공학석사 학위논문

Efficient Relaying Scheme in Heterogeneous V2V Communication Environments

이기종 차량간 통신 공존 환경에서의 효율적인 메시지 중계 기법

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Abstract

Today, there exist two types of vehicular communication technology, namely, Long Term Evolution-based vehicle-to-vehicle (LTE-V2V) and dedicated short range communications (DSRC). Although many studies dealing with vehicular communication have been conducted, the situation where separate groups of vehicles using different communication technologies coexist has never been studied. In the coexistence situation, the communication inability issue between vehicles using different communication technologies is raised. To resolve the problem, we propose a relaying system, called Nearest-first, where hybrid user equipments (UEs), which are equipped with both DSRC and LTE-V2V modules, are considered. When a hybrid UE receives a cooperative awareness message (CAM), the UE relays the CAM using the other communication technology.

keywords: Wireless communication, vehicular ad-hoc networks (VANET), relay networks

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Chapter 1

Introduction

As interest in autonomous driving grows recently, various technologies on intelligent vehicles are being developed aggressively. Besides cameras and sensors, which have been already known to be crucial in intelligent vehicles, vehicular communications also have a vital role in this area. Vehicular communications enable the vehicles to exchange their statuses with their nearby vehicles. This way of recognizing surrounding environments has advantages over utilizing sensors since it is less influenced by weather conditions such as fog, rain, and snow. Moreover, gathering information from non-line-of-sight (NLOS) relationships, such as vehicle locations behind a building, is not possible with sensors, but is possible with vehicular communications.

Today, there exist two standardized direct vehicle-to-vehicle (V2V) communication technologies, i.e., dedicated short range communication (DSRC) and Long Term Evolution-based vehicle-to-vehicle (LTE-V2V). DSRC was developed in 2010 [1], based on Wi-Fi employing orthogonal frequency division multiplexing (OFDM). On the other hand, 3GPP introduced LTE-V2V in Release 14 of LTE [2, 3] in 2016. According to [4], studies for autonomous driving with thousands of vehicles are being conducted with DSRC. The United States Department of Transportation and several automakers have formed a group for DSRC study [5]. In addition, commercial vehicles supporting DSRC have been already released or are to be released [6]. Studies

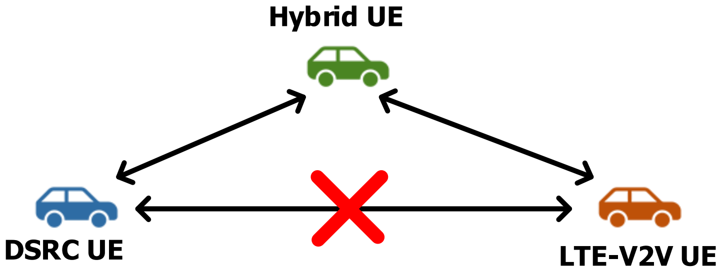

Figure 1.1: Hybrid UE.

on LTE-V2V in industry are also being actively conducted. Vehicle and communication companies have formed 5G Automotive Association (5GAA) for LTE-V2V study. Since LTE-V2V is more recently developed, there have not been commercial vehicles with LTE-V2V connectivity. Although LTE-V2V is behind DSRC in commercialization, better coding scheme and sensitivity to lower signal-to-interference-plus-noise ratio (SINR) of LTE-V2V make the technology expected to have potential competitiveness [7].

Since these two technologies have different advantages for being used commercially, it is highly likely that vehicle user equipments (UEs) with DSRC and LTE-V2V radio frequency (RF) modules (referred to as DSRC UEs and LTE-V2V UEs, respectively, for the rest of the paper) coexist on the road [8]. Even if one of the technologies might eventually dominates the market in the future, the two technologies would coexist during a transition period. Actually, there are separate groups of related companies concentrating on each technology [6,9]. Many countries are comparing both technologies with open possibilities deploying both technologies [10, 11]. Moreover, in some countries like South Korea, technologies using both DSRC and LTE-V2V are being studied [10]. Therefore, it is necessary to consider the coexistence situation where DSRC UEs and LTE-V2V UEs cannot communicate each other.

Considering the objective of vehicular communications, recognizing the nearby vehicles, the communication inability can be fatal for practical use. Therefore, vehicle

UE with both DSRC and LTE-V2V RF modules (referred to as hybrid UE for the rest of the paper) can be considered. Hybrid UEs can communicate with other nearby vehicles regardless of their vehicular communication type as illustrated in Fig. 1.1.

In this paper, we aim to restore the communication inability between DSRC UEs and LTE-V2V UEs. We first demonstrate the necessity for the relaying operation of hybrid UEs to enable information exchange between DSRC UEs and LTE-V2V UEs. However, like similar problems dealing with relaying, the motivation problem for relaying can be raised. Therefore, it is also stated that network operators, e.g., road transportation authority in government, can provide the environment for better services to its entire users by making hybrid UEs relay.

For more efficient relaying, we propose a relaying system for V2V communication, called Nearest-first. Nearest-first is inspired by the existing method, farthest-first scheme, a representative relaying scheme for vehicular ad-hoc network (VANET). Nearest-first is modified from farthest-first scheme for the objective of cooperative awareness message (CAM), a periodic packet to recognize surrounding environments in target range. Nearest-first is fit for the purpose of CAM, transmitting it to nearby vehicles in a broadcast manner, and reduces unnecessary relaying. Furthermore, Nearest-first is appropriate for the scenario where DSRC UEs and LTE-V2V UEs coexist in an urban environment.

The major contributions of this paper are as follows:

- To our best knowledge, it is the first framework that raises the communication inability issue between DSRC UEs and LTE-V2V UEs.
- We verify that there exist the incentives for network operators to attract hybrid UEs to relay CAMs from DSRC UEs and LTE-V2V UEs.
- We propose an efficient relaying scheme in the coexistence environments of heterogeneous vehicular communications suitable for an urban environment.

The rest of the paper is organized as follows. Related work is reviewed in Section 2. We present the preliminaries and system model respectively in Section 3 and Section 4. In Section 5, the proposed scheme, i.e., Nearest-first, is presented in detail. We comparatively evaluate the performance Nearest-first in Section 6. In the end, we conclude the paper in Section 7.

Chapter 2

Related Work

In this section, related studies are reviewed in two parts, i.e., relaying schemes in VANET environments and the coexistence of two vehicular communications.

2.1 Relaying in VANET

There are two main characteristics of relaying packets in VANET. The first characteristic is that packets are transmitted in a broadcast manner. Since packets in VANET are mainly for safety, it is more important to transmit to as many nearby vehicles as possible rather than to a specific vehicle. In addition, since vehicular communications require low latency, direct communication between vehicles is preferred in vehicular communications. When there are a large number of receivers (RXs) for one broadcast packet, all RXs can relay the packet. In this case, not only there will be too much superfluous relaying but also many packets are highly likely to collide. *Broadcast storm* is a term describing such a situation and there have been many efforts to solve the *broadcast storm* problem. We categorize the various protocols based on how they solve *broadcast storm*, following the criteria in [12].

The first method to deal with *broadcast storm* is delay-based relaying, which is allocating a different waiting time before relaying a received packet for each relaying vehicle. Additionally, in delay-based relaying, relaying vehicles cancel relaying if they receive a relayed version of the packet, which is about to be transmitted by them. This cancellation of already-relayed packet transmission reduces superfluous relaying. In addition, various relaying time provides different priorities to each relaying vehicle.

2.1.1 Farthest-first Relaying

The most popular way to allocate waiting time is farthest-first relaying, which assigns a shorter waiting time to a relaying vehicle with a longer distance from the original transmitter (TX) vehicle [13–17]. The proposed schemes in [13–15] are the modifications of farthest-first dissemination to fit urban environments in separate ways. In [16], the proposed scheme called efficient directional broadcast (EDB) exploits directional antennas for efficient relaying. The authors of [17] present Oppcast, a double-phase broadcast strategy to achieve both fast packet propagation and high reliability.

2.1.2 Other Delay-based Relaying Methods

There are also studies proposing relaying rules [18, 19] different from farthest-first. In [18], reliable broadcasting of life safety messages (RBLSM) proposes allocating shorter waiting time to nearer vehicles and achieves shorter latency to deliver packets to nearby vehicles. Packet-value-based dissemination protocol (PVCast) [19] also presents a novel waiting time allocation scheme considering prospective RXs of relayed packets. Different from all the studies based on DSRC, the scheme in [20] proposes a relaying system based on LTE-V2X using road side unit (RSU).

The other method to deal with *broadcast storm* in VANET is probability-based broadcasting, which prevents *broadcast storm* by relaying stochastically to limit the number of relaying events [21–23]. To be specific, different priorities can be given to different vehicles by allocating different relaying probability. The scheme proposed in [21] contains a probabilistic scheme that allocates the same probability to relay to all relaying vehicles. Slotted p-Persistence Broadcasting proposed in [22] assigns a larger probability to a relaying vehicle farther from the original TX. In [23], the proposed scheme, AutoCast, determines the probability to relay according to the nearby vehicle density.

Although the above-mentioned studies propose novel schemes appropriate for situations of their interest, they cannot be applied to our target environment where DSRC UEs and LTE-V2V UEs coexist. Above all, the basic objective of the farthest-first principle, effective dissemination of a packet to wider area, does not fit to safety packet delivery which is more crucial to nearby vehicles. In addition, they are not proper to be applied in our environment where even close vehicles cannot communicate with each other if they use different vehicular communications.

Probability-based relaying schemes also have limitations to be directly applied in our target environment. Although the scheme in [21] can mitigate *broadcast storm*, there does not exist a method to give different priorities to relaying vehicles. The probabilities to relay in Slotted p-Persistence Broadcasting [22] and Autocast are decided under the assumption that there is only one road segment. These schemes do not consider NLOS cases so packets are less likely to be disseminated to NLOS regions with the original TXs. Therefore, it is hard to apply them to urban environments.

2.2 Coexistence of Vehicular Communications

In the literature, situations where multiple vehicular communications coexist are addressed in several papers [24–26]. In [24], the coexistence situation, where both DSRC and IEEE 802.11ac operate in the 5.9 GHz band which is allocated for vehicular communications, is studied. In [25], a scheme for coexistence between DSRC and IEEE 802.22 is operated in TV white space band. The scheme proposed in [26] is based on an algorithm operated in the environment when DSRC and cellular LTE coexist. None of these papers studies the coexistence of DSRC and LTE-V2V and the communication inability between them. Both DSRC and LTE-V2V are studied in [27], but the authors only compare the performance of each communication.

Chapter 3

Preliminaries

3.1 DSRC

The physical (PHY) and medium access control (MAC) layers of DSRC, called IEEE 802.11p, is based on IEEE 802.11a but has some modifications adapted for a vehicular environment [5]. For PHY layer, OFDM and convolutional coding are utilized as in 802.11a. In most implementations of DSRC, 10 MHz is utilized for its bandwidth since it is appropriate for high mobility environments [5].

Focusing on MAC layer, its feature is the use of carrier sensing multiple access with collision avoidance (CSMA/CA) as described in Fig. 3.1(a). It is the way stations (STA) access resources and avoid collision in a fully distributed manner. Contention window (CW) size does not change because it is transmitted in a broadcast manner.[1] Immediately after each transmission, a backoff procedure is performed even if no additional transmissions are queued, which is called a "post" backoff procedure. STA which has finished a post backoff procedure is allowed to start transmission after ensuring that the channel is empty only for the duration of DIFS [28, 29].

