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Cognitive Radio Network (CRN) System for Vehicle Safety Applications

A dissertation submitted in partial satisfaction
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by

Jae Han Lim

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Abstract of the Dissertation

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Professor Danijela Cabric, Co-chair

Professor Mario Gerla, Co-chair

As the number of vehicle accidents increases, car manufacturers and academic researchers have developed a vehicular safety system. The key component of the safety system is vehicular communications, by which vehicles exchange their local status information with neighbor vehicles and disseminate a warning message within a specified area. The challenge lies in satisfying stringent communication requirements of the safety system, extremely reliable packet delivery and low communication latency. Unfortunately, the current de-facto standard for vehicular communications, Dedicated Short-Range Communication (DSRC) cannot meet the requirements especially in high vehicle density. Specifically, high operation frequency of the DSRC causes serious signal attenuation in Non Line-Of-Sight (NLOS) conditions and the frequent exchanges of vehicle status information make the network easily congested.

To overcome this challenge, we exploit extra TV White Space (TVWS), which Federal Communications Commission (FCC) allowed unlicensed users to access in the absence of license user's activities. The use of extra TVWS helps to improve the safety system because 1) adoption of extra frequency resource can mitigate the network congestion and 2) the excellent TVWS signal propagation improves

the reachability of the safety message dissemination. Thus, in this doctoral dissertation, we design and evaluate TVWS-based Cognitive Radio Network (CRN) systems as a solution for realizing the vehicular safety system. First, we evaluate various vehicular MAC protocols using network simulator (NS-2) and investigate whether the MAC protocols are feasible to the vehicular safety system when only using a frequency band allocated to the DSRC (i.e., DSRC band). Next, we propose a TVWS-based CRN system that is specialized for the safety message dissemination in the safety system. More specifically, we utilize an extra TVWS band for emergency safety message dissemination, and exploit a DSRC band for 1) the exchange of control data and 2) the compensation of the reception errors. Finally, we propose a TVWS-based CRN system that supports reliable safety message dissemination in a NLOS corner. Specifically, for reliable dissemination in the NLOS corner, the proposed system leverages the excellent propagation characteristics of a TVWS signal and further improves the reliability by adopting a novel retransmission mechanism. Through in-depth simulation studies, we show that the proposed system outperforms previous system designs and supports the safety systems well.

The dissertation of Jae Han Lim is approved.

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CHAPTER 1

Introduction

1.1 Background

1.1.1 Vehicular Safety System

As the number of vehicles increases, the vehicle accidents also grow, which can result in the death of a driver and induce huge amount of economic costs. In the United States, 33,561 people were killed and 2,362,000 people were injured from vehicular accidents in 2012 [1]. The estimated economic cost from the police-reported motor vehicle accidents is about $230 billion. The situations in Europe are very similar to those in the United States. Specifically, 43,000 people are killed and around 1,800,000 people are injured every year. The estimated economic cost is around 160 billion Euro [2].

In an attempt to reduce the accidents, many academic researchers and car manufacturers have developed safety systems that informed drivers of the possibility of accident before it happened. The previous safety systems do not exploit communication among vehicles. Researchers at Kansas University proposed a system that employed warning flashers to inform drivers of the possibility of crash in one-lane, two-way highway work zone [4]. However, it is difficult for the drivers to recognize flasher sign in daytime. In addition, if the area of work zone is very large, the drivers may not recognize the flasher sign. In addition to [4], many methods have been used to inform drivers of possibility of collisions in work zone, such as Variable Sign Message (VMS) and flagging [4]. However, the drivers might

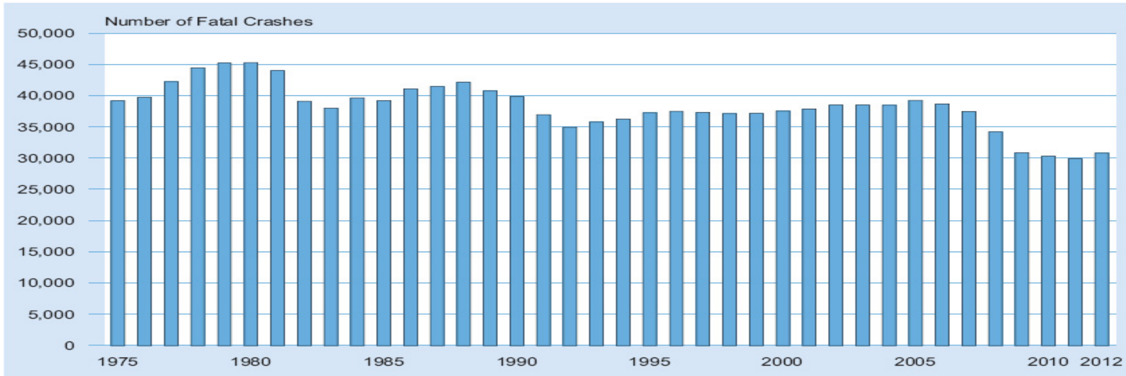


Figure 1.1: Statistics on fatal crashes in United States from 1975 to 2012

not recognize VMS signal when it is rainy. In case of flagging, flaggers are very dangerous when heavy vehicles (e.g. trucks) are approaching work zone with high speed. In addition, it is hard for drivers to recognize flaggers in night time. According to survey in [5], truck drivers answered that they rarely recognized flaggers in night time and were confused in the direction of the flagger.

The previous safety systems have several limitations in that the performance of sensors are affected by weathers and the range for recognizing the warning is limited. To meet this challenge, [6] proposed a safety system that exploited various types of devices and wireless communications for reducing collisions in intersection. The proposed system consists of 1) infra-structured sensors, 2) road-side relays, and 3) a local server. More specifically, the infra-structured sensors are deployed in the road for detecting positions and velocities of vehicles; and they deliver the sensing results to the road-side relays via wireless communications. Then, the road-side relays deliver the received sensing results to the local server. The local server determines whether or not there is possibility of collision from the received sensing results, and broadcast the warning message if finding the possibility of collisions.

1.1.2 Vehicular Ad-hoc NETwork

Vehicular Ad-hoc NETwork (VANET) is an emerging technology and has gained a lot of interest from industry and academic researchers. In VANET, vehicles and Road Side Units (RSU) cooperate to support several applications. More specifically, all components in VANET communicate with each other; types of communications can be categorized as follows: 1) Vehicle to Vehicle Communication (V2V), 2) Vehicle to Infrastructure Communication (V2I) and 3) Infrastructure to Vehicle Communication (I2V).

Most protocols for VANET originate from Mobile Ad-hoc NETwork (MANET), but the protocols for VANET are more challenging than those for MANET due to the following reasons. First, the speeds of vehicles are generally faster than those of mobile devices in MANET. Thus, the communication links between vehicles are not as reliable as those in MANET. Second, high vehicle mobility usually induces frequent topology change, which leads to frequent topology maintenance in routing protocol. Third, vehicles exploit broadcast addressing for packet transmissions. When exploiting broadcast addressing, we cannot support retransmission mechanisms such as Automatic Repeat reQuest (ARQ). Thus, previous mechanisms that have been designed for MANET cannot be directly applicable to VANET.

In VANET, several applications can be supported. The applications can be categorized into 1) non-safety applications (e.g., infotainment applications) and 2) safety applications. Non-safety applications are normally delay-tolerant and do not require high Packet Delivery Ratio (PDR). Instead, they require large bandwidth for distributing a lot of contents to other vehicles and usually require the access to an internet (e.g., emails, web-browsing, and audio-video streaming services). On the other hand, safety applications require low latency and high PDR. The representative examples are platooning, intersection collision warning, and pre-crash warning. The above-mentioned safety applications are realized via

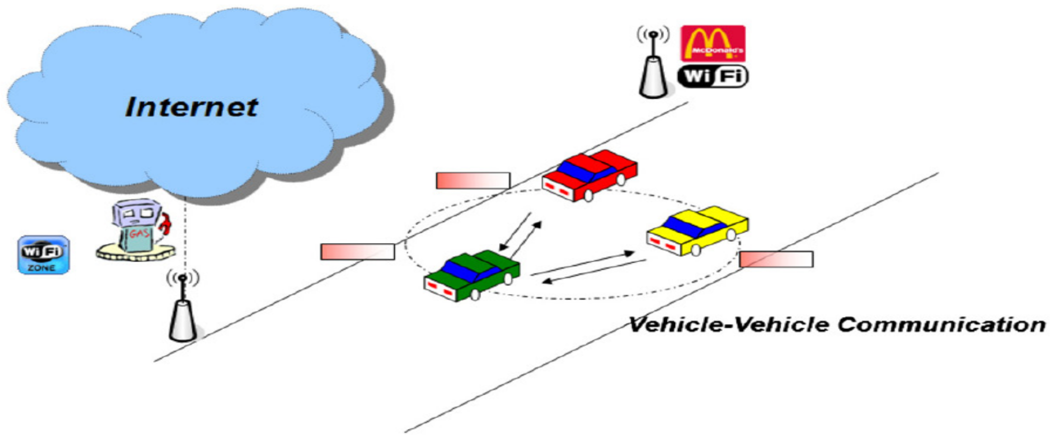


Figure 1.2: Data sharing: Car Torrent [7]

safety warning message dissemination and exchange of vehicular status information.

1.1.3 Dedicated Short Range Communications

Dedicated Short Range Communications (DSRC) is the de-facto standard for vehicular communications, which can be used for various applications in VANET. The primary goal for deploying DSRC was to support safety-related services [8]. According to the report by U.S. Department of Transportation (DOT), vehicular communications via DSRC can address 82% of accidents [8]. In addition to the safety services, DSRC can be exploited for supporting non-safety applications, including navigation, electronic payments, and commercial purpose. For example, DSRC has been deployed for supporting electronic payment systems in South Korea, which is referred to as 'Hi-pass' [9].

As illustrated in Fig.1.4, the DSRC standard specifies the protocols of several layers, including physical layer, Multiple Access Control (MAC) layer, network and application layers for multi-channel operation and security. In the physical and MAC layers, DSRC adopts IEEE 802.11p Wireless Access for Vehicular En-

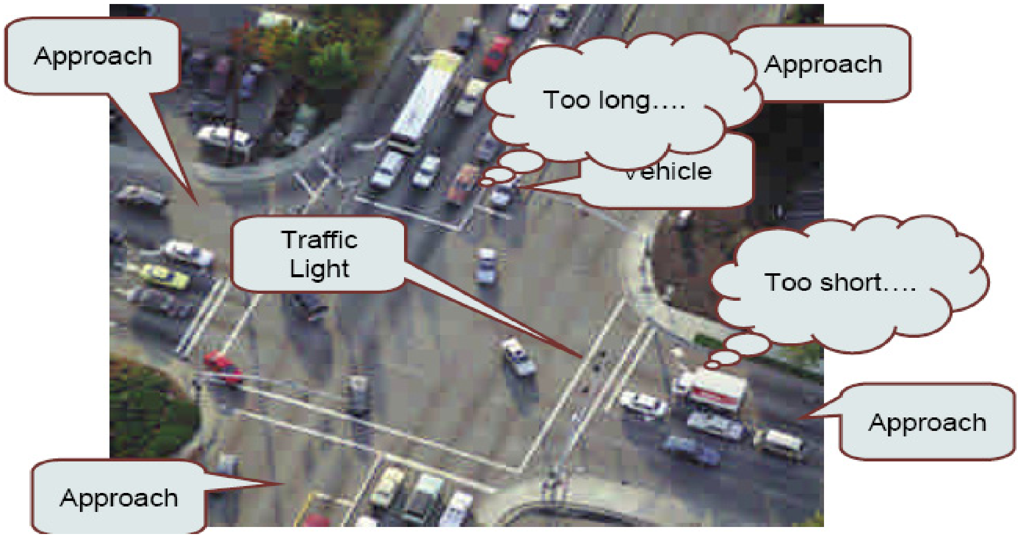


Figure 1.3: Safety related services in VANET: intersection collision warning

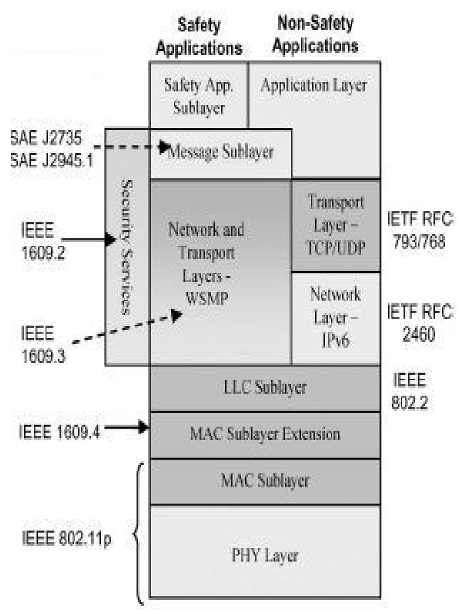


Figure 1.4: Architecture of DSRC stack [8]

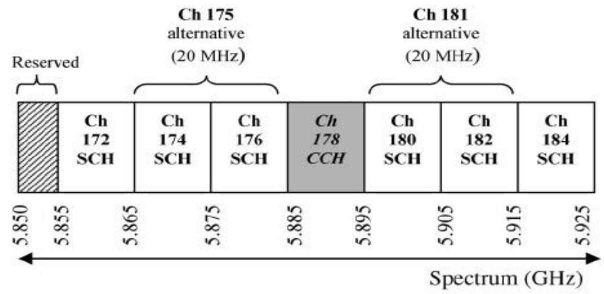


Figure 1.5: Designation of DSRC channels in 5.9GHz licensed band [8]

vironments (WAVE) [10]. Above the MAC layer, IEEE 1609 specifies several protocols for various functions. For example, IEEE 1609.2 defines security services and IEEE 1609.4 specifies multi-channel operations [12] [13]. The DSRC stack adopts the Society for Automotive Engineers (SAE) J2735 message set dictionary standard for specifying message format for communications [14].

1.1.3.1 Physical Layer of DSRC

Federal Communication Commission (FCC) allocates 75MHz around 5.9 GHz frequency for vehicular communication and the band is divided into seven channels, as depicted in Fig.1.5. The physical layer of DSRC is very similar to that of IEEE 802.11a, but the channel bandwidth of DSRC is 10MHz while that of IEEE 802.11a is 20MHz. Hence, the transmission data rate of DSRC is half of that of IEEE 802.11a [11].

1.1.3.2 MAC Layer of DSRC

1) Enhanced Distributed Channel Access (EDCA): EDCA is a mandatory channel access mechanism in IEEE 802.11e standard. EDCA is based on Distributed Coordination Function (DCF), which adopts Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) as a multiple channel access

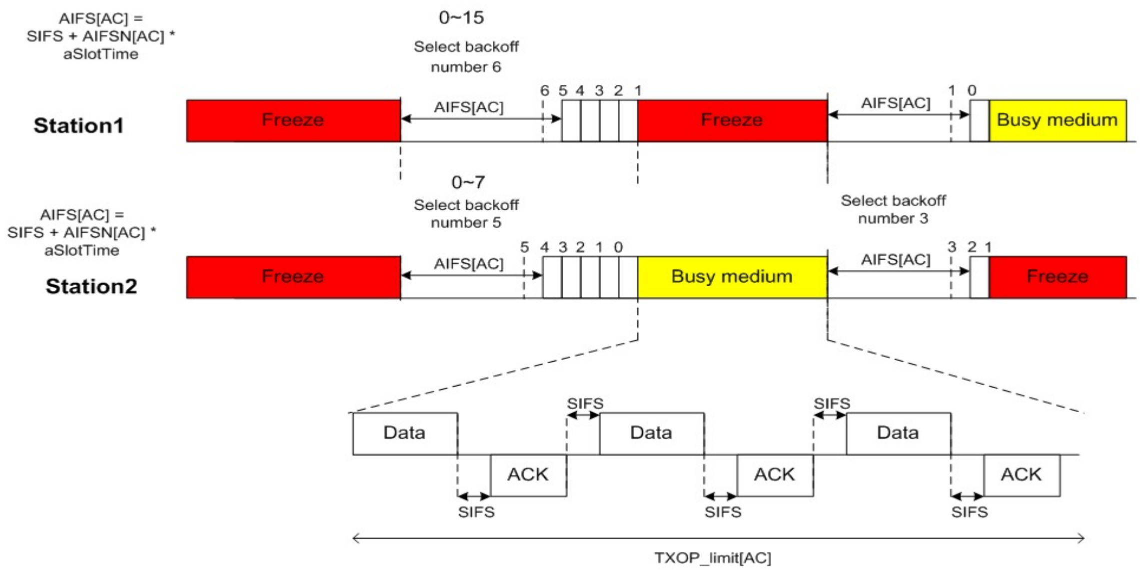


Figure 1.6: Multiple channel access mechanism in EDCA

coordination, as depicted in Fig.1.6. However, there are a number of differences between DCF and EDCA. First, EDCA defines four access categories (ACs) according to traffic types: AC_VO (voice), AC_VI (video), AC_BE (best effort), and AC_BK (background). In an EDCA-enabled station, there are four transmission buffers; each buffer is equivalent to each access category. Second, each transmission buffer is an independent backoff entity, which performs a backoff procedure for the MAC frame in the transmission buffer. Third, each access category has different configuration parameters (minimum contention window, maximum contention window, arbitration interframe space, transmission opportunity), which prioritize among different ACs. Fourth, an EDCA-enabled station has four independent backoff entities, so an internal collision in the same station can happen (virtual collision), as shown in Fig.1.7. If a virtual collision happens, AC with higher priority obtains a right to access channel and AC with lower priority acts as collision happens, such as doubling contention window and increasing backoff stage by one.

2) Hybrid Coordination Function (HCF) Controlled Channel Ac-

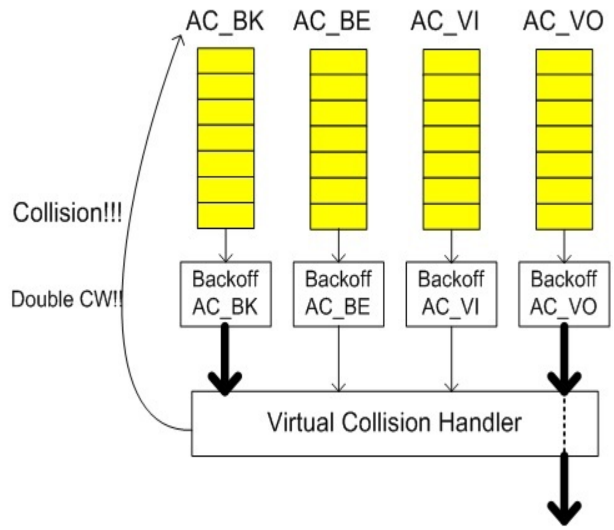


Figure 1.7: Mechanism for handling virtual collision in EDCA

cess (HCCA): HCCA is an optional channel access mechanism in IEEE 802.11e. HCCA is based on Point Coordination Function (PCF), which is a polling-based, contention-free channel access mechanism. In HCCA, Hybrid Coordinator (HC) reserves a channel for certain amount of time and allocates channel resources to backoff entities. Since the polling-based mechanism of HCCA does not cause any randomness in channel access, HCCA is appropriate for guaranteeing a delay bound of delay-sensitive applications. To reserve channel in HCCA, HC sends QoS CF-Poll message after waiting for PIFS. Since PIFS is shorter than any AIFS that EDCA devices must wait before a backoff countdown, HC can obtain the right for channel access earlier than the EDCA devices.

If a backoff entity wants to participate in HCCA operation, it sends traffic stream information to HC. For this purpose, a backoff entity sends Traffic SPECification (TSPEC) to HC and HC determines whether it allocates channel resources for the requested traffic stream. If HC decides to admit the traffic stream for HCCA, the HC schedules the channel access time and duration for each traffic stream. The default scheduler that is defined in 802.11e standard is Reference

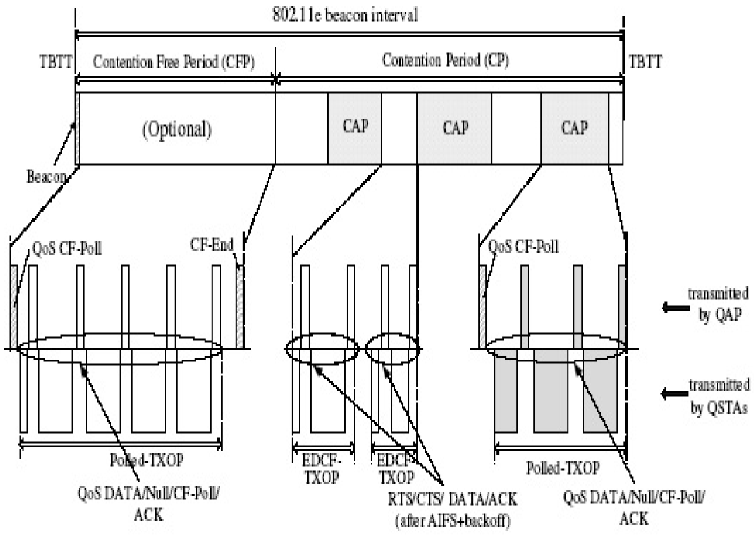


Figure 1.8: Coordination of multiple access in HCCA

Scheduler [11].

1.1.3.3 Multiple channel operation in DSRC

IEEE 1609.4 specifies multi-channel operations in DSRC, where up to seven channels are defined in 5.9GHz licensed band. Specifically, DSRC-equipped vehicles with one or more radios can switch among seven channels effectively for exploiting more channel resources [8]. However, in a device with a single radio, multiple devices must meet at the same channel, which is called rendezvous. For this purpose, as depicted in Fig.1.9, time is divided into sync period (e.g., 100ms) and sync period is also divided into Control CHannel (CCH) interval, when all vehicles tune their radios to control channel, and exchanges channel information for the rest of sync period, Service CHannel (SCH) interval. In general, safety messages are usually disseminated in CCH interval to reach all neighbor vehicles, while other application-specific messages are exchanged in SCH interval.

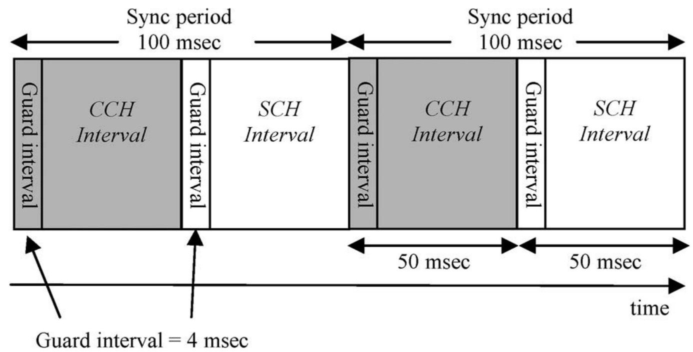


Figure 1.9: Multi-channel operations in DSRC

1.1.4 Safety System using VANET

Safety message dissemination is an important primitive in safety system using VANET. Specifically, vehicles notice the possibility of accidents by receiving the safety messages that are disseminated via vehicular communications. As the safety systems are critical to saving life, the safety message dissemination must satisfy low latency and high delivery ratio requirements. For example, in the Intersection Collision Warning (ICW) system, a safety message must be delivered to vehicles that are located in a 300m range from the center of an intersection within 100ms [15].

In the safety systems, two types of safety messages are exploited: 1) **Emergency Safety Message (ESM)** and 2) **Periodic Beacon Message (PBM)**. ESM is an application-specific, event-driven message. Specifically, when detecting application-specific emergency situation (e.g., finding emergency vehicles like ambulance or police car, pre-crash sensing), a vehicle generates and disseminates an ESM. As the ESM is generated in an event-driven fashion and used for warning other vehicles the emergency situation, the ESM must be disseminated within a specified area in real-time with high delivery ratio. In addition to the ESM, every vehicle periodically generates and transmits a PBM to advertise its own status, such as position, velocity, and acceleration. By periodic PBM exchanges, vehicles

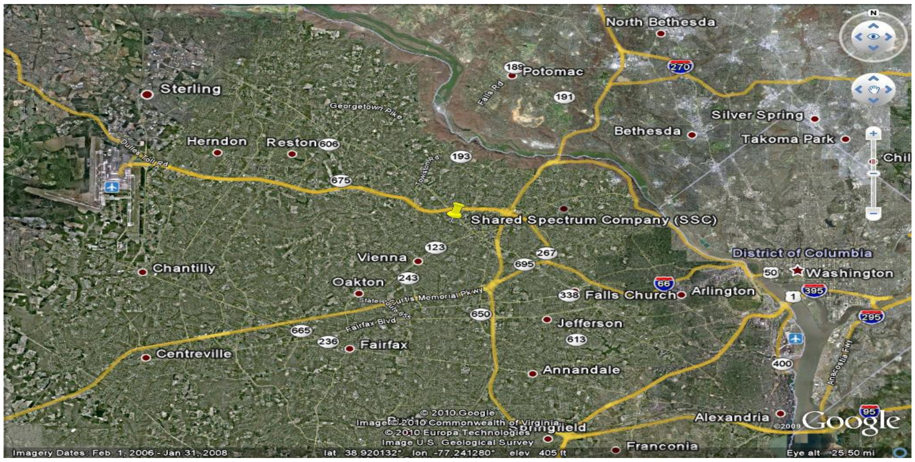


Figure 1.10: Measurement location for spectrum occupancy up to 3GHz

can figure out the real-time vehicular topology MAP; the vehicles can recognize the dangerous situation from the MAP. As PBMs are generated periodically, the failures of PBM deliveries can be compensated by new PBM transmissions; its communication requirements are not as stringent as those of an ESM.

1.1.5 Cognitive Radio Network

Due to the explosive increase of mobile devices, the shortage of available spectrum will happen in the near future, which hinders the seamless and high quality mobile services. The shortage of spectrum comes from the static spectrum allocation, even if the spectrum usage varies according time and location. Fig.1.11 illustrates the spectrum measurement results, which show the inefficiency of the static spectrum allocations. The measurement data had been collected from 500MHz up to 3GHz in Vienna, Virginia for three years [17]. The measurement results show that the spectrums are used in only small fraction of time, which implies the inefficiency of conventional static allocations.

