavior of ODRet. Vehicles initiate ODRet when they detect an ESM signal in a TVWS band\(^\text{14}\) and terminate the ODRet when the lifetime of the ESM expires. ODRet consists of three phases: 1) deferring phase, 2) jamming phase, and 3) retransmission phase, which we will elaborate in the following paragraphs.

In a deferring phase, vehicles initiate deferring PBM exchanges, and continue deferring until the lifetime of ESM expires in order to increase the efficiency of ODRet. Since PBM exchanges might interfere with ESM retransmission, holding on PBM exchanges during ODRet can improve the efficiency of ODRet. We justify deferring PBM exchange by two grounds: 1) ESM dissemination has higher priority than PBM exchange; and 2) the lifetime of an ESM is normally so short that only a few PBM exchanges are deferred.

However, a vehicle that failed in TVWS rendezvous cannot detect an ESM signal in a TVWS band, thereby being unable to participate in ODRet (e.g. VEC 1 in Fig.4(b)). To address this problem, ODRet adopts a jamming phase. In the jamming phase, if vehicles discover the start of ODRet (e.g. VEC 2 and VEC 3 in Fig.4(b)), they transmit a jamming signal in a DSRC band, as depicted in Fig.4(b). The jamming signal is modulated with simple on-off keying, and transmitted without Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), and can be detected with simple preamble detection. When a vehicle of rendezvous failure recognizes the jamming signal (e.g. VEC 1 in Fig.4(b)), it perceives that ODRet has started, and then defers PBM exchanges as the first step of ODRet. After a short while (predetermined duration for a deferring phase), the vehicle (e.g. VEC 1 in Fig.4(b)) switches to a jamming phase.

Unfortunately, as attenuation of signal strength during propagation is high in a DSRC band, a transmission of jamming signals may not cover a large service area. To remedy this challenge, a vehicle relays the signal if they hear a jamming signal (e.g. VEC 1 in Fig.4(b)). As a result, all vehicles within a service range can hear the jamming signal and know the start of ODRet.

In a retransmission phase, vehicles divide the time into multiple DSRC time frames and retransmit an ESM at each time frame in on-demand fashion, as shown in Fig.4(b). On-demand retransmission is effective in reducing congestion from ESM transmissions by multiple vehicles. Instead of ESM retransmissions by all vehicles, only vehicles that hear a DSRC tone signal retransmit an ESM. Hence, we can reduce the number of ESM retransmission attempts, thereby reducing congestion at a DSRC band caused by ESM retransmission. However, if there are many vehicles that fail in ESM reception, large request overhead might happen. To remedy this challenge, vehicles divide the time into multiple DSRC time frames; they transmit their request signals at a designated time

\(^{13}\)TCRA, each vehicle might scan unavailable TVWS channels in TVWS database as well. For example, as depicted in Fig.3(a), STA 2 scans channels 1∼7 including its unavailable channels 1, 3, and 5. In unavailable channels, interference by a TV broadcasting tower is not trivial, thus a vehicle might enter an ESM transmission phase just by sensing TV signal.

\(^{14}\)For initiating ODRet, vehicles need to know whether there is a transmission attempt of an ESM, and thus use a preamble detection for an ESM signal detection.
of the frame without CSMA/CA; nearby vehicles just detect the request signal without decoding. This will be elaborated in the following paragraphs.

We will explain behaviors of vehicles at a retransmission phase using simple example in Fig.4(b). In Fig.4(b), VEC 3 successfully receives an ESM in a TVWS band, and VEC 1, 2 fail in ESM reception in a TVWS band. In the beginning of the first time frame, VEC 3 transmits Start Of time Frame (SOF) signal to advertise the start of a DSRC time frame. The start time and the duration of DSRC time frame are piggybacked onto the ESM, and thus only VEC 3 can know when SOF should be transmitted. Meanwhile, only VEC 2 detects SOF and then perceives that a new time frame is started. As a next step, VEC 2 transmits a DSRC tone signal as a sign of their ESM reception failures. When VEC 3 detects the tone signal, the vehicle knows that there exist vehicles that failed in ESM reception around them and transmit an ESM.

However, as VEC 1 is out of transmission range of VEC 3, VEC 1 cannot hear SOF, thereby being unable to participate in the retransmission procedure in the first DSRC time frame. VEC 1 can join a retransmission procedure only when VEC 2 becomes an ESM holder. In the second DSRC time frame, VEC 1 can receive ESM via a procedure similar to the first DSRC time frame.

