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공학박사 학위논문

Performance Enhancement Techniques in LTE-V2X Communications

LTE-V2X 통신의 성능 향상 기법

2018년 8월

서울대학교 대학원

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지도 교수 최 성 현

이 논문을 공학박사 학위논문으로 제출함

2018년 7월

서울대학교 대학원

전기·정보공학부

박 승 일

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위 원 장: 박 세 웅 (인)

부위원장: 최 성 현 (인)

위 원: 심 병 효 (인)

위 원: 김 선 우 (인)

위 원: 김 재 현 (인)

Abstract

Vehicular communication has been studied in academia based on Wi-Fi technology called 802.11p over decades. However, with the advent of LTE-V2X announced by 3GPP in 2017, the need for research on new system-based vehicular communication technology has emerged since LTE-V2X operating in a synchronous manner is different from 802.11p operating in an asynchronous manner. In addition, the exchange of safety-related messages among vehicles requires a very high reception performance, which is the first priority to be solved before vehicular communication is commercialized.

In this dissertation, we consider the following three strategies to enhance the performance of LTE-V2X where broadcasting-based periodic safety messages are exchanged among vehicles: (i) Interference-aware resource selection algorithm, which utilizes an efficient feedback mechanism, (ii) RSU-assisted relaying system for V2V communications while maintaining the 3GPP standard compliant operation of UEs, and (iii) cooperative UE relaying scheme with a smart V2V connectivity prediction method.

First, an interference-aware resource selection algorithm is presented. This scheme improves the point that the UE in the conventional scheme cannot be aware of the status of the resource selected by itself as well as resources on the same time slot as it transmits. To resolve the problem, we propose an efficient feedback mechanism. Especially, feedback is included in an original safety message such that there is no additional resource for transmitting feedback. By utilizing the feedback mechanism, the efficiency of the conventional scheme is improved because the proposed algorithm changes resources only in the presence of interference. We find our scheme outperforms the conventional one in terms of MRR performance and it is more effective when the reception performance is vulnerable to interference.

Second, we propose an RSU relaying scheme in LTE-V2X systems where some resources of UEs are reused by RSU. In a distributed resource selection of LTE-V2X, UE often changes the resource, thus increasing instability in sensing-based resource selection. In the proposed scheme, RSU reuses the resource of UEs while minimizing the potential problems to UEs. Since our proposed scheme does not require any modifications to a UE side, UE maintains the current standard-compliant operation in 3GPP Release 14. Through extensive simulations, we verify that our model uses resources more efficiently than when RSU relaying is not supported. In addition, the proposed scheme outperforms the conventional relaying schemes in terms of MRR performance.

Finally, we propose a UE relaying scheme in LTE-V2X systems where UE cooperatively operates as relaying UEs to help each other. In the proposed scheme called Hidden Pair Awareness (HiPA), we develop an inventive method to predict the connectivity of any V2V pair by utilizing a feedback mechanism. Also, we utilize HiPA to determine relaying UEs and to relay messages in a priority-based manner. Through realistic simulations, we demonstrate that the proposed scheme outperforms the conventional scheme and the proposed connectivity prediction has high accuracy.

In summary, we have solved two major problems that may degrade the performance of LTE-V2X where broadcasting-based periodic safety messages are exchanged among vehicles. First, the resource selection is improved with an interference-aware mechanism. Second, the two ways to overcome NLOS channel between vehicles are proposed. The performances of the proposed schemes are validated by realistic vehicular communication simulations.

keywords: Vehicular communications, LTE-V2X, relaying, link performance prediction, road side unit (RSU).

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Chapter 1

Introduction

1.1 Motivation

Vehicular communication is considered to be a necessary technology to support numerous vehicular services such as accident prevention, traffic situation optimization, and autonomous driving. However, since the services are closely related to safety, a very high level of wireless communication performance is required. In particular, Long Term Evolution (LTE) technology, which has been widely used in mobile devices for years, ensures this high level of communication performance. Moreover, LTE has begun supporting vehicular communications, called LTE-Vehicle-to-Everything (V2X), since 3GPP Release 14. LTE-V2X includes Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Network (V2N).

