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

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Abstract—Vehicular safety system has been drawing considerable attention as a key application of Vehicular Ad-hoc NETworks (VANETs). In the safety system, there are two types of safety messages: Emergency Safety Messages (ESM) and Periodic Beacon Messages (PBM). The ESM has to be disseminated to vehicles within specified area and meet latency and delivery ratio requirements, while the PBM is transmitted periodically with vehicle information such as position, speed, and direction. For vehicular communications, Dedicated Short-Range Communication (DSRC), the de facto standard, has normally been used. However, the one-hop transmission range of the DSRC is so short that a multi-hop dissemination is required in order to cover a large dissemination area of ESM. The multi-hop dissemination with the limited number of DSRC channels induces channel collision and network congestion. Moreover, the coexistence with PBMs aggravates collision and congestion of DSRC channels, which makes 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 as a control channel for TV channel rendezvous. In this paper, we propose and analyze a distributed channel usage scheme between DSRC and TVWS bands for quality of service (QoS) of ESM disseminations under the existence of PBMs. Our scheme employs TVWS Channel Rendezvous Algorithm (TCRA) that is based on available TVWS channel map, 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 On-Demand Recovery Algorithm (ODRA) that uses a DSRC band for an ESM retransmission to reception failure vehicles. Through an in-depth simulation study, we show that the proposed scheme satisfies ESM requirements of latency and delivery ratio, and outperforms legacy DSRC systems with two interfaces under various vehicle speeds in highway area.

I. INTRODUCTION

As 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”. Conventional safety systems are standalone systems using sensors, but with the spread of wireless technologies they are evolving into inter-vehicle cooperative safety systems.

In the new approach for 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 (VANETs). ESM has to be disseminated to vehicles within a dissemination area and meet latency and delivery ratio requirements. The other type of message in VANET, Periodic Beacon Message (PBM) is transmitted to advertise its status information, e.g. position, speed, and direction.

The dominant standard for vehicular communications is a Dedicated Short-Range Communications (DSRC) [2], which uses 5.9GHz licensed band allocated by the Federal Communication Commission (FCC). In a DSRC band, however, a signal that is transmitted to faraway vehicles can be distorted by blocking and fading effect since the signal cannot pass through large-size obstacles, e.g. truck or bus. In other words, the effective transmission range of a DSRC protocol is short. For example, experimental study in [13] 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). Hence, a multi-hop transmission is necessary to support various safety applications with a required dissemination range of 300m and low delay bound (≤ 100ms) [8] [14].

It is well known that such a multi-hop dissemination causes contention and collisions, which are often associated with the broadcast storm problem [3]. The broadcast storm problem becomes more serious when many messages are generated by multiple sources. In VANET, unfortunately, all vehicles generate Periodic Beacon Messages (PBM) periodically to exchange the operating conditions of each vehicle such as position, speed, and direction. Such a periodic generation of PBMs can result in a broadcast storm problem in VANET. Hence, in the DSRC protocol, it is hard to satisfy the QoS requirements of the ESM dissemination in congested traffic situations (e.g. traffic jams on highways) [4] [5].

In order to overcome the limitation of the DSRC protocol, we propose to adopt a protocol with a large one-hop transmission range. For instance, Wi-Fi using a TV white space (TVWS) band enables the ESM to reach the dissemination area of the ESM by a single hop transmission [6]. Recently, the FCC allows unlicensed users to access the TVWS band if they do not disturb the services of licensed users [7]. Thus, vehicles can use the TVWS bands opportunistically based on spectrum availability data on each geo location, which was measured in advance [7].

In order to protect primary user services, secondary users must follow the channelization that primary users follow in a TVWS band. However, all the TVWS channels are not always available to unlicensed users due to primary user activity. This results in heterogeneity of available TVWS channels for each vehicle. Thus, rendezvous procedure is required in order to gather all vehicles in the same TVWS channel. Such a rendezvous procedure requires allocation of a common control channel that needs to be always available to vehicles. To this end, we exploits a DSRC band as a common control channel for TVWS channel rendezvous.