To address the limited available spectrum and the inefficiency of spectrum usage, research communities and government authorities proposed to use licensed

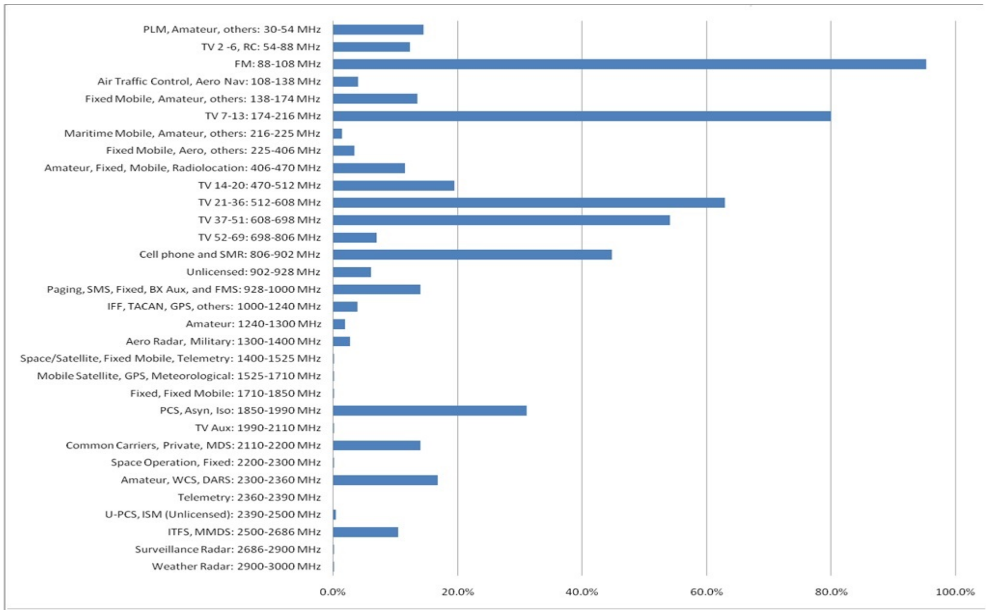


Figure 1.11: Measurement results on spectrum occupancy up to 3GHz

band when the unlicensed users (a.k.a. Secondary User (SU)) recognize no activity of licensed user (a.k.a. Primary User (PU) or incumbent user) in the band, which is referred to as Cognitive Radio (CR). In Cognitive Radio Network (CRN), SUs can access the licensed band when detecting the band is not occupied by PUs, but must vacate the band when detecting the signal of PUs [16].

Among several licensed bands (e.g., cellular bands, Ultra High Frequency (UHF) bands, or Very High Frequency (VHF) bands), UHF TV bands are frequently used for CR users due to following reasons. First, the Digital Switch Over (DFO) in TV broadcasting system results in more TV White Space (i.e., frequency spectrum allocated to broadcasting, but not use locally). Thus, the Federal Communications Commission (FCC) recently approved to use TV bands by SUs unless interfering with PU's operations. Second, the frequency of UHF TV bands is very low, thus, its propagation is very good (e.g., low signal attenuation in NLOS). This decision generates new chances for improving the spectrum efficiency without the restrictions of the conventional static spectrum access policy.

The regulation on TV band usage is different according to the mobility of SUs. More specifically, static SUs can transmit a signal up to 30 dBm (i.e., 1W) and can access any available TV channels. On the other hand, the maximum transmission power of portable SUs is 20 dBm (i.e., 100mW) and cannot access TV channels that are adjacent to the TV channels occupied by PUs.

1.2 Problem Statement

It is hard to support vehicular safety systems when only exploiting DSRC due to following reasons. First, high operation frequency of the DSRC causes serious signal attenuation in NLOS conditions, which reduces the reachability of safety message dissemination. However, the safety message must be delivered to large service region in vehicle safety systems. Second, a frequency resource that is allocated to DSRC protocol (i.e., a DSRC band) can be easily congested due to frequent exchanges of vehicle local information (e.g., all vehicles exchange their speeds and positions every 100ms). Third, the core access mechanism of DSRC is Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA is prone to packet collisions in high vehicle density. Moreover, the random nature of CSMA/CA causes unpredictable delay, which leads to frequent violation of latency requirement. Finally, due to frequent topology changes, it is hard to configure appropriate parameters (e.g., contention window size in EDCA and transmit power) in VANET. Specifically, inappropriate configuration usually induces serious performance degradation. However, frequent topology changes make it hard to adapt configurable parameters to current network conditions.

There have been previous approaches to improve the performance of DSRC for supporting vehicular safety systems. Some of them focused on the adaptive configuration of MAC parameters. However, evaluation results showed that performances were not satisfactory to realize vehicular safety systems. Other approaches proposed to exploit deterministic MAC protocols, such as Self-organized Time Division Multiple Access (STDMA). However, according to our evaluations in chapter 2, STDMA is not enough to satisfy the stringent requirements of the safety systems.

To overcome the limitations of DSRC, we proposed TVWS-based Cognitive Radio Network (CRN) systems for realizing vehicular safety systems. We believe that the adoption of CRN can overcome the challenges of DSRC due to the following reasons. First, we use extra frequency resource in addition to a DSRC band. As the communication capacity increases, we can divide the network traffic into two bands: a frequency band allocated to the DSRC (i.e., DSRC band) and a frequency band in TV Whitespace (i.e., TVWS band). Thus, network congestion can be significantly reduced. Second, the frequency of TVWS band (500$\sim$700MHz) is much lower than that of DSRC band (around 5.9GHz). This implies that the propagation characteristics in TVWS band is much better than that in DSRC band. For example, when the signal is propagated in NLOS conditions (i.e., obstacles between the signal path) via a DSRC band, a vehicle suffers from serious attenuation, which normally results in high signal distortion and packet loss. However, when propagating via TVWS band, the signal attenuation is significantly reduced compared to that in DSRC.

However, there were no previous works that developed a TVWS-based CRN system for vehicular safety system; no feasibility studies on TVWS-based CRN for vehicular safety system. Thus, in this dissertation, we propose and analyze TVWS-based CRN systems that are tailored to vehicular safety systems.

1.3 Contributions

In this dissertation, we design CRN systems that collaborate TVWS and DSRC bands for the safety systems and evaluate the proposed systems via network simulator. The contributions in this dissertation can be summarized as follows.

1) Evaluation of various MAC protocols for safety system in a DSRC band

We evaluate various MAC protocols in vehicular environments using network simulator NS-2. First, the hybrid MAC protocol system is evaluated whether it is feasible to work-zone safety system. Here, the hybrid system consists of Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function Controlled Channel Access (HCCA). The simulation results show that the hybrid system is not fit to support safety system in work-zone area. Several previous studies found that EDCA was not appropriate for services that required bounded delay and high reliability (e.g., vehicular safety system) due to its random access policy. Thus, we adopt Self-organized Time Division Multiple Access (STDMA) for a vehicular safety system and evaluate it in highway area. In-depth simulation studies show that STDMA is better than EDCA but still needs improvement for supporting the safety system.

2) CRN system design that focuses on optimal access policy among TVWS and DSRC bands for vehicular safety system

We propose a TVWS-based CRN system that supports QoS of safety message dissemination. 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 causes serious packet collisions and network congestion. To overcome the limitation of the DSRC, we utilize an extra TV White Space (TVWS) band that has a large communication range for safety message disseminations, and exploit a DSRC band for 1) the exchange of control data and 2) the compensation of ESM reception errors. Through an in-depth simulation study, we show that the proposed scheme satisfies the requirements for latency and packet delivery ratio, and outperforms previous approaches in various vehicular scenarios.

3) CRN system design for overcoming attenuation in NLOS intersections using TVWS

We try to support safety message dissemination in NLOS urban corner using a TVWS-based CRN. Due to DSRC high operation frequency, a signal suffers from serious attenuation when being propagated in NLOS conditions. To solve this problem, we propose a novel scheme that enables reliable dissemination in NLOS conditions by exploiting a TVWS band. Specifically, the proposed scheme leverages the excellent propagation characteristics of a TVWS signal even without relays. Simulation studies show that the proposed scheme outperforms the previous scheme in the delivery ratio of a safety message by 25%.

1.4 Organization of Dissertation

The remainder of this dissertation is organized as follows. In chapter 2, we evaluate several MAC protocols via NS-2 simulation and explore the feasibility of each MAC protocol for vehicular safety systems when only relying on a DSRC band. In chapter 3, we propose a TVWS-based CRN system for efficient and reliable ESM dissemination. Specifically, we focus on appropriate access to TVWS and DSRC by considering the characteristics of each band. In chapter 4, we propose a TVWS-based CRN system that supports reliable safety message dissemination even in NLOS intersections. In Chapter 5, we conclude this dissertation.

CHAPTER 2

Elaborate Study of Vehicular MAC Protocols for Vehicular Safety System

In this chapter, we evaluate several MAC protocols for vehicular safety systems. First, we evaluate a hybrid system that adopts two MAC protocols for work-zone safety service: 1) Enhanced Distributed Channel Access (EDCA) for vehicles and 2) HCF Controlled Channel Access (HCCA) for Road Side Units (RSU) . Second, we evaluate Self-organized Time Division Multiple Access (STDMA) protocol for vehicular safety system in highway area.

2.1 Motivations

2.1.1 Motivation on Studying EDCA and HCCA Hybrid System for work-zone safety service

In a work zone, a large fraction of accidents are fatal crashes and injury crashes. According to a report from Kansas State [4], more than half of fatal crashes and a third of injury crashes happen in work zones. In an attempt to reduce such crashes, academic and industrial researchers have made efforts in developing safety systems that employ wireless transceiver [15] [18]. In the safety systems, vehicles and Road Side Units (RSU) exchange vehicle status information and warning messages, and vehicles can recognize the risks of accidents when they receive the warning messages.

To improve safety, state and federal transport agencies (e.g., Caltrans) have developed smart cones that are equipped with wireless transceivers. Similar to RSUs, the smart cones are located in static position on the shoulder of a road and can communicate with vehicles for vehicle safety. More specifically, vehicles advertise their status information, (e.g., speed, position and acceleration), while smart cones generate a warning message after getting the status information and transmit the warning message to vehicles in a real-time manner.

Dedicated Short Range Communications (DSRC) [10] is considered as a de facto standard for vehicular communications, in which Enhanced Distributed Channel Access (EDCA) and HCF Controlled Channel Access (HCCA) are specified as MAC protocols. EDCA has been normally employed as a MAC protocol due to its ease of deployment and capability to adjust to fast topology changes of vehicular networks. However, EDCA may induce an unpredictable delay that comes from its statistical access mechanism (i.e., binary random backoff in CSMA/CA). In particular, when vehicles are densely deployed, such a statistical mechanism engenders a long delivery delay and low Packet Delivery Ratio (PDR) [19]. For example, simulation results in [19] show that EDCA produces only 50∼60% PDR when there are only 100 vehicles in 6.6km by 4.2km road segment. The other type of MAC protocol, HCCA, is specified for supporting real-time transmissions and allocates resources to time sensitive stations in time-division polled mode. However, to adapt to fast topology change of vehicular networks, HCCA may produce large protocol overheads (e.g., overhead for slot assignment, overhead for joining process). If smart cones are adopted in a work zone, they can forward the warning message to vehicles using HCCA; thus it seems that the delay and PDR requirements of work zone can be supported. However, HCCA is still not suitable for vehicle transmissions. Therefore, using only EDCA or HCCA is not enough to support real-time transmission in a rapidly changing topology, such as a work zone safety application in vehicular networks.

So, one may raise the question: "can we really improve a work zone safety system by leveraging EDCA and HCCA?". IEEE 802.11 defines a superframe structure for EDCA and HCCA coexistence, which works well when devices do not have high mobility and network size is small [23]. However, to the best of our knowledge, there have been no performance studies on EDCA and HCCA coexistence system when high mobility and large network size are considered. [19] examined performance of an IEEE 802.11 MAC protocol for a vehicle safety system. [20] compared EDCA and Point Coordination Function (PCF) in vehicular networks. [21] analyzed EDCA performance when EDCA is applied to vehicular safety messaging. [22] analyzed the delay of HCCA in vehicular networks. However, previous studies did not consider EDCA and HCCA coexistence scenario [19] [20] [21] [22] or did not consider vehicular situations [23]. Thus, in this paper, we perform a simulation study on EDCA and HCCA coexistence system in which smart cones and vehicles cooperate for work zone safety. Especially, we focus on how EDCA and HCCA interact with each other and the interaction affects system performance.

2.1.2 Motivation on Studying STDMA MAC protocol

In 2009, the U.S. government reported that more than 33,800 people were killed and more than two million people were injured from vehicle accidents [26]. In an attempt to reduce the accidents, many academic researchers and car manufacturers have developed active safety systems that relied on vehicular communications. Specifically, vehicles notice the possibility of an accident by exchanging their status information (e.g., position, speed, and acceleration), thereby being able to prepare for the accident before it happens.

The de-facto standard for vehicular communications is Dedicated Short Range Communications (DSRC), which exploits 5.9GHz licensed band [10]. In DSRC, Enhanced Distributed Channel Access (EDCA) is specified as a default MAC protocol. The core mechanism of EDCA is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which controls multiple access in a distributed manner. The distributed nature of CSMA/CA makes EDCA robust to frequent topology changes, thereby being appropriate to highly mobile network like vehicular networks.

However, EDCA is not suitable to vehicular safety applications, which require high delivery ratio and low latency [15]. This is because the random nature of CSMA/CA causes unpredictable delay, which leads to frequent violation of latency requirement. Even more, CSMA/CA is prone to packet collisions in high vehicle density, which decreases delivery ratio [21] [27]. Hence, EDCA may not support the requirements of the safety applications.

It is well-known that Time Division Multiple Access (TDMA) can address the above-mentioned challenges of EDCA. Specifically, when employing TDMA for vehicular communications, the upper bound of delay can be guaranteed and packet collisions rarely happen even in high vehicle density [28] [29]. This is due to a well-organized time schedule: at least one time slot is assigned to each vehicle within a period; we rarely assign the same time slot to more than two vehicles in vicinity. However, for organizing time schedule well, we require a central controller (e.g., Road Side Unit (RSU)), of which implementation and management is costly.

To address the challenges of EDCA and TDMA, several researchers proposed to adopt Self-organized TDMA (STDMA) as an alternative MAC for vehicular communications [31] [32] [33]. Fortunately, STDMA has both deterministic and distributed natures. More specifically, each vehicle transmits a packet according to a time slot schedule (deterministic) and chooses its own time slot by itself (distributed). Moreover, Automatic Identification System (AIS), which is a dominant application of STDMA, is quite similar to vehicular safety applications [30] [32]. Specifically, every ship periodically exchanges its status information (e.g., position, direction) for identifying ships in the vicinity. Thus, STDMA seems to be feasible to vehicular safety applications.

Despite successful STDMA employment in AIS, it is necessary to show the feasibility of STDMA to vehicular safety applications. This is because the mobility patterns are different between vehicles and ships. Specifically, vehicles move much faster than the ships, thus, the vehicular network is more dynamic than the network of ships. Moreover, the density of vehicles can be much higher than that of ships.

There have been previous simulation studies when STDMA is used for vehicular networks [31] [32] [33]. In [31], the authors focused on throughput of STDMA via simulation studies. In [32], the authors analyzed the real-time properties of CSMA/CA and STDMA via simulation studies in highway scenarios and revealed that STDMA was better than CSMA/CA. [33] pointed out that CSMA/CA was not suitable to vehicular safety applications and showed that STDMA outperformed CSMA/CA.

However, [31] [32] [33] are not enough to reveal the feasibility of STDMA to vehicular safety applications due to several missing points. First, [31] [32] [33] did not evaluate Packet Delivery Ratio (PDR) of STDMA-based vehicular systems, even if PDR is a very important measure in vehicular safety applications [27] [28]. Second, previous studies are based on only a single configuration, even though the STDMA has several configuration parameters. Hence, even if previous studies showed that STDMA was not feasible to vehicular safety applications in one configuration, one may insist that careful tuning of STDMA parameter makes STDMA feasible to vehicular safety applications.

Thus, in this paper, for verifying the feasibility of STDMA to safety applications, we conduct in-depth simulation studies on STDMA by considering the missing points of previous studies. Thus, it is possible to understand the impact and benefit of STDMA in vehicular safety applications. Moreover, based on simulation observations, we suggest guidelines for improving STDMA to fit in with vehicular safety applications.

2.2 MAC Protocols for Vehicular Communication

As we already explained the operations of EDCA and HCCA in chapter 1, we only explain the operations of STDMA.

STDMA is a deterministic MAC protocol, where vehicles can access wireless medium at their designated time slots. In STDMA, vehicles determine their own transmission schedules by themselves (i.e., select their own time slots) based on channel monitoring results. As shown in Fig.2.1, time is divided into frames and the frame is further divided into multiple time slots.

STDMA is composed of four phases: 1) initialization phase, 2) network entry phase, 3) first frame phase, and 4) continuous operation phase. In an initialization phase, vehicles listen to wireless channel and store channel activities during one time frame (e.g., the occupation of each slot and a position of the slot owner). In an entry phase, vehicles select their first time slots within a frame, which is denoted by Nominal Transmission Slot (NTS). The details of selecting a time slot will be explained in the following paragraph. In the first frame phase, the vehicle selects time slots for the rest of the frame using the mechanism similar to that used in the network entry phase. The last phase of STDMA is a continuous operation phase, where vehicles exploit NTSs that are chosen in the first frame phase. However, to adapt to network topology change, vehicles select new NTSs after n frames.

The mechanism for selecting time slot (i.e., NTS) in the network entry phase consists of four steps. First, a vehicle calculates a Nominal Increment (NI) by dividing an average report interval with the unit slot length. Second, a vehicle randomly chooses Nominal Start Slot (NSS) from current slot up to NI. Third, a vehicle sets Selection Interval (SI) around NSS, and randomly picks its NTS

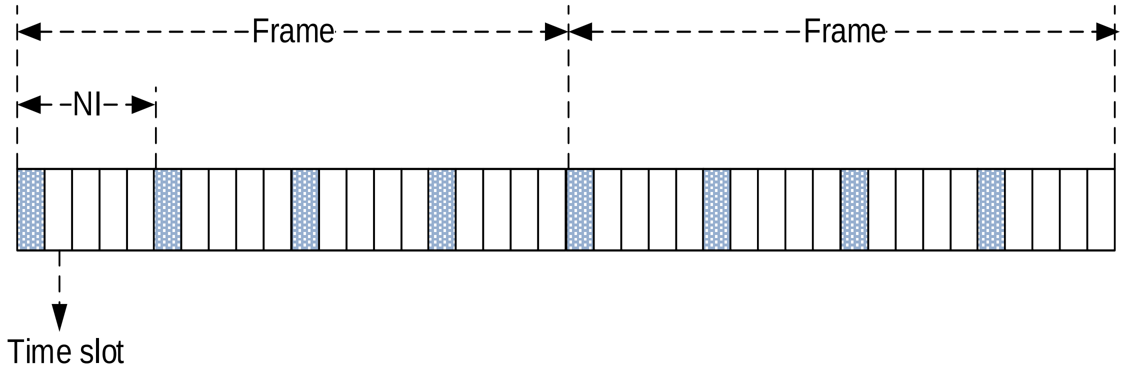


Figure 2.1: Time frame structure of STDMA

within SI. Finally, a vehicle checks an availability of NTS. More specifically, if the chosen NTS is occupied by someone else based on the previous monitoring results, a vehicle selects the closest unoccupied slot within SI. However, if all slots within SI are occupied, the vehicle selects the slot of which owner is furthest away from itself. This is because an amount of interference tends to be smaller as the distance from the interferer is getting longer.

2.3 Simulation studies on EDCA and HCCA Hybrid System for work-zone safety service

In this section, we perform a simulation study of the safety system based on EDCA (HCCA) for vehicles (smart cones) using NS-2 simulator [24]. Specifically, we investigate the system according to non-controllable parameters (the number of vehicles and the number of smart cones) and controllable parameters (Contention Window (CW) size of EDCA and packet size of vehicle traffic). We define simulation scenarios like this based on the belief that we can improve system performances by configuring the controllable parameters. For each simulation scenario, we focus on how an interaction between EDCA and HCCA affects system performances. In addition, we study a feasibility of the system for work zone safety.

2.3.1 Work Zone Safety System

As illustrated in Fig.2.3, a work zone safety system consists of vehicles and smart cones. Vehicles periodically generate and disseminate a message that includes status information of the vehicles. For accessing a wireless channel, vehicles employ EDCA since its distributed nature enables the EDCA to adapt to fast vehicle topology changes easily.

The other system components, smart cones, are located in static position on the shoulder of the road. The smart cones are different from conventional cones in that the smart cones have wireless transceivers, thereby being able to communicate with vehicles. The smart cones generate warning messages when they perceive a possibility of vehicle accidents (e.g., detection of 150km/h vehicle in urban area), which is usually an output of processing vehicle status information. The smart cones employ HCCA mechanism in transmitting a warning message due to following reasons: 1) The warning message is delay sensitive and requires high communication reliability, thus must be supported by a deterministic mechanism like HCCA, 2) smart cone's static position helps keep the overhead small in a deterministic mechanism (e.g., overhead for joining, scheduling).

To enforce HCCA transmission scheduling, we deploy a Base Station (BS) on the shoulder of the road, which employs HCCA mechanism. BS establishes transmission schedule of cones and sends a poll message to each cone in a time slot designated for the cone. When receiving a poll message from BS, the cone is permitted to access the wireless channel.

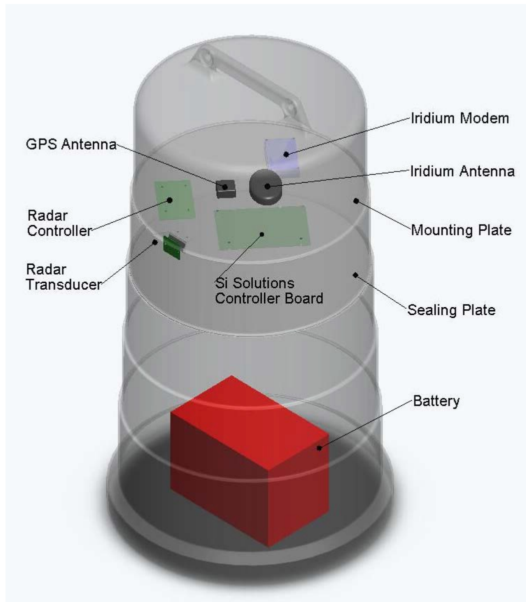


Figure 2.2: Smart cone

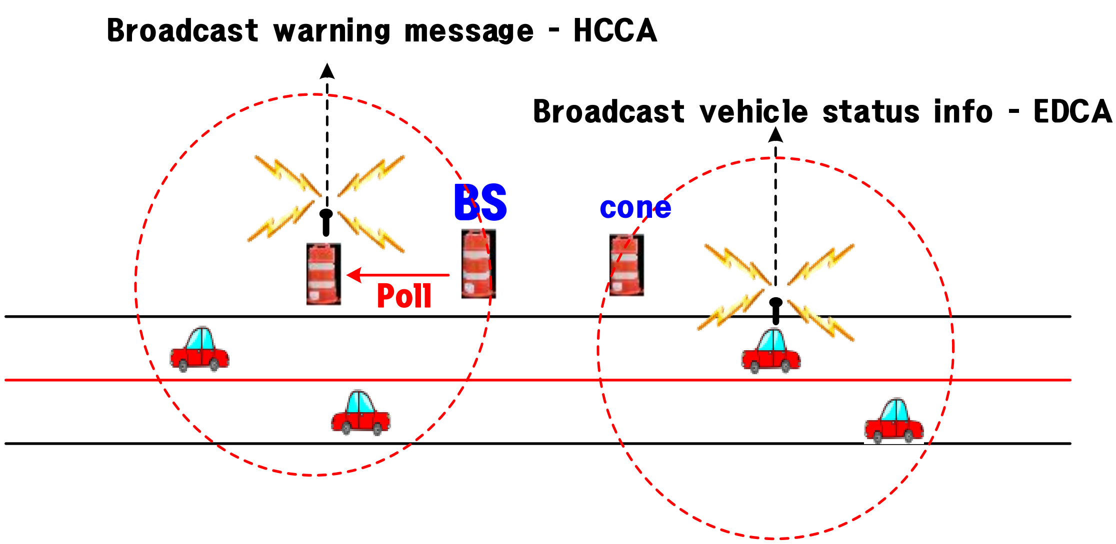


Figure 2.3: Work zone safety system that employs smart cones

2.3.2 Simulation Setup

Fig.2.4 illustrates a topology for our simulation study. In the simulation, we consider a two-way one mile road segment with four lanes for mimicking work-zone in a highway. Vehicles move along the road with a speed of 70km/h and smart cones are deployed on the shoulder of the road and located within a work zone of which length is 300m. In the middle of the road, BS is deployed.

We summarize default simulation settings in Table 2.1. For PHY layer protocol, we follow IEEE 802.11p [10]. In MAC layer setting, we use default values of IEEE 802.11 [11] for backoff configuration parameters of EDCA (e.g., CW size, AIFS). In HCCA, we do not implement the Contention Free Period (CFP) due to following reasons. First, using CFP is not mandatory in IEEE 802.11 standard [11] since BS can provide transmission opportunity to stations (i.e., sending poll message to station) during Contention Period (CP). Second, in our topology, BS cannot reserve the channel for the entire network due to a limited transmission range, thus contention may happen during CFP. BS generates and sends poll message every 200ms. This means that each smart cone can grab an opportunity to access channel every 200ms. Vehicles (smart cones) generate status info message (warning message) every 100ms (200ms) [1] and broadcast the message. This setting mimics a situation where smart cones gather vehicle information for 200ms and generate a warning message from that information. If there is no a possibility of accident during an interval, smart cones need not send warning message every interval. In this setting, when there is no possibility of accident, "sending message" refers to sending void message, which includes only the notification of work zone.

[1] Society for Automotive Engineers (SAE) [14] defines 100ms to be a default generation period for periodic vehicle message. [15] suggests one second for generation period of work zone warning message, but [15] only considers I2V communications, which is somewhat different from our situations. Thus, as a generation period of warning message, we choose 200ms which is close to average value of message generation period in [15]. However, these values are just default settings, which can change for more elaborate performance study.

It is noted that even though EDCA is generally used for prioritized services, we only consider single service in our studies to focus on the interaction between EDCA and HCCA. Thus, we just use one Access Category (AC) for EDCA in our simulations.

We note that in our simulation, smart cones do not use EDCA together with HCCA. This is because HCCA is more likely to support high PDR than EDCA. To be specific, in HCCA transmissions, BS reserves a channel for smart cone's transmission by annotating poll message with required duration (i.e., set Network Allocation Vector (NAV)). As a result, a fraction of vehicles defer their transmissions by overhearing the poll messages. On the other hand, in EDCA, there is not a mechanism for reserving channel before data transmission, thus, lot of transmission attempts by vehicles can induce packet collisions. Thus, sending warning message with HCCA is less likely to suffer from packet collision.

Table 2.1: Default system parameters for NS-2 simulation

Transmission range	500m
physical transmission rate	6Mbps
Slot Schedule for HCCA	Round Robin method
Channel model	Two Ray Ground
Message generation	345byte / 100ms
Number of vehicles	Variable (80 is default)
Number of smart cones	Variable (10 is default)

2.3.3 Performance Measures

Performance measures that are used in this study are as follows

- **Packet Delivery Ratio (PDR):** a ratio of the number of vehicles that receive a packet ($n_{receive}$) to the number of vehicles within a Zone of Interest (ZoI)

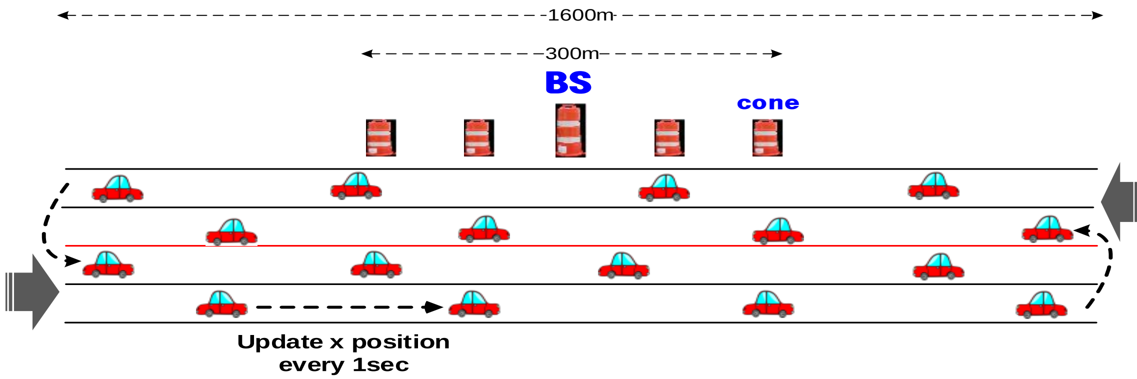


Figure 2.4: Topology used in simulation study

(n_{target}). Here, we set the size of ZoI to be 500m, which is equal to the transmission range of a DSRC.