In this thesis, we focus on enabling vehicles to exchange safety-related messages better. Safety-related messages are transmitted periodically with a short interval, and they are broadcast messages including the transmitting vehicle's status. When a broadcast message is transmitted, the transmitting vehicle does not know whether or not the transmission of the message is successful. There are two typical reasons why the transmission of a broadcast message fails. First, the transmission fails due to the existence of an interfering vehicle using the same resource as the transmitting vehicle. How-

ever, in LTE-V2X, a transmitting vehicle cannot sense the resource of the same time as it is transmitting and there is no feedback from neighboring receivers. Therefore, the transmitting vehicle cannot notice the existence of an interfering vehicle. Being motivated by this, we propose a feedback mechanism and a resource change trigger algorithm with zero (or low) overhead while maintaining the fully distributed operation of vehicles.

Second, the transmission often fails due to bad wireless channels. Of course, since the target range to be transmitted per message is given, it is not a problem that transmission fails when the distance between the transmitting and receiving vehicles is over the target range. However, it is frequently observed that the channel is bad due to the influence of the buildings between the transmitting and receiving vehicles. In such a case, it is recommended that nearby vehicles or other entities relay the message of transmitting vehicles. Conventionally, such relaying methods and algorithms have been proposed for decades while most of work is based on 802.11p, where the operation of vehicle in 802.11p is totally different from that of vehicle in LTE-V2X. Therefore, we discover the potential problems, which can occur when the proposed schemes based on 802.11p are applied to LTE-V2X. Then, we propose a relaying operation which can be applied to LTE-V2X offering huge performance gain. The relaying operations are proposed in two ways, one using Road Side Unit (RSU) and one using vehicle. Each relaying operation has pros and cons, which will be discussed in each chapter.

1.2 Overview of Existing Approaches

1.2.1 Resource selection in LTE-V2X

Greedy algorithm [1] is adopted as a Resource Unit (RU) selection method of periodic messages in LTE-V2X. In greedy algorithm, UE selects an RU based on sensing results of energy level on each RU in the previous round. The performance of greedy algorithm has been studied in various ways. In [2, 3], the authors analytically show that the

performance of greedy algorithm is bounded to a certain level and prove their claim by both proof and simulation. In [4], the authors derive the performance of greedy algorithm asymptotically (i.e., when the number of nodes goes to infinity). In [5], the authors use the number of collisions as performance metric, and show that it is bounded to a certain level.

However, greedy algorithm adopted in LTE-V2X has been slightly modified compared to the algorithm analyzed in the above-mentioned papers because of protocol and hardware limitations. In those papers, only asynchronous greedy algorithm has been considered, which changes the resource of only one node at a particular moment and recognizes the changed resource immediately by all other nodes. However, greedy algorithm in LTE-V2X operates in a synchronous manner, i.e., multiple nodes change their resources simultaneously and the change is not recognized by other nodes until the transmission of message. Therefore, we need to study the characteristics of synchronous greedy algorithm with protocol and hardware limitations.

1.2.2 RSU Relaying in Vehicular Communications

In vehicular communications, many studies propose to use Road Side Unit (RSU) assisted relaying schemes for enhancing performance. Authors in [6–9] have a common argument that RSU relaying is an efficient solution to enhance the performance of V2V link. However, since the papers propose RSU relaying schemes based on 802.11p, the operation on LTE-V2X protocol is unclear. In addition, they allocate additional resources for RSU relaying, so they do not study the efficiency of resource utilization when UE and RSU are using resources together. Moreover, even in resource sharing relaying schemes [10–12], the properties of resource selection in LTE-V2X are not considered. Thus, we need to study RSU relaying system, which can coexist with UEs in LTE-V2X.

Meanwhile, efficient RSU deployment strategies [13–17] have been studied a lot. In [13, 14], the authors study cost-efficient RSU deployment to maximize their own

performance metric, e.g., spatio-coverage. The authors of [15] propose an RSU deployment scheme which aims at minimizing cost while satisfying an objective. In [16, 17], the authors focus on overlapped area covered by different RSUs such that RSU coverage area is maximized by minimizing overlapped area. By being motivated those papers, we also propose an RSU deployment strategy utilizing our own utilization function.

In addition, there have been efforts to utilize D2D communication for vehicular communication instead of using 802.11p. The authors of [18] analytically predict the performance of LTE-D2D based vehicular communication, showing that LTE systems are suitable for vehicular communication. The authors of [19, 20] propose resource management policies, satisfying given latency and reliability constraints for D2D based vehicular communication. The authors of [21] consider optimizing performance when different types of links (i.e., V2V and V2I links) exist in the same resource pool. However, in these studies, the performance is optimized in terms of unicast communication, which is out of scope of this work. The authors of [22] consider broadcast communication of vehicular communication, yet the approach is based on 3GPP Release 12, where the resource pool structure is different from that of 3GPP Release 14. Accordingly, it is difficult to be applied to our work.