There have been previous approaches that aimed at satisfying QoS requirements using a DSRC band with single interface in

1Emergency events can happen under high vehicle density such as appearance of fire engine, malfunctioning of brake system, and airbag explosion
VANET. [22] [23] proposed prioritized channel access mechanisms by tuning DSRC configuration parameters [22] or channel access parameters like EDCA [23]. However, [22] [23] still do not satisfy QoS requirements especially in high network traffic condition, which was shown in the simulation studies of DSRC operation [4]. Many schemes that use multiple interfaces have been proposed aimed at satisfying QoS requirements in VANET. [10] proposed a multi-channel MAC system that is equipped with two interfaces for QoS provisioning. [11] proposed cognitive network system that has two network interfaces, one for an exclusive usage band such as a DSRC band and the other for a cognitive usage band like a cellular band. However, [10] [11] are based on clustering mechanism which causes large overhead when topology is changed frequently like VANET.

In this paper, we propose and analyze a distributed channel usage scheme between TVWS and DSRC bands for the ESM dissemination with two network interfaces. For the goal of supporting QoS of ESM dissemination, we investigate the characteristics of two bands and then determine how to use each band efficiently in a fully distributed manner. Moreover, we analyze the proposed scheme via simulations in various vehicle scenarios.

When a vehicle generates an ESM, the vehicle checks the available TVWS channels using TVWS channel database, and then disseminate an ESM in one TVWS channel. However, due to heterogeneity of available TVWS channels over location and a lack of centralized coordination of the proposed scheme, it is difficult for vehicles to expect the TVWS channel and the time that ESM is transmitted without an additional mechanism. To overcome this challenge, our scheme employs TVWS Channel Rendezvous Algorithm (TCRA) that uses a DSRC channel for exchanging available TVWS channel information among vehicles.

However, the ESM signal in a TVWS band can be distorted so severely from path-loss, fading and blocking that some vehicles in dissemination area fail in decoding ESM signal. To compensate the decoding error, our scheme adopts an On-Demand Recovery Algorithm (ODRA) that the ESM is further transmitted by neighbor vehicles using a DSRC band only after the neighbor vehicles listen to a recovery request. The transmission by DSRC neighbors in a DSRC band is efficient in decoding an ESM, since line of sight (LOS) between a sender and a receiver can be guaranteed with high probability.

Intensive simulation studies show that our scheme outperforms previous DSRC systems with two interfaces by 20~125% in delivery ratio of ESM under various speed scenarios. Further, through optimal parameter selection, our system supports high delivery ratio of ESM with delay bound constraints under various vehicle scenarios.

In summary, the contributions of this paper are as follows:

- Propose a novel interplay scheme between TVWS and DSRC bands, which exploits advantages of each band for the ESM dissemination.
- Analyze the performance of the proposed scheme.

To the best of our knowledge, this is the first attempt to propose an interplay scheme between TVWS and DSRC bands for the ESM dissemination.

The remainder of this paper is organized as follows. In section 2, we explain system model. In section 3, we explain characteristics of DSRC and TVWS band and propose a novel scheme for efficient ESM dissemination using interplay between DSRC and TVWS bands. In section 4, we evaluate the proposed scheme. This paper is concluded in section 5.

II. SYSTEM MODEL

A. Network Components

Similar to previous works [10] [11], 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 [2] on a DSRC interface and IEEE 802.11 with 5MHz option [12] on a TVWS interface. Hence, the transmission rate of a TVWS interface is half of the interface for a DSRC channel in which bandwidth of single channel is 10MHz. In a TVWS band, we define that the TV broadcasting towers are the primary users and vehicles are secondary users. We consider scenario where other unlicensed users are rarely found, e.g., highway scenario with many junctions. In this scenario, even if signal from other unlicensed users is found, the signal might be weak due to power limitation in a TVWS band and their locations. Therefore, the interference from other unlicensed users may not degrade the performance of the proposed scheme. According to [7], the secondary users can access available TVWS channels using a "TVWS channel database" when a user has Global Positioning System (GPS) equipment. The database specifies available TVWS channels and maximum transmission power for the secondary user according to position. Since it is generally assumed that every vehicle has GPS, every vehicle knows available TVWS channels in its current position using the TVWS channel database. Channel availability in the TVWS channel database is semi-stationary over driving time since the availability of each TV channel is rarely changed within driving time in the same position; broadcasting tower continuously broadcasts signal during TV broadcast hours. Therefore, each vehicle knows the available TV channels by searching in a preloaded TVWS channel database during its driving.