• **Communication delay:** an interval between a packet generation time and a packet reception time.

• **Poll collision rate:** a ratio of the number of poll messages collided at smart cones ($n^{poll}_{collision}$) to the number of poll messages sent by BS (n^{poll}_{sent}).

It is noted that we define a new metric, a poll collision rate, to analyze unpredictable simulation results, which are caused by interactions between EDCA and HCCA. Specifically, in Fig.2.6, delay of HCCA is not bounded and its value is very large. Our conjecture on these counter-intuitive results is that poll messages collide with "*hidden terminal*" vehicle traffic. To prove this conjecture, we measure poll collision rate for each scenario.

2.3.4 Impact of Number of Vehicles

In Fig.2.5, we observe that PDR of EDCA (i.e., PDR of vehicle traffic) and that of HCCA (i.e., PDR of smart cone traffic) decrease as the number of vehicles increases. Obviously, the increase in the number of vehicles makes a network more congested, which leads to the decrease in PDR of EDCA. The interesting

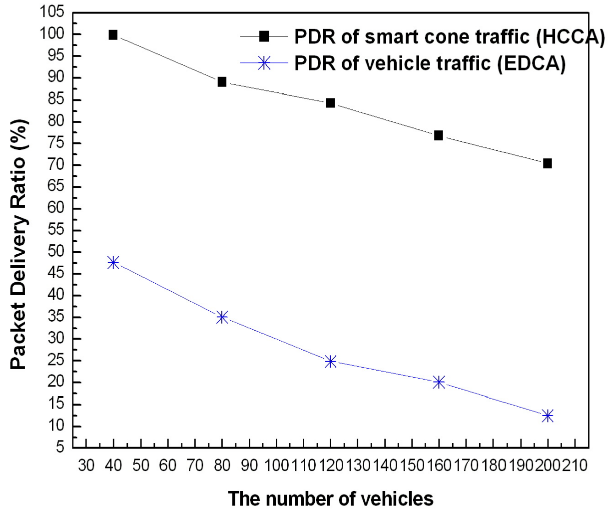


Figure 2.5: PDR of EDCA and HCCA according to the number of vehicles

finding in Fig.2.5 is that PDR of HCCA also diminishes as the number of vehicles grows. By and large, it is believed that PDR of HCCA does not depend on the network load due to its deterministic characteristics. However, in this system, interactions with EDCA induce packet collision of HCCA, thereby reducing PDR of HCCA.

Fig.2.6 shows that delays of HCCA and EDCA are augmented as the number of vehicles increases. It is obvious that the growth in the number of vehicles leads to the increase in delay of EDCA due to EDCA's intrinsic CSMA/CA mechanism. However, the delay of HCCA is also increasing, which is somewhat counter-intuitive. Moreover, delay of HCCA is long, which means that HCCA is no more suitable for most safety applications including "work zone safety system" [15]. The clue for this unpredictable outcome is an interaction between HCCA and EDCA. More specifically, our conjecture is that poll messages (i.e., traffic of HCCA) collide with vehicle status info message (i.e., traffic of EDCA) sent by hidden vehicles, thereby smart cones cannot send their warning messages at their designated time.

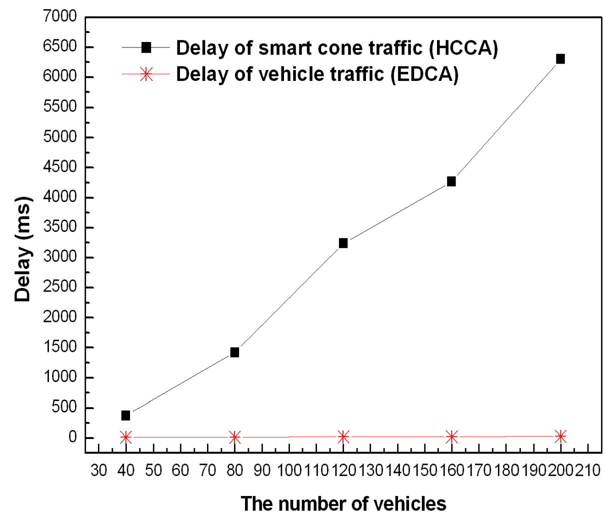


Figure 2.6: Delay of EDCA and HCCA according to the number of vehicles

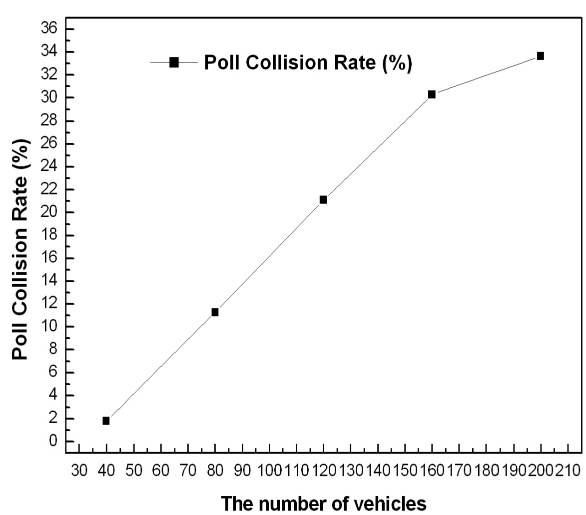


Figure 2.7: Poll collision rate according to the number of vehicles

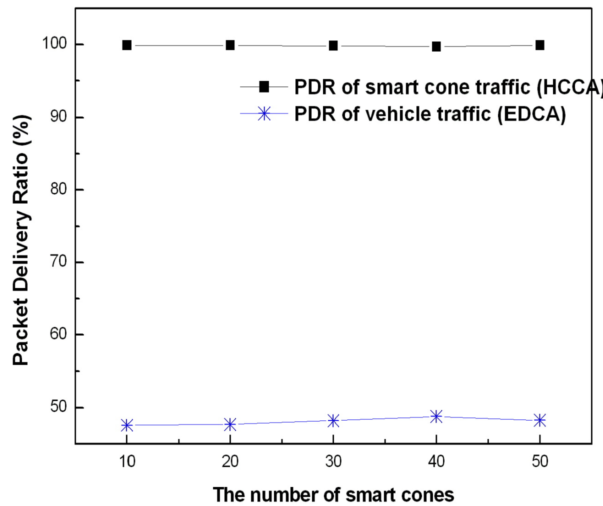


Figure 2.8: PDR of HCCA and EDCA according to the number of smart cones when there are 40 vehicles

Instead, the smart cones have to defer their transmissions until receiving the poll message in the next interval (e.g., after 200ms), but BS cannot send the poll message immediately after collision because a retransmission mechanism is not specified for poll message in HCCA. Unfortunately, a warning message may be generated within this interval, which leads to an increase in queuing delay. This conjecture is proved in Fig.2.7, which shows that poll collision rate rises as the number of vehicles increases.

2.3.5 Impact of Number of Smart Cones

In Fig.2.8, we observe that PDRs of EDCA and HCCA do not depend on the number of smart cones. This is because network congestion does not increase even if the number of smart cones grows. In detail, only one smart cone attempts to access a wireless channel at a time. Thus, the number of devices that contend for channel access is same (i.e., one smart cone and multiple vehicles) even though

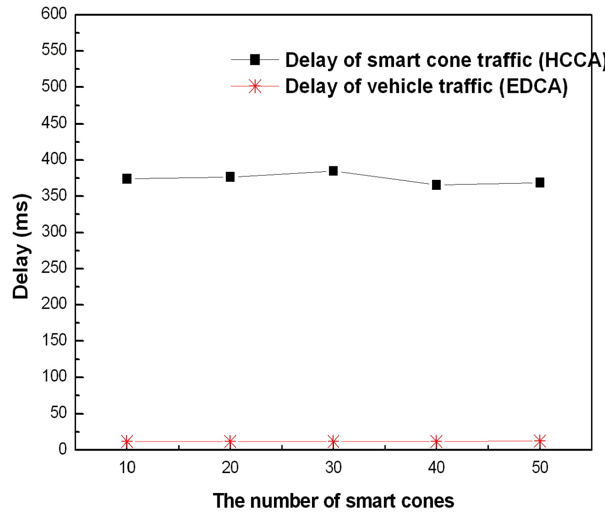


Figure 2.9: Delay of HCCA and EDCA according to the number of smart cones when there are 40 vehicles

the number of smart cones changes. The same argument can be applied to Fig.2.9, on which delays of HCCA and EDCA traffic do not change as the number of smart cones varies.

2.3.6 Impact of Contention Window (CW) Size

As shown in Fig.2.5, PDR of EDCA is below 50%, which is relatively low for supporting Quality of Service (QoS) of work zone safety applications. This is due to two properties of the broadcast mechanism: 1) lack of retransmission mechanism and 2) usage of fixed CW size (i.e., minimum CW size). Thus, CW size cannot adapt to variable network load, which results in low PDR. (e.g., 20% PDR when there are 200 vehicles in Fig.2.5.) Based on the belief that control of CW size improves network performance [25], we observe performances according to CW size.

In Fig.2.10, we observe that PDR of EDCA is augmented as CW size increases,

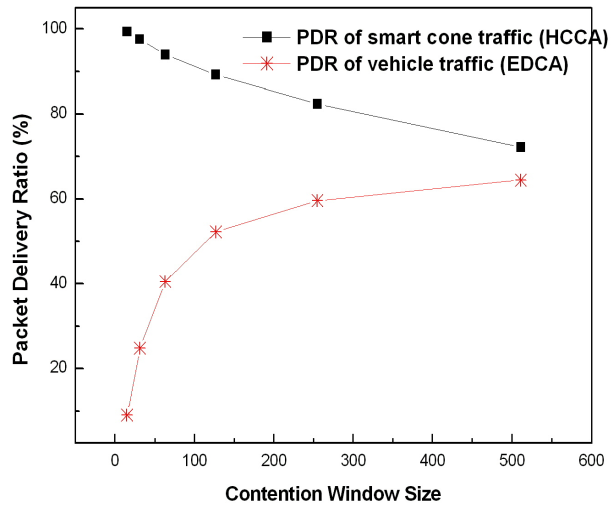


Figure 2.10: PDR of HCCA and EDCA according to CW size when there are 80 vehicles

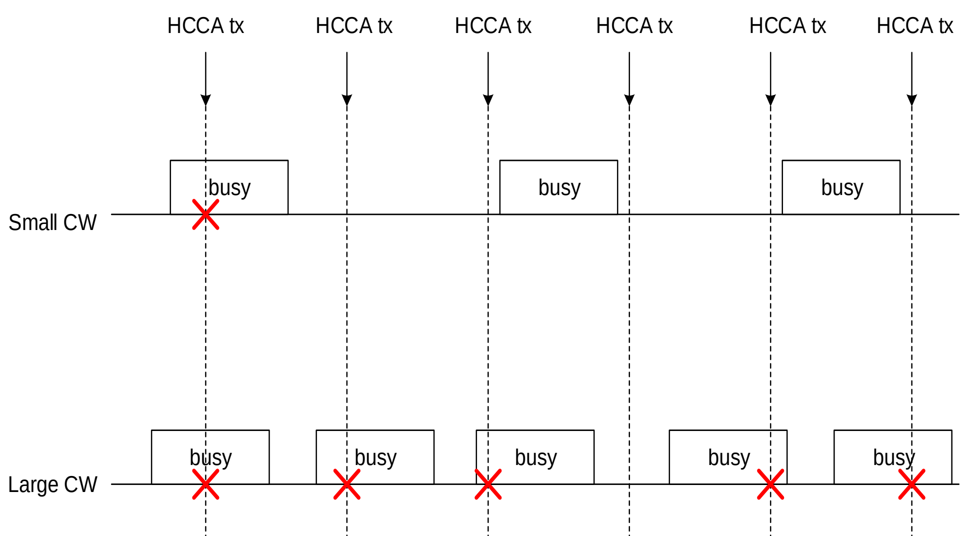


Figure 2.11: Comparison of channel occupancy and packet collision among vehicles and HCCA traffic between 1) when CW size is small and 2) when CW size is large

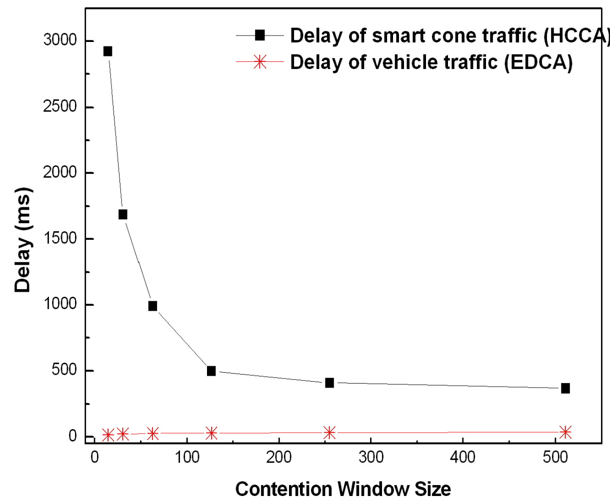


Figure 2.12: Delay of HCCA and EDCA according to CW size when there are 80 vehicles

which is quite obvious. An interesting observation in this figure is that PDR of HCCA decreases as CW size increases. Similar to Section 2.3.4, an interaction between HCCA and EDCA accounts for this result. In detail, when smart cones receive poll messages, they start packet transmission without carrier sensing. In other words, smart cones transmit packets regardless of whether channel is busy or not. Hence, as the channel is more occupied by others, corruptions of the smart cone's packets happen more frequently. However, as is shown in Fig.2.11, the fraction of channel-busy time caused by vehicle traffic grows as the CW size increases, which comes from reduction of collisions among vehicle traffics. As a result, a probability of collision between EDCA (i.e., vehicle status information message) and HCCA traffic (i.e. warning message) increases as CW size increases.

In Fig.2.12, we observe that delay of EDCA increases and delay of HCCA decreases as CW size increases. The delay pattern of EDCA is obvious, but that of HCCA is somewhat counter-intuitive. The latter can be explained by

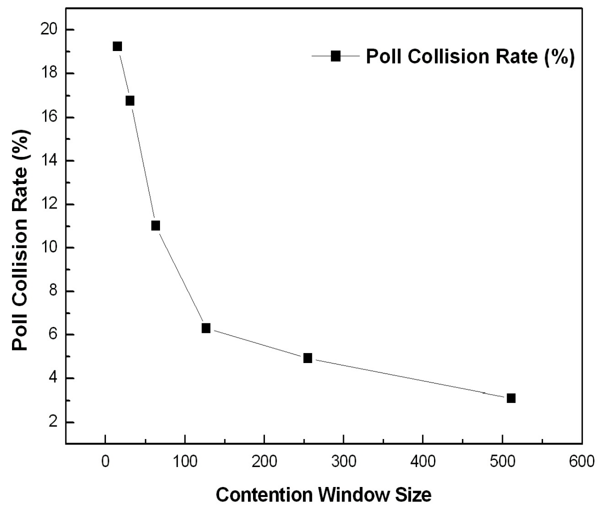


Figure 2.13: Poll collision rate according to CW size when there are 80 vehicles

Fig.2.13, which shows that poll collision rate decreases as the CW size increases. To be specific, BS employs carrier sensing for poll transmission, and thus poll transmission is regarded as following CSMA/CA mechanism with PIFS and zero backoff count. Thus, the pattern of poll collision rate complies with pattern of EDCA. As a result, the poll collision rate decreases as CW size increases, which leads to a reduction of delay in HCCA.

2.3.7 Impact of Packet Size

In this subsection, we estimate performances according to packet size of EDCA traffic. It is noted that a generation rate of application-level data remains the same since application-level data are generated before packetizing the data. (i.e., the data generation rate is independent of a packet size.) Thus, a packet generation interval necessarily changes when the packet size varies. For example, if the packet size of EDCA traffic is doubled, the packet generation interval should also be doubled, so the data generation rate remains the same.

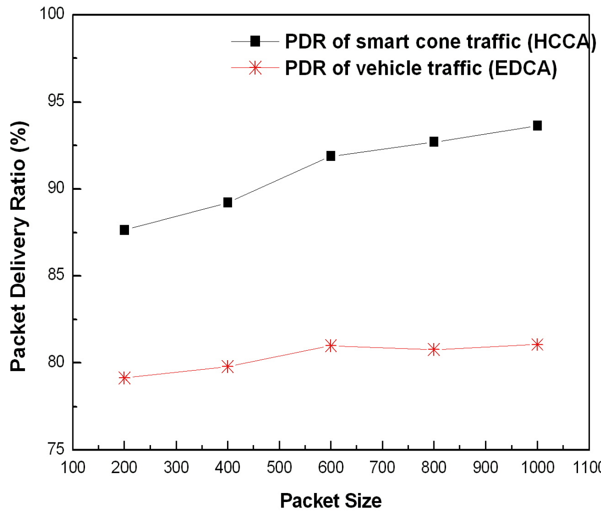


Figure 2.14: PDR of HCCA and EDCA according to packet size of vehicles when there are 80 vehicles

As depicted in Fig.2.14, we observe that PDRs of EDCA and HCCA increase as packet size increases. This is because the contention among vehicles and smart cones is reduced. Specifically, as the packet size grows, vehicles transmit less frequently, which leads to a reduction in the number of transmission attempts at a time. It is obvious that a reduction of transmission attempts leads to the decrease in contention, which in turn reduces packet collisions.

In Fig.2.15, we observe that delay of EDCA increases as packet size of vehicles transmission grows. This is because the duration for transmitting EDCA packets is increased. On the other hand, the delay of HCCA is decreased as the packet size increases. As we explained in Section 2.3.4, delay of HCCA in this system is dominated by poll collisions. But, as depicted in Fig.2.14, packet collision of EDCA and HCCA traffic is reduced, which can also be applied to poll message. As a result, the delay of HCCA diminishes as the packet size grows.

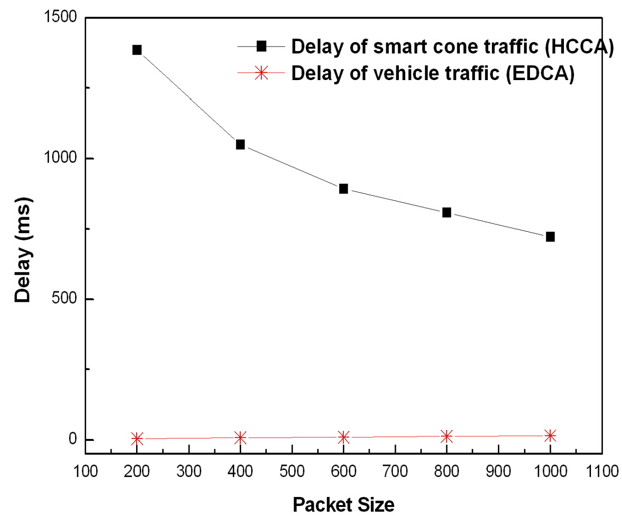


Figure 2.15: Delay of HCCA and EDCA according to packet size of vehicles when there are 80 vehicles

2.3.8 Discussion

We found that HCCA delay grows unacceptably large when many vehicles occupy the road[2]. As we explained in the previous section, the delay of HCCA is mainly caused by poll collision. Thus, to improve delay performance, we must guarantee reliable transmission of poll message. Simple methods are to use Automatic Repeat reQuest (ARQ) that is employed in IEEE 802.11 standard [11] or Forward Error Correction (FEC).

As we discuss in Section 2.3.4, we also need to improve PDR of EDCA when many vehicles share the channel. The reasons of low PDR are two-folds: 1) lack of adaptation of parameters to network conditions and 2) lack of retransmission

[2] In our study, we deploy up to 200 vehicles, which results in a quite long delay for most safety applications. However, in practical situations, the maximum number of vehicles can be larger than 200 (e.g., up to 300 vehicles in four lane one mile road according to talk with Caltrans staff) even with high speed. When there are more vehicles, we can easily expect without further experiments that delay of HCCA is much longer than scenario of 200 vehicles.

mechanism in broadcasting. As we can see in Section 2.3.6, the increase in CW size improves PDR of EDCA and delay of HCCA. However, the increase in CW size also decreases PDR of HCCA. Thus, we have to find a balance between PDR of EDCA, delay of HCCA and PDR of HCCA in controlling CW size. Also, we find that the increase of packet size of vehicle traffic induces improvements in PDR of EDCA and delay of HCCA. However, as we explained in Section 2.3.7, long packet size should be accompanied with long packet generation interval. In this case, smart cones may not have enough vehicle information and cannot generate warning message at a right time. Clearly, one must find the appropriate packet size. Another suggestion is to develop a reliable broadcasting technique that acknowledges packet receptions.

2.4 Simulation studies on STDMA for vehicular safety service

In this section, we perform an in-depth simulation study on STDMA using NS-2 simulation [24]. For the in-depth analysis, we isolate the impact of peripheral device (GPS) errors and the impact of configurable parameters. First, we compare the performance of STDMA with that of EDCA. Then, we investigate STDMA according to configurable parameters (i.e., STDMA system parameters, CS threshold, and physical transmission rates), based on the belief that we can improve system performances by tuning the parameters carefully. To focus on the impact of the parameters, we assume that there are no peripheral device (GPS) errors (i.e., no time synchronization error). Next, we focus on the impact of peripheral device (GPS) errors, which can happen in practical operations: when time synchronization happens.

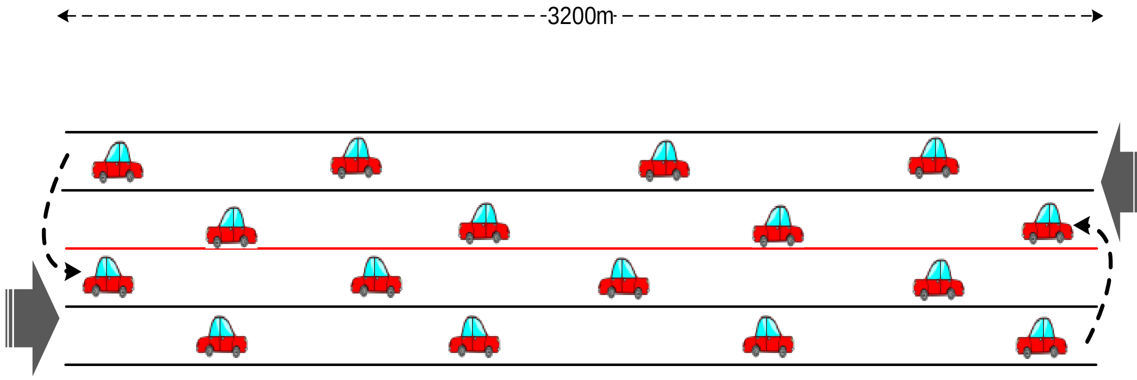


Figure 2.16: Topology used in simulation study

2.4.1 Simulation Setup

Fig.2.16 illustrates a topology that is used in our simulation study. In the study, we consider a two-way two mile road segment with four lanes as we can find in many highways. We summarize default simulation settings in Table 2.2. For PHY layer protocol, we follow IEEE 802.11p [10]. In MAC layer setting, we use STDMA system parameters that are calculated from message size (345byte), message generation interval (100ms) and physical transmission rate (3Mbps). More specifically, the size of unit time slot is derived by dividing a message size by physical transmission rate [32]. Then, we can obtain NI by dividing an average report interval by the size of a unit time slot. Finally, we calculate SI based on NI. The default setting of SI is one fifth of NI [31] [32] [33]. However, this is just a default setting, which can change for further improvement.

In the simulation, we consider up to 400 vehicles, which is upper bound in practical vehicular situations. More specifically, according to [34], the life-critical accidents happen at least once per year when the speed is above 35mph. Moreover, the normal gap between two vehicles is around 1.5sec, which is equivalent to 30m gap [35]. Thus, as considering 4-lane road with 2mile, we consider the number of vehicles can be up to 400.

Table 2.2: Default system parameters for STDMA study

Transmission power	20 dbm
Carrier sensing threshold	-78 dbm
physical transmission rate	Variable (3Mbps is default)
Channel model	Nakagami fading model
Message generation	345byte / 100ms
Number of vehicles	Variable (80 is default)
Noise power (dbm)	-104 dBm
Parameters for STDMA	Variable ((NI, SI, slot size) = (90, 18, 1.1ms) are default set)

2.4.2 Performance Measures

We exploit two important performance measures for vehicular safety applications: Packet Delivery Ratio (PDR) and Communication delay [15]. The two performance measures are defined as follows.

- **Packet Delivery Ratio (PDR)**: a ratio of the number of vehicles that receive a packet ($n_{receive}$) to the number of vehicles within a ZoI of a sender (n_{target}).

- **Communication delay**: an interval between a packet generation time and a packet reception time.

2.4.3 Comparison between STDMA and EDCA

In Fig.2.17, we observe that the PDR of STDMA is higher than that of EDCA and the improvement over EDCA is up to 63%. This is because STDMA is based on the synchronous channel access while EDCA employs asynchronous channel access. To be specific, time is divided into multiple slots; and the vehicles that

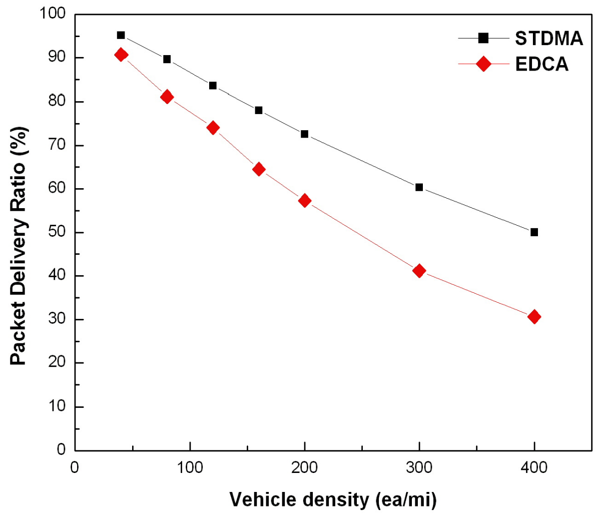


Figure 2.17: Comparison between PDR of STDMA and that of EDCA according to vehicle density

employ STDMA can only access the channel at the start of each time slot. On the other hand, vehicles that employ EDCA are not synchronized in time and they can access the channel regardless of the slot start. It is well-known that the synchronous access improves performance over asynchronous access. However, for synchronous access, vehicles need time synchronization, which is normally realized with Global Positioning System (GPS).