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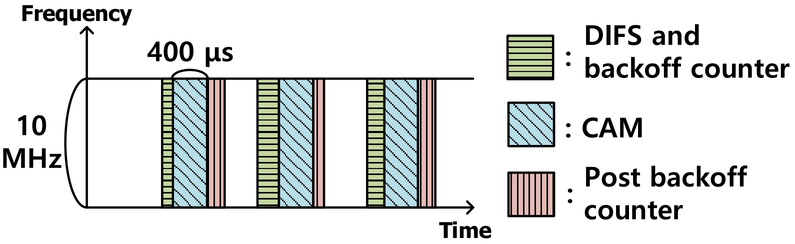
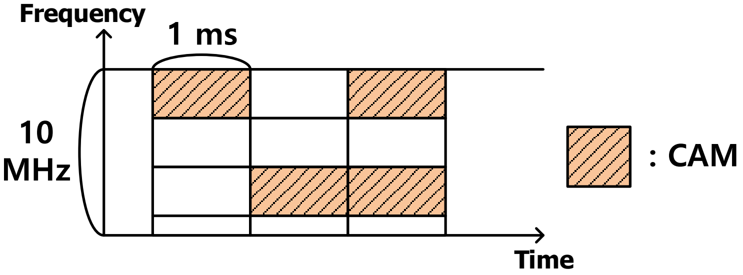
[1] Note that in unicast, CW is doubled each time transmission fails.



(a)



(b)

Figure 3.1: Utilizing resources in DSRC and LTE-V2V: (a) Channel access in DSRC and (b) Resource allocation in LTE-V2V.

3.2 LTE-V2V

Much part of LTE-V2V has been inherited from LTE-based device-to-device (LTE-D2D). LTE-V2V provides both 10 MHz and 20 MHz as its channel bandwidth options. The smallest unit for LTE-V2V resource allocation is a resource block (RB) pair and 10 MHz bandwidth is divided into 50 RBs in the frequency domain. In contrast to DSRC, a channel in LTE-V2V can be divided into multiple subchannels. Thus, multiple UEs can use resources in the same time resource, i.e., one subframe, as described in Fig. 3.1(b). It also provides better coding schemes and higher multiplexing than DSRC in virtue of the use of orthogonal frequency resources [7].

LTE-V2V UEs can access resources under control of either eNodeB (sidelink mode 3) or in a distributed manner (sidelink mode 4). In sidelink mode 4, resource selection is performed based on sensing previous resources. In sidelink mode 4, UE selects a resource from candidate resource pool based on energy level sensing results in the previous 1,000 ms. Candidate resource pool contains the resources from now to 100 ms later. To prevent collisions with near UEs which decide to change their resource simultaneously, UEs choose not the resource with the lowest received energy but the resource randomly selected among the resources with the lowest 20% received energy. A single transmission is possible for event-driven transmission.

Sensing-based semi-persistent scheduling (SPS) [2] is utilized for periodic transmissions. UE randomly selects a counter value in the range of $[5, 15]$ when changing the resource for transmission. The counter is decremented by one for each transmission. When the counter becomes zero, UE changes the resource for transmission of its packet from candidate resource pool and reselects a counter value again.

3.3 Industry Trends and Motivation

DSRC and LTE-V2V are in different stages of vehicle industry. As DSRC was standardized earlier, commercialization of DSRC precedes that of LTE-V2V. Commercial vehicles equipped with DSRC connectivity have been launched or planned to be launched on the market [6]. For commercialization of LTE-V2V, various vehicle vendors and telecommunications companies compose 5GAA [30]. Although commercialized chipset has been released [31], commercialized vehicle supporting LTE-V2V connectivity has not been introduced to the market.

Debates on LTE-V2V and DSRC are still in progress also among governments [10, 26, 32]. The government of the United States assigns 5.85–5.925 GHz for DSRC communications and proposed to make DSRC required in all newly produced vehicles. However, the importance of the decision is downgraded by the new administration and vendors are calling that LTE-V2V can be used. In South Korea, many trial tests are based on DSRC and policy amendment is currently underway to support LTE-V2V simultaneously [10]. Debates about incompatiblities between DSRC and LTE-V2V are also held in EU [11] and the EU remain technology neutral between DSRC and LTE-V2V [32].

In summary, it is still debatable which vehicular communication technology will lead the industry. Different governments support different vehicular communication technologies. There are some countries supporting both vehicular communication technologies like EU and South Korea. For the situation that neither vehicular communication technology seizes an initiative, the coexistence of DSRC UEs and LTE-V2V UEs should be studied. Even though one vehicular communication technology takes the initiative, it might take a long time to completely dominate the market. During the transition period, DSRC UEs and LTE-V2V UEs should be on the same road simultaneously.

Using different communication technologies can apparently cause the communication inability among nearby vehicles. The simplest way to resolve the inability problem is to use both communication technologies in a single vehicle. However, installing both communication modules in all vehicles cost a significant amount of money. Moreover, since it is closely related to various vehicle vendors and governments, the solution enforcing all vendors and governments is not realistic.

However, if hybrid UEs convert the packets from other UEs into heterogeneous type of packets and retransmit, DSRC UEs and LTE-V2V UEs can communicate with each other via hybrid UEs as Fig. 1.1. This solution has an advantage that one hybrid UE can benefit many nearby DSRC and LTE-V2V UEs. Besides, it is a viable solution because it enforces not entire governments, but only hybrid UEs. Although an individual hybrid UE may not be self-motivated to relay packets, considerably more LTE-V2V UEs or DSRC UEs can benefit from the relaying of hybrid UEs. Therefore, network operator would have a strong motive to promote the relaying of hybrid UEs like subsidizing or tax privilege.

Chapter 4

System Model

In this section, the system model in consideration and baseline relaying scheme are presented. Independent channels in 5.9 GHz band are allocated for vehicular communications in many countries. The model in this paper also allocates separate channels for DSRC and LTE-V2V with a band gap as shown in Fig. 4.1. It is assumed that hybrid UE has two communication modules for each of DSRC and LTE-V2V. Thus, hybrid UE is able to simultaneously receive a packet on each of DSRC and LTE-V2V channels unless it is transmitting its packet.

There are two representative types of packets in vehicular communication, which is CAM and decentralized environmental notification message (DENM). Both types of packets are transmitted in a broadcast manner and include the basic status of TX vehicles such as their ID, position, velocity, acceleration, and direction [33, 34]. The difference between two packets is that DENM is transmitted only when some accidents, e.g., vehicle collision and sudden change of traffic situation, are detected.

CAM is generated periodically regardless of the occurrence of special events. We assume that there is only CAM traffic in the channel of our interest and the period of CAM generation is 100 ms, which is a typical option for CAM. There exists target range for each CAM transmission. Unless specified, the target range of CAM is 150 m and it is determined according to the urban scenario rule specified in [35]. For CAM

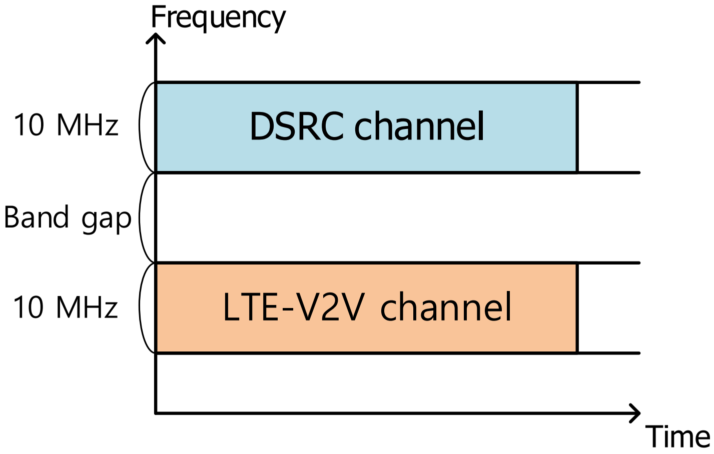


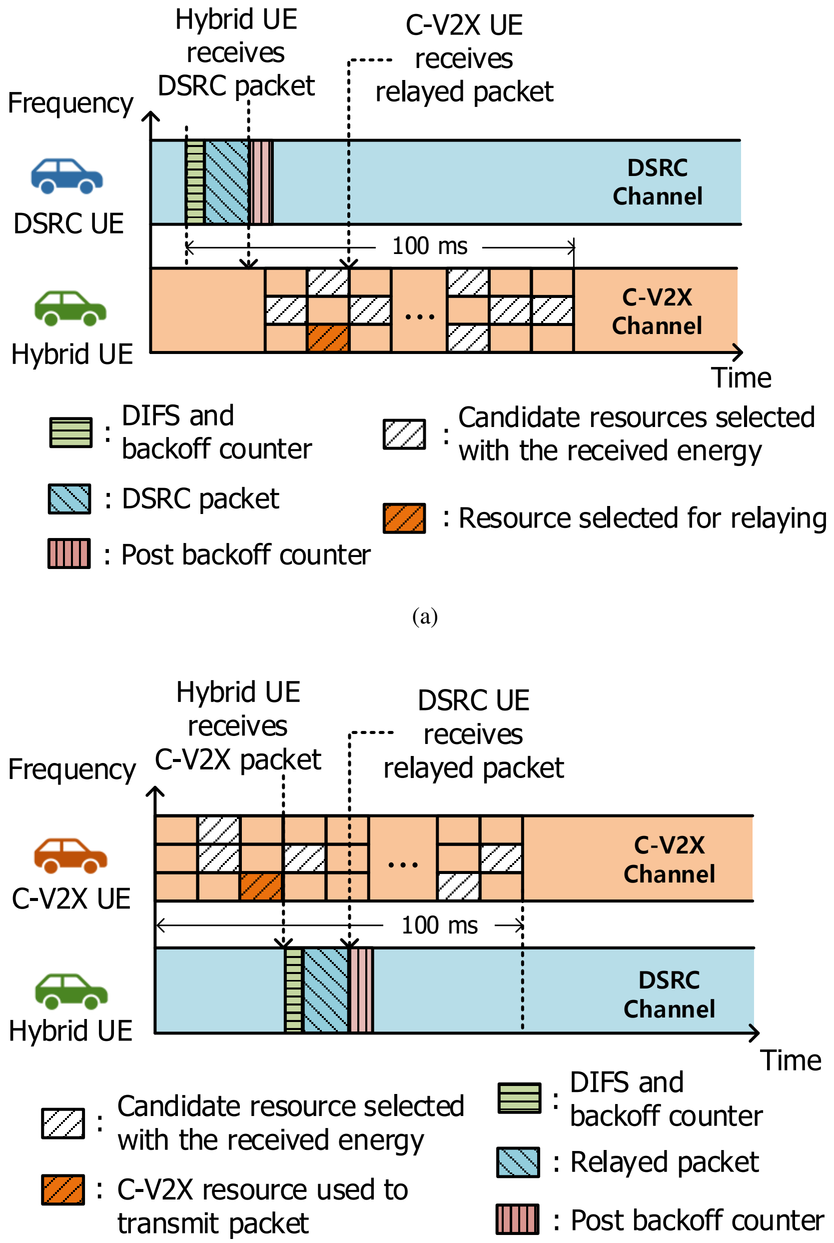
Figure 4.1: Channel allocation for DSRC and LTE-V2V in our system model.

transmission in LTE-V2V channel in this paper, a resource unit (RU), a set of resources in LTE-V2V, is utilized. A dashed rectangle in Fig. 3.1(b) corresponds to one RU. Every resource selection is done in units of RU. The specific size of RU used in our simulation is specified in Section 6.1.

4.1 Baseline Relaying Scheme

In this subsection, we present a baseline relaying scheme based on the specifications [33, 34]. The baseline scheme is introduced in two parts, i.e., relaying packets from DSRC UEs and relaying packets from LTE-V2V UEs. In the scheme, hybrid UEs select RUs for relaying in a similar way to transmitting their own CAMs.