In a retransmission phase, simple modulation (e.g. on-off keying) and detection (e.g. energy detection) methods are used for DSRC tone and SOF signals. In addition, vehicles transmit two signals without multiple access control (e.g., CSMA/CA), thus no backoff delay happens for transmissions of the signals. In the retransmission phase, vehicles can transmit only DSRC tone, SOF or ESM signals, however, vehicles cannot differentiate among these signals by using only simple detection method. To address this problem, vehicles pre-define and share the length of each signal before system starts; they can check the length of the signal after sensing the busy channel.

However, as multiple vehicles concurrently send DSRC tone or SOF signals, there might be a discrepancy between the length of detected signal and the pre-defined length; or SOF and DSRC tone signals can be overlapped with each other unless time is synchronized among vehicles. Fortunately, vehicles can realize time synchronization with GPS, which has a global time clock.

We should note that vehicles of rendezvous failure may send PBM in a jamming phase since they do not defer PBM exchanges until they recognize the start of ODRet. In this case, the vehicles may transmit PBMs during the existence of a jamming signal, thereby being unable to detect the jamming signal via preamble detection. Fig.5 illustrates a solution to address this challenge. When there is no jamming signal (Fig.5(a)), the channel is sensed idle during DCF Inter-Frame Space (DIFS) right after PBM transmission. However, when there is jamming signal (Fig.5(b)), the channel is sensed busy right after the PBM transmission. Therefore, by sensing the channel after PBM transmission, the vehicles can recognize the existence of the jamming signal.

15The start time and duration of DSRC time frame are determined by a vehicle that generates an ESM. The vehicle gets DSRC time frame by solving an optimization problem, which will be explained in section IV. In addition, the vehicle calculates the start time of DSRC time frame from two values: 1) an expected end time of its ESM transmission and 2) duration of jamming phase. The vehicle generating an ESM assigns suitable value to the duration of jamming phase; the duration must be longer than expected number of hops for covering a service area multiplied by the duration of each jamming signal.
At every scanning phase of TCRA, each vehicle selects one spectrum map coverage and relies on the maps within the service area. To perform a PU detection for all TV channels, each vehicle changes the channel for a PU detection in the next scanning phase.

Notably, the hybrid scheme is feasible to an ESM dissemination. To ensure the feasibility, a harbinger signal (i.e., reference tone signal) must be shorter than a delay bound of an ESM. In our scheme, the length of a harbinger signal is equal to the maximum duration of a scanning phase, which is around 7.45ms (= 2.45 + 5). Moreover, the hybrid scheme fulfills FCC requirements of PU detection since each vehicle conducts the detection more than once within 2 sec.

To select a transmission channel, each vehicle must know all the available channels of vehicles within a service area. When relying on physical sensing, vehicles can share sensing results by annotating their PBMs with the results. However, due to limitation of a DSRC transmission range, vehicles can obtain the results only from vehicles nearby. To address this challenge, vehicles piggyback their sensing results as well as the results included in the received PBM.

**G. Discussion on Using a Cellular Interface**

A cellular communication is considered as a candidate technology to realize vehicular safety dissemination due to its prevalence and high data rate support. However, the current cellular system alone may not be an efficient solution for ESM dissemination due to the following reasons. First, a cellular system covers the limited data transmission area in U.S. [35]. Second, one must pay for using a cellular band, while one can access a TVWS band for free if not interfering with PUs. Third, the ESM must be communicated to a Base Station (BS) before reaching the vehicles nearby, even if a sender is closely located to the vehicles. If the BS is far away from the vehicles, the link quality is bad, which leads to a failure of ESM receptions. The problem becomes worse especially in a cell-boundary area due to high path loss and inter-cell interference. Finally, cellular capacity can be overloaded due to an explosive increase in smart phone users. As a result, even if adopting a scheduled access scheme, the cellular system might not guarantee bounded delay and guaranteed reliability.

However, we believe that the collaborative usage of a cellular interface and a TVWS interface will help compensate the limitations of a cellular system. For example, to compensate the first, the third and final limitations, vehicles disseminate an ESM via a TVWS interface in an area in which a cellular connection for data service is not supported or in poor quality. Moreover, to remedy the second limitation, vehicles exploit a TVWS interface as long as using a TVWS interface satisfies requirements of ESM dissemination; otherwise vehicles adopt a cellular interface. We will consider the detailed design of the collaborative system as our future work.

---

17.45ms is much shorter than typical delay bound of an ESM (100ms). Moreover, in physical sensing, vehicles configure very conservative settings for reducing false alarm. This is because 1) an ESM is related to driver’s safety; 2) the ESM does not frequently happen, thereby rarely interfering with primary users. To compensate such interference, we give incentives to primary users.