As shown in Fig.2.18, the delay of STDMA is longer than that of EDCA. This is because vehicles can only access the channel in their own slots even if having packets to transmit in STDMA. Thus, the dominant factor in STDMA delay is the queuing delay, which is only affected by transmission slot and message generation time. As the generation time is independent of vehicle density, the delay of STDMA remains to be the same. On the other hand, in EDCA, the vehicles can attempt to access the channel through waiting random amount of time; their Contention Window (CW) size is small; no retransmission mechanism

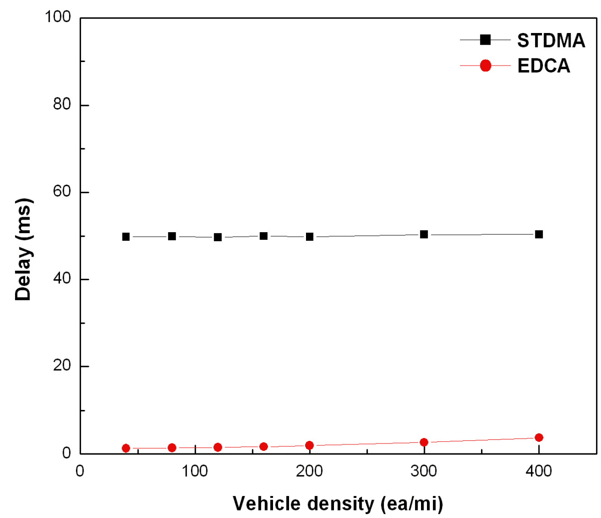


Figure 2.18: Comparison between delay of STDMA and that of EDCA according to vehicle density

is adopted. Thus, their delay is shorter than that of STDMA.

2.4.4 Impact of Carrier Sensing Threshold

According to the previous studies on EDCA [39], CS threshold significantly affects the performance of a mobile network system that adopts EDCA as its MAC protocol. This is because a mobile device can sense hidden devices well if the carrier sensing range is wide (i.e., small CS threshold). However, the mobile device might frequently lose the channel access opportunities if the CS threshold is too small. This, in turn, induces long transmission delay and such a long delay makes the packet out-of-date. Thus, [39] suggested to find the appropriate CS threshold that balances between mitigation of hidden terminal problem and long delay. Based on the belief that CS threshold affects the performance of the system with STDMA as well, we evaluate the performance of STDMA by varying the CS threshold.

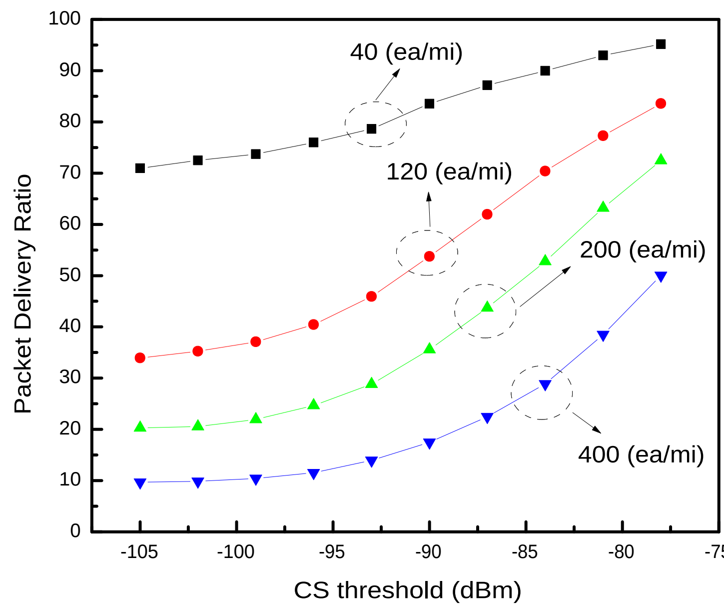


Figure 2.19: PDR of STDMA according to the CS threshold when the number of vehicles is 40, 80, 200, and 400.

In Fig.2.19, we observe that the PDR of a STDMA decreases as the CS threshold decreases. The pattern in Fig.2.19 is somewhat different from the pattern in EDCA. This is because of the inefficient slot selection mechanism of STDMA. Specifically, instead of backing off the channel access when detecting busy channel (i.e., CSMA/CA), vehicles with STDMA record the busy slots and select their transmission slots among only idles slot periodically. For this reason, as the CS threshold decreases, the number of idle slots within a period is reduced, which increases the probability of selecting the same slot among vehicles. Since vehicles with STDMA do not conduct carrier sensing in their transmission slots, selecting the same slot leads to packet collisions with one hundred percent.

Even more, when finding all slots in Service Interval (SI) to be busy, vehicles must select the slot that is occupied by a vehicle furthest away from themselves. However, to recognize the distance from their neighbors, vehicles can decode packets during a monitoring phase. In selecting transmission slot, vehicles must choose

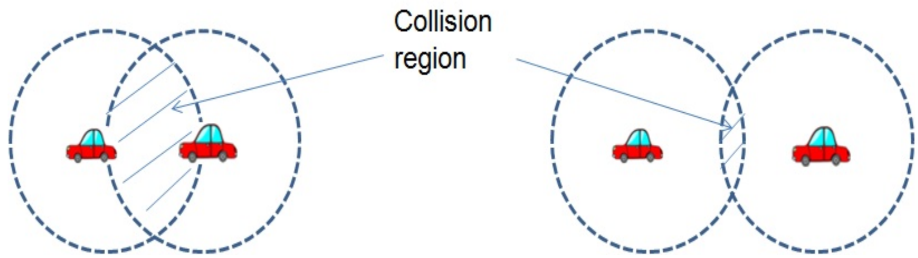


Figure 2.20: The collision region according to the distance between concurrent transmitters

Nominal Transmission Slot (NTS) among decodable slots. The fact that vehicles can decode received packet successfully implies that the distance from the packet senders is close. Selection of the same slot by close vehicles may cause more receivers to suffer from packet collisions, as shown in Fig.2.20.

Fig.2.21 illustrates the delay of STDMA according to a CS threshold. Similar to evaluation results in section 2.4.3, the delay does not change as CS threshold changes.

2.4.5 Impact of STDMA parameters

In Fig.2.22, we observe that the PDR of STDMA remains the same despite the change of SI, which is somewhat counter-intuitive. In STDMA, packet collisions happen when more than two vehicles select the same time slot, however, the probability of selecting the same time slot rarely changes due to SI misalignment among vehicles. More specifically, for selecting the same time slot, two vehicles must satisfy following two conditions simultaneously: 1) SIs of two vehicles must be overlapped and 2) two vehicles must select the same slot within their own SIs. It seems that the increases in SI reduces the probability of selecting the same slot since the second event becomes less probable. However, the rise in SI leads to the increase in the probability of the first event. Therefore, the probability that more

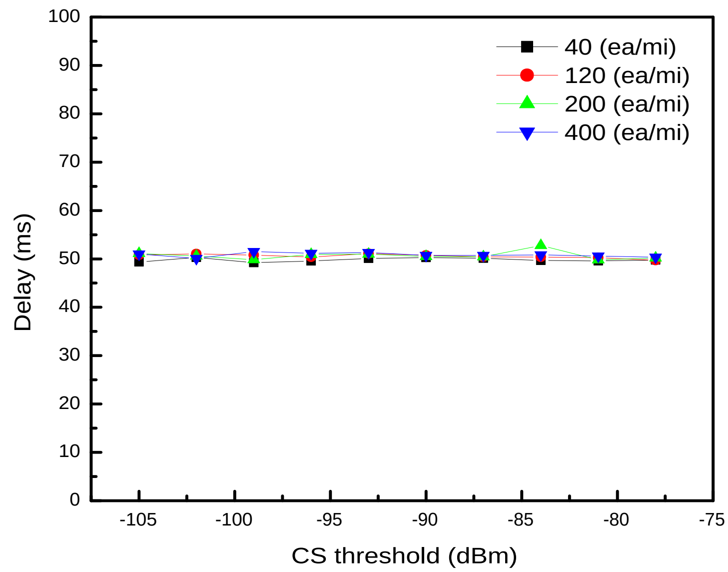


Figure 2.21: Delay of STDMA according to the CS threshold when the number of vehicles is 40, 80, 200, and 400.

than two vehicles select the same slot rarely changes as SI varies.[3]

As shown in Fig.2.23, the delay of STDMA remains the same as SI varies. This is because the dominant factor of the delay is queuing delay, which is determined by the message generation time and vehicle's designated time slot. It is obvious that the message generation time does not rely on SI. Moreover, the vehicle's designated time slot is rarely affected by the size of SI. Instead, it is affected by the location of SI (i.e., NSS or NS), which is randomly selected within NI. As a result, the delay is not affected by the size of SI.

[3]Simple mathematical calculation reveals that the probability that the first event and the second event happen simultaneously is independent of SI, if we do not consider the case of selecting another slot due to busy slot selection at the first time.

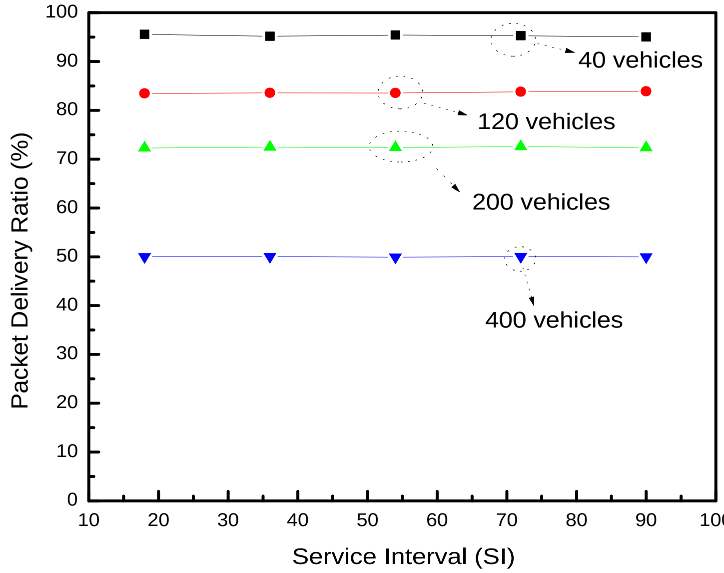


Figure 2.22: PDR of STDMA according to Service Interval (SI) when the number of vehicles is 40, 80, 200, and 400

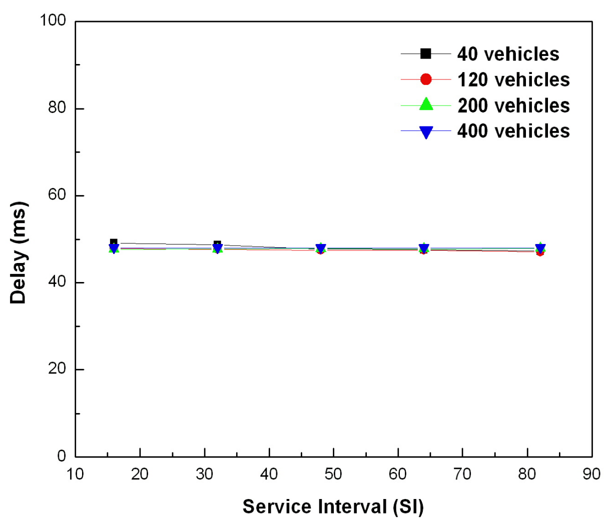


Figure 2.23: Delay of STDMA according to Service Interval (SI) when the number of vehicles is 40, 80, 200, and 400

2.4.6 Impact of Physical Transmission Rate

Even if the DSRC physical layer (i.e. IEEE 802.11p) supports multiple transmission rates, previous studies on EDCA [21] [27] assumed that only the lowest rate was adopted for safety message transmission. This is because the decoding reliability is maximum when the lowest rate is exploited, while the collision probability is rarely affected by transmission rates in EDCA.

However, in STDMA, both the decoding reliability and the collision probability are affected by the transmission rate. In detail, the increase in the transmission rate can diminish the collision probability. This is because we can locate more time slots within NI, which comes from the reduction of a unit slot time size[4]. However, the increase in the transmission rate reduces the decoding reliability. Therefore, it is necessary to study the STDMA performance when we apply various physical transmission rates.

Fig.2.24 demonstrates that the lowest transmission rate is not always optimal in terms of PDR. More specifically, when the number of vehicles is small, a low transmission rate tends to become optimal (e.g. 6Mbps when there are 40 and 80 vehicles). This is because a decoding failure is a dominant factor of reception failures rather than a packet collision when the vehicle density is small. Thus, the adoption of lower transmission rate leads to higher PDR. On the other hand, when the number of vehicles is large, a high transmission rate is normally an optimal rate in terms of PDR (e.g., 18Mbps when there are 400 vehicles). This is because a packet collision is a dominant factor rather than a decoding error in high vehicle density.

Similar to previous section, the delay is not affected by the transmission rate as well as the number of vehicles, as depicted in Fig.2.25. This is because the queuing delay, which accounts for the large portion of the delay, is determined

[4] We can customize a slot size to the transmission time of the safety message.

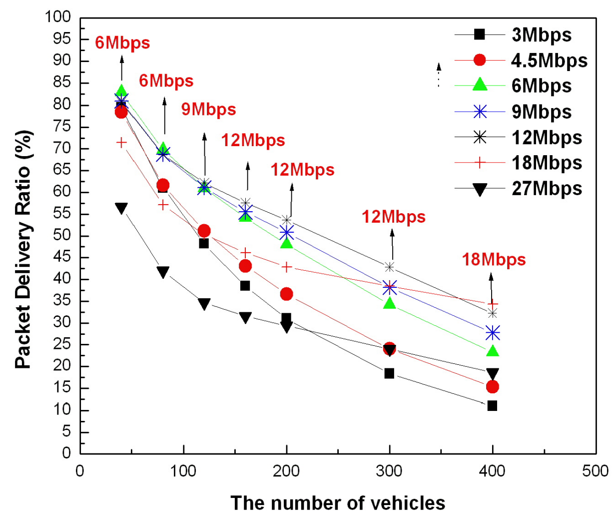


Figure 2.24: PDR of STDMA according to the number of vehicles when various physical transmission rates are used.

by the message generation time and a slot time that is assigned for each vehicle. Obviously, both are independent of a transmission rate. Hence, the delay does not depend on the transmission rate.

2.4.7 Impact of Time Synchronization Errors

In STDMA, time synchronization is important since the slot misalignment caused by synchronization error induces additional packet collision. For example, even if two vehicles in the vicinity select different time slots, there might exist an overlap between their transmissions, which comes from slot misalignment. Obviously, this overlap causes packet collision, which degrades network performance. Thus, it is necessary to study STDMA performance when time synchronization error exists.

In practical situations, time synchronization error happens when vehicles fail in receiving Global Positioning System signal due to large obstacles (e.g., bridges).

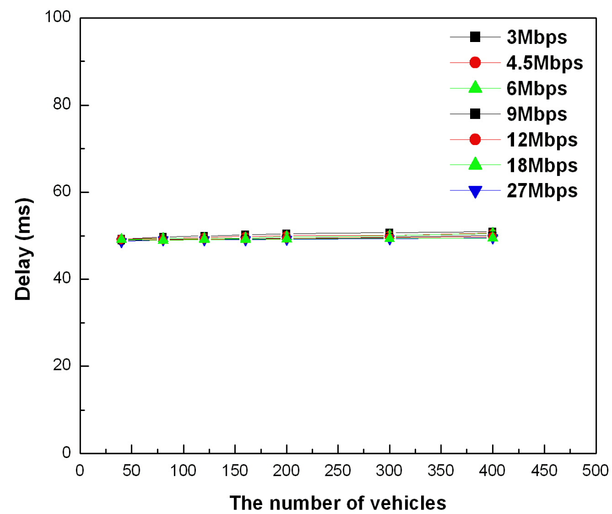


Figure 2.25: Delay of STDMA according to the number of vehicles when various physical transmission rates are used.

More specifically, vehicles cannot update its local time to global GPS clock when failing in GPS signal reception. In this case, vehicles suffer from time synchronization error since local clock generator of each vehicle has slight difference. In our simulation studies, we assume that vehicles fail in receiving GPS signal when located under the bridge and suffer from time synchronization errors with a 100ppm clock skew rate [36]. Regarding bridge placement, we consider a wide bridge with 10 lanes, which can be found in I-405 freeway area in Los Angeles [37].

Fig.2.26 shows that the time synchronization error induces additional packet collision in STDMA. More specifically, as the number of bridges increase, PDR of vehicles is getting lower. This is because the increase in the number of bridges causes more GPS reception errors. Thus, the packet collision that comes from slot misalignment induces the decrease in PDR.

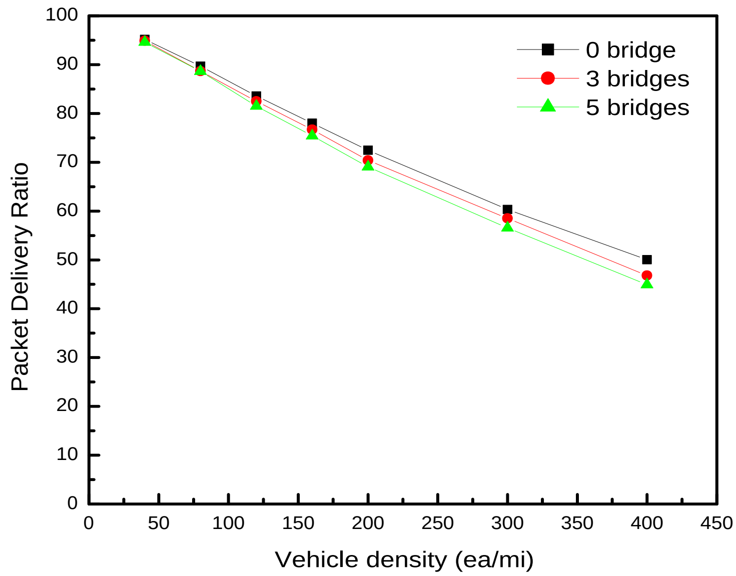


Figure 2.26: PDR of STDMA according to the number of vehicles when time synchronization errors sporadically happen.

2.4.8 Discussion

In STDMA, an upper bound of delay is guaranteed, however, PDR of STDMA is not high enough to support various safety applications. The PDR will be lower when the number of vehicles is larger than 400 within 2 mile. Thus, we need to improve PDR of STDMA when many vehicles share the channel.

The reasons of low PDR are three-folds. First, STDMA lacks in an organized schedule due to its distributed time slot selection mechanism. Specifically, a random selection plays an important role in STDMA's time slot selection - NSS (or NS) is selected randomly within NI and time slot is selected randomly within SI. In STDMA, there is a flavor of an organization based on channel measurements. However, the selection mechanism based on measurement has limitations. In STDMA, if the chosen time slot is occupied by others, the closest unoccupied slot is selected. Unfortunately, as vehicles in the vicinity have similar measurements, it is highly probable to select the same slot if their SIs are very close. In this case, packet collision happens since carrier sense mechanism is not employed in STDMA. Second, current STDMA lacks in adapting their configurable parameters to network conditions. As shown in section 2.4.6, the careful selection of a physical transmission rate can improve PDR of STDMA (e.g., Fig.2.26 shows that PDR improves up to 40%.). Our suggestions to improve the PDR of STDMA are as follows. First, we should adopt a more organized slot schedule than current STDMA. Unfortunately, the big problem in an organized schedule is the usage of a central controller, which is not appropriate to highly mobile network, including vehicular networks. To remedy this challenge, we suggest to exploit a clustering mechanism, by which an organized schedule is possible within a cluster (i.e., the schedules of vehicles in the vicinity can be organized). The second suggestion is to employ an adaptive transmission rate selection. However, the adaptive rate selection might induce another problem. Specifically, the improvement of an adaptive rate selection comes from a customization of slot size to message transmission time. However, unorganized customization of slot size may induce heterogeneity of transmission rates among vehicles in the vicinity. The heterogeneity, in turn, causes slot misalignment, which can be a reason of packet collision. Fortunately, a cluster-based mechanism has benefits in making cluster members share the same parameters (e.g., transmission rate). Therefore, as the future work, we will propose a new mechanism that improves STDMA based on a clustering mechanism. Final suggestion is to adopt the advanced broadcasting algorithm that employs with an acknowledgement and retransmission mechanism.

2.5 Conclusion

In this chapter, we studied the performances of two MAC protocols: 1) DSRC hybrid MAC protocol where EDCA and HCCA coexist to support work zone safety and 2) STDMA when it is adopted for vehicular safety applications.

Regarding the first protocol, the hybrid MAC protocol, we find that the interactions between EDCA and HCCA affect system performance, in some cases producing somewhat counter-intuitive effects. Moreover, we observe that the current combination of EDCA and HCCA causes large delay in HCCA and low PDR in EDCA, making it not suitable for supporting work-zone safety service. Through an analysis of simulation results, we notice that poll message collisions and high network load account for large delay of HCCA and low PDR of EDCA, respectively. These results pave the ground for possible improvements of the current system, which will be the objective of our future work.

Regarding the second MAC protocol, STDMA, we find that STDMA guarantees an upper bound of delay, but its PDR is not high enough to support vehicular safety applications, especially when the density of vehicle is high. Through an in-depth analysis of simulation results, we notice that a non-organized slot selection mechanism and a static parameter configuration account for low PDR of STDMA.

CHAPTER 3

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

3.1 Motivation

As vehicle accidents increase, developing new technologies for preventing vehicle accidents becomes a top priority for the U.S Department of Transportation (DOT) [40]. 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 ($\leq$ 100ms) [15]. 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 a Dedicated Short-Range Communications (DSRC) [10], 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 $\sim$ 1000m) [15] [42] [43]. 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 [41], additional path loss induced by obstructions (i.e., blocking by truck, bus, or trees) is 10 $\sim$ 20dB (i.e., comparable to range reduction by 3.16 $\sim$ 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) [19] [45] [1], which will be shown in Fig.3.13.

There have been previous approaches for mitigating network congestion of VANET in a DSRC band [46] [47]. [46] proposed a multi-hop dissemination scheme for reducing redundant rebroadcasts. However, [46] did not employ a mechanism for supporting high delivery ratio of safety message. [47] addressed this issue by proposing an acknowledgement-based broadcast mechanism. However, [47] 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

[1]Emergency events can happen under high vehicle density such as appearance of fire engine and malfunctioning of brake system

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 [48]. This is because the operation frequency of a TVWS band is much lower than a DSRC band [49] [50]. 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 [45]. Thus, vehicles can use the TVWS band opportunistically based on spectrum availability data on each geo location, which was measured in advance [51].

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 [52] [53]. [52] proposed to use additional TVWS band when estimated contention delay in DSRC band is larger than a pre-defined threshold. However, in [52], Road Side Unit (RSU) is necessary for making decision on accessing a TVWS band. [53] proposed a cognitive network system that had two network interfaces, one for an exclusive usage band such as DSRC band and the other for a cognitive usage band like TVWS band. However, [53] is based on a clustering mechanism, which induces large overhead when topology changes frequently like in VANET. Given all of the above, [52] [53] 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 chapter, 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 disseminate an 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 a 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) [44]. 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 [43] [55].

Intensive simulation studies show that our scheme outperforms legacy DSRC systems with two interfaces by 64 (86)% and [53] by 17 (56) % in highway (2X2 Manhattan grid) situation. Further, our system supports high reachability of ESM with delay bound constraints under various scenarios.[2]

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

- Propose a novel interplay strategy between TVWS and DSRC bands, which leverages the advantage of each band for ESM dissemination.
- The interplay strategy is robust to dynamic vehicular topology changes.
- Establish a new analytical model that captures delay bound of ESM.

3.2 Interplay Between TVWS Band and DSRC Band

3.2.1 System Model

Similar to previous works [53] [54], we assume that every vehicle uses two radio interfaces.[3] 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 [10] on a DSRC interface and IEEE 802.11 with 5MHz option [11] on a TVWS interface.[4] 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). However, 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. Differentiation

[2] However, implementation cost of our system is not large since only frequency change of radio interface is needed.

[3] Compared to cost of a vehicle, cost of using two radio interfaces is very small.

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

between ESM and typical user signals can be done via preamble detection.

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 [14]. 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 [55].

It is noted that multiple vehicles can generate ESMs from the same emergency event in certain safety systems. In this case, a CSMA/CA with a random back-off 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 needs to be delivered. Since vehicles that see the same emergency event are located in a vicinity, the vehicles can receive an ESM signal with high SNR. So, many vehicles can suppress their ESM transmission attempts.

3.2.2 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 [56] 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).

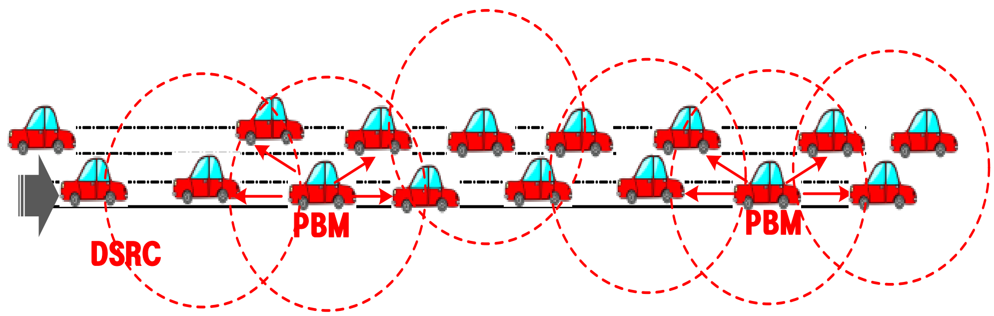
On the other hand, a transmission range of a TVWS band is large due to operation in a low frequency band. This is because path loss and penetration loss is relatively small in a low frequency band. For example, the Wi-Fi in a TVWS band has a larger transmission range than IEEE 802.11 in 2.4GHz by 3 times [48]. Thus, a large transmission range of a TVWS band makes it possible to cover a dissemination area of most safety applications [15] [42] [48].

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 [57], 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.

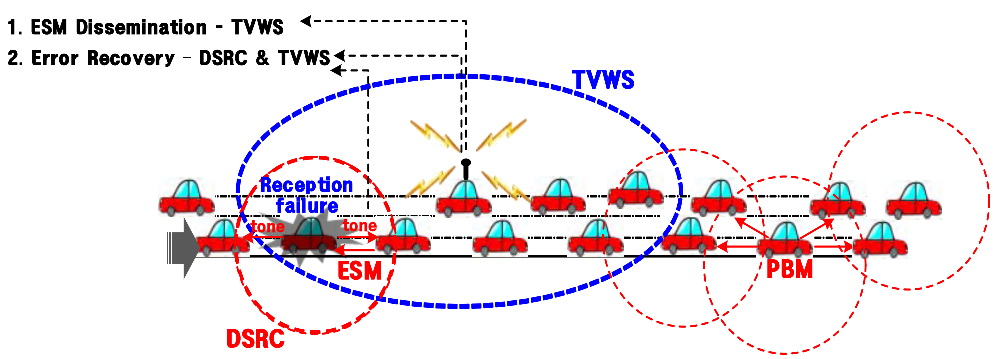
On the other hand, a DSRC band is always available to vehicles since it is dedicated to vehicular communication. In multiple-channel protocols, control data is usually exchanged among vehicles via a channel that is always accessible by all vehicles. Hence, the DSRC band can be used for a common control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

3.2.3 Overview of the Proposed System

Fig.3.1 depicts an overall operation of the proposed scheme. In normal situations (Fig.3.1(a)), vehicles periodically exchange PBMs with each other using a DSRC interface. When detecting an emergency event (Fig.3.1(b)), a vehicle generates and disseminates an ESM to the vehicles within a service area using a TVWS



(a) When emergency event does not occur



(b) When emergency event occurs

Figure 3.1: Basic operation of proposed system (a) when emergency event does not occur and (b) when emergency event occurs

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.