The difference from original transmission comes from CAM lifetime. CAM lifetime is decided by the period of its generation because it is expired when new CAM of the same UE is generated. Since the period of CAM generation is 100 ms, CAM lifetime is also set to 100 ms. Thus, when a hybrid UE tries to relay a packet, the remaining lifetime of the packet is shorter than 100 ms. If hybrid UE follows the same rule mentioned in Section 3.2 for relaying with the original transmission, expired pack-



(a)

(b)

Figure 4.2: Baseline relaying scheme: (a) Relaying packets from DSRC UEs and (b) Relaying packets from LTE-V2V UEs.

ets might be transmitted. Thus, the baseline scheme should be modified with shortened lifetime. The performance of the baseline scheme is compared with Nearest-first in Section 6.

For packets from both DSRC and LTE-V2V UEs, the packet scheduling should be cancelled with some criteria to prevent *broadcast storm* problem. The criteria in the baseline scheme is as follows. If hybrid UE receives a packet relayed by other hybrid UEs and the packet is scheduled to be transmitted by the hybrid UE, it cancels the schedule for relaying the packet. In addition, hybrid UEs outside target range of an original TX UE do not relay the packets from the original TX UE. Since CAM includes information on position, whether a hybrid UE is outside the target range of the TX UE or not can be calculated by the hybrid UE.

4.1.1 Relaying Packets from DSRC UE to LTE-V2V

Fig. 4.2(a) describes a resource selection to relay packets from DSRC UEs. As soon as receiving a CAM from a DSRC UE, hybrid UE starts to schedule the RU for relaying the CAM. Specifically, hybrid UE chooses an RU among candidates where it receives the lowest 20% energy during the past 1,000 ms as single transmission in mode 4. Since DSRC UE waits for a random amount of time to transmit its CAM and it also takes as much time as packet length in time, the remaining lifetime of the CAM is less than 100 ms. To deliver valid information, candidate resource pool of hybrid UE for relaying contains the RUs from now to the remaining lifetime of the CAM to be delayed, which is shorter than 100 ms. In summary, for relaying, the RU is chosen randomly among the RUs that receives the lowest 20% energy in the shorter candidate resource pool than the original CAM transmission.

4.1.2 Relaying Packets from LTE-V2V UE to DSRC

Relaying packets from LTE-V2V UE is illustrated in Fig. 4.2(b). As in the case of relaying packets from LTE-V2V, hybrid UE utilizes CSMA/CA following the baseline

DSRC protocol. Upon receiving the whole packet from LTE-V2V UE, hybrid UE begins to try to access DSRC channel by sensing channel during distributed inter frame space (DIFS) and time for decreasing backoff counter. For expired packets, hybrid UE relinquishes relaying.

Chapter 5

Proposed Scheme

In this section, we present the motivation and the detailed algorithm of proposed relaying scheme, namely Nearest-first. The detailed algorithm is explained in two parts like baseline scheme, relaying packets from DSRC UEs and relaying packets from LTE-V2V UEs.

5.1 Motivation for Nearest-first

In this subsection, brief motivation and the basic principles of Nearest-first are explained.

The objectives of conventional VANET relaying schemes that have been studied are disseminating packets as far as possible. However, in the situation of our interest, the purpose of relaying is different from the conventional relaying schemes. Specifically, instead of forwarding a packet far away, delivering a packet to as many vehicles in a target range of the original TX vehicle as possible becomes the primary purpose of relaying of hybrid UEs. Moreover, since an original packet and a corresponding relayed packet are transmitted by utilizing different technologies, RXs of the relayed packet do not overlap with RXs of the original packet. Therefore, it is better that a packet is relayed by nearer hybrid UE so that target communication areas of the origi-

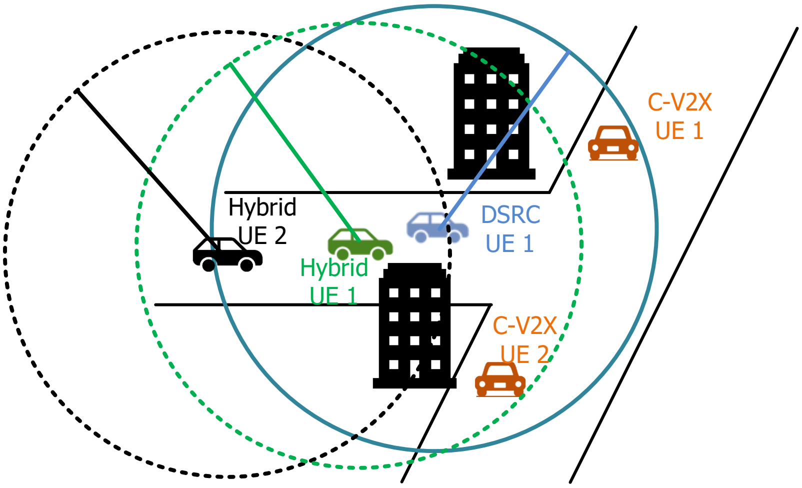


Figure 5.1: Prioritization according to distance.

nal TX UE and relaying hybrid UE overlap more. A target communication area denotes the circle centered at the packet TX and whose radius is the target range.

In Fig. 5.1, there are two hybrid UEs, hybrid UE 1 and hybrid UE 2. Circle is the border line of target communication areas. Target communication area of original TX UE overlaps more widely with dashed circle centered at hybrid UE 1 than that centered at hybrid UE 2. It implies that hybrid UE 1 can cover wider region of target communication area of original TX UE. In other words, it is proper that giving priority to a relaying UE closer from the original TX UE.

5.2 Common Rules for Relaying Packets Both from DSRC UEs and LTE-V2V UEs

To fit the objective of CAM, delivering packets in the target range, and to prevent *broadcast storm* problem, re-relaying relayed packet is prohibited in Nearest-first. To prevent unnecessary relaying, relaying UEs outside target range of original TX UE do not relay the received packets. The cancellation rule explained in Section 4.1 is also applied in Nearest-first.

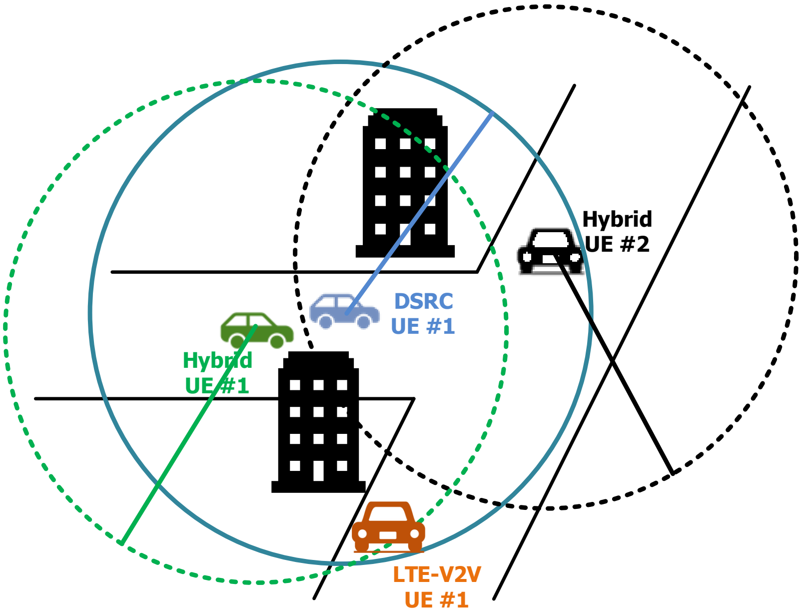


Figure 5.2: An exception of cancellation for NLOS cases.

In NLOS relationship, path loss is so large that reliable communication may not be possible between two vehicles in the target range of each other. To solve this issue, another rule should be added. The rule is that hybrid UE does not cancel relaying if it receives a relayed packet of which the TX UE is located in another street blocked with a structure. It is assumed that the information about the road segment, where relaying UE is located, is added to the relayed copy of CAM to make this operation viable.

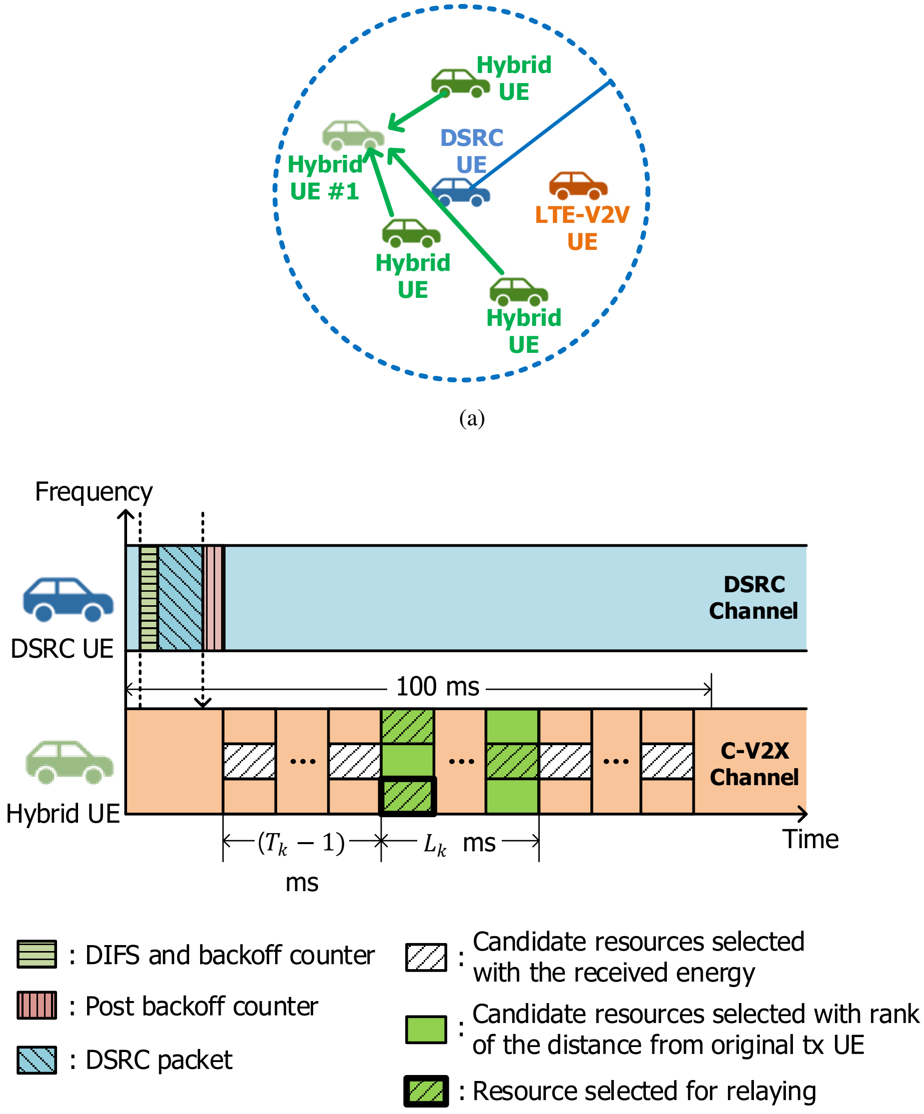
An example situation is explained in Fig. 5.2. As in Fig. 5.1, the dashed circle centered at hybrid UE 1 overlaps wider area with the circle centered at DSRC UE 1. However, if a packet is relayed only by hybrid UE 1, LTE-V2V UE 1 might not receive relayed packets. This is because the LTE-V2V UE 1 and hybrid UE 1 are in NLOS relationship. However, if hybrid UE 2 also relays the packet, LTE-V2V UE 1 can receive relayed packets and the additional rule enables this type of relaying. Even though two hybrid UEs are on the same street, there might be the case that one UE is on another street simultaneously such as the case the UE is at the intersection. In that case, the UE on the another street simultaneously does not cancel the schedule for relaying if it receives from the UE on only one street.