20. In the future, the above-mentioned collaboration can be achieved with a single radio interface with a Software-Defined Radio (SDR) technique [32].
III. Mathematical Model of ESM Reachability

In this section, we establish a mathematical model of ESM reachability for finding optimal configurations in our system. As shown in simulation results, the reachability is close to one when two retransmission mechanisms (i.e., ODRet and PTrRet) are employed, while the reachability is relatively low when only ODRet is used. This implies that optimal configuration is not necessary when both mechanisms are adopted. Thus, we only consider ODRet for a retransmission mechanism in our model.

A. Assumptions

We make two assumptions for establishing a mathematical model. First, we assume that all TVWS rendezvous failures can be recovered during a jamming phase of ODRet. In our scheme, vehicles can recover the rendezvous failures when they detect a jamming signal using preamble detection. In general, a detection probability grows as the length of a signal increases. Fortunately, the jamming signal in our scheme is long enough to make the probability of detecting the signal close to one even in low Signal to Noise Ratio (SNR) regime.

Second, we assume that vehicles can detect DSRC tone and SOF signals with probability one. In ODRet, an exchange of a PBM is deferred, and thereby SOF and DSRC tone signals do not interfere with any signals. In addition, SOF and DSRC tone signals are sent at pre-defined time with their own lengths. For this reason, if vehicles use energy detection and check the detection time and the length of the signal, the vehicles do not fail in detecting SOF and DSRC tone signals.

B. Reachability of ESM

Fig. 6 illustrates vehicle activities for an ESM dissemination in TVWS and DSRC bands and the mathematical notations on the activities. When a vehicle (e.g., 'VEC-S' in Fig.6) generates an ESM, the generator delivers the ESM to vehicles within a service range via two separate routes: 1) a TVWS band and 2) a DSRC band. Since ESM receptions via two routes are mutually exclusive, an ESM reachability, \( P_{s,total} \), can be expressed as

\[
P_{s,total} = P_{s,tvws} + P_{s,dsrc}
\]

where \( P_{s,tvws} \) is the probability of ESM reception in a TVWS band and \( P_{s,dsrc} \) is the probability of ESM receptions in a DSRC band.

To successfully receive the ESM in a TVWS band, vehicles must make rendezvous with the ESM initiator (e.g., VEC-S in Fig.6) at the same TVWS channel and succeed in decoding the ESM. Thus, \( P_{s,tvws} \) can be expressed as

\[
P_{s,tvws} = P_{rendez} \cdot P_{dec, tvws}
\]

As shown in simulation results, the reachability is close to one even in low SNR regime. Therefore, \( P_{s,dsrc} \) can be expressed as

\[
P_{s,dsrc} = (1 - P_{s,tvws}) \cdot P_{r,dsrc}
\]

where \( P_{s,tvws} \) is the probability of ESM reception via ODRet, which will be derived in the following subsection.

C. Probability of ESM Reception via On-Demand DSRC Retransmission

As shown in Fig.6, the duration of ODRet consists of a deferring phase (\( \Delta \)), a jamming phase (\( T_{jam} \)), and a retransmission phase. Likewise, a retransmission phase can be divided into multiple DSRC time frames (\( T_{frame} \)). In each DSRC time frame, vehicles of reception failure have opportunities for receiving an ESM, and thus \( P_{r,dsrc} \) can be derived as follows

\[
P_{r,dsrc} = 1 - \prod_{k=1}^{n_{frame}} (1 - p_{s,dsrc}(k))
\]

where \( p_{s,dsrc}(k) \) is a probability of ESM reception in \( k^{th} \) DSRC time frame. \( n_{frame} \) is the number of DSRC time frames in a retransmission phase of ODRet (e.g., two in Fig.6) and is calculated as

\[
n_{frame} = \left\lceil \frac{D_{ESM} - t_{ref}^\text{tvws} - \epsilon - t_{esm}^\text{tvws} - \Delta - T_{jam}}{T_{frame}} \right\rceil
\]

where \( \lceil \cdot \rceil \) is a ceiling function.