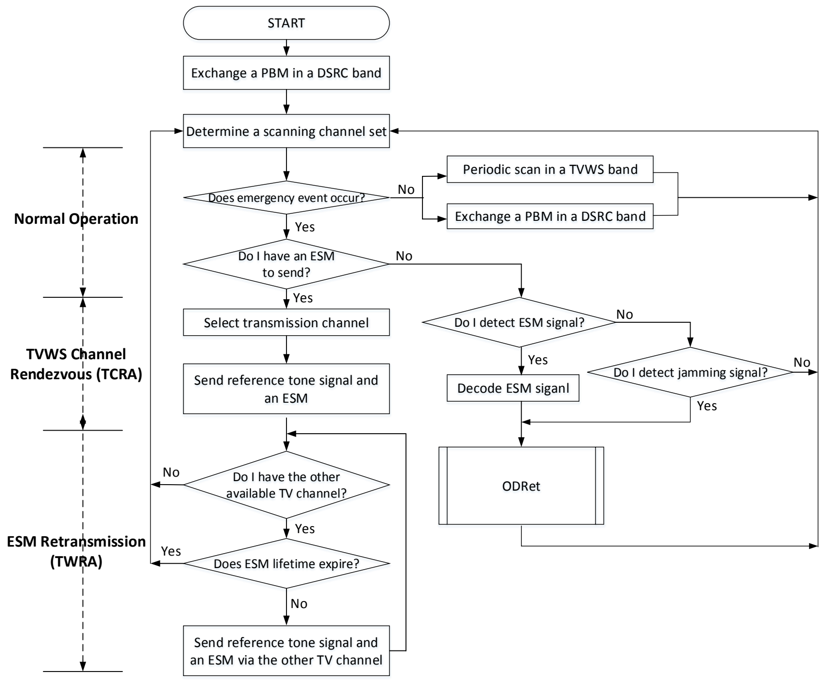
Many government authorities (FCC in U.S. and IDA in Singapore) declared that the secondary users are required to rely on "TVWS channel database" for accessing to TVWS channels, and the authorities eliminate the requirements of a physical sensing [72] [73]. The database specifies available TVWS channels 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$\sim$12 hours [72] [73]) 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 [69][5].

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[6]. 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.

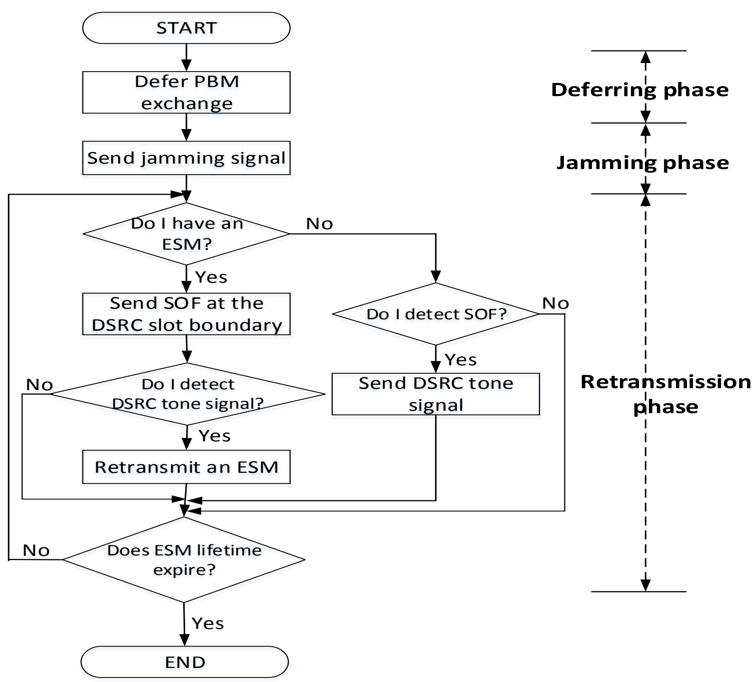
Sometimes, there is a case when a vehicle has more than two available channels with the maximum count. In this case, the vehicle selects the channel with a minimum background signal strength (i.e., the signal strength that a vehicle measures when a preamble of an ESM is not detected). Specifically, during a periodic scan process (see Fig.3.2(a) and section 3.2.4 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 as the background signal strength that a vehicle measures is small,

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

[6]The vehicle obtains neighbors' position by exchanging a PBM, which includes sender's position as well as neighbors' positions.



(a) Flowchart for an overall operation



(b) Flowchart for ODRet

Figure 3.2: Flowcharts for (a) an overall operation of the proposed scheme and (b) On-demand DSRC Retransmission (ODRet)

a TV broadcasting tower tends to be far from the vehicle. Thus, vehicles within a service range usually suffer from less interference generated by the broadcasting tower. Sometimes, a 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. The details on this will be explained in section 3.2.5.

For example, in Fig.3.3(a), VEC 2 should select channel 7 for its transmisssion channel, since channel 7 is available to both VEC 1 and VEC 2, while other channels (channels 4∼6) is only available to VEC 2. The criteria for selecting a transmission channel is based on the belief that interference by a TV broadcasting tower tends to be small in the available channel. Thus, using this mechanism for transmission channel selection, the largest number of 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.

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.

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 Clarkes model, we can estimate coherence time as $65 \sim 92$ ms ($512 \sim 698$MHz) when the relative speed is 10km/h[7] [59] [60].

Fig.3.2(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 procedure, which we will further explain in section 3.2.4. 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

[7]Since the vehicle moves by platoon, the relative speed is small.

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 3.2.5.

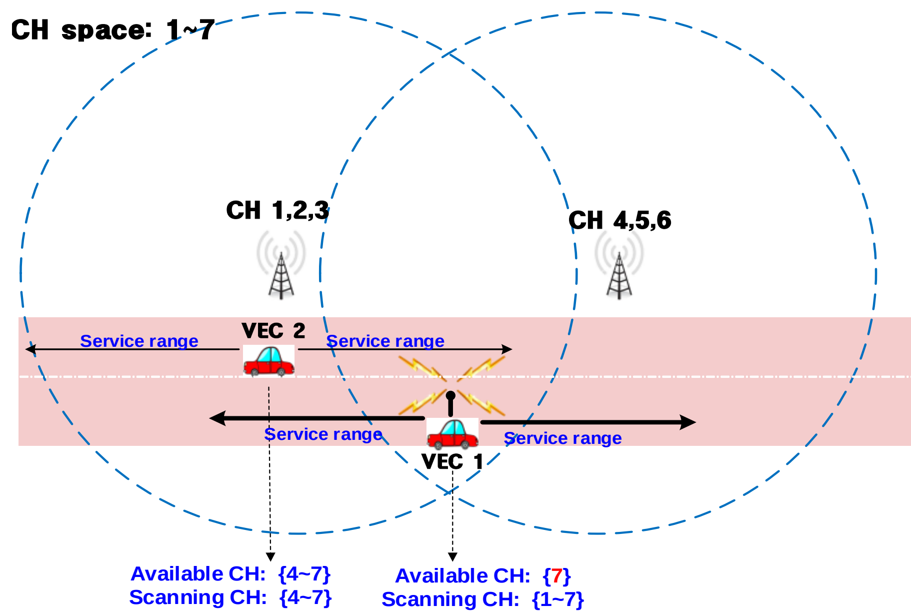
3.2.4 Rendezvous Algorithm among multiple TVWS channels

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.

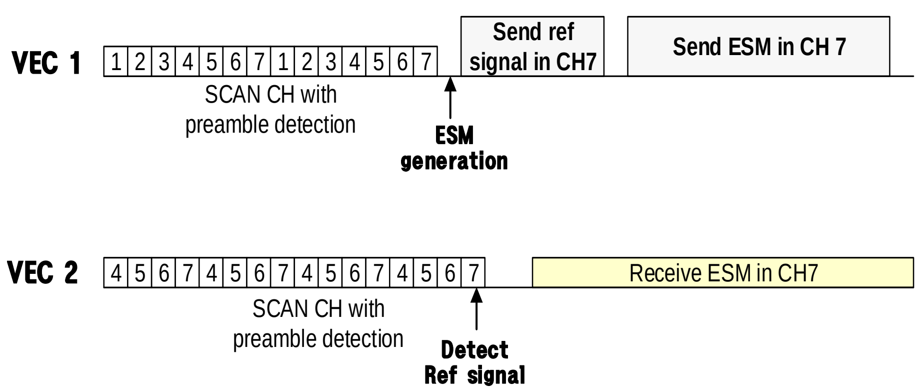
Frequency domain challenge is that vehicles must know which frequency channel is used for transmitting an ESM. In order to overcome this challenge, vehicles scan all the available TVWS channels within their service area (scanning channel list) periodically. Vehicles can find all the available TVWS channels within a service area by inquiring available TVWS channels of a TVWS database for each position.[8] As a vehicle scans all the available channels periodically, the vehicle can detect an ESM signal transmitted by another vehicle within its service area.

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

[8]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 [58].



(a) Available channel set and scanning channel set



(b) Behavior at scanning phase and ESM transmission phase

Figure 3.3: Operation of TCRA - (a) how scanning channel set is established and (b) behavior at scanning phase and ESM transmission phase

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.

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 [58], 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 [60] and the duration of preamble detection is 64us in TVWS band [11]. Therefore, the duration of reference tone signal is at most 2.205ms, which is much shorter than delay bound of an ESM (100ms).

Notably, in TCRA, each vehicle might scan unavailable TVWS channels in TVWS database as well. For example, as depicted in Fig.3.3(a), STA 2 scans channels 1$\sim$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.

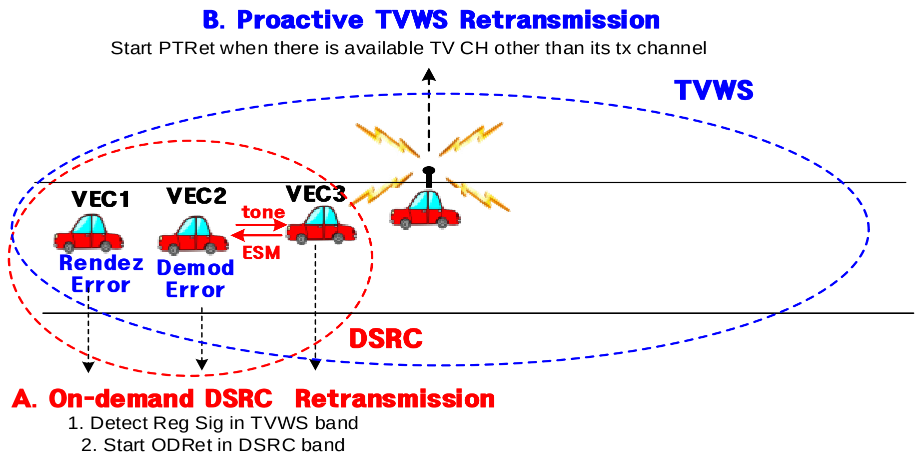
We should note that a detected signal in a TVWS band can be either a reference tone signal by a vehicle or a signal by a TV broadcast tower. To differentiate the two types of signals, a vehicle performs a preamble detection. To be specific, every vehicle knows a sequence for preamble generation in advance. When a vehicle senses a busy channel in a scanning phase, it calculates a correlation between the known sequence and a received signal, and determines that the signal is a reference tone signal if the correlation is above threshold. Using this procedure, 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.3.3. Fig.3.3(a) illustrates how a scanning channel list is determined for VEC 1 and VEC 2. Within the service range of VEC 1, channels 1$\sim$3 are available on the left side of service area; channels 4$\sim$6 are available on the right side of service area. Hence, even if channels 1$\sim$3 and channels 4$\sim$6 are not available to VEC 1, the scanning list of VEC 1 includes channels 1$\sim$7. Similarly, VEC 2 sets its scanning list to channels 4$\sim$7.

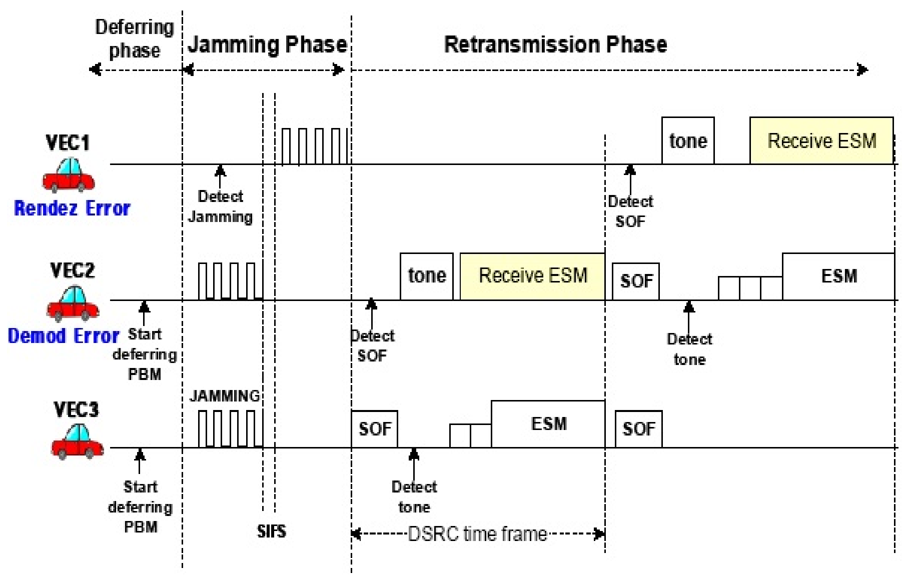
We explain the TCRA procedure with a simple example. Fig.3.3(b) illustrates the behaviors of VEC 1 and VEC 2 in scanning and ESM transmission phases. In a scanning phase, VEC 1 and VEC 2 periodically scan channels 1$\sim$7 and channels 4$\sim$7, respectively. When VEC 1 generates an ESM, the vehicle stops a scan process and sends a reference tone signal via channel 7. Meanwhile, VEC 2 detects the reference tone signal at a channel 7, and then stops its scan process. In an ESM transmission phase, VEC 1 sends an ESM via the channel 7 after transmission of a tone signal. When VEC 2 notices that the reference tone signal is ended, it receives an ESM.

3.2.5 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)



(a) Overview of TWRA: A) ODRet and B) PTRet



(b) Behavior in ODRet

Figure 3.4: Two-Way Recovery Algorithm (TWRA) (a) Overview of TWRA and (b) behavior at jamming detection phase and retransmission phase in ODRet

optional Proactive TVWS Retransmission (PTRet), as depicted in Fig.3.4(a).

3.2.5.1 On-demand DSRC Retransmission (ODRet)

Fig.3.4(b) illustrates the behavior of ODRet. Vehicles initiate ODRet when they detect an ESM signal in a TVWS band[9] 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.3.4(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.3.4(b)), they transmit a jamming signal in a DSRC band, as depicted in Fig.3.4(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.3.4(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),

[9]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.

the vehicle (e.g. VEC 1 in Fig.3.4(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.3.4(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.3.4(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 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 on simple example in Fig.3.4(b). In Fig.3.4(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.

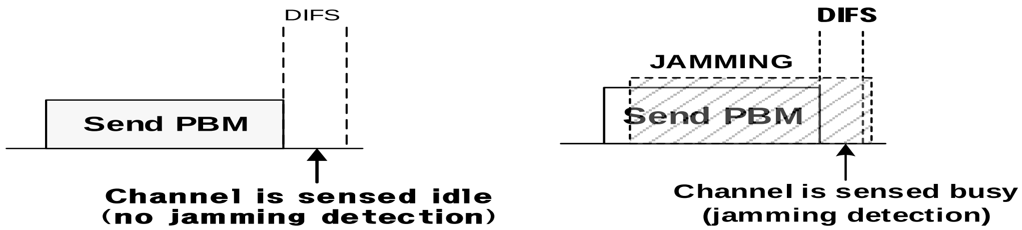
However, as multiple vehicles concurrently send DSRC tone or SOF signals, there might be a discrepancy between the length of detected signal and the predefined length; or SOF and DSRC tone signals can be overlapped with each other unless time is synchronized among vehicles. Fortunately, vehicles can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

Fig.3.2(b) illustrates a flow of ODRet operation. A vehicle triggers an ODRet when 1) detecting an ESM signal in a TVWS band during a TCRA procedure or 2) detecting a jamming signal in a DSRC band. When starting ODRet, the vehicle defers its PBM transmission (deferring phase). Then, the vehicle sends a jamming signal for letting other vehicles of rendezvous failure know the start of ODRet. (jamming phase). Thus, after jamming phase, all vehicles can start ODRet and ready to move on to the next phase (retransmission phase). In the retransmission phase, if having an ESM to send, the vehicle transmits a SOF to advertise the start of a DSRC time frame and retransmits an ESM. However, if the vehicle does not have an ESM, the vehicle notices the start of the DSRC time frame by detecting the SOF, and advertises its reception failure via sending a DSRC tone signal. Then, the vehicle receives an ESM. This procedure is repeated until a lifetime of the ESM expires.

It is noted that the probability of packet collision might be high when many vehicles concurrently send an ESM as a response to a DSRC tone signal. To cope with this undesirable situation, vehicles control Contention Window (CW) size, which can be performed via optimal parameters selection in section IV.

Notably, the 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 3.4. 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 service area multiplied by the duration of each jamming signal.

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.3.5 illustrates a solution to address this challenge. When there is no jamming signal (Fig.3.5(a)), the channel is sensed idle during DCF Inter-Frame Space (DIFS) right after PBM transmission. However, when there is jamming signal (Fig..3.5(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.



(a) When there is no jamming signal (b) When there is jamming signal

Figure 3.5: Method for recognizing jamming signal when a vehicle sends a PBM

3.2.5.2 Proactive TVWS Retransmission (PTRet)

To further improve the reachability of an ESM, TWRA adopts a TVWS band as a supplementary channel that goes with a DSRC band. More specifically, an original ESM sender (e.g., vehicle located in center of Fig.3.4(a)) retransmits the ESM only if there are available TV channels except the originally sent channel in a proactive manner.

It is noted that vehicles are not aware of whether the signal that is detected in a TVWS band is from an ESM retransmission or not. If detecting the signal caused by an ESM retransmission, vehicles must not start a new ODRet session, (i.e., transmitting jamming signal). If vehicles start a false ODRet session, signals in the false session might interfere with signals in a current session. To address this problem, in a TVWS band, the sender retransmits the ESM only at *the retransmission phase* to indicate that current transmission is for *ESM retransmission*. When detecting an ESM signal during a retransmission phase, vehicles do not start another ODRet session. Specifically, after going through jamming phase, vehicles within a service range notice that they are in retransmission phase. Thus, all vehicles within a service range can discern whether the detected signal is from an ESM retransmission or not. Through this mechanism, we can solve the above-mentioned issue.

It is noted that several vehicles may generate ESM for the same emergency situation and some of them may be transmitted in a retransmission phase, as explained in section 3.2.1. In this case, vehicles do not start new ODRet session since the ESM generated by other vehicles have the same emergency info. This implies that vehicles within a service range necessarily receive at least one ESM among them. Thus, the ESM dissemination by nearby vehicles can be regarded as ESM retransmission by proxy senders.

3.2.6 Operation Outside a Spectrum Map Coverage

Most drivers set driving routes in a navigator and follow directions of the navigator. However, drivers sometimes deviate from their routes if encountering work-zone areas or traffic jam. In this case, vehicles go beyond their spectrum maps coverage, which causes failure in getting available TV channels.[10] To remedy this challenge, we propose a hybrid scheme: vehicles conduct a physical sensing outside their spectrum maps coverage and rely on the maps within the coverage.

In the hybrid scheme, we incorporate a physical sensing into the scanning phase of TCRA. Specifically, a scanning channel set includes all TV channels that are allowed for mobile SUs. At every scanning phase of TCRA, each vehicle selects one channel for a physical sensing for a PU detection; the vehicle performs a preamble detection for the rest of channels in the set. 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

[10] We can reduce the possibility of this problem by carrying a spectrum map of more than one routes. (e.g., Google map supports two or three routes for each pair of start and destination points.)

+ 5)[11]. 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.

3.2.7 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. [70]. 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.

[11] 7.45ms 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.

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.[12] We will consider the detailed design of the collaborative system as our future work.

3.3 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 PTRet) 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.

3.3.1 Assumptions

We make three 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

[12] In the future,the above-mentioned collaboration can be achieved with a single radio interface with a Software-Defined Radio (SDR) technique [67].

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. We will analyze the reliability on detecting jamming signal, which is composed of 802.11 preambles. According to [61], the detection probability of 802.11 preamble is close to one if Signal to Noise Ratio (SNR) is equal to 1 db. In our case, a jamming signal is larger than PBM length ($\geq$100us), which means that the jamming signal is longer than short preamble by 12 times. Hence, even if the SNR is much lower than 1db, the probability of detecting the jamming signal is close to one.

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.

Third, we assume that time is slotted into mutiple expected slot and all events happen in a slot boundary, as most previous mathematical models did [68]. Here, slot is a interval between consecutive events. For example, a slot is equal to unit backoff duration in an idle channel, while a slot is equal to packet transmission time in a busy channel. All events actually happen at the start of slot. Thus, this assumption is reasonable.

3.3.2 Reachability of ESM

Fig.3.6 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.3.6) 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

Table 3.1: List of mathematical notations

$P^{esm}_{s,total}$	Reachability of ESM
$P^{esm}_{s,tvws}$	Probability of ESM reception in a TVWS band
$P^{esm}_{s,dsrc}$	Probability of ESM reception in a DSRC band
P_{rendez}	Probability of rendezvous success within a service rang
$P^{esm}_{e,tvws}$	Probability of channel errors in a TVWS interface
$P^{esm}_{s,dsrc}(i)$	Probability of ESM reception in a i-th DSRC time frame
n_{frame}	the number of DSRC time frames in ODRet
$E[slot]$	expected time slot
t^{DSRC}_{ESM}	transmission delay of ESM in a DSRC band
t_{SOF}, t_{tone}	durations of SOF and tone signal
σ	unit backoff slot length
τ	transmission attempt probability at each DSRC time frame
P_{busy}	Probability that the DSRC channel is busy
d_{dsrc}	transmission range of DSRC
ϕ	average density of vehicle
$P_{err}(i)$	probability that vehicles fail in ESM reception until i-th DSRC time frame

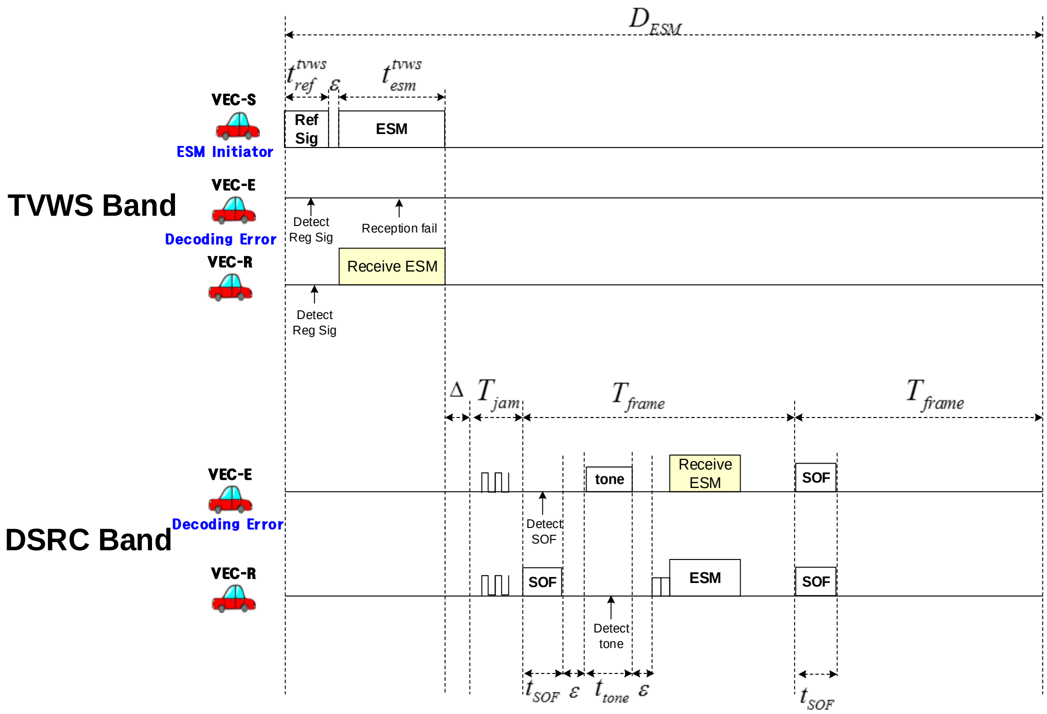


Figure 3.6: Time diagram that describes vehicle activities for ESM dissemination in TVWS and DSRC bands

reachability, $P^{esm}_{s,total}$, can be expressed as

$$P^{esm}_{s,total} = P^{esm}_{s,tvws} + P^{esm}_{s,dsrc} \tag{3.1}$$

where $P^{esm}_{s,tvws}$ is the probability of ESM reception in a TVWS band and $P^{esm}_{s,dsrc}$ 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 initiatior (e.g., VEC-S in Fig.3.6) at the same TVWS channel and succeed in decoding the ESM. Thus, $P^{esm}_{s,tvws}$ can be expressed as

$$P^{esm}_{s,tvws} = P_{rendez} \cdot p^{esm}_{dec,tvws} \tag{3.2}$$

where P_{rendez} is the probability of successful rendezvous between the ESM initiator and vehicles within a service area, and $p^{esm}_{dec,tvws}$ is the probability of decoding an ESM in a TVWS band. Vehicles succeed in the rendezvous with the ESM initiator when detecting a reference tone signal (i.e., "Ref Sig" in Fig.3.6). Hence, we can derive P_{rendez} from a probability of preamble detection, which can be obtained from a curve fitting in [61]. Likewise, we can easily calculate $p^{esm}_{dec,tvws}$ from a curve fitting in [11].

On the other hand, in a DSRC band, vehicles receive an ESM during ODRet to compensate ESM reception errors in a TVWS band. Therefore, $P^{esm}_{s,dsrc}$ is expressed as

$$P^{esm}_{s,dsrc} = (1 - P^{esm}_{s,tvws}) \cdot P^{esm}_{r,dsrc} \tag{3.3}$$

where $P^{esm}_{r,dsrc}$ is a probability of ESM receptions via ODRet, which will be derived in the following subsection.