5.3 Nearest-first for Relaying Packets from DSRC UEs

First, we look into a detailed algorithm of Nearest-first in relaying packets from DSRC UEs to LTE-V2V UEs. All common rules mentioned in Section 5.2 are applied to relaying packets from DSRC UEs. The relaying rule basically follows the principle that a higher priority is given to a UE closer from original TX UE. LTE-V2V RUs are reserved earlier than transmission and transmitted in the appointed time. If transmission time is determined only by the distance, there is no way to avoid selecting RUs used by other UEs. It will lead to resource collision and should be avoided as sensing-based SPS in LTE-V2V does. Therefore, both collision avoidance and prioritization according to distance should be considered at the same time.

Nearest-first is designed for handling both problems. In Nearest-first, a relaying UE divides its candidate resources into subgroups of the number of potential relaying UEs of the packet in the view of the relaying UE. The potential realying UEs include hybrid UEs in the target range of original TX UE and the relaying UE itself. The relaying UE finds potential relaying UEs by receiving the packet of hybrid UEs. The relaying UE compares the distance from the original TX UE with the other hybrid UEs and determines which subgroup for relaying according to the distance rank. Collision avoidance is achieved in this method because different relaying UEs use different subgroups. Since an earlier subgroup is allocated to a relaying UE nearer to the original TX UE, relaying vehicles are prioritized according to the distance.

The detailed procedure to select an RU for relaying is as follows. First, a relaying UE receiving a packet counts n, which is the number of hybrid UEs in the target range of the TX UE of the original packet. The number of hybrid UEs can be counted by receiving and reading their packets delivered on either DSRC channel or LTE-V2V



(a)

(b)

Figure 5.3: Nearest-first for relaying packets from DSRC UEs: (a) Situation where the packet from DSRC UE is relayed and (b) Channel access for relaying packets from DSRC UE.

channel. We assume that whether packets originally generated from hybrid UEs is distinguishable. In Fig. 5.3(a), for instance, n is given by 3 for hybrid UE 1 when it is to relay a packet from DSRC UE 1 since it receives packets from 3 hybrid UEs in the target range of DSRC UE 1 during the past 100 ms. The relaying UE then divides candidate resource pool into $(n+1)$ subgroups. All subframes from when hybrid UE 1 receives a packet from DSRC UE 1 to the end of CAM lifetime are included in the candidate resource pool for relaying.

Next, the relaying UE determines which subgroup to use with the rank of distance. Since CAM contains position information, the relaying UE can compare the distances from the original TX UE with the hybrid UEs whose packets are received by the relaying UE. The relaying UE ranks itself among itself and n hybrid UEs by the distance from original TX UE. If the rank is k $(1 \leq k \leq n+1)$, i.e, the distance from the original TX UE is the kth shortest, the relaying UE uses the kth subgroup.

The detailed subgroup selection is as follows. Let the length of the candidate resource pool for relaying L. Let r the remainder obtained by dividing L by $(n+1)$. The time length L_k of the kth subgroup of candidate resource pool is determined as

$$L_k = \begin{cases} \left\lfloor \dfrac{L}{n+1} \right\rfloor + 1, & \text{if } k \leq r, \\ \left\lfloor \dfrac{L}{n+1} \right\rfloor, & \text{otherwise.} \end{cases} \tag{5.1}$$

Within the candidate resource pool, the first subframe T_k of the kth subgroup is determined as

$$T_k = \begin{cases} 1 + \left(\left\lfloor \dfrac{L}{n+1} \right\rfloor + 1 \right)(k-1), & \text{if } k \leq r, \\ 1 + \left\lfloor \dfrac{L}{n+1} \right\rfloor (k-1) + r, & \text{otherwise,} \end{cases} \tag{5.2}$$

where $\lfloor x \rfloor$ denotes the largest integer less than or equal to x. The example configuration is described in Fig. 5.3(b).

After the selection of a subgroup, the relaying UE should determine which RU to use. For collision avoidance, the technique used in sensing-based SPS is applied with some modifications. As sensing-based SPS, RUs where the relaying UE received the 20% lowest energy is chosen as candidates to be used for transmission. It is dashed RUs in Fig. 5.3(b). The final candidate RUs are the intersection of the subgroup determined with the rank of the distance from original TX UE and RUs determined with the received energy. Among the final candidate RUs, the RU used for relaying is chosen randomly.

It is possible that the intersection of the kth subgroup and the candidate RUs chosen according to energy is an empty set. In that case, the relaying UE selects an RU among the intersection of the $(k+1)$th subgroup and the candidate RU where the relaying UE received low energy. If the subgroup is the last in time in the candidate RUs and the intersection of the subgroup and candidate RU selected with energy is empty, the relaying UE renounces the relaying. The rule to reselect subgroup when the intersection set is empty is added to give more certain priority to closer UEs.

5.4 Nearest-first for Relaying Packets from LTE-V2V UEs

Since DSRC provides CSMA/CA, a distributed collision avoidance protocol, relaying packets from LTE-V2V UEs to DSRC UEs is simpler than relaying packets from DSRC UEs. Like relaying packets from DSRC UEs, relaying packets from LTE-V2V UEs in Nearest-first also follows the common rules in Section 5.2.

Similar to the conventional delay-based relaying in the environment with only DSRC, relaying UE sets a waiting time proportional to the distance from original TX UE. Let t_{DIFS} be the time duration of DIFS, t_{slot} be the slot time of DSRC, $CW_{\min}$ be the CW, and size, and t_{CAM} be the time duration of a CAM. Please note that the CW size is fixed to $CW_{\min}$ because packet is transmitted in a broadcast method. Then, the maximum deferring time to transmit a packet in an idle DSRC channel, $T_{\max}$, is calculated with the equation below.

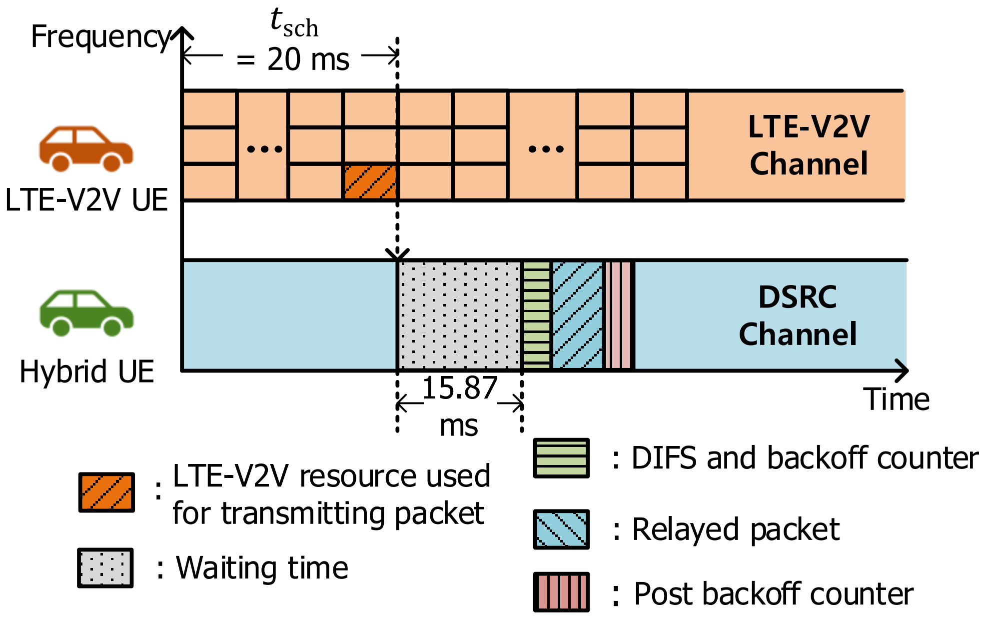


Figure 5.4: Nearest-first for relaying packets from LTE-V2V UEs.

$$T_{\max} = t_{\text{DIFS}} + t_{\text{slot}} \cdot CW_{\min} + t_{\text{CAM}}. \tag{5.3}$$

Let T be the period of CAM transmission, R be the target range of CAM, d be the distance between the relaying UE and the original TX UE, , and t_{sch} be the time difference between when a CAM is generated and when CAM transmission is finished. The exact waiting time is calculated with the equation below.

$$T_w = \frac{d}{R}\big(T - (t_{\text{sch}} + T_{\max})\big), \tag{5.4}$$

where T_w is waiting time of the relaying UE for relaying received CAM. After waiting for T_w, the relaying UE begins to transmit CAM in a DSRC channel.

In the situation in Fig. 5.4, there are two UEs, hybrid UE and LTE-V2V UE. Let two UEs 30 m apart from each other and $R = 150$ m. Then, the waiting time for hybrid UE is $(30/150) \times \big(100 - (20 + 0.4 + 0.058 + 0.013 * 15)\big) = 15.87$ ms.

Chapter 6

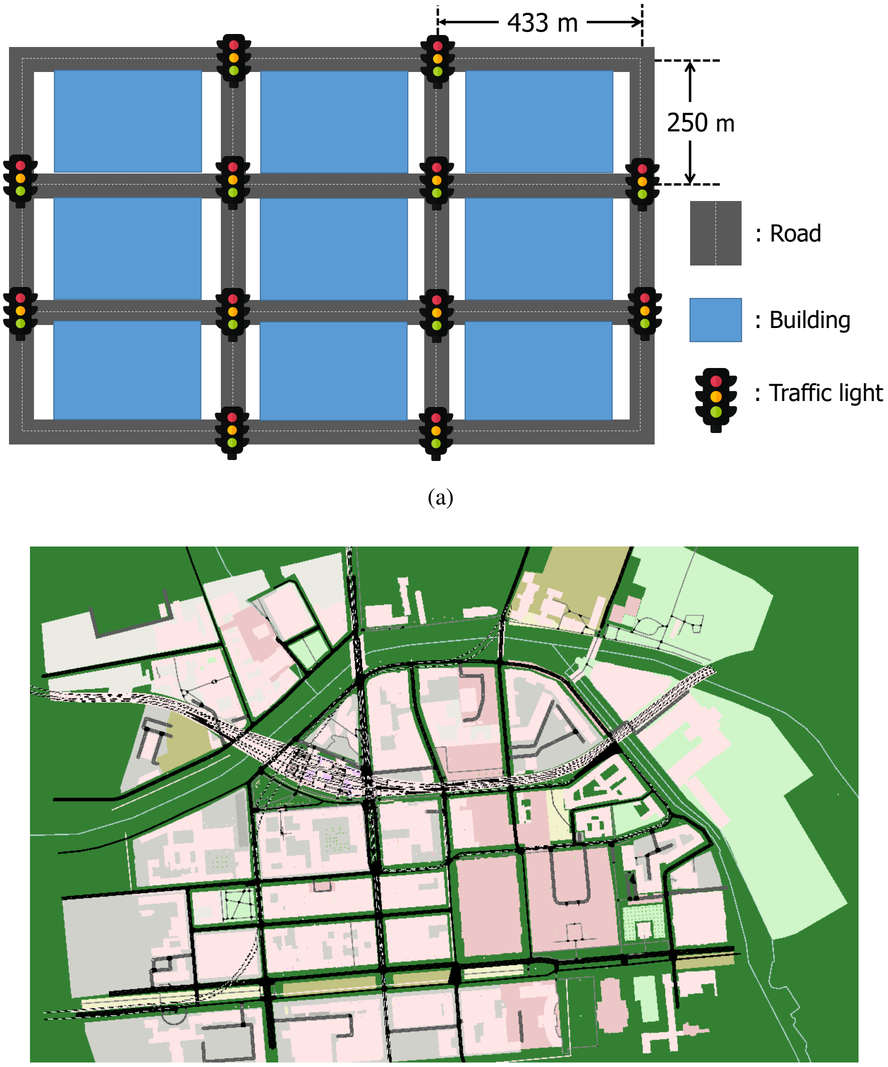
Evaluation

In this section, the performance supporting assertions of this paper is presented into several parts. First, simulation environments and various metrics deployed to analyze the results are explained. In the following subsection, the results championing that there exist benefits of relaying for network operators are also provided. Finally, overall performance in various environments are analyzed from diverse perspectives.