B. Message Types

In vehicular networks, two types of messages: periodic beacon message (PBM) and emergency safety message (ESM), are generally considered. PBM is transmitted periodically to exchange vehicle status information among vehicles, such as position, speed and acceleration. ESM is transmitted only when an emergency situation happens, e.g., car accidents that threat a driver’s safety and emergency vehicles like fire engine and police cars. One example of the ESM is “intersection collision warning”, which should be disseminated within 300m range in a real-time manner (??100ms) [8]. In general, the ESM should have a higher priority with low delay bound than the PBM.

In the proposed system, PBM is transmitted periodically on a DSRC channel to exchange vehicle status information. Additionally, we utilize PBM to exchange an available TVWS channel list. In our system, the main object of exchanging PBMs is to make rendezvous at the same TVWS channel among vehicles within the dissemination area of ESM. Thus, PBM must be disseminated within the same dissemination area to that of ESM with best effort. Since we do not aim at proposing most efficient dissemination mechanism, we employ a simple but generally used mechanism.
like probabilistic flooding [3]\(^5\). 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 a dissemination of the ESM in the network [9].\(^6\)

III. INTERPLAY BETWEEN TVWS BAND AND DSRC BAND

A. Characteristics of DSRC and TVWS bands

One-hop transmission range of a DSRC band is short due to operation in high frequency band [13] [14]. Due to the short transmission range, the DSRC band has high channel resiliency. However, one-hop transmission range of the DSRC band is not large enough to reach simultaneously all vehicles in a dissemination area [13] [14]. Therefore, a multi-hop transmission is necessary to cover all vehicles in the dissemination area. The larger a dissemination area of safety application grows, the more number of hops is necessary, which increases the end-to-end delay. Moreover, as the amount of network traffic increases (i.e. periodic beacon messages by all vehicles), the probability of packet collisions increases, i.e., broadcast storm problem [3] which further increases average delay and reduces reachability. Here, the reachability is defined as the ratio of the number of received vehicles to the number of vehicles within a dissemination area.

On the other hand, the one-hop transmission range of a TVWS band is larger than that of IEEE 802.11 in 2.4GHz by 3 times [6]. Thus, a large one-hop transmission range of TVWS band makes it possible to cover all vehicles within a dissemination area of most safety applications [6] [8].

However, a TVWS band is not always available to vehicles since vehicles are secondary users that can opportunistically access TVWS band in absence of activity of TV tower. When we search available TVWS channels for portable devices in [15], we can find only 2~3 available channels with transmission power 40mW (16dbm) in Los Angeles. Even more, available channels are different according to location, since the protected service contour of each TVWS channel is determined by the position of a TV broadcasting tower and TV operation hour. Here, "protected service contour" is the area where the receivers of TV signal should be protected from secondary user. Therefore, we have to make channel rendezvous algorithm in a TVWS band.

On the other hand, as a DSRC band is dedicated to vehicular communication, it is always available to vehicles. Hence, the DSRC band can be used for a control channel, where TVWS channel availability and network status information, i.e. position, speed and configurable parameters of probabilistic flooding, can be exchanged.

B. Overview of the Proposed System

In normal situations, PBM is propagated periodically using a DSRC interface to let vehicles within a service range know vehicle conditions. When an emergency situation happens, ESM is generated and disseminated to the vehicles within a dissemination 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 in a dissemination area. Even if a TVWS band is appropriate for an ESM dissemination, some vehicles have not received ESM in a TVWS interface. To remedy reception error of ESM in a TVWS interface, our system employs a recovery algorithm for ESM reception error.

PBM is generated periodically by multiple vehicles and disseminated within a dissemination area. Hence, PBM is transmitted by an interface for DSRC channel which is always available to vehicles and has large bandwidth. On the other hand, ESM is generated infrequently by a specific vehicle and required to be disseminated within a dissemination area with stringent delay and reliability requirements. However, it is difficult to satisfy strict requirements of ESM in a DSRC channel, since the channel is already crowded by multiple PBM disseminations. Furthermore, multi-hop communication caused by short transmission range makes the latency of ESM longer. Therefore, we use a TVWS interface for disseminating ESM in our system.