3.3.3 Probability of ESM Reception via On-Demand DSRC Retransmission

As shown in Fig.3.6, the duration of ODRet consists of a deferring phase (Δ), a jamming phase (T_{jam}), and a retransmission phase. Likewise, a retransmission

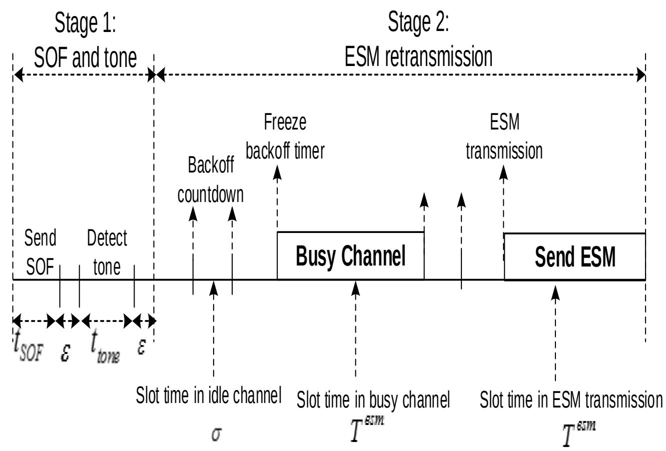


Figure 3.7: Slotted operation in each DSRC time frame of ODRet

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 $P^{esm}_{r,dsrc}$ can be derived as follows

$$P^{esm}_{r,dsrc} = 1 - \prod_{k=1}^{n_{frame}} (1 - p^{esm}_{s,dsrc}(k)) \tag{3.4}$$

where $p^{esm}_{s,dsrc}(k)$ 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.3.6) and is calculated as

$$n_{frame} = \left\lceil \frac{D_{ESM} - t^{tvws}_{ref} - \epsilon - t^{tvws}_{esm} - \Delta - T_{jam}}{T_{frame}} \right\rceil \tag{3.5}$$

where $\lceil \cdot \rceil$ is a ceiling function.

As depicted in Fig.3.7, 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; ϵ 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, $E[slot(i)]$ and all events happen in a boundary of the slot. $E[slot(i)]$ is obtained by

$$E[slot(i)] = T^{esm} \cdot p_{busy}(i) + \sigma \cdot (1 - p_{busy}(i)) \tag{3.6}$$

where T^{esm} is a transmission delay of ESM[13] and σ is a unit backoff time, and $p_{busy}(i)$ 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, $p_{busy}(i)$ can be expressed as

$$p_{busy}(i) = 1 - (1 - \tau(i))^{n_{vec}^{esm}(i)} \tag{3.7}$$

where $\tau(i)$ is a transmission attempt probability in a time slot of i^{th} frame and $n_{vec}^{esm}(i)$ is the number of vehicles that try to transmit an ESM at i^{th} frame. Fortunately, [68] 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

$$\tau(i) = \frac{2}{1 + CW} \cdot \frac{min(m(i), CW)}{CW} \tag{3.8}$$

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

$$m(i) = \left\lfloor \frac{T_{frame} - (t_{SOF} + 2\epsilon + t_{tone})}{E[slot(i)]} \right\rfloor \tag{3.9}$$

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

[13] Since freeze of backoff timer is caused by ESM transmission by other vehicles, we approximate that duration of backoff timer freeze is equal to T^{esm}.

within a DSRC transmission range (we call these vehicles *DSRC neighbors*) of a tone sender, they can hear the DSRC tone signal. Thus, $n_{vec}^{esm}(i)$ is calculated as

$$n_{vec}^{esm}(i) = 2 \cdot d_{dsrc} \cdot \phi \cdot \big[1 - (1 - P_{s,tvws}^{esm}) \cdot \prod_{k=1}^{i-1}(1 - p_{s,dsrc}^{esm}(k))\big] \tag{3.10}$$

where d_{dsrc} is a DSRC transmission range and ϕ is a density of vehicles.

In VANET, a hidden node problem frequently occurs, and thus we should consider an external collision as well as an internal collision [55]. Fortunately, there is an established model that considered both collisions [62], which we adopt for deriving $p_{s,dsrc}^{esm}(i)$

$$\begin{aligned} &p_{s,dsrc}^{esm}(i) = n_{vec}^{esm}(i) \cdot \tau(i) \cdot (1 - \tau(i))^{(c(i)-1+h(i)\cdot k)} \\ &k = \frac{2 \cdot T^{esm}}{E[slot(i)]} \end{aligned} \tag{3.11}$$

where $c(i)\big(h(i)\big)$ is the number of vehicles that can induce an internal(external) collision at a DSRC tone sender in i^{th} frame. Internal collision happens if DSRC neighbors transmit concurrently. Thus, $c(i)$ can be calculated as

$$\begin{aligned} c(i) = &\frac{1}{d_{dsrc}} \cdot \int_{x=-d_{dsrc}}^{0} (2 \cdot d_{dsrc} + x) \cdot \phi \cdot \\ &\big[1 - (1 - P_{s,tvws}^{esm}) \cdot \prod_{k=1}^{i-1}(1 - p_{s,dsrc}^{esm}(k))\big]\, dx \\ = &\frac{3}{2} \cdot d_{dsrc} \cdot \phi \cdot \big[1 - (1 - P_{s,tvws}^{esm}) \cdot \prod_{k=1}^{i-1}(1 - p_{s,dsrc}^{esm}(k))\big]. \end{aligned} \tag{3.12}$$

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

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

3.3.4 Model Validation

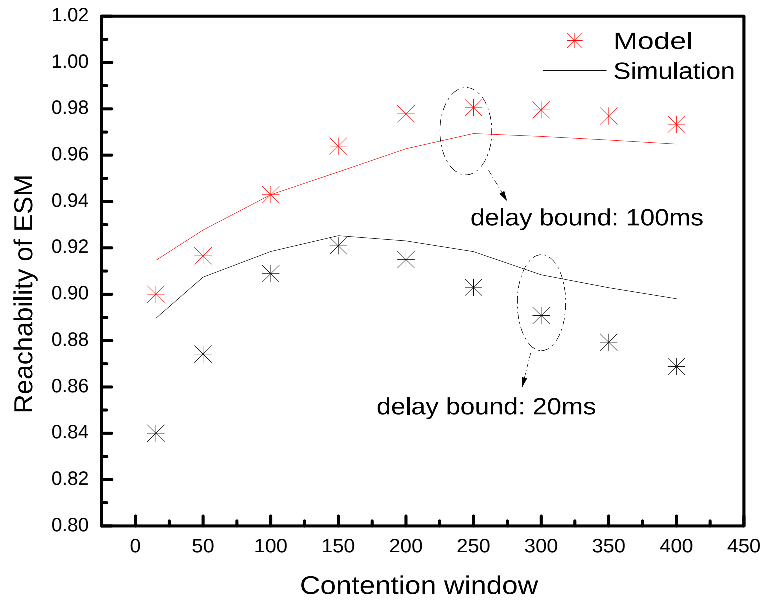
To validate our model, we compare the numerical results of the model with those of Qualnet simulation. We adopt simulation parameters in table.4.1. In the validation, we focus on whether the proposed model follows the pattern of ESM reachability according to two configurable parameters: 1) CW and 2) T_{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.3.8, we observe that the model well-predicts the pattern according to the parameters and the deviation from simulation results is within 1 to 10%.

3.4 DESIGN PARAMETER OPTIMIZATION

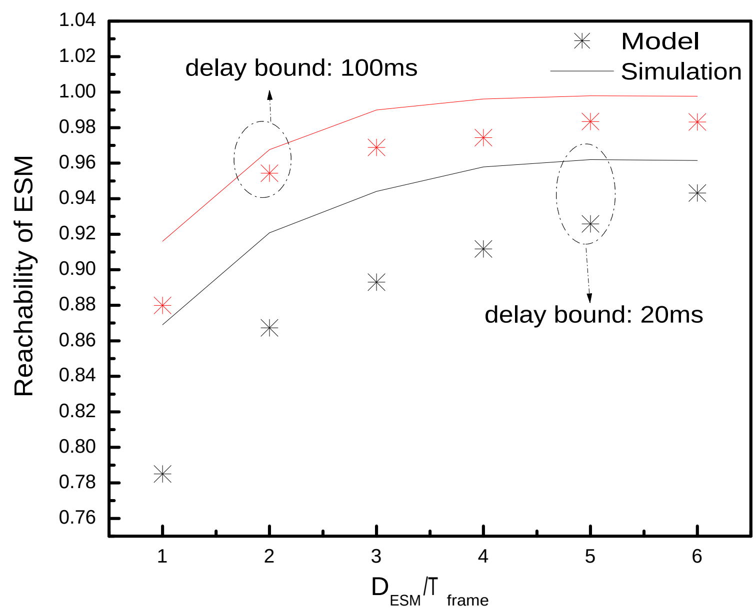
3.4.1 Problem Formulation

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_{frame} and 2) CW size. Reachabilty of an ESM depends on the efficiency of a recovery algorithm, which is affected by T_{frame} and CW size. More specifically, T_{frame} determines the number of recovery sessions (i.e. D_{ESM}/T_{frame}) and the efficiency of each recovery session, both of which are important in determining reachability of an ESM. Specifically, 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}. 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. To be specific,



(a) According to CW



(b) According to D_{esm}/T_{frame}

Figure 3.8: Comparison between numerical results of our model and those of Qualnet simulation according to (a) CW and (b) D_{esm}/T_{frame}

when 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. 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.[14] 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

$$\begin{aligned} &(CW, T_{frame}) = arg_{(CW,T_{frame})}\big(Max(P^{esm}_{s,total})\big) \\ &CW \geq 1, T_{frame} < D_{ESM} \end{aligned} \tag{3.13}$$

It is noted that we do not need to find optimal T_{frame} and CW size when both PTRet and ODRet are used. When an ESM initiating vehicle retransmits an ESM via a TVWS channel, all vehicles within a service range can hear the ESM signal, which leads to high recovery efficiency. This, in turn, results in high reachability of the ESM. This statement is supported by simulation results in section 3.5, where the reachability of an ESM is close to one when both retransmission mechanisms are adopted.

3.4.2 Implementation Issues

In order to implement an optimization process in the proposed scheme, we must consider three issues: 1) how to find optimal configuration parameters in a real-time manner, 2) how to share the measured conditions (speed, TVWS error), and 3) how to share the optimal parameters among vehicles.

[14]From 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 [63]. However, since measuring TVWS channel error and vehicle density are not main scope of our work, we do not explain further on measurements.

To find optimal configuration parameters in a real-time manner, we establish an optimal configuration table by pre-calculating an optimal configuration with '*Brute-force search*' [15] and preload the table in vehicles. The table is indexed with a pair of input conditions: a vehicle density and TVWS error. Under this setting, vehicles can find their optimal configuration parameters by searching the preloaded table with the two keywords: 'vehicle density' and 'TVWS error'. However, if the values for those keywords are not found in the table, we can estimate optimal parameters using a regression technique.

To overcome the challenge of sharing measured values, vehicles piggyback the values onto the PBM. The overhead for sharing their measured values is not large since only TVWS error information needs to be piggybacked onto PBM. When each vehicle receives PBMs, they extract vehicle density and TVWS error information from PBMs and average over many vehicles. Then, each vehicle applies the averaged values into an optimization problem as given conditions.

It is noted that vehicles do not rebroadcast a PBM when they receive the message. In order to find optimal parameters, a vehicle needs information that is measured within large area. However, a vehicle can get information only from nearby vehicles without rebroadcasting a PBM. To address this challenge, a vehicle piggybacks its measured values as well as values in the received PBM. We explain the solution using a simple example, as illustrated in Fig.3.9. VEC 1 is located in a position where it cannot receive a PBM from VEC 3. However, VEC 1 can get measured values of VEC 3 by receiving a PBM of VEC 2, since VEC 2 includes its measured values as well as the measured values of VEC 3 in the PBM. Using this method, VEC 1 can obtain measured data of VEC 2 and VEC 3.

However, if a vehicle piggybacks all received information onto its PBM, a size of the PBM can be very large. To avoid information overload, the vehicle

[15] Since these calculations are conducted before a system starts, the calculation time is not a problem.

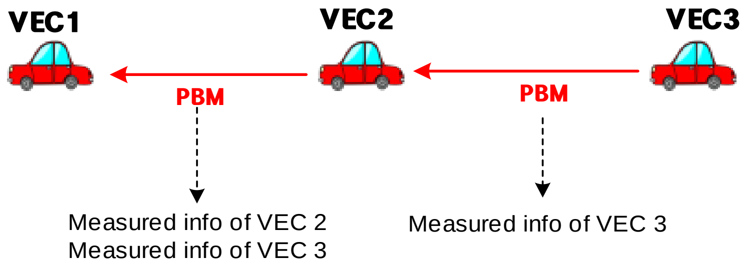


Figure 3.9: Sharing measured info among three vehicles

Table 3.2: Default parameter settings

Data rate of DSRC interface	3Mbps
Data rate of TVWS interface	1.5Mbps
Tx range of DSRC interface	500m
Tx range of TVWS interface	1km
Radius of service area	500m
PBM Interval	100ms
Delay bound of ESM	100ms
Average ESM interval	10s
number of iterations	10

selects information for its PBM generation only if the information is generated by vehicles within a service range. For this purpose, a vehicle piggybacks the position of vehicle that generates the information onto the PBM.

To share optimal configurations among vehicles, each vehicle piggybacks the configurations onto the ESM. When vehicles receive the ESM, they extract the optimal configuration parameters and use them for retransmitting the received ESM in ODRet.

3.5 Performance Evaluation

3.5.1 Simulation Setup

We use Qualnet [64] for performance evaluation. For investigating performance of the proposed scheme (section 3.5.3∼ 3.5.5), we consider highway area with two lanes where vehicles move in one direction.[16] For comparing our scheme with previous works (section 3.5.6), we consider 2X2 Mahattan grid with two lanes as well. For vehicle mobility, we use a car-following model that is developed by Gipps [65].

We summarize default simulation settings in table 4.1. 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 [41]. Each vehicle generates ESMs with random interval, which follows an exponential distribution with an average of 10 second.

3.5.2 Performance Metrics

In the simulation study, we use 1) reachability of ESM, 2) an efficiency of TWRA, and 3) a probability of decoding error in a DSRC band as performance metrics. An efficiency of TWRA is defined as $\frac{N_{TWRA}}{N_{failure}}$. Here, $N_{failure}$ is the number of vehicles that are located within a service range but do not receive an ESM before TWRA starts. N_{TWRA} is the number of vehicles that have received the ESM via TWRA within the service range. A probability of decoding error in a DSRC band means a probability of decoding failure of incoming PBM or ESM signals in a DSRC

[16] In commute time, many vehicles moves in one direction while we rarely find vehicles in other directions

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 correlation between a DSRC channel condition and QoS of ESM dissemination in the following simulation studies.

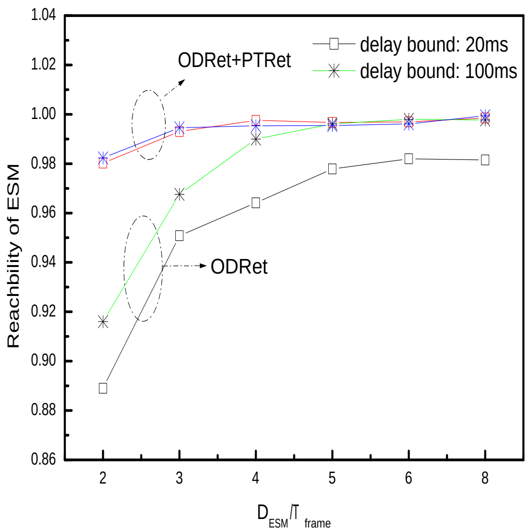
3.5.3 Impact of DSRC time frame

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.

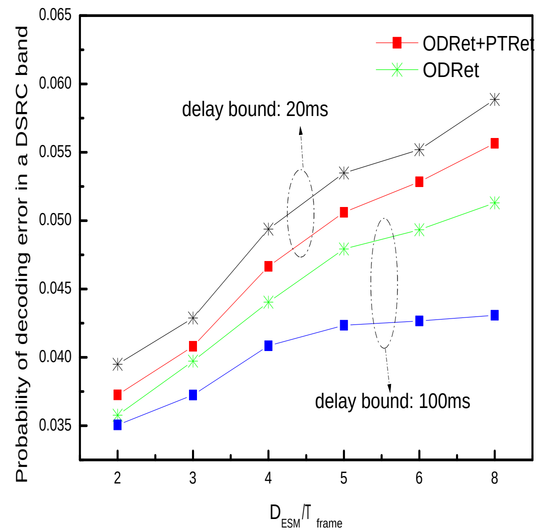
First, we focus on the case when only ODRet is considered. In Fig.3.10(a), we observe that the reachability of ESM increases as the ratio (D_{ESM}/T_{frame}) increases. From the equation 5 in section 3.5.3, we notice that the ratio is almost equivalent to the number of DSRC time frames (n_{frame}). Thus, 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.3.10(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.

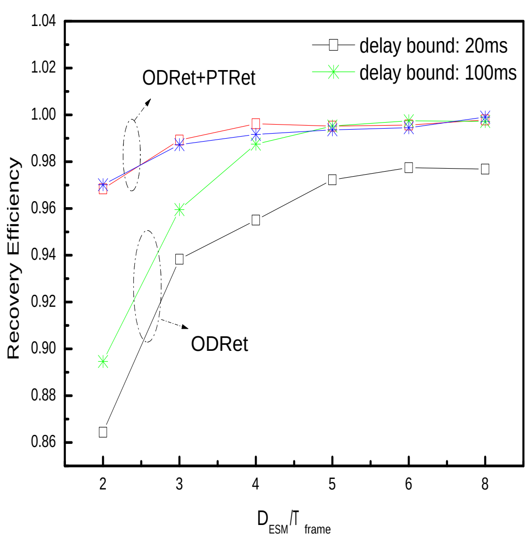
We note that the network congestion increases as the ratio increases in Fig.3.10(b). However, in our scheme, a dominant factor that affects the reachability of ESM is not a network congestion but n_{frame}. This is because network load in a DSRC band is reduced during TWRA as exchanges of PBM are deferred. This conjecture is proved by Fig.3.10(c), which shows recovery efficiency grows along with



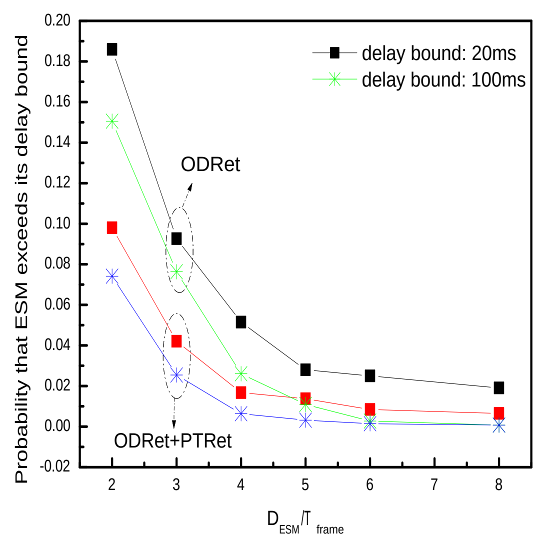
(a) Reachability of ESM



(b) Probability of decoding error in a DSRC band



(c) Efficiency of TWRA



(d) Probability that an ESM is not transmitted within a delay bound

Figure 3.10: (a) Reachability of ESM, (b) Probablity of decoding error in a DSRC band, (c) Efficiency of TWRA, and (d) Probability that an ESM is not transmitted within a delay bound according to the ratio of length of DSRC time frame to delay bound of ESM (D_{ESM}/T_{frame}) when there are 50 vehicles.

the ratio.

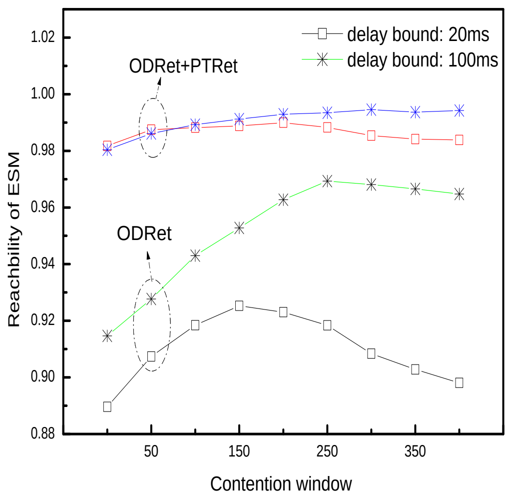
Notably, Fig.3.10(d) shows that a growth in the ratio reduces the probability that an ESM cannot be transmitted within a delay bound. This is because the higher ratio implies that vehicles have more chances to retransmit the ESM at the earlier stage of ODRet. Thus, the increase in the ratio reduces the 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.3.10(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.

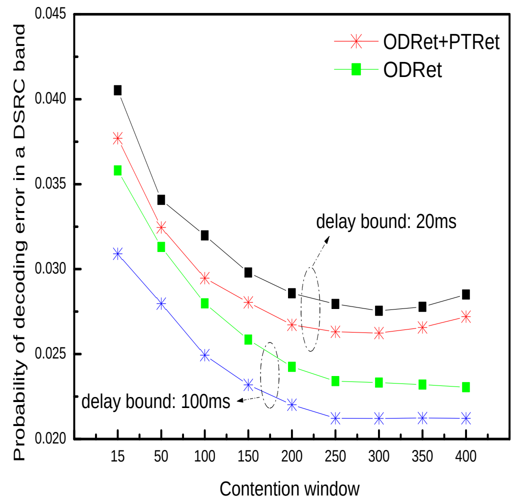
3.5.4 Impact of Contention Window Size

In this subsection, we study the performance of our scheme according to the contention window size (CW) for ODRet. Similar to section 3.5.3, we take two situations into account.

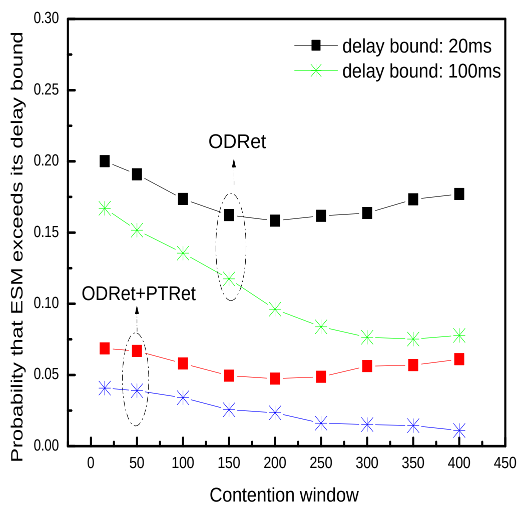
First, we take a look at the case when only ODRet is used. As shown in Fig.3.11(a), when a delay bound of ESM is 20ms (100ms), the reachability of ESM grows as a CW size increases until the CW size reaches 150 (250). This is because the increase of CW size causes the sharp decrease of network congestion until the CW size reaches the crossover points (e.g., 150 (250) for 20ms (100ms) delay bound), as demonstrated in Fig.3.11(b). In addition, as shown in Fig.3.11(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.3.11(a) shows that the reachability of ESM decreases as the CW size passes the crossover points. As depicted in Fig.3.11(b), the network congestion rarely decreases after these points, which



(a) Reachability of ESM



(b) Probability of decoding error in a DSRC band



(c) Probability that an ESM is not transmitted within a delay bound

Figure 3.11: (a) Reachability of ESM and (b) Probablity 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.

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.3.11(c), where the probability that an ESM is not transmitted within a delay bound increases after the crossover points.

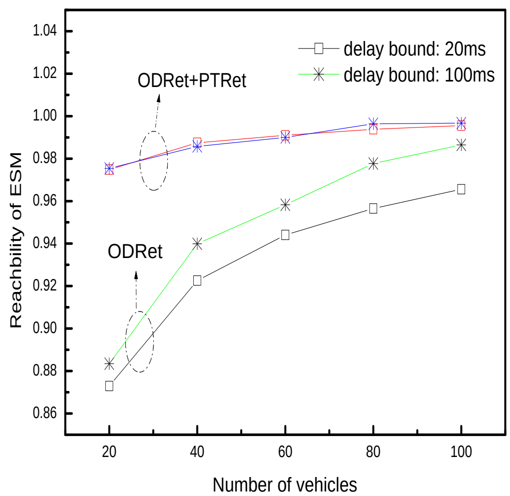
Second, when both ODRet and PTRet are used, the reachability of ESM is close to one for all values of CW size, as shown in Fig.3.11(a). This implies that optimal configuration of the CW size is not necessary if both PTRet and ODRet are employed.

3.5.5 Impact of the Number of Vehicles

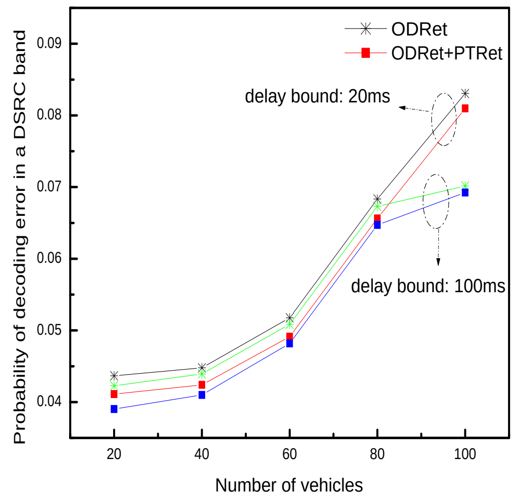
Similar to section 3.5.3 and 3.5.4, we take two simulation settings into account. Since the performance of the second setting (i.e., both ODRet and PTRet are used) proves to be strikingly similar to what the previous subsections have suggested (i.e., the reachability of ESM is close to one for all values of the number of vehicles), we will mainly analyze performances of the first situation (when only ODRet is used).

In Fig.3.12(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.3.12(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.

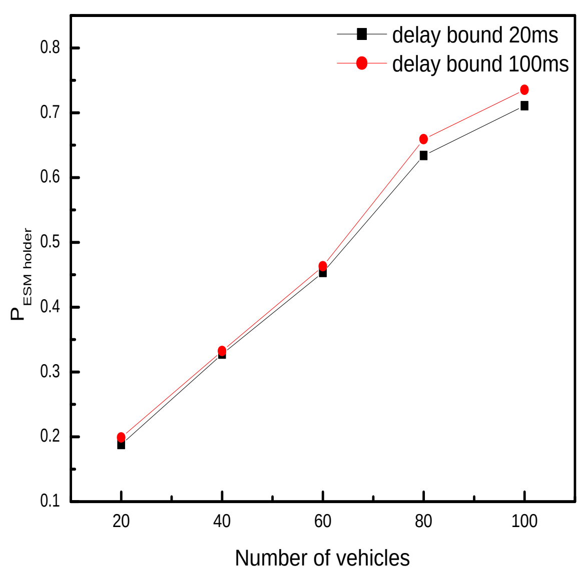
To find the reason for this pattern, we concentrate on the other factor: whether vehicles that have received an ESM are located around the vehicle of sending a DSRC tone signal. In detail, a vehicle cannot be recovered from ESM reception failure if there is no vehicle that responds to the DSRC tone signal. When the



(a) Reachability of ESM



(b) Probability of decoding error in a DSRC band



(c) Probability of neighbor vehicles responding to DSRC tone signal

Figure 3.12: (a) Reachability of ESM, (b) Probablity of decoding error in a DSRC band, and (c) Probability of neighbor vehicles responding to DSRC tone signal according to the number of vehicles.