As depicted in Fig.7, each DSRC time frame is composed of two stages: one for transmitting SOF and tone signals (stage 1) and the other for retransmitting an ESM (stage 2). In stage 1, vehicles transmit SOF and tone signals without CSMA/CA, and thus the length of stage 1 can be calculated as \( t_{SOF} + 2\epsilon + t_{tone} \). Here, \( t_{SOF} \) is a duration of a SOF signal; \( t_{tone} \)
is a duration of a DSRC tone signal; $\epsilon$ is a guard interval. In stage 2, a vehicle retransmits an ESM with CSMA/CA. Regarding the ESM retransmission, three events are defined: 1) backoff countdown, 2) a freeze of backoff timer, and 3) ESM transmission. For analytical tractability, we approximate that a stage 2 of $i^{th}$ DSRC time frame is divided into expected time slots with an equal length, $E[\text{slot}(i)]$ and all events happen in a boundary of the slot. $E[\text{slot}(i)]$ is obtained by

$$E[\text{slot}(i)] = T^{\text{esm}} \cdot \rho_{\text{busy}}(i) + \sigma \cdot (1 - \rho_{\text{busy}}(i)) \quad (6)$$

where $T^{\text{esm}}$ is a transmission delay of ESM and $\sigma$ is a unit backoff time, and $\rho_{\text{busy}}(i)$ is the probability that a channel is busy at the expected time slot of $i^{th}$ frame. Since channel is busy due to ESM transmissions, $\rho_{\text{busy}}(i)$ can be expressed as

$$\rho_{\text{busy}}(i) = 1 - (1 - \tau(i))^{n^{\text{esm}}_{\text{vec}}(i)} \quad (7)$$

where $\tau(i)$ is a transmission attempt probability in a time slot of $i^{th}$ frame and $n^{\text{esm}}_{\text{vec}}(i)$ is the number of vehicles that try to transmit an ESM at $i^{th}$ frame. Fortunately, [33] already derived a transmission attempt probability of IEEE 802.11 ($\frac{2}{1+CW}$). In our scheme, however, vehicles lose their transmission opportunities if they select backoff numbers larger than the number of slots in stage 2. Since vehicles select a backoff number between 0 and CW, $\tau(i)$ is calculated by

$$\tau(i) = \frac{2}{1 + CW} \cdot \frac{\min(m(i), CW)}{CW} \quad (8)$$

where $CW$ is a CW size that is used for retransmitting an ESM. $m(i)$ is the number of slots in stage 2 of $i^{th}$ frame and expressed as

$$m(i) = \left[\frac{T_{\text{frame}} - (t_{\text{SOF}} + 2\epsilon + t_{\text{tone}})}{E[\text{slot}(i)]}\right]$$

where $\lfloor \cdot \rfloor$ is a floor function.

In stage 2, vehicles can transmit an ESM if they hear a DSRC tone signal and have received the ESM. According to the second assumption, if vehicles are located within a DSRC transmission range (we call these vehicles DSRC neighbors) of a tone sender, they can hear the DSRC tone signal. Thus, $n^{\text{esm}}_{\text{vec}}(i)$ is calculated as

$$n^{\text{esm}}_{\text{vec}}(i) = 2 \cdot d_{\text{dsr}} \cdot \phi \cdot \left[1 - (1 - p^{\text{esm}}_{s,tvws}) \cdot \prod_{k=1}^{i-1} \left(1 - p^{\text{esm}}_{s,dsrc}(k)\right)\right] \quad (10)$$

As only DSRC neighbors of a DSRC tone sender can make collision at the sender, $h(i)$ is equal to $n^{\text{esm}}_{\text{vec}}(i) - c(i)$.

Equations (3)~(12) describe a non-linear system with unknowns $\tau(i)$ and $\rho_{\text{busy}}(i)$ ($i \leq n_{\text{frame}}, i \in N$). The non-linear system can be solved using numerical techniques, e.g., Newton method.

D. Model Validation

To validate our model, we compare the numerical results of the model with those of Qualnet simulation. We adopt simulation parameters in table.I. In the validation, we focus on whether the proposed model follows the pattern of ESM reachability according to two configurable parameters: 1) CW and 2) $T_{\text{frame}}$. This is because the purpose of proposing this model is to find the optimal system configurable parameters rather than to calculate actual system performance. In Fig.8, we observe that the model well-predicts the pattern according to the parameters and the deviation from simulation results is within 1 to 10%.

IV. DESIGN PARAMETER OPTIMIZATION

A. Problem Formulation

Most safety applications require high reachability of an ESM and delivery of the ESM within a delay bound. Thus, we formulate an optimization problem for maximizing reachability of the ESM with a delay bound constraint.