6.1 Simulation Environments

The general parameters for simulation environments are arranged in Table 6.1. Additionally, the basic parameters for DSRC and LTE-V2V are summarized in Table 6.2 and Table 6.3, respectively. Please note that separate channels are allocated to each of DSRC and LTE-V2V with 20 MHz band gap as Fig. 4.1.

Topology and vehicle mobility model: We consider Manhattan grid and Berlin topologies. In Manhattan grid topology, there are 9 grids and the size of each grid is 433 m × 250 m, a typical option for urban scenario [35]. Traffic lights are installed at each intersection. Berlin is also considered to reflect more realistic mobility. OpenStreetMap (OSM) [40] provided by SUMO links the real map information to our simulator. Traffic lights are also installed at each intersection in Berlin topology. In both topologies, mobility



(a)

(b)

Figure 6.1: Simulation topology: (a) Manhattan grid topology and (b) Berlin topology.

Table 6.1: Basic simulation environments.

Carrier frequency	5.9 GHz
System bandwidth	10 MHz (each for DSRC and LTE-V2V)
Topology	Manhattan grid [35] and Berlin
Vehicle mobility model	SUMO [36]
Link performance model	Yans error rate model [37] & LTE error model [38] (each for DSRC and LTE-V2V)
Channel model	Fast fading + shadowing + pathloss + in-band emission [35] + out-of-band emission [39]
TX power of UE	23 dBm
Noise figure	9 dB
Noise power	-174 dBm/Hz
Packet size	300 B
Packet generation period	100 ms
Simulation time	50 s
Band gap between DSRC and LTE-V2V channel	20 MHz

model generated by SUMO is used. We use Manhattan grid scenario and Berlin scenario as the terms incorporating the topology and mobility for each of Manhattan grid and Berlin, respectively.

According to the medium traffic case in [35], the entire number of UEs is determined to 500 in Manhattan grid scenario. In Berlin scenario, the number of UEs is 200 and the number is determined to make the UE density equal to Manhattan grid scenario. With the given number of UEs, various cases with different ratios of the number of DSRC, LTE-V2V, and hybrid UEs are tested for thorough feasibility evaluation.

Channel model: WINNER+ B1 model is adopted for the pathloss model [41]. Shadowing model follows the model in [35] which is log-normal distribution with each of 3 dB and 4 dB standard deviation for LOS and NLOS, respectively. For fast fading, ITU-R IMT UMi model in [42] is utilized. The model in [43] is used for modelling in-band emission which is undesired emission to subchannels in the same channel and at the same time slot. Finally, out-of-band (OOB) emission, i.e., undesired emission to

Table 6.2: Basic simulation parameters for DSRC.

Backoff slot time	13 μs
DIFS	58 μs
CW$_{\min}$	15
Symbol duration (including GI)	8 μs
Constellation	QPSK
Code rate	0.5
Time duration of one packet	400 μs (50 symbol durations)

Table 6.3: Basic simulation parameters for LTE-V2V.

System bandwidth in RB	50 RBs
Modulation	QPSK
Code rate	0.529
Time duration of one packet	1 ms (1 subframe)
No. subchannels / subframe	3

other channels at the same time slot, is modelled according to the model in [39].

Link performance model: For both LTE-V2V and DSRC models, the model in ns-3 [44] is used for a link performance model of our simulation. For DSRC, Wi-Fi error model for 10 MHz is used. LTE model is used for LTE-V2V error model since both communications use an OFDM.

Configuration of resources for CAM: For DSRC, quadrature phase-shift keying (QPSK) and code rate of 0.5 are a typical option [45]. Since 48 subcarriers in 10 MHz channel carry bits for data, one symbol can carry 24 bits. Therefore, 50 symbols are needed for one packet transmission and its duration is 400 μs. For LTE-V2V, 177 bits can be included in one RB pair when QPSK and code rate of 0.529 are used. To carry one CAM of 300 B, 15 RB pairs are needed and they constitute one RU. Considering that 10 MHz bandwidth can support up to 50 RBs, the number of subchannels is $3\ (=\lfloor 50/15 \rfloor)$.[1]

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[1] The configuration does not change when the lane information is added to the relayed copy of CAM.

6.2 Performance Metrics

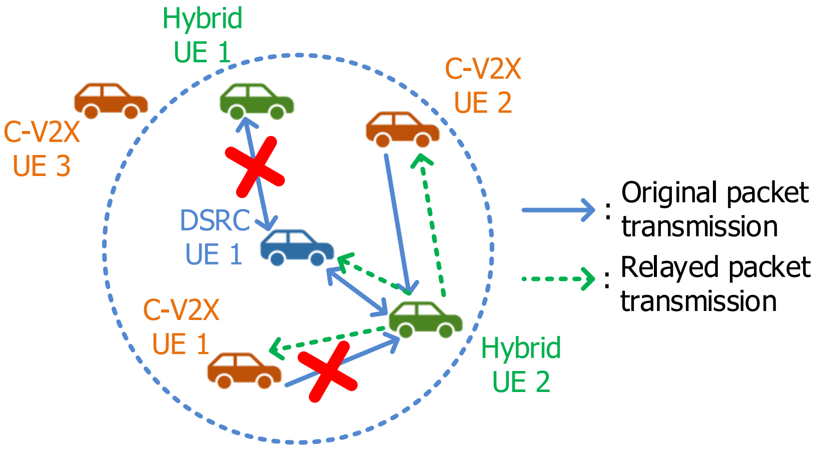
The performance of Nearest-first is compared with that of other relaying systems and without relaying with various metrics. Probability-based relaying, which is compared with Nearest-first, is based on Autocast, proposed in [23]. Different from baseline scheme and Nearest-first, relaying UEs do not cancel relaying even if they receive relayed packets which they are scheduled to relay.

The most basic metric for evaluating the performance is message reception ratio (MRR). For a given packet, MRR is calculated by X/Y, where Y denotes the number of UEs in the target range of the packet and X denotes the number of UEs successfully receiving the packet among Y UEs. Successful reception of a packet includes reception of the relayed copies of the packet. Effective communication distance is the distance where average MRR becomes 90%, which is the MRR requirement for reliable communications stated in [35]. In Fig. 6.2(b), for example, effective distances using baseline, probability-based, and Nearest-first schemes are 75 m, 83 m, 120 m, respectively.

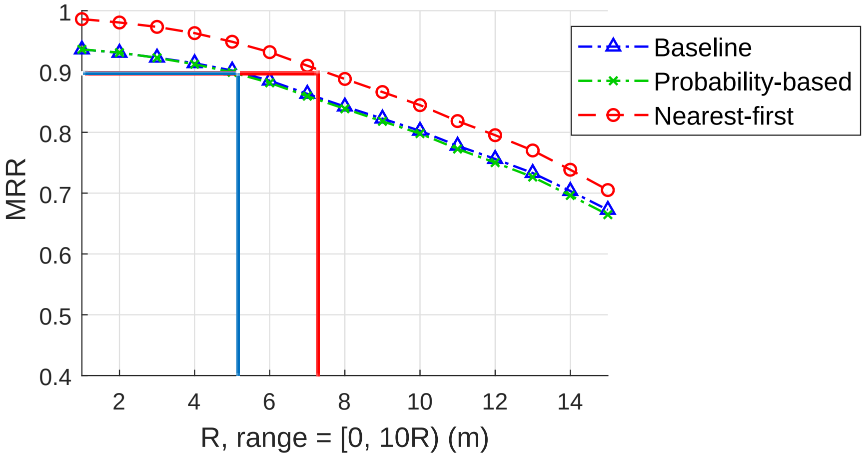
Finally, NLOS MRR is calculated by X/Y like MRR, where Y denotes the number of UEs in the target range of a packet while in NLOS relationship with TX UE, and X denotes the number of UEs successfully receiving packet in target range among Y UEs. NLOS effective communication distance is defined as the distance where average NLOS MRR becomes 90%.

To evaluate performance of a separate group utilizing DSRC channel (or LTE-V2V channel), DSRC (or LTE-V2V) intra-MRR is defined. The calculation of DSRC intra-MRR takes only UEs equipped with DSRC RF module, i.e., DSRC UEs and hybrid UEs into account. DSRC intra-MRR is also calculated by X/Y, where Y denotes the number of DSRC UEs and hybrid UEs in the target range and X denotes the number of UEs successfully receiving packets among Y UEs. LTE-V2V intra-MRR is defined in a similar way to DSRC intra-MRR.

The size of lane information on CAM is 4 B [33] and 15 RB pairs are able to carry 331 B.



(a)



(b)

Figure 6.2: Example situation for explaining metrics: (a) Example situation to explain various types of MRR and (b) Example effective distances.

To evaluate relaying performance of DSRC and LTE-V2V, DSRC (or LTE-V2V) inter-MRRs are defined. DSRC (or LTE-V2V) inter-MRR takes only UEs equipped with DSRC (or LTE-V2V) RF module, i.e., DSRC (or LTE-V2V) UEs into account. For a given packet originally transmitted in DSRC channel, DSRC inter-MRR is calculated by X/Y, where Y denotes the number of LTE-V2V UEs in the target range and X denotes the number of UE successfully receiving packets relayed by hybrid UEs among Y UEs. LTE-V2V inter-MRR is defined in a similar way to DSRC inter-MRR.

In addition, RX MRR is used for evaluating performance. For a given RX, RX MRR is defined as the ratio between the number of UEs whose packet is successfully received by the RX and the total number of UEs in the target range.

Fig. 6.2(a) shows an example situation. In the example, DSRC UE 1 located at the center broadcasts its packet. Hybrid UE 2 receives the packet and both LTE-V2V UE 1 and LTE-V2V UE 2 receive the packet relayed by hybrid UE 2. The number of UEs successfully receiving the packet in the target range is three and the number of UEs in the target range of DSRC UE 1 is four. Therefore, MRR of DSRC UE is $3/4$. DSRC inter-MRR is $2/2 = 1$ since both the number of LTE-V2V UEs and the number of LTE-V2V UEs successfully receiving the relayed packet are two. DSRC UE 1 receives a packet of hybrid UE 2 and a packet of LTE-V2V UE 2 relayed from hybrid UE 2. Therefore, RX MRR of DSRC UE 1 is $2/4 = 0.5$.

6.3 Advantage of Relaying from Network Operator Perspective

Fig. 6.3 shows the RX MRRs of UEs with DSRC module and LTE-V2V module for different ratios of the number of DSRC, LTE-V2V, and hybrid UEs. Compared with the performance without relaying, represented by “No relay,” the performance of relaying schemes is improved by up to 45% and 51% for the UEs using DSRC and LTE-V2V, respectively. In contrast to “No relay,” the performance gain is observed regardless of the type of schemes. Taken together, relaying can benefit UEs using LTE-V2V even though the number of hybrid UEs is small. In conclusion, to provide better quality of communication to vehicle UEs, network operators can be encouraged to provide incentive to relaying UEs to make them relay packets.