Vehicles should find available TVWS channels among set of multiple TVWS channels. In order to find available TVWS channels, each vehicle downloads TVWS channel database before driving and searches available TVWS channels during its driving. However, a channel rendezvous algorithm in a TVWS band is necessary since available TV channels are different according to the position of a vehicle. For the channel rendezvous, vehicles within the same dissemination area exchange control data. For this purpose, common control channel which is always available to all vehicles is necessary. Therefore, we use a DSRC channel to exchange control data for channel rendezvous algorithm. The detail on rendezvous algorithm is in following subsection.

However, we do not guarantee the successful decoding of ESM even if rendezvous among vehicles is successful in the available TV channel. This is because 1) vehicles may suffer from interference by TV towers; 2) scattering and multi-path effect may happen since line-of-sight (LOS) is not guaranteed between a sender and a receiver; and 3) the transmission power of the vehicle in the TVWS band is limited to protect TV receivers in the protected service contour [7].

To compensate a reception error of the ESM in a TVWS interface, we use a DSRC interface for the retransmission of ESM for three reasons. At first, TVWS channel condition is rarely changed within a lifetime of ESM since there is a small vehicle position change (around 1.7m if the lifetime is 100ms and vehicle speed is 60km/h) and infinitesimal change of TV broadcasting tower operation. Hence, ESM reception error by 1) and 3) cannot be solved using retransmission in TVWS channel. Secondly, it is hard to guarantee LOS if the distance between a sender and receivers is large. For example, large-sized vehicles may exist between sender and receivers and hinders the LOS guarantee. However, we use a single-hop transmission for an ESM dissemination to reach distant vehicles in a TVWS interface. Thus, ESM reception error by 2) cannot be solved. However, if the ESM is retransmitted by close neighbor vehicles with a DSRC interface, it is more probable to guarantee LOS between a sender and a receiver. Moreover, a short transmission range is beneficial since concurrent ESM retransmissions by multiple vehicles are possible owing to channel reusability. Finally, retransmission of the ESM in a TVWS interface cannot solve ESM reception errors caused by rendezvous failure. If the vehicle tunes its TVWS interface to different channel from that of ESM initiator, the vehicle is unable to realize the ESM reception error. However, if the ESM
is retransmitted in a DSRC interface, the vehicles of rendezvous failure can be compensated by overhearing the ESM that is resent in a DSRC interface.

C. Rendezvous Algorithm among multiple TVWS channels

Since our system is a fully 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 the TVWS channel of transmitted ESM among multiple TVWS channels. In order to overcome this challenge, vehicles scan all the available TVWS channels within their dissemination area periodically. All the available TVWS channels within a dissemination area can be found by exchanging position information and searching available channels in TVWS channel database, as depicted in Fig.1. Since a vehicle scans all the available channels periodically, the vehicle can detect a signal transmitted by another vehicle within its dissemination range. Vehicles can exchange their position information using PBM and a DSRC interface. This approach is supported by the current standard of Society of Automotive Engineers (SAE), where position field is specified in the message structure of PBM [16].

Time domain challenge is that vehicles must know when ESM is transmitted in a TVWS channel. To remedy this problem, we divide TVWS interface operation time into two phases: 1) pre-ESM phase and 2) ESM phase. In pre-ESM phase, a sending vehicle advertises its transmission attempt of ESM by sending reference tone signal in a transmission channel. Here, the reference tone signal is simple on-off keying waveform with a purpose of letting vehicles know the existence of an ESM transmission attempt. The duration of reference tone signal should be long enough to cover maximum scan period of vehicles within a dissemination area. Vehicles within a service range of transmitted ESM can detect reference signal since they scan all the available TVWS channels of sending vehicle periodically. In ESM phase, the sending vehicle transmits ESM in the same channel with reference tone signal. Target vehicles tune their TVWS interfaces to the detected TVWS channel and receive ESM.

We should note that a detected signal in a TVWS band can be from reference signal by vehicles or from signals by TV broadcast towers. Hence, a vehicle should know whether the detected signal is from reference signal by vehicles or from TV broadcasting. For this purpose, a vehicle checks the gradient of signal power instead of checking just absolute signal power. Since TV broadcasting signal is continuously transmitted during its broadcasting hours, the variance of detected signal power is small within a period of scanning unless the signal is transmitted by vehicles. However, if reference signal is transmitted by vehicle, the detected power increases abruptly. Therefore, regardless of signal power of TV tower, vehicles can detect reference signal by checking gradient of detected power, as depicted in Fig.2.