In order to maximize the reachability of an ESM, we need to find optimal values of two configurable parameters, 1) $T_{\text{frame}}$ and 2) CW size. Reachability of an ESM depends on the efficiency of a recovery algorithm, which is affected by $T_{\text{frame}}$ and CW size. More specifically, $T_{\text{frame}}$ determines the number of recovery sessions (i.e. $D_{\text{ESM}}/T_{\text{frame}}$) and the
efficiency of each recovery session, both of which are important in determining reachability of an ESM. In addition, CW size determines the level of network congestion and the number of ESM retransmission opportunities within each recovery, which affects the efficiency of each recovery session. Thus, we try to find these two configurable parameters in our optimization problem. The given conditions in an optimization formulation are TVWS channel error and vehicle density, which are measured periodically. In addition, a constraint in an optimization formulation is a delay bound of an ESM since the outdated ESM can be discarded. Hence, the optimization problem can be formulated by

\[
(CW, T_{frame}) = \arg\{CW, T_{frame}\}(\max(P_{s,total})
\]

\[
  CW \geq 1, T_{frame} < D_{ESM}
\]  

It is noted that we do not need to find optimal \(T_{frame}\)

23For example, small \(T_{frame}\) engenders a lot of recovery sessions. However, too small \(T_{frame}\) causes low efficiency of each recovery session since only small number of vehicles can send an ESM within a short \(T_{frame}\).

24When CW size is large, it reduces network congestion in a DSRC band, but backoff waiting time for each vehicle can be so long that some vehicles cannot access the channel within a recovery session.

25From periodic scan of TVWS channel, vehicles get background noise power and can infer the probability of TVWS channel error. In addition, vehicle density can be drawn from vehicle speed [29]. However, since measuring TVWS channel error and vehicle density are not main scope of our work, we do not explain further on measurements.

26Since these calculations are conducted before a system starts, the calculation time is not a problem.
V. PERFORMANCE EVALUATION

A. Simulation Setup

We use Qualnet [30] for performance evaluation. For investigating performance of the proposed scheme (section V-C,D, and E), we consider a highway area with two lanes where vehicles move in one direction. For comparing our scheme with previous works (section V-F), we consider 2X2 Manhattan grid with two lanes as well. For vehicle mobility, we use a car-following model that is developed by Gipps [31].

We summarize default simulation settings in table 1. As a MAC layer of DSRC and TVWS bands, we use a method of multiple access control that is employed in IEEE 802.11 DCF. In a PHY layer setting, we follow IEEE 802.11a except the data transmission rate for DSRC and TVWS bands. To reflect low permeability of signal in a DSRC band, we additionally consider 12 dB loss when there are obstacles between a sender and a receiver [3]. Each vehicle generates ESMs with random interval, which follows an exponential distribution with an average of 10 second.

B. Performance Metrics

In the simulation study, we use 1) reachability of ESM, 2) an efficiency of TWRA, and 3) a probability of decoding failure of incoming PBM or ESM signals in a DSRC band. In a DSRC band, as a decoding error is mainly caused by packet collision, the probability of decoding error can translate into how much the DSRC band means a probability of decoding failure of incoming PBM or ESM signals in a DSRC band. In a DSRC band, as a decoding error is mainly caused by packet collision, the probability of decoding error can translate into how much the DSRC band is congested. Using these metrics, we can see a correlation between a DSRC channel condition and QoS of ESM dissemination in the following simulation studies.

C. Impact of DSRC time frame

We analyze the performance of our scheme according to the ratio of delay bound of an ESM to the length of DSRC time frame ($D_{ESM}/T_{frame}$). In this study, we consider two situations: 1) when only ODRet is used and 2) when both ODRet and PTRet are used.

First, we focus on the case when only ODRet is considered. In Fig.10(a), we observe that the reachability of ESM increases as the ratio ($D_{ESM}/T_{frame}$) increases. From the equation 5 in section III-C, we notice that the ratio is almost equivalent to the number of DSRC time frames ($n_{frame}$). Thus, as the ratio increases, the vehicles that fail to receive an ESM have more opportunities to advertise their failures (i.e., more opportunities to send tone signal) and the vehicles that successfully receive the ESM have more chances to retransmit the ESM.

Sometimes, the increase of the ratio leads to the decrease of the reachability. We can observe this statement in Fig.10(a) when the ratio changes from 6 to 8. When the ratio is 8, DSRC time frame ($T_{frame}$) is so short that vehicles have few chances of retransmission within each DSRC frame. Thus, we need to find an optimal DSRC frame size for maximizing reachability of ESM.

We note that the network congestion increases as the ratio increases in Fig.10(b). However, in our scheme, a dominant factor that affects the reachability of ESM is not a network congestion but $n_{frame}$. This is because network load in a DSRC band is reduced during TWRA as exchanges of PBM are deferred. This conjecture is proved by Fig.10(c), which shows recovery efficiency grows along with the ratio.