6.4 Overall Performance Comparison

Fig. 6.4 and Fig. 6.5 shows effective communication distances of various cases in Berlin and Manhattan grid scenarios. The results without relaying are not included since the 90% MRR is not achieved in any transmission range in every ratio case. Performance gain in terms of effective communication distance by up to 91% is achieved compared to the comparison schemes. To figure out the cause of performance gain, we observe diverse metrics mentioned in Section 6.2 in the following.

DSRC inter-MRR and LTE-V2V inter-MRR over distance in Berlin scenario are shown in Fig. 6.6(a) and Fig. 6.6(b). The results without relaying are not shown in Fig. 6.6 since DSRC/LTE-V2V inter-MRR is 0 without relaying. Especially, the performance gain in LTE-V2V inter-MRR is more significant than that of DSRC inter-MRR. In baseline and probability-based scheme, multiple hybrid UEs which have finished a post backoff procedure wait only for DIFS and relay the received packet simultaneously if the channel is idle, thus incurring collisions. In contrast, waiting time in Nearest-first makes hybrid UEs access DSRC channel at separate times from each other despite post backoff procedures.

One of the most important issues in relaying in VANET is *broadcast storm*, caused by numerous superfluous relaying events. Too many relaying events are also a burden to hybrid UEs since hybrid UEs cannot receive packets when they are transmitting their packets in both DSRC and LTE-V2V channels. Fig. 6.7 presents the average number of relaying events per one hybrid UE during 100 ms in both scenarios. It is shown in Fig. 6.7 that Nearest-first also reduces the number of relaying by up to 50%.

As the ratio of hybrid UEs increases, the number of relaying events per hybrid UEs decreases. In baseline and Nearest-first scheme, the cancellation rule, explained in Section 4.1 and Section 5.2, leads the reduction. In probability-based relaying, decline in relaying probability due to the increase in the hybrid UE density causes the drop of the number of relaying events.

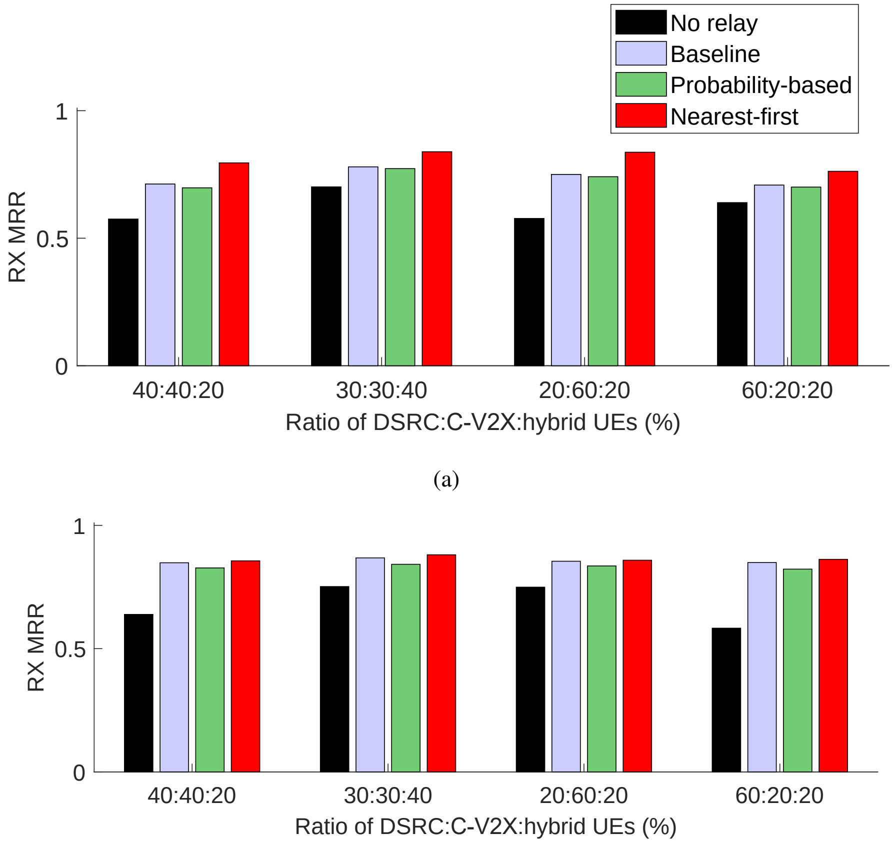
As the ratio of LTE-V2V UEs increases with the fixed ratio of hybrid UEs, the number of relaying events utilizing baseline scheme increases while that utilizing probability-based scheme decreases. The number of relaying events utilizing probability-based relaying is higher than that utilizing Nearest-first. This is because there is no cancellation rule in probability-based relaying. When relaying packets from LTE-V2V UEs deploying baseline scheme, multiple hybrid UEs try to relay at the same time. This phenomenon contributes to the considerable number of relaying packets from LTE-V2V UEs to DSRC channel.

Fig. 6.8 shows that intra-MRR performances without relaying outperform the performance with relaying. The reason is that the congestion level increased by relaying affects transmission of originally transmitted packets. Since the number of original packet transmission is fixed, congestion level is determined with the number of relaying events. For DSRC intra-MRR, Nearest-first outperforms other schemes as shown in Fig. 6.8(a). It is compliant to the result in Fig. 6.9(a), the number of events relaying packets from LTE-V2V UEs is smallest when utilizing Nearest-first.

The result from the view point of packets is shown in Fig. 6.9(b). Considering the topology of Manhattan grid scenario, the maximum number of road segments within target range is three. In Fig. 6.8(b), 93.6% of packets are relayed at most three times. It is shown that Nearest-first operates properly as we desire. In contrast, only 62.2% and 53.3% of packets are relayed up to three times when deploying baseline and probability-based scheme. Furthermore, more than 10% of packets are relayed more than seven times in both comparison schemes, while no packet is relayed more than seven times utilizing Nearest-first. It shows that Nearest-first makes the number of relaying to be more suitable for the topology than both comparison schemes.

The trend between intra-MRR and the number of relaying events is also applied to LTE-V2V intra-MRR and the number of events relaying packets from DSRC UEs. Both DSRC and LTE-V2V intra-MRR without relaying outperforms those of Nearest-first. LTE-V2V intra-MRR of baseline scheme slightly outperforms that of Nearest-first. However, it is hard to say that baseline scheme and "No relay" outperform Nearest-first generally. It is because DSRC inter-MRR performance in baseline scheme and inter-MRR performances in "No relay" are lower than those in Nearest-first. Furthermore, in effective communication distances, which reflect overall performance, Nearest-first outperforms baseline scheme and "No relay".

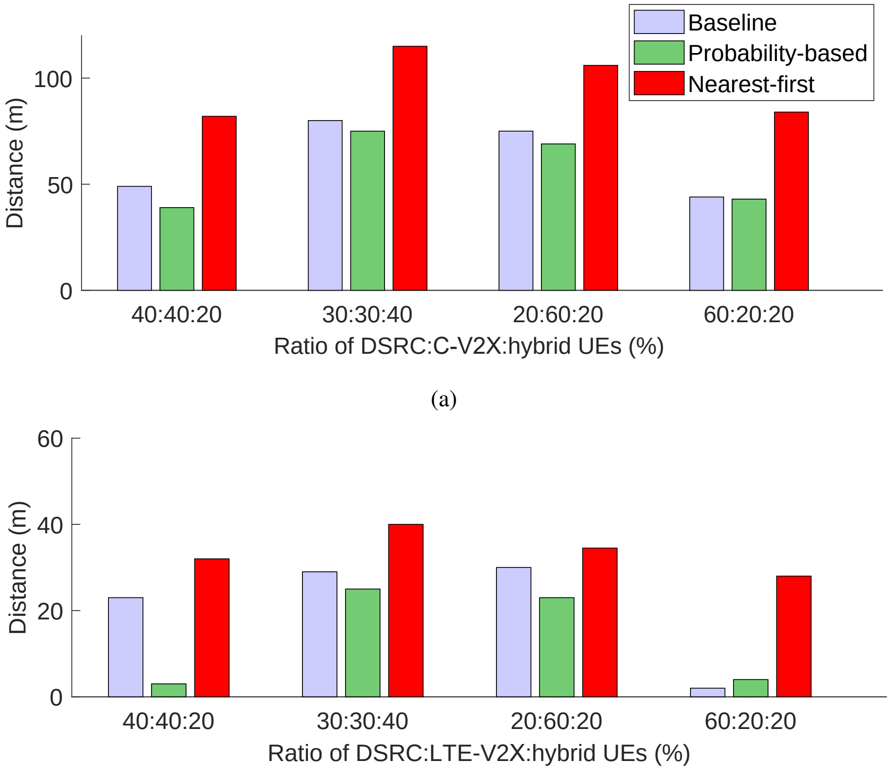
Taken together the results presented above, it is verified that relaying packets via hybrid UEs benefits overall UEs. Among relaying schemes, Nearest-first shows several advantages over other comparison schemes. Above all, longer effective communication distances and NLOS effective communication distances are achieved with Nearest-first than comparison schemes. Nearest-first lets relaying UEs avoid collisions by making times for accessing channel different. Furthermore, it can be said that Nearest-first operates efficiently since the number of relaying in Nearest-first is significantly smaller than comparison schemes.



(a)

(b)

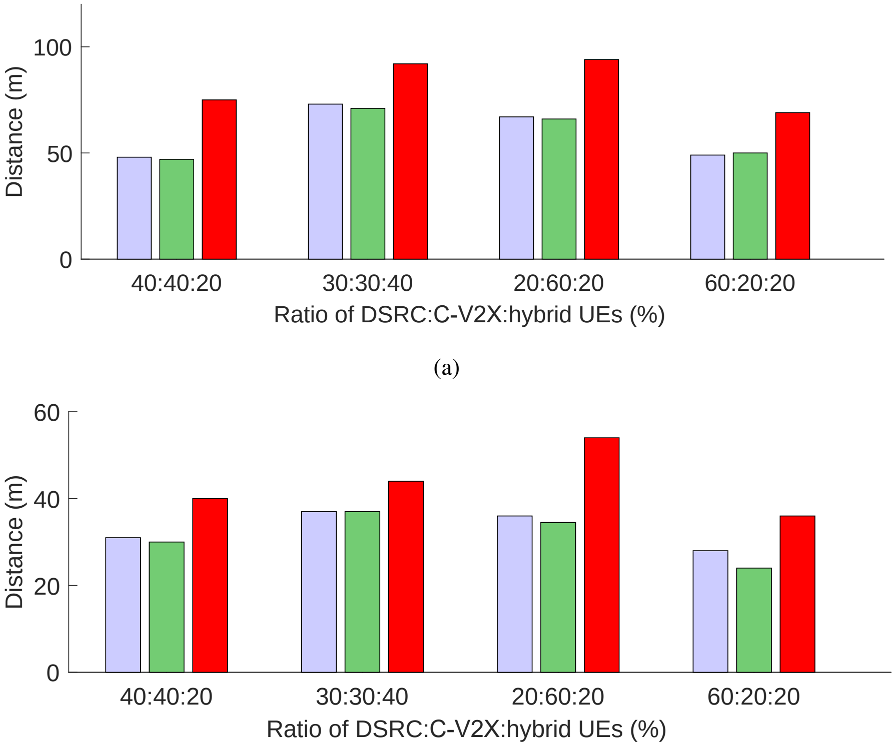
Figure 6.3: RX MRR of UEs using the same communication in Manhattan grid scenario: (a) RX MRR of DSRC UEs and hybrid UEs and (b) RX MRR of LTE-V2V UEs and hybrid UEs.



(a)

(b)

Figure 6.4: Effective communication distances in Manhattan scenario: (a) Effective distances, (b) NLOS effective distances.