One may insist that TCRA is possible by querying all available positions within a dissemination area to a database and obtaining all available TVWS channels. However, such a brute-force search has two issues. First, required time and computation resource might be too large to work in a real-time manner. Second, the number of channels that are obtained from brute-force search can be too large that the reference signal must be long, which in turn leads to failure in meeting the delay requirements of ESM. These two problems become worse as the required dissemination range is larger and larger. However, our system narrows down the required positions for a database search by exchanging PBMs. Since PBMs are typically exchanged in VANETs, additional overhead is not necessary while the performance is better. Therefore, in this work, we just consider the method that uses PBM exchanges.

Considering solutions for two-domain challenges, we propose

8The maximum scan period can be derived by number of available channels multiplied by duration of energy detection. In practical situation, the number of available channels is much less than total number of TVWS channels. For example, the maximum number of available channels among all cities is 30 [25]. Moreover, the duration of energy detection is 80us in TVWS band [17]. Therefore, the maximum duration of reference tone signal is less than 2.4ms, which is much shorter than delay bound of ESM (100ms).

9In TCRA, each vehicle might scan unavailable TVWS channels in TVWS database as well. For example, as depicted in Fig.1, STA 2 scans channels 1~7 including its unavailable channels 1, 3, and 5. In unavailable channels, interference by TV broadcasting tower is not trivial, thus a vehicle might enter ESM phase just by sensing TV signal.

10As a future work, we leave an advanced method that solves two problems of the brute-force search. In the advanced method, PBM errors will not degrade TVWS channel rendezvous.
TVWS Channel Rendezvous Algorithm (TCRA) whose procedure is as follows.

**Step 1 (pre-ESM phase):** Once vehicles know all available TVWS channels within its dissemination area, the vehicles scan all the available TVWS channels using energy detection continuously.

**Step 2 (pre-ESM phase):** *(Receiver side)* If the gradient of detected power is above the threshold in current scanned channel, the vehicle stops scanning and sets its TVWS channel to the current scanned channel. *(Transmitter side)* If ESM is generated, the vehicle stops scan process and sets its channel to its optimal transmission channel. Then, send reference tone signal.

**Step 3 (ESM phase):** *(Receiver side)* The receiver vehicles wait until reference signal is ended. Then, the vehicles receive ESM. *(Transmitter side)* The transmitter vehicle sends ESM in an optimal transmission TVWS channel.

### D. Recovery of ESM Reception Error in TVWS band

We propose On-Demand Recovery Algorithm (ODRA) to compensate the decoding error of ESM that is transmitted using a TVWS interface. The ODRA must be a solution to the following challenges: 1) it must compensate a failure of ESM reception from decoding error and rendezvous error; and 2) it must retransmit ESM within a short time in congested DSRC channel.

To compensate a failure of ESM reception errors, a recovery algorithm should support detection of ESM decoding error and TVWS rendezvous error. Vehicle can know ESM decoding error by detecting signal but decoding failure in a TVWS interface. However, it is difficult to detect TVWS rendezvous error since there is no indication of rendezvous failure. Thus, ESM reception failure by TVWS rendezvous error can be compensated in an indirect way, i.e. overhearing ESM retransmission by other vehicles in a DSRC interface. Once ESM decoding error is detected, the vehicle initiates recovery process by broadcasting NACK to vehicles within DSRC one-hop transmission range (we call these vehicles ”DSRC neighbor”) in a DSRC interface. The reason of broadcasting NACK is that a vehicle which fails in decoding ESM does not know which vehicles successfully receives ESM. In the NACK, there are information on the TVWS channel and the time that decoding failure happens. DSRC neighbors check if they already received the ESM that matches reception time and TV channel in NACK. If the DSRC neighbors found the ESM in their receiving buffer, they send the ESM to a NACK sender in a DSRC interface by unicast, which leads to reliable transmission of ESM.

11In our scheme, TVWS rendezvous error is insignificant. In practical situation, vehicles located in close distance tend to share the available TV channels. Hence, a vehicle can make a full list of available channels within its dissemination area despite a few transmission PBM errors.

12Time synchronization among vehicles can be realized using GPS.