Notably, Fig.10(d) shows that a growth in the ratio reduces the probability that an ESM cannot be transmitted within a delay bound. This is because the higher ratio implies that vehicles have more chances to retransmit the ESM at the earlier stage of ODRet. Thus, the increase in the ratio reduces the number of “at the last minute” retransmissions, which decreases the failure of ESM transmissions within a delay bound.

Second, when both ODRet and PTRet are considered, the reachability of ESM is close to one for all values of the ratio, as shown in Fig.10(a). This is because a retransmission in a TVWS band covers a large area, and thus many vehicles can be recovered from ESM reception failures.

D. Impact of Contention Window Size

In this subsection, we study the performance of our scheme according to the contention window size (CW) for ODRet. Similar to section V-C, we take two situations into account.

First, we take a look at the case when only ODRet is used. As shown in Fig.11(a), when a delay bound of ESM is 20ms (100ms), the reachability of ESM grows as a CW size increases until the CW size reaches 150 (250). This is
because the increase of CW size causes the sharp decrease of network congestion until the CW size reaches the crossover points (e.g., 150 (250) for 20ms (100ms) delay bound), as demonstrated in Fig.11(b). In addition, as shown in Fig.11(c), such a sharp decrease leads to a decrease in the probability that an ESM cannot be transmitted within a delay bound, which is another factor to determine the reachability pattern in this regime. However, Fig.11(a) shows that the reachability of ESM decreases as the CW size passes the crossover points. As depicted in Fig.11(b), the network congestion rarely decreases after these points, which means that the network congestion is no more a main factor that determines the reachability. Instead, vehicles have less opportunities to retransmit an ESM until the lifetime of the ESM expires, since their backoff waiting time becomes longer. This conjecture is proved by Fig.11(c), where the probability that an ESM is not transmitted within a delay bound increases after the crossover points.

Second, when both ODRet and PTRet are used, the reachability of ESM is close to one for all values of CW size, as shown in Fig.11(a). This implies that optimal configuration of the CW size is not necessary if both PTRet and ODRet are employed.

E. Impact of the Number of Vehicles

Similar to section V-C and V-D, we take two simulation settings into account. Since the performance of the second setting (i.e., both ODRet and PTRet are used) proves to be strikingly similar to what the previous subsections have suggested (i.e., the reachability of ESM is close to one for all values of the number of vehicles), we will mainly analyze performances of the first situation (when only ODRet is used).

In Fig.12(a), we observe that reachability of ESM increases as the number of vehicles increases. In addition, the network congestion increases as the number of vehicles grows, as depicted in Fig.12(b). In general, the network congestion reduces the reachability, and thus we can anticipate that the reachability of ESM must diminish as the number of vehicles increases. However, the pattern is different from our conjecture.

To find the reason for this pattern, we concentrate on the other factor: whether vehicles that have received an ESM are located around the vehicle of sending a DSRC tone signal. In detail, a vehicle cannot be recovered from ESM reception failure if there is no vehicle that responds to the DSRC tone signal. When the number of vehicle is small, it
is less probable that vehicles can respond to the DSRC tone signal. To prove this conjecture, we define a new performance metric ($P_{\text{ESMholder}}$) and obtain it during simulation. Here, $P_{\text{ESMholder}}$ is a probability that a vehicle detects an ESM signal after sending a DSRC tone signal. In Fig.12(c), we can see a dramatic increase in $P_{\text{ESMholder}}$ as the number of vehicle increases (by 3.5 times), however, the probability of decoding error is very low. This observation implies that the dominant factor that affects the reachability of ESM is not a network congestion but $P_{\text{ESMholder}}$. 

Fig. 11. (a) Reachability of ESM and (b) Probability of decoding error in a DSRC band, and (c) Probability that an ESM is not transmitted within a delay bound according to contention window size for ODRet when there are 50 vehicles.

Fig. 12. (a) Reachability of ESM, (b) Probability of decoding error in a DSRC band, and (c) Probability of neighbor vehicles responding to DSRC tone signal according to the number of vehicles.
This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

LIM et al.: INTERPLAY BETWEEN TVWS AND DSRC: OPTIMAL STRATEGY FOR SAFETY MESSAGE DISSEMINATION IN VANET

Fig. 13. Comparison of the proposed scheme with legacy DSRC system with dual interfaces and [17] in (a) highway and (b) 2X2 Manhattan grid.

F. Performance Improvement over legacy DSRC with dual radio interfaces and [17]

We compare our scheme with two previous works: 1) legacy DSRC system with two radio interfaces with two orthogonal channels28 and 2) clustering mechanism with cognitive channel management [17]. In this comparison, we consider two situations for our scheme: 1) when both ODRet and PTRet are adopted and optimal configuration is not used (“SCHEME 1”) and 2) when only ODRet is used and optimal configuration is employed (“SCHEME 2”).