(a)

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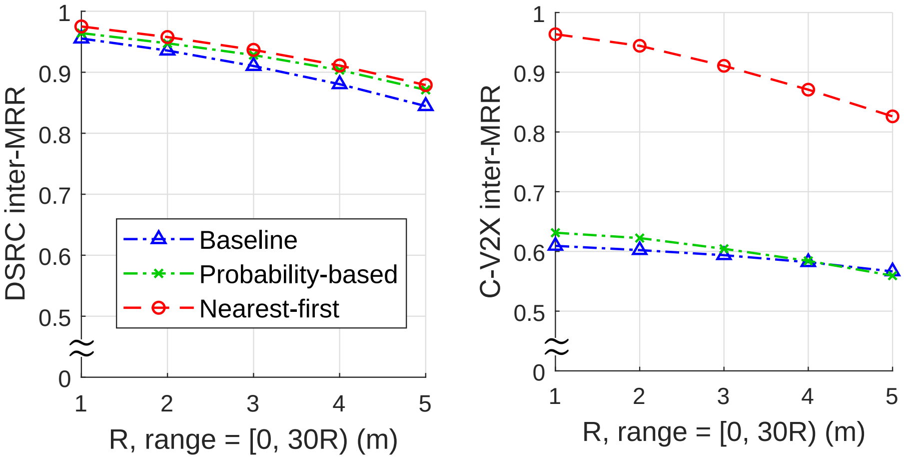
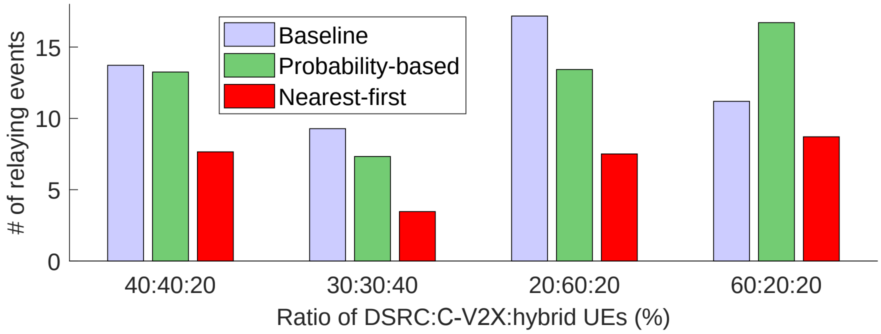
Figure 6.5: Effective communication distances in Berlin scenario: (a) Effective distances, (b) NLOS effective distances.



(a) (b)

Figure 6.6: Inter-MRR performances in Manhattan grid scenario (The ratio among DSRC:LTE-V2V:hybrid UEs = 40:40:20 (%)): (a) DSRC inter-MRR and (b) LTE-V2V inter-MRR.



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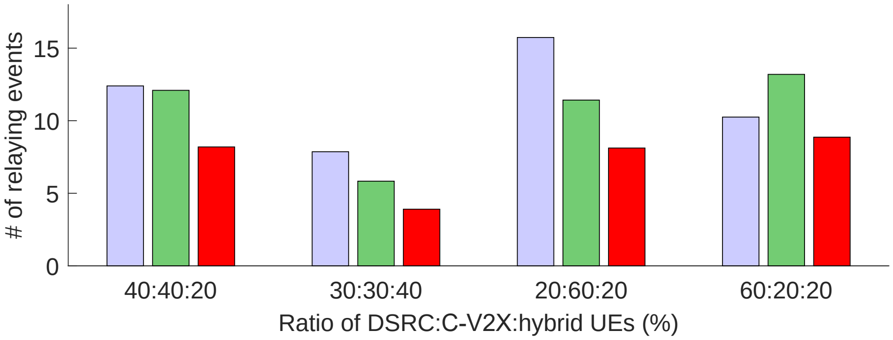
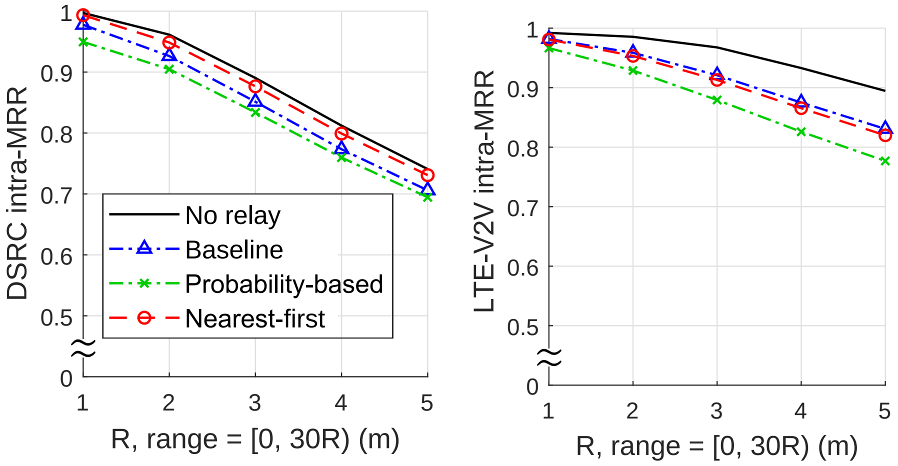


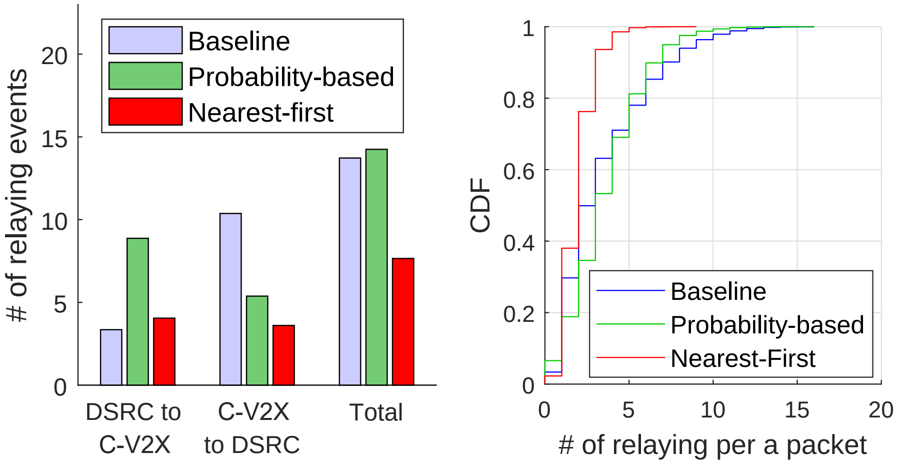
(b)

Figure 6.7: The number of relaying events per a hybrid UE during 100 ms: (a) Manhattan grid scenario and (b) Berlin scenario.



(a) (b)

Figure 6.8: Inter-MRR performances in Manhattan grid scenario (The ratio among DSRC:LTE-V2V:hybrid UEs = 40:40:20 (%)): (a) DSRC inter-MRR and (b) LTE-V2V inter-MRR.



(a) (b)

Figure 6.9: The number of relaying events in Manhattan grid scenario (The ratio among DSRC:LTE-V2V:hybrid UEs = 40:40:20 (%)): (a) The number of relaying events per one hybrid UE during 100 ms and (b) The number of relaying events per one packet.

Chapter 7

Conclusion

In this paper, we try to improve reliability performance in the coexistence situation of heterogeneous vehicular communications. With the simulation considering the environment where DSRC UEs, LTE-V2V UEs, and hybrid UEs coexist, we show that the communication inability can be solved by relaying operation of hybrid UEs and the relaying is beneficial to network operators. For efficient management of relaying, Nearest-first is proposed. Large-scale simulations based on realistic topology and mobility model are performed to investigate the performance gain of Nearest-first. It is shown that Nearest-first yields longer effective communication distances with smaller number of relaying events compared with comparison schemes. Effective communication distances increase by up to 91% and the number of relaying events decreases by up to 50%. In summary, the results demonstrate that Nearest-first manages relaying operation of hybrid UEs effectively and resolves the communication inability issue in heterogeneous V2V environments efficiently.

Bibliography

[1] IEEE 802.11p, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Amendment 6: Wireless Access in Vehicular Environments," July 2010.

[2] 3GPP TR 36.213, "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); physical layer procedures," ver. 14.2.0, Mar. 2017.

[3] 3GPP TR 36.321, "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); medium access control (MAC) protocol specification," ver. 14.2.0, Mar. 2017.

[4] Website of the Transportation Research Institute of the University of Michigan. [Online]. Available: https://www.aacvte.org/

[5] J. B. Kenney, "Dedicated short-range communications (dsrc) standards in the united states," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, 2011.

[6] Z. MacHardy, A. Khan, K. Obana, and S. Iwashina, "V2x access technologies: Regulation, research, and remaining challenges," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1858–1877.

[7] Seo, Hanbyul and Lee, Ki-Dong and Yasukawa, Shinpei and Peng, Ying and Sartori, Philippe, "LTE Evolution for Vehicle-to-Everything Services," *IEEE Commun. Mag.*, no. 6, pp. 22–28, June 2016.

[8] MX. Punithan, ”Vision for C-ITS beyond Day-1”. [Online]. Available: https://www.etsi.org/news-events/10-news-events/events/865-2015-03-etsi-its-workshop/

[9] 5G Americas white paper, “V2X cellular solutions,” Oct. 2016. [Online]. Available: http://www.5gamericas.org/files/2914/7769/1296/5GA_V2X_Report_FINA_for_upload.pdf

[10] 5GAA White paper, “White Paper on ITS spectrum utilization in the Asia Pacific Region,” July 2018. [Online]. Available: http://5gaa.org/news/white-paper-on-its-spectrum-utilization-in-the-asia-pacific-region/

[11] GSMA, “GSMA position on C-V2X in Europe September 2017,” Sept. 2017.

[12] S. Panichpapiboon and W. Pattara-Atikom, “A review of information dissemination protocols for vehicular ad hoc networks,” *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 784–798, Aug. 2012.

[13] Martinez, Francisco J and Toh, Chai-Keong and Cano, Juan-Carlos and Calafate, Carlos T and Manzoni, Pietro, “A street broadcast reduction scheme (”sbr”) to mitigate the broadcast storm problem in vanets,” *Wireless personal Commun.*, vol. 56, no. 3, pp. 559–572, 2011.

[14] G. Korkmaz, E. Ekici, and F. Ozguner, “An efficient fully ad-hoc multi-hop broadcast protocol for inter-vehicular communication systems,” in *Proc. IEEE ICC*, vol. 1, June 2006, pp. 423–428.

[15] E. Fasolo, A. Zanella, and M. Zorzi, “An effective broadcast scheme for alert message propagation in vehicular ad hoc networks,” in *Proc. IEEE ICC*, June 2006, pp. 3960–3965.

[16] Li, Da and Huang, Hongyu and Li, Xu and Li, Minglu and Tang, Feilong, “A distance-based directional broadcast protocol for urban vehicular ad hoc network,” in *Proc. IEEE WiCom*, Sept. 2007, pp. 1520–1523.

[17] M. Li, K. Zeng, and W. Lou, “Opportunistic broadcast of event-driven warning messages in vehicular ad hoc networks with lossy links,” *Comput. Netw.*, vol. 55, no. 10, pp. 2443–2464, 2011.

[18] M. M. Taha and Y. M. Hasan, “Vanet-dsrc protocol for reliable broadcasting of life safety messages,” in *Proc. IEEE ISSPIT*, Dec. 2007, pp. 104–109.

[19] Xiang, Qiao and Chen, Xi and Kong, Linghe and Rao, Lei and Liu, Xue, “Data preference matters: A new perspective of safety data dissemination in vehicular ad hoc networks,” in *Proc. IEEE INFOCOM*, Apr. 2015, pp. 1149–1157.