For a NACK and a ESM transmissions, CSMA/CA is used. This is because a DSRC channel is already overloaded by PBM disseminations. However, NACK and ESM should be transmitted with higher priority, since ESM should be received within a short time.

Considering above-mentioned solutions, we propose recovery algorithm whose procedure is as follows:

**Step 1:** Vehicles which detects signal but fails in decoding signal in TVWS band, broadcast a NACK in a DSRC channel.

**Step 2:** Among DSRC neighbors, vehicles which already receive ESM in the same TVWS channel send ESM to a NACK sender in a DSRC channel.

**Step 3:** If NACK sender successfully receives ESM, the NACK sender responds with ACK in a DSRC channel.

### IV. Performance Evaluation

#### A. Simulation Setup

We use Qualnet [19] for performance evaluation. For a simulation topology, we consider highway area with two lanes where car moves in one direction. For vehicle mobility, we use the car-following model which is implemented in Simulator for Urban Mobility (SUMO) [20]. In order to apply the car-following model to Qualnet, we generate mobility trace file in highway using SUMO and convert the output of SUMO into Qualnet mobility trace file using VERGILIUS [21].

In MAC layer setting, we adopt multiple access control scheme from IEEE 802.11 DCF for a DSRC interface and a TVWS interface. In PHY layer setting, we follow IEEE 802.11a except the data transmission rate for a DSRC interface and a TVWS interface. Specifically, the data rates are 3Mbps and 1.5Mbps for a DSRC interface and a TVWS interface, respectively. Each vehicle generates ESMs at random time, and its generation interval per vehicle is 1 second in average. The delay bound of ESM is 100 ms and the dissemination range of ESM is within a circle of 300m radius from an initiator. PBM is generated by each vehicle every 100ms and the dissemination range is same with that of ESM. The simulation settings can be shown in table 1.

#### B. Performance Metrics

In the simulation study, we use 1) reachability of ESM, 2) an efficiency of ODRA, and 3) a probability of decoding error in a DSRC interface as performance metrics. An efficiency of ODRA is defined as a ratio of the number of vehicles which receive ESM in ODRA to the number of vehicles which do not receive ESM in a TVWS band within a dissemination area. A probability

### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate of DSRC interface</td>
<td>3Mbps</td>
</tr>
<tr>
<td>Data rate of TVWS interface</td>
<td>1.5Mbps</td>
</tr>
<tr>
<td>Tx range of DSRC interface</td>
<td>150m</td>
</tr>
<tr>
<td>Tx range of TVWS interface</td>
<td>450m</td>
</tr>
<tr>
<td>Radius of dissemination area</td>
<td>300m</td>
</tr>
<tr>
<td>PBM Interval</td>
<td>100ms</td>
</tr>
<tr>
<td>Average ESM interval</td>
<td>1s</td>
</tr>
</tbody>
</table>

13In commute time, many vehicles moves in one direction while we rarely find vehicles in other directions.

14Even if an emergency event may happen with long interval, the average interval in each vehicle can be small since multiple vehicles generate the same ESM for the same emergency event.
of decoding error in a DSRC interface means a probability of decoding failure of incoming PBM or ESM signals in a DSRC interface. In a DSRC interface, a decoding error is mainly caused by packet collision. Hence, we can regard the probability of decoding error as how much a DSRC channel is congested.

Using these metrics, we can see correlation between a DSRC channel condition and QoS of ESM dissemination. Moreover, we can see that our scheme outperforms the legacy DSRC systems with two radio interfaces.

C. Impact of PBM load

![Fig. 4. Probability of decoding error in a DSRC band according to maximum hop count of PBM when vehicle speeds are 10m/s and 30m/s](image)

As can be seen in Fig.4, the probability of decoding error in a DSRC band is increasing as the maximum hop count of PBM is increasing. This is because large traffic load results in high congestion in wireless networks. However, the slope is decreasing as the maximum hop count of PBM is increasing. This is because each vehicle does not relay an incoming message when they already have the same message. Hence, the number of transmission at each hop will be decreased as the number of hop is increased, which explains the tendency of decreasing slope in Fig.4. Moreover, we observe that the probability of decoding error of '30m/s' speed is smaller than that of '10m/s' speed. Since 'car following model' is used in our simulation, a low speed results in high vehicle density. Hence, a wireless network becomes more congested.