Fig. 13(a) compares the reachability of ESM of our schemes with those of previous works in highway situation. In this figure, we found two key observations. First, the reachability in SCHEME 1 is almost the same with that in SCHEME 2, both of which are almost close to one. This observation implies that our schemes work well regardless of whether PTRet is used (i.e., there are TVWS channels other than originally sent channel). Second, both SCHEME 1 and 2 outperform the legacy DSRC system and [17]. Specifically, we observe that improvement over the legacy DSRC system and [17] are maximally 64% and 17%, respectively. This is because our scheme leverages the advantages of DSRC and TVWS bands for ESM dissemination, while the legacy DSRC system and [17] do not.

Fig. 13(b) demonstrates the reachability of ESM of our schemes and previous works in 2X2 Manhattan grid. Similar to Fig. 13(a), we find that the reachability in SCHEME 1 is similar to that in SCHEME 2, which is almost close to one. In addition, Fig. 13(b) shows that our schemes outperform the legacy DSRC system and [17] by 86% and 56%, respectively.

It is noted that the amount of improvement in Manhattan grid situation is larger than that in highway situation. This is caused by large clustering management overhead of [17] in Manhattan grid setting, which leads to performance degradation. More specifically, topology of vehicular network in Manhattan grid changes more frequently than highway situation. Such a frequent topology change induces more clustering management overhead. However, our scheme does not suffer from clustering management overhead, since our scheme is independent of a clustering algorithm and a centralized device during its operation. Thus, the reachability of ESM in our scheme is not affected by simulation environments.

We find an interesting point that reachability in our schemes remains above 95% both in a highway area and Manhattan grid. This is induced by our two key contributions: 1) smart usage of TVWS and DSRC bands and 2) robustness to dynamic topology changes. For this reason, the reachability of our scheme stays above 95% even if vehicle density varies both in highway and Manhattan grid settings. This implies that our system is appropriate for safety applications which require at least 95% reliability on every vehicle density. Moreover, we found that less than 5% of an ESM is not transmitted within a delay bound both in a highway area and Manhattan grid. However, we omit a graph due to page limitation.

We also note that as shown in Fig. 13, the reachability of ESM decreases by only 2~3% in both highway and Manhattan grid settings when each vehicle transmits 20kbps data traffic in a DSRC band. In the proposed system, vehicles exchange control messages via a DSRC band to share inputs for optimal configurations. Thus, the data traffic hinders sharing the inputs, which may lead to sub-optimal configurations. However, as shown in section V-C and V-D, the impact of sub-optimal configurations is small. Thus, the impact of data traffic on a reachability of ESM is negligible.29

G. Performance Evaluation outside Spectrum MAP Coverage

As mentioned in section II-F, vehicles may not find positions in their spectrum maps when changing their routes, leading to failure in getting available TV channels. In this case, vehicles must defer an ESM transmission until accessing a central TVWS database or re-entering the locations in the spectrum map. Such deferment may cause an ESM drop at the sender. To quantify such a drop, we define $P_{obs}^{esm}$ as a probability of discarding obsolete ESMs caused by the deferment.

Fig. 14(a) shows that $P_{obs}^{esm}$ is 2.8% (1.25%) when one (five) APs are deployed every kilometer. In this simulation, we set a

28In the legacy DSRC system, loads of PBM and ESM are equally divided into two interfaces

29The reachability of PBM decreases by 15.5% in the same situation. In general, the PBM does not include an emergency event but vehicle status info, thus, the PBM transmission does not require stringent delay and reliability requirements.
probability that drivers deviate from a route to 6.25%, which is a very conservative value [36]. Notably, $P_{\text{obs}}^{\text{esm}}$ when one AP is deployed is larger than when five APs are deployed. This is because as more APs are deployed, it is more probable that the vehicles can find APs and get recent available channels by contacting a TVWS channel database. Accordingly, in five APs, deferring ESMs happens less than in one AP, which reduces $P_{\text{obs}}^{\text{esm}}$.

To address the above-mentioned problem, we propose a hybrid scheme in section II-F. As shown in Fig. 14(a), the hybrid scheme can reduce $P_{\text{obs}}^{\text{esm}}$ down to zero. This is because each vehicle can update available channels with physical sensing, thereby acquiring available channels although no connections to a central TVWS database. Moreover, Fig. 14(b) demonstrates that the reachabilities of an ESM are above 93% in both highway and Manhattan grid settings.