[20] S. Park, B. Kim, H. Yoon, and S. Choi, “RA-eV2V: relaying systems for LTE-V2V communications,” *J. Commun. Netw.*, vol. 20, no. 4, pp. 396–405, 2018.

[21] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, and J.-P. Sheu, “The broadcast storm problem in a mobile ad hoc network,” *Wireless Netw.*, vol. 8, no. 2-3, pp. 153–167, 2002.

[22] Wisitpongphan, Nawaporn and Tonguz, Ozan K and Parikh, Jayendra S and Mudalige, Priyantha and Bai, Fan and Sadekar, Varsha, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84–94, 2007.

[23] Wegener, Axel and Hellbruck, Horst and Fischer, Stefan and Schmidt, Christiane and Fekete, Sándor, “AutoCast: An adaptive data dissemination protocol for traffic information systems,” in *Proc. IEEE VTC*, Oct. 2007, pp. 1947–1951.

[24] G. Naik, J. Liu, and J.-M. J. Park, “Coexistence of dedicated short range communications (DSRC) and Wi-Fi: Implications to Wi-Fi performance,” in *Proc. INFOCOM*, May 2017, pp. 1–9.

[25] Y. Han, E. Ekici, H. Kremo, and O. Altintas, “Resource allocation algorithms supporting coexistence of cognitive vehicular and ieee 802.22 networks,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 1066–1079, 2017.

[26] J. Härri and J. Kenney, “Multi-channel operations, coexistence and spectrum sharing for vehicular communications,” in *Veh. ad hoc Netw.*, 2015, pp. 193–218.

[27] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault, “On the performance of IEEE 802.11p and LTE-V2V for the cooperative awareness of connected vehicles,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10 419–10 432, 2017.

[28] IEEE 802.11, “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” Mar. 2012.

[29] B. G. Lee and S. Choi, *Broadband wireless access and local networks: mobile WiMAX and WiFi,* Artech House, 2008.

[30] 5GAA White paper, “Coexistence of C-V2X and 802.11p at 5.9 GHz,” June 2017. [Online]. Available: http://5gaa.org/news/position-papercoexistence-of-c-v2x-and-802-11p-at-5-9-ghz/

[31] A special report based on GSA’s continuous LTE and 5G research programme, “C-V2X Market Report,” Apr. 2018. [Online]. Available: https://www.satasec.net/downloads/GSA/180406-GSA-C-V2X-Market-Status-2-April-2018.pdf

[32] 5GAA White paper, “An assessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safet in the EU,” Dec. 2017. [Online]. Available: http://5gaa.org/news/an-assessmentof-lte-v2x-pc5-and-802-11p-direct-communications-technologies-forimproved-road-safety-in-the-eu/

[33] ETSI TS 302 637-2, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service,” V1.3.2, Nov. 2011.

[34] ETSI TS 302 637-3, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specification of Decentralized Environmental Notification Basic Service,” V1.3.2, Nov. 2014.

[35] 3GPP TR 36.885, “Technical Specification Group Radio Access Network; Study on LTE-based V2X Services,” V2.0.0, June 2016.

[36] Simulation of urban mobility. [Online]. Available: http://sumo.dlr.de

[37] G. Pei and T. R. Henderson, “Validation of ofdm error rate model in ns-3,” *Boeing Res. Technol.*, pp. 1–15, 2010.

[38] M. Rupp, S. Schwarz, and M. Taranetz, *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation*, 1st ed., ser. Signals and Communication Technology. Springer Singapore, 2016.

[39] 3GPP TS 36.101, “UE radio transmission and reception,” ver. 15.1.0, Jan. 2018.

[40] OpenStreetMap. [Online]. Available: https://www.openstreetmap.org/

[41] Draft new Report ITU-R M.[IMT.EVAL], “Guidelines for Evaluation of Radio Interface Technologies for IMT-Advanced,” 2008.

[42] WINNER+ Deliverables, “WINNER+ Final Channel Models,” D5.3, June 2010.

[43] 3GPP TR 36.843, “Technical Specification Group Radio Access Network; Study on LTE Device to Device Proximity Services; Radio Aspects,” V12.0.1, Mar. 2014.

[44] The network simulator-3. [Online]. Available: https://www.nsnam.org/

[45] D. Jiang, Q. Chen, and L. Delgrossi, “Optimal data rate selection for vehicle safety communications,” in *Proc. ACM VANET*, Sept. 2008, pp. 30–38.

초 록

최근 주목을 받고 있는 vehicule-to-vehicle(V2V)통신 기술에는 dedicated short-range communications(DSRC), Long Term Evolution-based vehicle-to-vehicle(LTE-V2V)기술, 이렇게 두 가지 기술이 있다. 지금까지 많은 V2V 통신 기술 연구가 진행되었지만, 다른 통신 기술들을 지원하는 차량들이 혼재하는 상황에 대한 연구는 진행되어진 바가 없다. 두 통신 기술이 혼재하는 상황에서는, 다른 통신 기술을 지원하는 차량 간에 통신 불능 문제가 대두될 수 있다. 이 잠재적인 문제를 해결하기 위해서, 우리는 Nearest-first라는 이름의 메시지 중계 방식을 제안했다. Nearest-first 에서는, DSRC와 LTE-V2V 모두를 지원하는 차량의 존재를 가정하고, 이를 hybrid UE라고 부른다. Hybrid UE가 차량 안전 정보를 담은 cooperative awareness message(CAM)을 받으면, hybrid UE는 그 CAM이 원래 전송되어진 통신 기술과 다른 통신 기술로 중계한다. 우리는 사실적인 차량 움직임과 도로 상황을 포함한 다양한 환경에서 시뮬레이션을 수행했다. 시뮬레이션 결과, Nearest-first는 현재 사용되어지고 있는 차량간 통신에서의 중계 기법에 비해 유효 통신 거리를 91% 증가시켰다.

주요어: 무선 통신, 차량간 애드혹 네트워크, 메시지 중계 네트워크

학번: 2017-27631

감사의 글

아직 길지 않은 시간을 살았기 때문에 이런 말을 하기 조금 부끄럽지만, 제 생의 다른 기간을 모두 합친 것보다 멀티미디어 무선통신망 연구실에서의 2년 동안 더 많은 것을 배운 것 같은 기분이 듭니다. 그 이유는 습득한 지식의 절대적인 총량 때문이라기보다는, 저 혼자는 배울 수 없었던 것들을 주위 사람들로부터 가르침으로, 또는 보고 느끼면서 배운 것이 다른 때보다 훨씬 많았기 때문인 것 같습니다. 이렇게 저의 석사과정 중 저에게 여러 도움과 가르침을 주신 분들께 감사의 말씀 전하고자 합니다.

먼저, 최성현 교수님께 존경의 마음을 담아 깊은 감사의 말씀 올립니다. 연구를 시작하고, 진로를 결정해야 하는 단계에 있던 저에게, 교수님의 연구에 대한 깊은 통찰과 진로의 방향에 대해서 해주셨던 조언은 연구와 진로에서의 방향설정에 모두에 있어 가장 큰 힘이 되었습니다. 또한, 교수님께서 강조하시고, 직접 보여주셨던 교수님의 진취적이고 적극적인 삶의 태도는 석사과정동안 제가 가장 배우고 싶었던 것이고, 그래서 또 그렇게 변화하려 노력했던 것 같습니다. 앞으로도 교수님이 해주셨던 말씀과 보여주신 모습을 기억하면서 적극적인 삶의 태도를 이어나가도록 하겠습니다.

제 학위 논문 심사위원장을 맡아주신 심병효 교수님께 큰 감사의 말씀 전합니다. 바쁘신 와중에도 논문 심사에 참여해 조언으로 큰 도움을 주시고, 박사 진학에 관해서도 아낌없이 격려와 조언해 주신 것에 감사드립니다. 또한, 날카로운 통찰력으로 연구실원들의 연구에 완성도를 더해 주시는 임종한 교수님께도 감사 말씀 드립니다. 박사 진학 학교 선정에 있어서 주셨던 조언은 저에게 큰 도움이 되었고, 또 학위

논문 심사위원으로 참석해주셔서 주셨던 격려와 관심은 학위 논문 작성에 큰 힘이 되었습니다.

제 진로에 있어서 필요한 도움과 조언을 많이 해주셨던 조준호, 이남윤 교수님께도 깊이 감사드립니다. 학부 때부터 좋은 수업으로 제가 통신 분야에 흥미를 갖게 해주시고, 또 진로 설정에 있어서도 많은 격려 주셔서 무사히 박사과정에 진학 할 수 있었던 것 같습니다. 찾아 뵐 때마다 많은 격려 주셨던 두 교수님들께 감사의 말씀 드립니다.

2년 동안 함께한 선후배님들과 동기들에게 감사드립니다. 먼저, V2X 팀에서 함께 연구했던 박승일 형님, 윤호영 형님, 황선욱 형님, 이주헌, 김민우에게 감사드립니다. 학업적, 인간적인 부분 모두 배울 점이 많은 선후배님들과 함께 같은 팀으로 연구할 수 있었던 것은 저에게 큰 영광이고 행운이었습니다. 깊은 통찰력으로 제 첫 논문을 지도해 주셨던 김성원 형님께도 감사드립니다. 비슷한 시기에 대학원 시작을 함께했던 허재원, 권휘재, 이강현, 장민석 형님, 임수훈, 이경진에게도 감사드립니다. 훌륭한 동기들과 함께할 수 있어서 낯선 대학원 생활에 적응하는데 큰 도움이 되었던 것 같습니다. 멀티미디어 무선통신망 연구실의 일원으로서 함께 의미 있는 시간을 보냈던 손위평 형님, 신연철 형님, 변성호 형님, 구종회 형님, 윤강진 형님, 박태준 형님, 이규진 형님, 양창목 형님, 김선도 형님, 손영욱 형님, 김지훈 형님, 이재홍 형님, 김준석 형님, 최준영, 이기택 형님, 곽철영 형님, 이지환, Martin, 양희진, 이진명, 배한여름에게도 감사의 말씀 드립니다.

낯선 대학원 생활에 적응할 수 있도록 도와준 연구실 밖의 친구들에게도 감사드립니다. 학부 신입생때부터 여러 고민을 나눴던 경수에게 감사의 인사를 전합니다. 고등학생 때부터 서로의 가장 친한 친구이자 조언자가 되어왔던 성범, 정찬에게도 감사합니다. 이 친구들의 도움 덕분에 무사히 석사과정을 마칠 수 있었던 것 같습니다. 앞으로도 이 친구들과 소중한 우정 이어 나가면 좋겠습니다.

마지막으로, 사랑하는 가족에게 감사드립니다. 적지 않은 나이 차에도 편한 친구처럼 대해주는 누나에게도 고맙다는 말을 하고 싶습니다. 학자의 길을 먼저 걷고 계시고, 도움 청할 때마다 아낌없는 조언을 주시는 자형에게도 감사의 인사 드립니다. 그리고, 너무나 귀여운 조카 서현, 규현에게도 고마운 마음을 전합니다. 마지막

으로 부모님께 감사인사 드립니다. 성실하신 모습으로 모범이 되어주시는 아버지께 감사의 마음 전합니다. 적지 않는 나이에도 항상 도전하시는 모습은 제 삶에 큰 귀감이 되어왔습니다. 가족을 사랑으로 돌보시고, 또 남들보다 더 오래 공부하고 있는 저에게 항상 믿음과 격려를 주시는 어머니께도 감사드립니다. 항상 믿음 주셔서 감사드리고, 두 분의 넘치는 사랑에 보답할 수 있는 아들이 되도록 노력하겠습니다.

이상 모든 분들께 감사의 말씀 드리며 글을 마칩니다.

2019 년 7월
김병준 올림