Since ODRA operates in a DSRC band, the efficiency of ODRA depends on the congestion in a DSRC band. Hence, the efficiency of ODRA is decreasing as the maximum hop count of PBM is increasing, which is shown in Fig.5.

Here, it is noted that the efficiency of ODRA is increased as maximum hop count is changed from one to two. This is mainly because a rendezvous probability drops sharply when the maximum hop count of PBM decreases below a threshold which is equal to 'dissemination range/transmission range of DSRC'. Since PBM cannot reach all vehicles in a dissemination range with one-hop transmission, there are many vehicles which cannot receive ESM due to rendezvous failure. However, when a maximum hop count of PBM is two, PBM can reach most of vehicles in dissemination area, which results in high rendezvous probability. Hence, the efficiency of ODRA at maximum hop count '1' is smaller than that at '2', even if the congestion in DSRC is decreasing.

D. Impact of vehicle speed

![Fig. 6. Probability of decoding error in a DSRC band according to vehicle speed when max hop count for PBM are 1 and 3](image)

The probability of decoding error in a DSRC band is decreasing as the vehicle speed is increasing, which is shown in Fig.6. Due to usage of a car following model in the simulation, higher vehicle speed results in lower vehicle density, which in turn, leads to lower level of congestion in a DSRC band. Moreover, we observe that the probability of decoding error at maximum hop count '3' is higher than that at '1'. This is because the level of congestion in a DSRC band is higher at '3' than '1' due to larger traffic load caused by PBM dissemination.

In Fig.7, we observe that the reachability of ESM grows as the vehicle speed is increasing. As we can see in Fig.6, higher vehicle speed causes the lower probability of decoding error in a DSRC band, which in turn, increases the efficiency of ODRA. Thus, we
can know that the reachability of ESM gets larger as the vehicle speed increases.

It is noted that reachability of ESM at maximum hop count ‘1’ is less than 90% when the vehicle speed is lower than 30m/s. Especially, when the vehicle speed is 10m/s, the reachability of ESM is around 75%, which is not appropriate for safety applications. From this observation, we find that careful selection of maximum hop count is necessary, which is done through optimization process in our scheme.

E. Performance Improvement over legacy DSRC with dual radio interfaces

As is shown in Fig.8, the proposed scheme with optimal configuration parameters\(^{15}\) outperforms the legacy DSRC systems with two network interfaces with two orthogonal channels. The legacy DSRC systems have two different settings 1) ‘mixed usage’ setting and 2) ‘separate usage’ setting. In the mixed usage setting, loads of PBM and ESM are equally divided into two interfaces. In the separate usage setting, one interface is dedicated for PBM dissemination and the other interface is for ESM dissemination.

As can be seen in Fig.8, improvement over a legacy system with ‘mixed usage setting’ is maximally 125% and decreases as the vehicle speed increases. When we compare the proposed system with legacy system with ‘separate usage setting’, improvement is maximally 60% and decreases as the vehicle speed increases.

We can find an interesting point that the reachability of ESM of proposed system remains above 90% as the vehicle speed is changed. This is because our system avoids DSRC congestion by jumping to a TVWS band for an ESM dissemination. Moreover, low connectivity due to high speed does not degrade the performance of the proposed system since transmission range in a TVWS interface is large enough to cover topology change from high vehicle speed. For this reason, the reachability of our scheme remains above 90% even if vehicle speed varies. The result in Fig.8 implies that our system is appropriate for safety application which requires at least 90% reliability on every vehicle speed.

Moreover, we have to know that our system only requires frequency change of front-end device and 802.11 option setting (5MHz mode), which can be realized by register settings or using Software Defined Radio [18] [24]. This means that implementation cost of our system is not increased much over legacy DSRC systems with dual interfaces. However, performance of the proposed system improves significantly over legacy DSRC systems with dual interfaces.

V. CONCLUSION

We proposed and analyze a novel cooperative channel usage scheme between DSRC and TVWS bands for supporting QoS of safety message dissemination in a fully distributed way. We first investigated the characteristics of DSRC and TVWS bands and then proposed an interplay scheme between two bands that can fully exploit advantages of two bands. The simulation results show that the proposed scheme can support QoS of safety message dissemination in both high speed and low speed regimes.

REFERENCES