**VI. CONCLUSION**

We proposed and analyzed a novel interplay scheme that leverages advantages of DSRC and TVWS bands in a distributed manner for supporting QoS of ESM dissemination. We first investigated the characteristics of DSRC and TVWS bands and then determined how to use each band efficiently.

To maximize the efficiency of the proposed scheme, we formulated an optimization problem where configurable parameters for a recovery algorithm are controlled. We established a new mathematical model on the reachability of ESM that considered delay bound of a safety message. The simulation results showed that the proposed scheme could support QoS of safety message dissemination under various vehicle scenarios.

**REFERENCES**


Jae-Han Lim received the B.S. degree in Electrical Engineering from Seoul National University (SNU), Seoul, Korea in 2004, and the M.S. degree in Electrical Engineering and Computer Science from SNU in 2006. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering at University of California, Los Angeles. From 2006 to 2009, he worked as a researcher in Electronics and Telecommunications Research Institute, Daejeon, Korea. His research interests are in the area of system design, analysis, modeling for wireless networks. He is a student member of the IEEE.

Wooseong Kim received his BS degree from the Department of Electrical Engineering, University of Seoul, Korea, in 2000. He received his MS and PhD degree from the Department of Computer Science, Korean Advanced Institute of Science and Technology, Korea, in 2004 and University of California, Los Angeles, U.S., in 2012. He was a researcher at the Research and Development Center of LG Electronics and Hyundai Motor until 2012. Since 2013, he has been a research director and 3GPP delegate in Samsung Electronics. His research interests include LTE, cognitive radio, cross-layer architecture, and vehicular communication.

Katsuhiro Naito received the B.S. degree in Electronics Engineering from Keio University, Japan in 1999, and received the M.S. and Ph.D. degrees in Information Engineering from Nagoya University, Japan in 2001 and 2004, respectively. He is currently an Assistant Professor in the Department of Electrical and Electronic Engineering at Mie University, Japan. From 2001 to 2004, he was a research fellow of the Japan Society for the Promotion of Science at Nagoya University, where he performed research on wireless Internet communication. He joined the faculty of Mie University in 2004. He was a visiting scholar at University of California, Los Angeles in 2011. His current research interests include wireless communication for Internet access systems, network mobility systems, Intelligent Transport Systems, and multi-hop networks.

Ji-Hoon Yun is currently an assistant professor in the Department of Electrical and Information Engineering, Seoul National University of Science and Technology (SeoulTech), Seoul, Korea. Before joining SeoulTech in March 2012, he was with the Department of Computer Software Engineering, Kumoh National Institute of Technology (KIT) as an assistant professor. He was a postdoctoral researcher in the Real-Time Computing Laboratory (RTCL) at The University of Michigan, Ann Arbor, U.S.A. in 2010 and a senior engineer at the Telecommunication Systems Division, Samsung Electronics, Suwon, Korea from 2007 to 2009. He received the B.S. degree in Electrical Engineering from Seoul National University (SNU), Seoul, Korea in 2000, and both the M.S. and Ph.D. degrees in Electrical Engineering and Computer Science from SNU in 2002 and 2007, respectively. His current research focuses on wireless networks and efficient computing of mobile devices.

Danijela Cabric received the Dipl.Ing. degree from the University of Belgrade, Serbia, in 1998, and the M.Sc. degree in electrical engineering from the University of California, Los Angeles, in 2001. She received her Ph.D. degree in electrical engineering from the University of California, Berkeley, in 2007, where she was a member of the Berkeley Wireless Research Center. In 2008, she joined the faculty of the Electrical Engineering Department at the University of California, Los Angeles as an Assistant Professor. Dr. Cabric received the Samueli Fellowship in 2008, the Okawa Foundation Research Grant in 2009, Hellman Fellowship in 2012 and the National Science Foundation Faculty Early Career Development (CAREER) Award in 2012. She serves as an Associate Editor in IEEE Journal on Selected Areas in Communications (Cognitive Radio series) and IEEE Communications Letters, and TPC Co-Chair of 8th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) 2013. Her research interests include cognitive radio systems and spectrum sensing, VLSI architectures of signal processing and digital communication algorithms, and their performance analysis and experiments on embedded system platforms.

Mario Gerla is a Professor in the Computer Science Department of University of California, Los Angeles. His research interests include the design, performance evaluation, and control of distributed communication systems and networks. His current research projects cover: design and performance evaluation of protocols and control schemes for Ad Hoc wireless networks; routing, congestion control and bandwidth allocation in wide area networks; and traffic measurements and characterization (see http://www.cs.ucla.edu/NRL for recent publications).