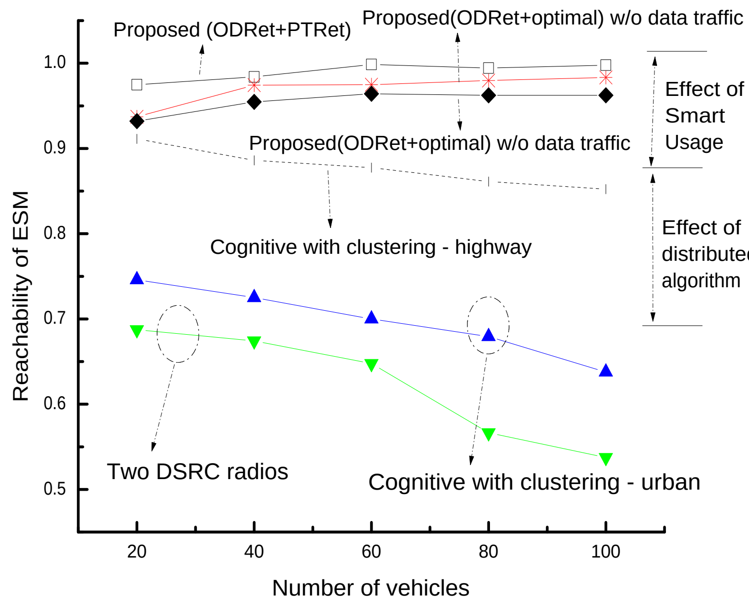
number of vehicle is small, it is less probable that vehicles can respond to the DSRC tone signal. To prove this conjecture, we define a new performance metric ($P_{ESMholder}$) and obtain it during simulation. Here, $P_{ESMholder}$ is a probability that a vehicle detects an ESM signal after sending a DSRC tone signal. In Fig.3.12(c), we can see a dramatic increase in $P_{ESMholder}$ 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 $P_{ESMholder}$.

3.5.6 Performance Improvement over legacy DSRC with dual radio interfaces and [53]

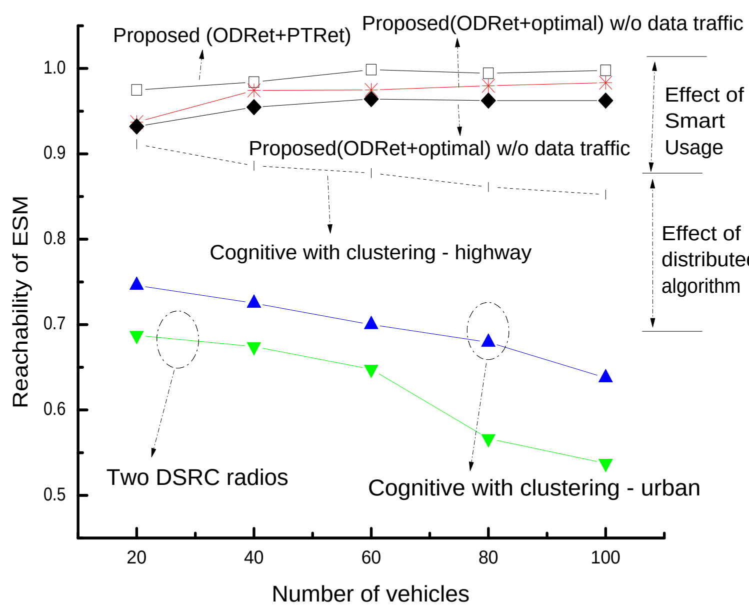
We compare our scheme with two previous works: 1) legacy DSRC system with two radio interfaces with two orthogonal channels[17] and 2) clustering mechanism with cognitive channel management [53]. In this comparison, we consider two situations for our scheme: 1) when both ODRet and PTRet are adopted and optimal configuration is not used ("SCHEME 1") and 2) when only ODRet is used and optimal configuration is employed ("SCHEME 2").

Fig.3.13(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 [53]. Specifically, we observe that improvement over the legacy DSRC system and [53] 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 [53] do not.

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



(a) Highway



(b) 2X2 Manhattan grid

Figure 3.13: Comparison of the proposed scheme with legacy DSRC system with dual interfaces and [53] in (a) highway and (b) 2X2 Mahattan grid.

Fig.3.13(b) demonstrates the reachability of ESM of our schemes and previous works in 2X2 Manhattan grid. Similar to Fig.3.13(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.3.13(b) shows that our schemes outperform the legacy DSRC system and [53] 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 [53] 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 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 highway area and Manhattan grid. However, we omit a graph due to page limitation.

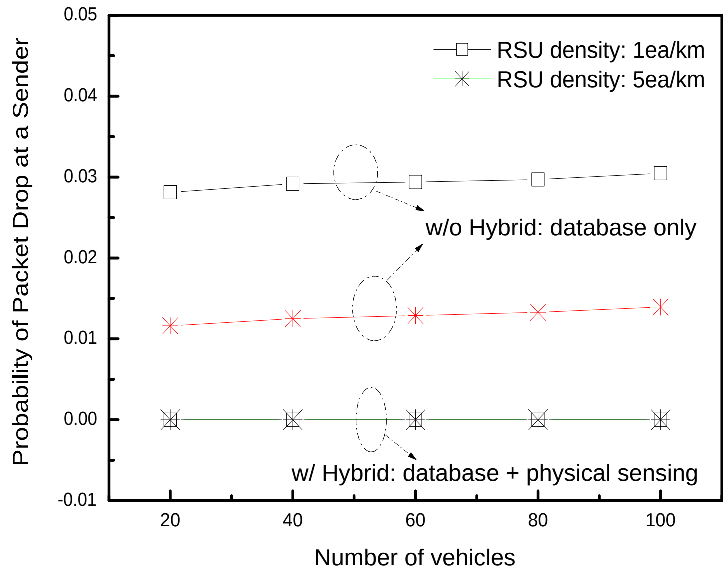
We also note that as shown in Fig.3.13, the reachability of ESM decreases by only 2$\sim$3% in both highway and Manhattan grid settings when each vehicle transmits 20kbps data traffic in a DSRC band. In the proposed system, vehicles exchange control messages via a DSRC band to share inputs for optimal configurations. Thus, the data traffic hinders sharing the inputs, which may lead to sub-optimal configurations. However, as shown in section 3.5.3 and 3.5.4, the impact of sub-optimal configurations is small. Thus, the impact of data traffic on a reachability of ESM is negligible. Moreover, the 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.

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 [66] [67]. This means that implementation cost of our system is not much higher than legacy DSRC systems with dual interfaces and [53]. However, performance of the proposed system improves significantly over the legacy DSRC system and [53].

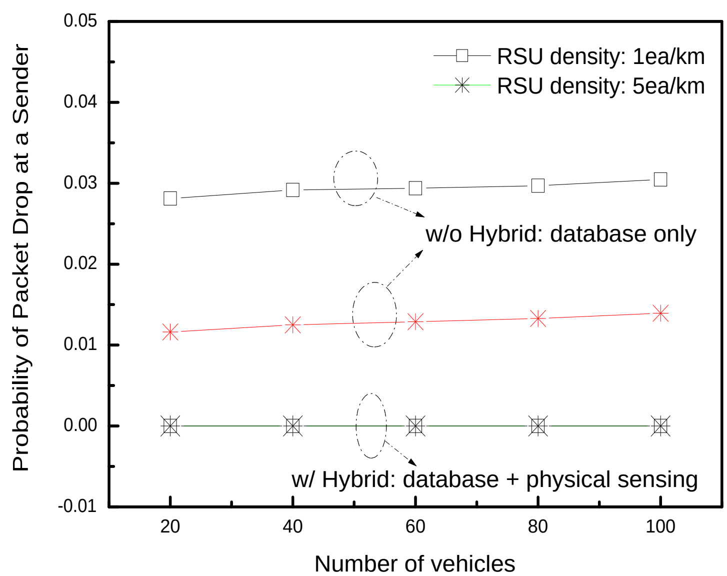
3.5.7 Performance Evaluation outside Spectrum MAP Coverage

As mentioned in section 3.2.6, 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.3.14(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 probability that drivers deviate from a route to 6.25%, which is very conservative value [71]. Notably, P_{obs}^{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_{obs}^{esm}.



(a) P_{obs}^{esm} w/ or w/o a hybrid scheme



(b) Reachability of ESM with a hybrid scheme

Figure 3.14: (a) P_{obs}^{esm} according to whether a hybrid scheme is used or not and (b) reachability of ESM with a hybrid scheme

To address the above-mentioned problem, we propose a hybrid scheme in section 3.2.6. As shown in Fig.3.14(a), the hybrid scheme can reduce P_{obs}^{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.3.14(b) demonstrates that the reachabilities of an ESM are above 93% in both highway and Manhattan grid settings.

3.6 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 determine 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 establish a new mathematical model on the reachability of ESM that considers delay bound of a safety message. The simulation results show that the proposed scheme can support QoS of safety message dissemination under various vehicle scenarios.

CHAPTER 4

Safety Message Dissemination in NLOS Environments of Intersection using TV White Space

4.1 Motivation

In 2009, the U.S. government reported that more than 33,800 people were killed and more than two million people were injured from vehicle accidents [26]. Of those reported vehicle accidents, a large fraction of the accidents happened in intersections (specially, 26% of all crashes and 25% of fatal crashes in the United States) [3]. In an attempt to reduce the accidents in intersections, many automotive companies and research institutes developed intersection safety systems, which informed drivers of the possibility of vehicle accidents.

Vehicular communications are the basis for establishing intersection safety systems. Specifically, vehicles notice the possibility of accidents by exchanging their status information (e.g., a position, a velocity, and an acceleration) and disseminating safety messages via vehicular communications. As intersection safety systems are critical to saving life, the safety message dissemination must satisfy low latency and high delivery ratio requirements. For example, in the Intersection Collision Warning (ICW) system, a safety message must be delivered to vehicles that are located in a 300m range from the center of an intersection within 100ms [16].

The Dedicated Short-Range Communication (DSRC) is a dominant standard for vehicular communications, which uses 5.9 GHz licensed band [10]. In a DSRC band, however, a signal cannot pass through large-size obstacles (e.g. buildings or trees), which induce severe signal distortion at receivers in None Line-Of-Sight (NLOS) conditions. Unfortunately, in urban intersections, it is difficult to guarantee Line-Of-Sight (LOS) between vehicles that are located in different road segments. Thus, a vehicle usually fails in delivering safety messages to vehicles in different segments with direct communications in a DSRC band [74]. Measurement campaign in [75] showed the difficulty in successful reception when a sender and a receiver are located in different road segments. More specifically, Packet Error Rate (PER) is close to 100% when a sender and a receiver are apart from the center of intersection by 60m and 80m, respectively. However, most intersection safety services require their dissemination ranges larger than 250m [16]. Thus, we cannot realize intersection safety systems with direct DSRC communications.

There have been previous approaches that enabled message delivery in NLOS conditions by exploiting relaying vehicles ([76] [77]) or centralized units ([78] [79]). In [76], a sender selects vehicles that have LOS to the sender for relaying messages. However, when the vehicle density is low, vehicles might not find relay nodes [77]. In [77], the authors exploited parked vehicles for relaying messages to vehicles in other segments. However, we cannot guarantee the existence of parked vehicles that have LOS with a sender and a receiver. More specifically, parked vehicles are likely to have LOS with a sender and a receiver when being located close to the center of an intersection. However, in most intersections of America, parking is prohibited nearby the center of an intersection. In [78], each vehicle sends its safety message to Road Side Unit (RSU) and RSU disseminates the message to vehicles around the intersection. However, implementing RSUs in all intersections represents a significant money and time investment. In [79], the authors proposed a cluster-based mechanism that exploited two radio interfaces, one for inter-cluster communications in a LTE band and the other for intra-cluster communications in an ISM band. However, the use of a LTE band is not free, the band is often congested due to smart phone traffic and the delays are high.

So, we must raise an important question: "can a vehicle disseminate a safety message in NLOS conditions around an intersection, regardless of the existence of centralized units or relaying vehicles?". To meet this challenge, we require a link with good signal propagation characteristics in NLOS conditions for reliable Inter-Vehicle Communication (IVC). It is well-known that a signal propagates better (e.g., small path loss and penetration loss) in NLOS conditions as the operation frequency becomes lower [49] [80]. Recently, the Federal Communications Commission (FCC) allowed unlicensed users to access the TV White Space (TVWS) band if there are no activities of licensed users [51]. Thus, in this chapter, we propose a novel scheme that depends on a TVWS band for leveraging its good propagation characteristics. To further improve the delivery ratio at the corner of an intersection, the proposed scheme adopts a novel retransmission mechanism called RRSD (Repetitive Retransmissions via Spatial Diversity), ensuring that a vehicle that is supposed to deliver most reliably is selected as a sender in each retransmission attempt.

The good propagation characteristics of a TVWS band lead to a large interference range. Thus, if all vehicles use a TVWS band for their transmissions, network congestion becomes serious. The proposed scheme meets this challenge via a cluster approach that exploits a TVWS band for inter-cluster communications, and a DSRC band for intra-cluster communications and cluster managements.

Intensive simulation studies show that our scheme outperforms [79] by 25% in urban intersection scenarios. In summary, the contributions of this chapter are as follows:

- Propose a novel safety message dissemination scheme that does not depend on special relaying units (e.g., RSU, LTE Base Station, moving or parked vehicles) in NLOS conditions around an intersection.

• Propose an efficient retransmission mechanism that exploits spatial diversity for reliable dissemination in NLOS conditions.

• Show that the proposed scheme is feasible to safety applications in an intersection

4.2 Proposed Scheme

4.2.1 System Model

In the proposed scheme, all vehicles have two radio interfaces, one for a DSRC band (DSRC radio) and the other for a TVWS band (TVWS radio). A DSRC radio employs an IEEE 802.11p protocol [10] with 10 MHz bandwidth and is always located on a DSRC Control Channel (CCH). On the other hand, a TVWS radio adopts an IEEE 802.11af protocol with 5 MHz bandwidth [80] and selects its channel among multiple TVWS channels. In addition to vehicles, there are TV broadcasting towers as Primary Users (PU) in a TVWS band.

A vehicle transmits two types of messages, a **Periodic Beacon Message (PBM)** and an **Emergency Message (EM)**. Every vehicle periodically broadcasts a PBM that contains vehicle's local parameters (e.g., position, velocity, and acceleration), while a vehicle disseminates an EM to warn other vehicles when detecting the possibility of accidents (e.g., locating vehicles in a "dilemma" zone [81]). In the proposed scheme, the EM has higher priority than the PBM and has to be disseminated to vehicles within a service range with stringent delay requirement. Thus, in this chapter, we focus on a reliable EM dissemination.

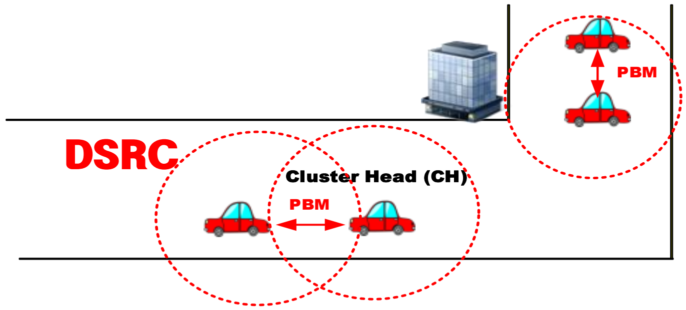
4.2.2 Assumptions

In the proposed scheme, we make assumptions as follows. First, all vehicles have map information and Global Positioning Systems (GPS). With this assumption, vehicles achieve time synchronization; they get their geographical coordinates (e.g., latitude and longitude) and relative locations at intersections (e.g., current road segments info). This assumption is reasonable since most drivers have navigators or smart phones with GPS antenna and map information (e.g., google MAP). Second, in a TVWS band, vehicles can distinguish a vehicle signal from other signals (e.g., signals from TV broadcasting towers). For detecting a vehicle signal, our scheme depends on a preamble detection that compares the received signal with the pre-defined preamble sequence for a vehicle [82]. Fortunately, a previous work showed that a mobile device could accurately detect a protocol signal even in noisy channel via preamble detection in IEEE 802.11 [61]. Third, we assume that an EM can be generated only within a safety region. Here, the safety region refers to a road segment that covers the ranges of safety services and is defined in each direction of an intersection[1]. This makes sense since vehicles outside the safety region (e.g., 300m from the center of intersection for ICW) rarely cause accidents at the center of an intersection within delay requirements (e.g., 100ms for ICW).

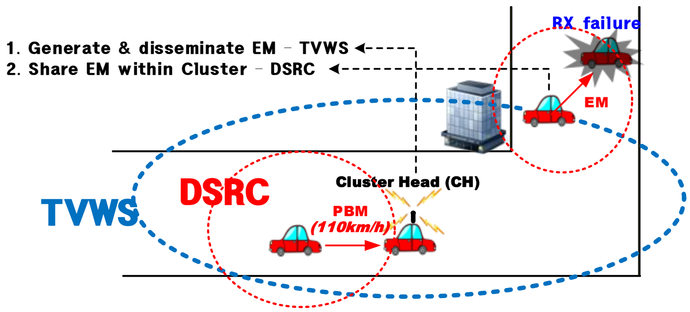
4.2.3 Overview of the Proposed Scheme

Fig.4.1 illustrates overall operations of the proposed scheme. When approaching an intersection, vehicles in the same road segment form a cluster. All vehicles periodically exchange PBMs via a DSRC radio; the cluster head keeps checking the possibility of accidents based on the received PBMs (Fig.4.1(a)). When detecting the possibility of accidents (i.e., within 300m from intersection), the cluster head

[1] The range of most safety applications for intersection is less than 300m, which can be covered by one-hop communication of a DSRC radio [16].



(a) Normal operation



(b) Emergency situation

Figure 4.1: Overall operations: (a) normal operation and (b) emergency situation

generates and disseminates an EM within a service range via a TVWS radio (Fig.4.1(b)). If at least one vehicle receives the EM, the vehicles share the EM within a cluster via a DSRC radio[2]. However, the use of a TVWS band for reliable safety message dissemination raises two technical challenges: 1) finding available TV channels and 2) rendezvous among vehicles at the same TV channel.

Vehicles obtain available TVWS channels by searching a pre-computed spectrum map [82] [69][3]. More specifically, vehicles establish a local spectrum map indexed by positions of a driving route via accessing a centralized database, and obtain available TVWS channels by table look-up, using positions as an index at run-time. This approach is reasonable since the activity of a primary user does

[2]For simplicity, we adopt a flooding with time-to-live (TTL) one, which can be replaced with other efficient mechanisms. However, finding the best forwarding mechanism is not our main scope.

[3]In most urban areas, there are more than one available TV channels when we search available TVWS channels for portable devices in [83].

not change frequently, thereby an updating interval of the database is long. (e.g., one day in FCC [72]).

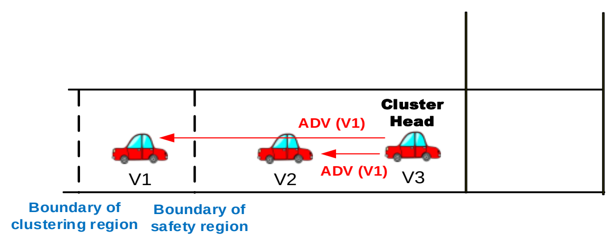
As available channels may be different according to a position, vehicles need to make rendezvous at the same TVWS channel. For this purpose, our scheme employs a rendezvous mechanism similar to [82]. Specifically, a vehicle determines a transmission channel when generating an EM and transmits a harbinger signal before sending an EM; neighbor vehicles tune their TVWS radios to the channel. Each vehicle selects the lowest channel of its available channels for its transmission since a signal propagates well in a low frequency band. Then, neighbor vehicles tune their TVWS radios to the channel as follows. As the first step, each neighbor vehicle gathers all available channels by table look-up within its service area[4]. In the second step, the neighbor vehicle periodically scans the channels that are gathered in step 1. Finally, when detecting the harbinger signal in one of channels, the vehicle tunes a TVWS radio to the channel and receives the EM.

Recall that our scheme leverages good signal propagation characteristics of a TVWS band for reliable safety message dissemination. The benefit of using low frequency band can be augmented when integrated with an efficient retransmission mechanism. This is because safety message might not be delivered reliably just with direct communications in harsh NLOS conditions (e.g., the corner of urban intersections). Specifically, in the urban intersections, large obstacles could be so densely deployed around the corner that communication links in TVWS band may be unreliable. For example, an experimental study in [84] showed that 80% PER occurred when there were tall buildings at the corner, and a sender and a receiver in different segments are 150m away from the corner. Accordingly, the delivery ratio of a safety message is so low that the proposed scheme cannot satisfy the communication requirements of the safety services. To address this problem, we

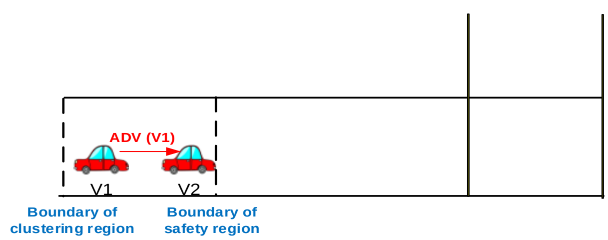
[4]In practical situations, the range of TV broadcasting tower is very long. Thus, each vehicle does not need to search all locations to find available channels within a service area. The practical value for updating available channels is 50m [58].

propose a Repetitive Retransmission via Spatial Diversity (RRSD) that selects a sender that has the best TVWS link quality with the cluster (TVWS sender) in each retransmission attempt. The detailed design of RRSD will be explained in section 4.2.5.

In urban intersections, the overhead for managing a cluster can be large since a topology of a vehicular network frequently changes. More specifically, vehicles join a cluster when approaching an intersection and leave the cluster when crossing an intersection, which happen very frequently in urban intersections. The join and leave processes in the previous mechanisms cause huge network overhead [53] [54]. Hence, our scheme requires a clustering mechanism with low clustering overhead. For this purpose, our scheme employs Light-Weight Clustering mechanism (LWC), which will be explained in more detail in section 4.2.4.



(a) Normal selection process



(b) Initial selection process

Figure 4.2: Selection of a cluster head in LWC: (a) normal selection process and (b) initial selection process

4.2.4 Light-Weight Clustering mechanism (LWC)

LWC does not rely on the exchanges of join/leave messages for managing cluster memberships. Instead, LWC depends on position information of vehicles. More specifically, the vehicles locate themselves on the MAP and manages their memberships based on their current positions in the MAP. For example, when located in the road segment 1, the vehicle recognizes that it is the member of cluster in road segment 1. When crossing the intersection, the vehicle keeps locating itself on the MAP and finds that it is in the road segment 2. Then, the vehicle changes its membership from 'the cluster of road segment 1' to 'that of the road segment 2'.

The procedure for selecting a cluster head is divided into 1) 'normal selection process' and 2) 'initial selection process' according to whether there is an existing cluster head in the road segment. In LWC, a cluster head piggybacks its role as a cluster head onto the PBM; a vehicle can recognize the existence of a cluster head by receiving a PBM from a cluster head. More specifically, when receiving a PBM from a cluster head, vehicles start 'normal selection process'. Otherwise, the vehicles start 'initial selection process'.

It is noted that the vehicles might not receive a PBM from a cluster head due to packet collisions. To address this challenge, the vehicles wait to receive PBMs from other vehicles without sending anything for a while when being about to enter the safety region. However, in the safety region, a vehicle must exchange its PBM periodically for generating an EM. Thus, vehicles must determine '*which selection process is used*' before entering the safety region. For this purpose, we set the clustering region, which is located before the safety region and the length of the region is d[5], as shown in Fig.4.2(a).

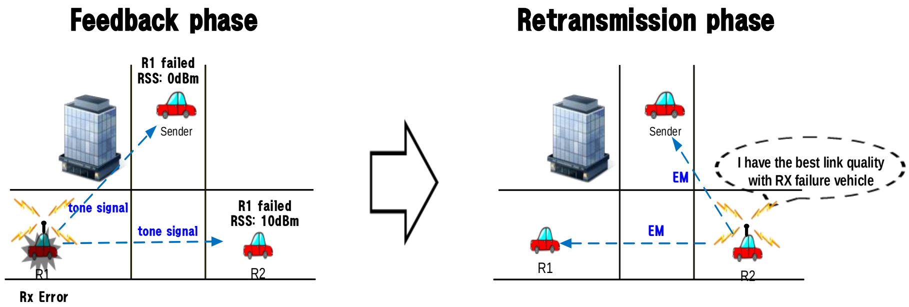
[5] A vehicle should complete LWC before entering a safety region. Thus, d can be calculated by (the maximum allowed speed * processing time of LWC). The processing time is equal to the duration for waiting PBM. The duration is chosen by setting lower bound of the duration within which a vehicle can successfully receive more than one PBM.

Fig.4.2(a) illustrates the operation of a normal selection process. In this case, when being about to reach the center of an intersection, an existing cluster head (e.g. V3 in Fig.4.2(a)) delegates its role to one of vehicles (e.g., V1 in Fig.4.2(a)) in the same road segment. For this purpose, the cluster head annotates its PBM with an ID of the most appropriate vehicle and the time to retire as a cluster head. When the time for retirement approaches, the existing cluster head (e.g., V3 in Fig.4.2(a)) does not integrate its PBM with their role of cluster head any more. Instead, the candidate vehicle (e.g., V1 in Fig.4.2(a)) becomes a cluster head and declares that it becomes a cluster head by integrating its PBM with the election result.

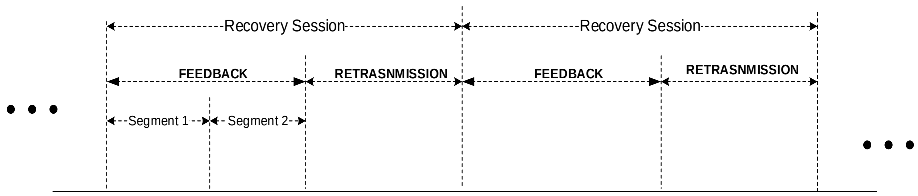
It is noted that a cluster head delegates its role as a head to a vehicle that is farthest from the center of intersection. This is because the vehicle can reside in the segment for longer time, as getting further from the center of intersection. The long reside time implies that the cluster head delegation is not so frequent. Thus, when being about to leave the current segment, the cluster head chooses the vehicle that is farthest away from the center of intersection.

Fig.4.2(b) illustrates an operation of an initial selection process. As there is no existing cluster head, vehicles in the segment compete for being a cluster head. Specifically, when vehicles (e.g., V1 in Fig.4.2(b)) want to become a cluster head, they piggyback their intentions to become a cluster head onto PBMs. When receiving the PBMs, neighbor vehicles (e.g., V2 in Fig.4.2(b)) suppress their intentions to become a cluster head.

However, some vehicles may not receive the PBM due to packet collision. In this case, they also integrate their PBMs with the intentions even after the other vehicle already declared to become a cluster head. As a result, multiple cluster heads can be located in a cluster. To address this undesirable situation, vehicles continuously declare to become a cluster head, and stop the declaration when receiving the PBMs from a vehicle that is more appropriate for a cluster head.



(a) Tone-based feedback



(b) Structure of RRSD

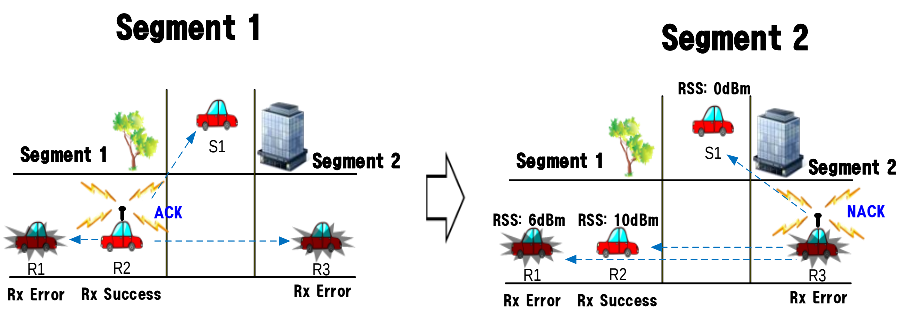
Figure 4.3: Repetitive Retransmission via Spatial Diversity (RRSD): (a) Tone-based feedback and (b) Structure

4.2.5 Repetitive Retransmission via Spatial Diversity (RRSD)

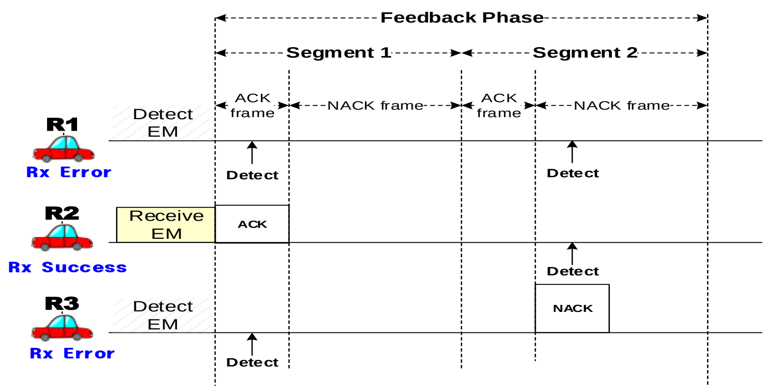
Repetitive Retransmission via Spatial Diversity (RRSD) relies on spatial diversity to increase a delivery ratio of an EM in each retransmission attempt. Specifically, we select a vehicle that is supposed to deliver an EM most reliably (TVWS sender) in each attempt. This is because link qualities are location-dependent and vary from vehicle to vehicle and with time. For this purpose, RRSD must overcome two challenges: 1) reliable acknowledgement in NLOS conditions and 2) link measurements with several vehicles.

As shown in Fig.4.3(a), RRSD meets these challenges via a tone-based feedback mechanism. Here, a tone signal consists of a PN sequence that is encoded with a simple on-off keying and decoded via cross-correlation with a known sequence set. It is well-known that an on-off keying and a cross-correlation mapping are robust to signal distortion, thereby leading to reliable acknowledgement in NLOS conditions. Moreover, vehicles estimate link qualities for an EM retransmission from received tone signals due to channel reciprocity [86].

Fig.4.3(b) illustrates a time structure in a RRSD. A vehicle initiates a RRSD when detecting an EM via a TVWS radio and terminates the RRSD when recognizing that all vehicles have received the EM or the lifetime of the EM expired. A RRSD consists of 'recovery session', which is composed of two phases: 1) a feedback phase and 2) a retransmission phase.



(a) Operations



(b) Time diagram that describes vehicle activities in a feedback phase

Figure 4.4: Feedback phase in RRSD: (a) operations and (b) a time diagram

1) Feedback phase: In a feedback phase, each vehicle transmits an ACK (NACK) tone signal via a TVWS radio to advertise the success (failure) of an EM reception within a service area. In RRSD, whenever detecting the tone signal, vehicles need to figure out 1) type of the signal (i.e., ACK or NACK) and 2) the road segment ID that the signal comes from[6]. For this purpose, vehicles identify the tone signal with a signal detection time, which can be realized by adopting a Time Division Multiple Access (TDMA)[7]. Specifically, a feedback phase is divided into time blocks for each cluster (i.e., the segment ID); each time block consists of ACK and NACK frames (i.e., the type), as depicted in Fig.4.4(b)[8].

In an ACK frame, a vehicle that has received an EM (e.g., R2 in Fig.4.4(a) and Fig.4.4(b)) transmits an ACK tone signal. When detecting the signal, vehicles in the same cluster (e.g., R1 in Fig.4.4(a) and Fig.4.4(b)) notice that more than one vehicle have received an EM within a cluster. In this case, even if failing in an EM reception, the vehicles do not send any NACK tone signal in the following NACK frame since they can easily share the EM within a cluster via a DSRC forwarding (e.g., see no NACK tone in the NACK frame of segment 1 in Fig.4.4(b)). However, if an ACK tone signal is not detected, vehicles recognize that there are no vehicles that have received the EM within a cluster (e.g., see no ACK tone in the ACK frame of segment 2 in Fig.4.4(b)). In this case, the vehicles in the cluster transmits NACK tone signals (e.g., R3 in Fig.4.4(a) and Fig.4.4(b)).

When receiving a NACK tone signal, vehicles estimate link quality with a NACK sender by measuring Received Signal Strength (RSS)[9]. For example, as depicted in Fig.4.4(a), S1, R1, and R2 can estimate the link qualities with R3 by measuring RSS of the NACK tone signal from R3, respectively.

Concurrent NACK transmissions by multiple vehicles may lead to an error in estimating a link quality. Thus, we divide the NACK frame into multiple time slots and each cluster member transmits a NACK tone signal in its own time

[6]In RRSD, the retransmission is optimized for maximizing the number of clusters that at least one member have received an EM. This is because the vehicles in the same segment usually have LOS conditions, thereby being able to easily share the EM via a DSRC radio.

[7]When detecting an EM, vehicle reserves a TVWS band during a feedback phase

[8]We can assign a time block to each cluster via MAP info (e.g., N:1st, S:2nd). However, the assignment mechanism is not our main scope.

[9]RSS has large correlation with PDR if the transmission rate is small [87].

slot[10].

2) Retransmission phase: In a retransmission phase, a vehicle retransmits an EM via a TVWS radio, which follows a three-step procedure. First, to give access priority according to link quality, each vehicle determines its Contention Window (CW) size based on its measured value. Second, each vehicle checks whether it has the EM in its buffer. Third, a vehicle retransmits the EM based on CW if it has received the EM.

It is noted that multiple vehicles may attempt to retransmit the same EM in a retransmission phase, which can cause huge network congestion. To reduce the number of transmitters, we employ a suppression mechanism with CSMA/CA. Specifically, if detecting an EM signal via a preamble detection, other vehicles suppress their transmission attempts.

3) Discussion: In RRSD, a tone signal can be identified only when at most one EM is generated at a time. To validate the identification of the tone signal, we analyze a distribution of an EM generation via a trace-based analysis. We obtain the mobility traces of vehicles using SUMO [88]. Specifically, we acquire a tiger MAP on an urban area (Fairfax ave & Beverly BLVD in Los Angeles)[11] and use the MAP for SUMO simulation. We assume that an emergency event happens when a vehicle violates the speed limit and an EM is generated every 100ms by aggregating all emergency events in each cluster. From the mobility trace, we count the number of an EM generation and the number of emergency events every 100ms.

From the trace-based analysis, we found that less than one EM is generated at a time, thus the identification method in RRSD is feasible. Specifically, only one event happens in 91% of all epochs with event generation. Even if more than two

[10]For example, each cluster member can determine its time slot based on its own position information.

[11]The MAP is a rectangular shape with 5km edge, which is larger than a TVWS transmission range for mobile secondary user.

events happen with 9%, such concurrent events happen in the same road segment, which means that the events can be included in a single EM. Thus, we can validate the identification method through this trace-based analysis.

4.3 Performance Evaluation

In this section, we evaluate the proposed scheme using Qualnet [64]. First, we study the performance of the proposed scheme in various scenarios. Then, we compare the proposed scheme with a previous scheme [79], which relies on two radio interfaces.

4.3.1 Simulation Setup

As discussed in section 4.2.5, concurrent EM generations do not happen in an urban area. Thus, we focus on 2x2 Manhattan Grid (i.e., a single intersection) with two lanes where vehicles move in both directions. At the corner of an intersection, large size buildings can be located. To model vehicle mobility, we use a car-following model that was developed by Gipps [65].

We summarize default simulation parameters in Table.4.1. In this simulation, a cluster head generates an EM when finding vehicles located in dilemma zone [81]; the cluster head should disseminate the EM within 300m from the center of an intersection with a 100ms lifetime [16]. Similar to [82], all vehicles generate PBMs every 100ms.

In MAC layer settings, we use CSMA/CA for both DSRC and TVWS radios[12]. In physical layer settings, both TVWS and DSRC radios follow a IEEE 802.11 communication system with the lowest transmission rate (i.e., 3Mbps for a DSRC radio and 1.5Mbps for a TVWS radio). For realistic signal propagation at the corner, we adopt CORNER as a path loss model [89]. However, CORNER assumes

[12] A TVWS radio follows a TDMA during a feedback phase of RRSD.

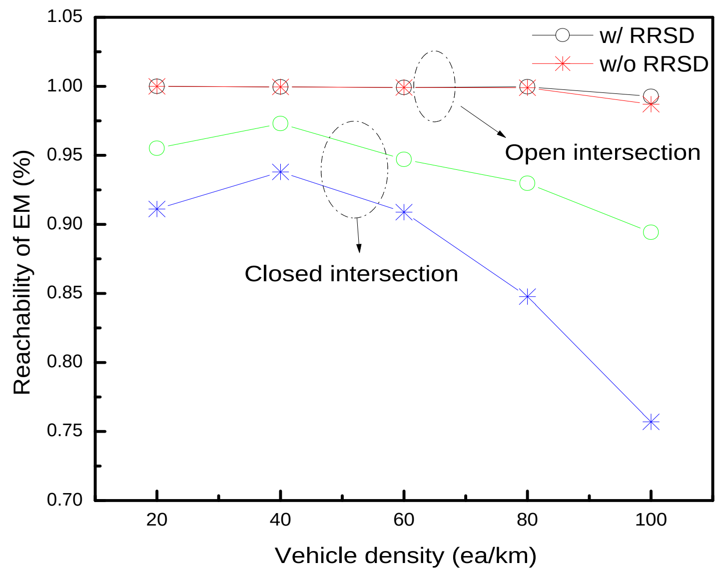
Table 4.1: Default simulation parameters

Radius of safety region	300m
Delay bound of EM	100ms
Generation interval of PBM	100ms
Data rate of a TVWS radio	1.5Mbps
Data rate of a DSRC radio	3Mbps
Minimum Contention Window	15
Number of iteration	10

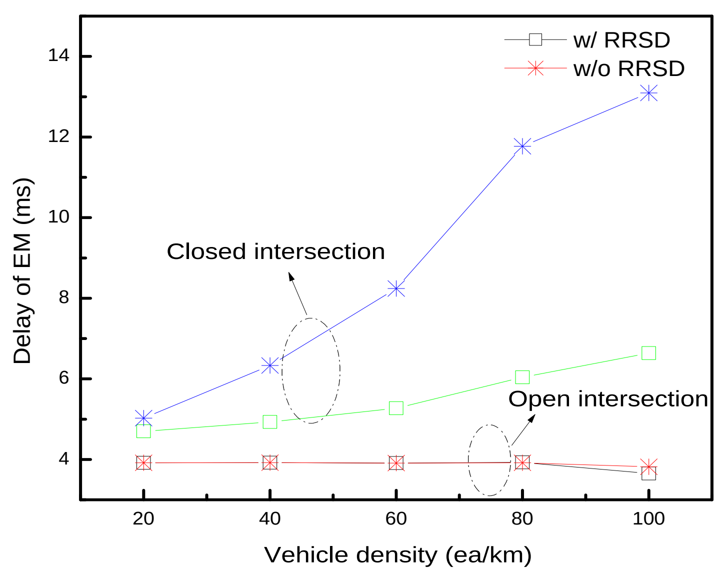
that large-size buildings are located at every corner of an intersection; a pair of vehicles in different road segments around the corner always suffer from large signal attenuation caused by the buildings. However, in practical situations, a building may not exist at certain corners. Hence, we consider a NLOS path loss model of CORNER only when a building is deployed at the corresponding corner. In addition, we consider a Rayleigh fading model to consider statistical propagation characteristics of vehicular communications [90].

4.3.2 Performance Measures

To analyze the proposed scheme, we use 1) reachability of an EM and 2) delay of an EM as performance measures. The reachability refers to a fraction of vehicles that successfully received an EM among the target vehicles (i.e., vehicles within a service region of the EM). Delay is defined as an interval between EM generation time and EM reception time. It is noted that the delay implies that how many recovery sessions are necessary until the successful delivery of an EM. Thus, we can infer the efficiency of RRSD from the delay.



(a) Reachability of EM



(b) Delay of EM

Figure 4.5: System performances according to the vehicle density: (a) reachability of an EM and (b) delay of an EM

4.3.3 Impact of the Vehicle Density

In this subsection, we investigate the performance of the proposed scheme according to the vehicle density. To see the importance of selecting a TVWS sender, we consider two configurations in the proposed scheme: 1) 'w/ RRSD' where a TVWS sender is selected for each retransmission attempt and 2) 'w/o RRSD' where only an EM generating vehicle can retransmit the EM. Moreover, we consider two different intersections: 1)'closed intersection' where there are large obstacles at all corners, and 2) 'open intersection' where there are no obstacles at the corner.

In Fig.4.5(a), we observe that reachability in both configurations (e.g., 'w/ and w/o RRSD') is close to one in an open intersection. This is because an EM retransmission rarely happens in an open intersection. Specifically, LOS can be guaranteed between vehicles in the different road segments, thus, vehicles in other road segments are likely to succeed in an EM reception at the first EM transmission attempt. The results in Fig.4.5(b) prove this conjecture, where delay in an open intersection is very short in both configurations.

However, in a closed intersection, the reachability with 'w/ RRSD' is higher than that with 'w/o RRSD' as depicted in Fig.4.5(a). This is because an EM generator is unlikely to have good link qualities with other vehicles in the closed intersection (i.e., w/o RRSD). Hence, repetitive retransmissions by the same vehicle (i.e., EM generator) is not efficient for a successful delivery. However, if we select a vehicle with better link qualities for retransmission (i.e., w/ RRSD), an EM retransmission is more likely to succeed. This argument is supported by the results in Fig.4.5(b). Specifically, a delay with 'w/ RRSD' is shorter than that with 'w/o RRSD', which implies that the number of recovery session until successful delivery is reduced with 'w/ RRSD' configuration.

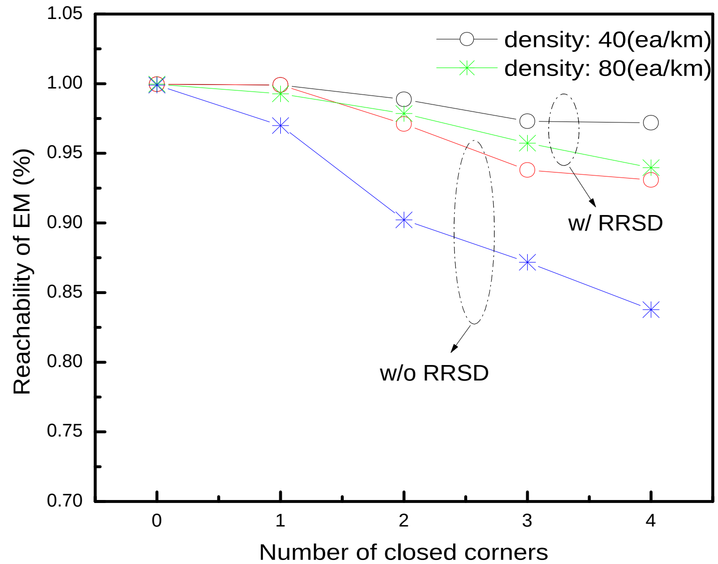
Notably, the reachability grows until the vehicle density reach 40 in a closed intersection. This is due to the increase in the spatial diversity. Specifically, as the vehicle density grows, the probability that more than one vehicle in each road segment receive the EM increases. However, the reachability decreases when the density passes 40. This is because network congestion becomes worse, which is a dominant factor to reachability after 40.

4.3.4 Impact of the Closed Corner in an Intersection

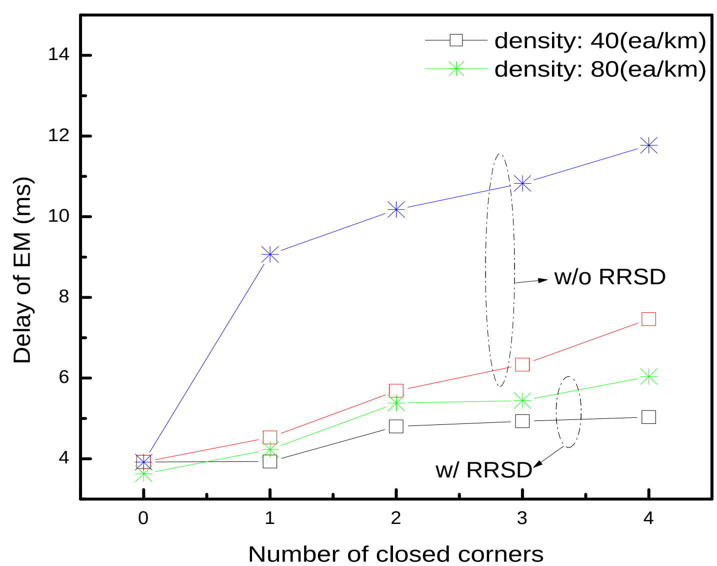
In this subsection, we analyze the performance of proposed scheme according to the number of closed corners in an intersection. Here, a closed corner refers to a corner where a large-size building is deployed. Similar to section 4.3.3, we consider two configurations of the proposed scheme: 'w/ RRSD' and 'w/o RRSD'.

As shown in Fig.4.6(a), we observe that the reachability of an EM is rarely affected by the number of closed corners when the proposed scheme has 'w/ RRSD' configuration. This is because we select a vehicle with better link qualities for each retransmission attempt in this configuration. Thus, an EM retransmission succeeds with high probability even if most of corners are closed. We can prove this conjecture in Fig.4.6(b), where delays are short in 'w/ RRSD' configuration.

However, in 'w/o RRSD' configuration, the reachability is affected by the number of closed corners as illustrated in Fig.4.6(a). This is because the same vehicle retransmits an EM repetitively, even though it has the bad link qualities with the failed vehicles. Thus, an EM retransmission is not successful with high probability, leading to the low reachability. This conjecture can be proved by the results in Fig.4.6(b), where we can find that delay increases as the number of closed corners rise. The increase in delay implies that more recovery sessions are necessary for an EM delivery. Thus, an EM may not be delivered successfully until the lifetime expires, especially when many corners are closed.

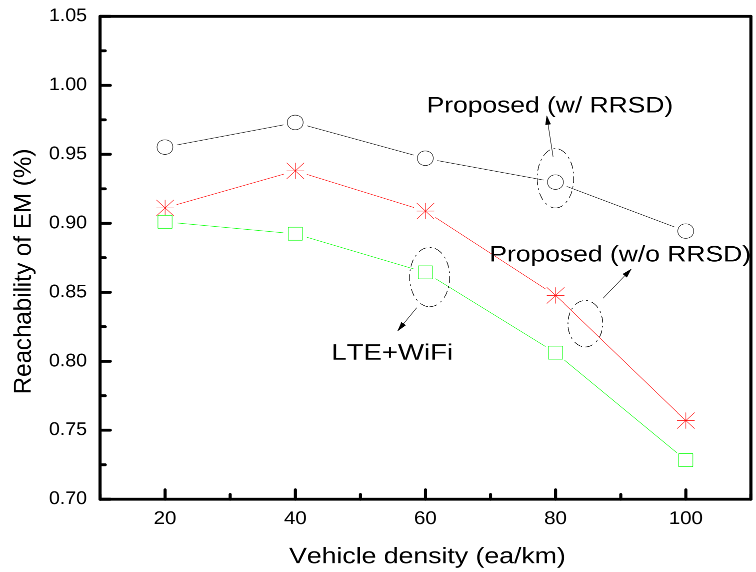


(a) Reachability of EM

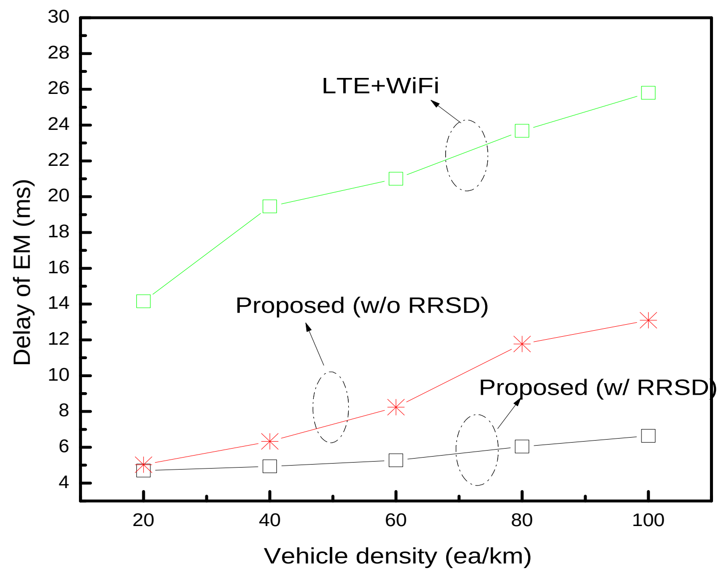


(b) Delay of EM

Figure 4.6: System performances according to the number of closed corners in an intersection: (a) reachability of an EM and (b) delay of an EM



(a) Reachability of EM



(b) Delay of EM

Figure 4.7: Comparison of system performances between the proposed scheme and [79] according to the vehicle density: (a) reachability of an EM and (b) delay of an EM

4.3.5 Improvement over Previous Work

In this subsection, we compare the proposed scheme with a clustering scheme that employs two radio interfaces, one for the LTE and the other for the Wi-Fi [79]. Similar to section 4.3.3 and 4.3.4, we use two configuration settings in the proposed scheme: 'w/ RRSD' and 'w/o RRSD'[13]. To consider realistic LTE scenario, we set Inter-Site Distance (ISD) to 1.7km, which is normally recommended by [91]. From the ISD value, we calculate the average distance between LTE Base Station (BS) and center of intersection to 425m.

In Fig.4.7(a), we observe that the proposed scheme outperforms the previous scheme. In particular, the proposed scheme with 'w/ RRSD' configuration improves the reachability over [79] by up to 25%. This improvement comes from two reasons. First, LTE transmission for inter-vehicle communications is not efficient. More specifically, even if an inter-vehicle distance is short, a vehicle transmits the EM to far away BS first, and then BS forwards the EM to the Gateway. The gateway then transmits the EM to the affected intersection cluster heads on separate LTE band. Thus, low BS-station link quality and Inter-Cell Interference (ICI) reduces a delivery ratio of the EM. Second, [79] relies on a single cluster-head for inter-cluster communications. More specifically, to reduce the cost of using LTE, only cluster-heads have connections with BS and are capable to communicate with the BS. Hence, [79] produces low delivery ratio when the link quality between BS and the cluster head is low. In contrast, our scheme leverages spatial diversity, as one of its main contribution. Specifically, to improve a delivery success, multiple receivers can receive an EM. Therefore, even if a cluster head fails in receiving the EM, other vehicles can compensate for the reception failure.

Fig.4.7(b) shows that a delay of [79] is longer than that of proposed schemes by up to 150%. This is because the scheduling mechanism of the LTE data channel

[13]For fair comparison, even if [79] depends on multiple Wi-Fi channels, we only use one Wi-Fi channel, but without interference.

usually induces a large delay when the LTE band is crowded by typical background smart-phone traffics. In contrast, the proposed scheme depends on CSMA/CA, which produces good performance when the network is not crowded. Fortunately, the proposed scheme exploits a TVWS band, which is used by only a few vehicles (e.g., a cluster head or a TVWS sender).

4.4 Conclusion

We proposed and analyzed a reliable dissemination scheme in NLOS conditions around an intersection without special relaying nodes. To leverage the good propagation characteristics, the proposed scheme depended on a TVWS band for EM dissemination in NLOS conditions. More specifically, vehicles in the same road segment form a cluster. Vehicles exploited TVWS band for inter-cluster communications, and DSRC band for intra-cluster communications and cluster managements. To further enhance the delivery ratio at the corner, the proposed system features a RRSD retransmission scheme that exploits a spatial diversity. The simulation results showed that the proposed scheme outperformed a previous cluster-oriented scheme based on LTE instead of TVWS for inter-cluster communications.

CHAPTER 5

Conclusion

In this dissertation, we proposed Cognitive Radio Network (CRN) systems that exploited extra TV White Space (TVWS) for supporting vehicular safety applications. We made progress on answering following questions. (1) Are various MAC protocols for vehicular communications feasible to the vehicular safety systems when only using a DSRC band? (2) Does TVWS-based CRN help to improve the vehicular safety systems? (3) Can we support reliable safety message dissemination in NLOS intersection via TVWS-based CRN?

To answer the first question, we evaluated various MAC protocols in vehicular environments using network simulator NS-2. The first MAC protocol is the hybrid system that consists of Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function Controlled Channel Access (HCCA) for work-zone safety systems. The simulation results showed that the hybrid system was not enough to support the safety systems in work-zone area. The second MAC protocol is Self-organized Time Division Multiple Access (STDMA). We evaluated the STDMA in highway area and the in-depth evaluation studies showed that STDMA outperformed EDCA, but still needed improvement for supporting the safety systems.

To answer the second question, we proposed a TVWS-based CRN that supported QoS of safety message dissemination. The effective transmission range in the DSRC-based IVC is short since a signal can be attenuated due to blocking by obstacles, which induces network congestion to cover large service area. To overcome the limitation of the DSRC, we utilized an extra TVWS band for safety message disseminations, and exploited a DSRC band for a control channel and the compensation of ESM reception errors. In-depth simulation studies showed that the proposed scheme could support well the requirements for latency and packet delivery ratio, and outperformed previous approaches in various vehicular scenarios.

To answer the third question, we proposed a TVWS-based CRN system for overcoming attenuation in NLOS intersections. Due to DSRC high operation frequency, a signal suffers from serious attenuation when being propagated in NLOS conditions. To solve this problem, we proposed a CRN system that enabled reliable dissemination in NLOS conditions by exploiting a TVWS band. Specifically, the proposed scheme leverages the excellent propagation characteristics of a TVWS signal even without relays. Simulation studies showed that the proposed scheme was better than the previous scheme in the delivery ratio of a safety message by 25%.

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