1.2.3 UE Relaying in Vehicular Communications

A lot of previous work has been proposed relaying schemes of broadcasting messages based on 802.11p, which mainly minimizes the number of retransmissions within the target range by imposing a stochastic relaying opportunity on each UE. Authors in [10] propose to assign different rebroadcast probability values to UEs according to distance between a message transmitter and a message receiver. Authors in [23, 24] consider traffic density of vehicles to assign rebroadcast probability values. Authors in [25] consider both distance and traffic density for probability values.

In order to use a more deterministic approach than the probabilistic approach, a

method of imposing a different waiting delay before retransmission is also considered [11, 12, 26–33]. The common idea is to assign a shorter waiting delay to a specific UE considering distance, traffic density, and message generation time as described above. However, adjusting the waiting delay to give priority to UE is suitable for DSRC where slot time is relatively short, but it is not good for LTE systems with relatively long slot time (1 ms). The above-mentioned papers have been proposed through the general assumptions such that the wireless communication performance decreases with distance, and the retransmitted message will have a high success rate. However, since wireless communication between vehicles is affected by the existence of buildings, it is difficult to assume that the performance is constantly decreased according to the distance. In addition, actual performance is difficult to predict depending on the number of users using the same resource pool, the MCS level, and the existence of interfering UEs. Also, since the retransmission efficiency of a UE that is largely hidden in a building is lowered, it is more advantageous to adjust the retransmission opportunity according to the expected transmission performance of the UE. However, unlike the relaying schemes of unicasting messages [34–39], which can determine the success of the actual transmission with ACK, it is difficult to determine whether the transmission is successful in relaying schemes of broadcasting messages.

1.3 Main Contributions

1.3.1 FAGA: Feedback-Aided Greedy Algorithm for Periodic Messages in LTE-V2X Communications

We propose Feedback-Aided Greedy Algorithm (FAGA) to complement the drawback of greedy algorithm. First, by usig FAGA, UEs are aware of the status of their resources for message transmissions. Second, a resource changing mechanism is improved since UEs can trigger a resource change only when their resources are encountering interference.

The main contributions of the chapter are as follows.

- We propose a noble feedback mechanism to enhance the message reception performance. By utilizing residual bits of every transmission, it can achieve zero-overhead property.
- We propose a wise resource change trigger algorithm for enhancement of greedy algorithm.
- We evaluate the performance via realistic simulation, which adopts realistic vehicle mobility and road situations, such as real city map layout and the operation of traffic lights.

1.3.2 RA-eV2V: Relaying Systems for LTE-V2V Communications

We propose a relay-based V2V system, called Relay-Assisted enhanced V2V (RA-eV2V). In general, the communication performance drops sharply as distance increases if the communication channel is in a Non-Line-of-Sight (NLOS) situation. In order to solve this problem, we propose a scheme for relaying V2V messages by using Road Side Units (RSUs) installed on the road, especially, near road intersections.

The main contributions of the chapter are as follows.

- To our best knowledge, it is the very first framework that proposes relaying system and RSU resource control algorithm in LTE-V2X communications.
- We closely examine whether RA-eV2V is compatible with current standard operation. In particular, it has been shown that the performance of V-UEs can be greatly improved even when the standard-compliant operation is maintained by V-UEs.
- Adaptive resource control algorithm of RSU has been proposed so that the RSU can operate independently without having to communicate with enhanced Node B's (eNBs) or other entities.

- Through realistic simulation, the characteristics of the proposed algorithm have been studied thoroughly and the MRR performance is hugely improved.

1.3.3 HiPA: Hidden Pair Awareness for Efficient UE Relaying Algorithms in LTE-V2X Communications

We introduce an UE relaying scheme for cooperative relaying operations of vehicles. First, we propose a smart way to predict the connectivity of any V2V pair based on the real data by utilizing an efficient feedback mechanism. Then, we propose a cooperative relaying operation of UE and a priority-based CAM selection algorithm.

The main contributions of the chapter are as follows.

- We propose a way to predict the connectivity of any V2V pair, which is challenging in case of broadcasting messages due to absence of response to the result of transmission from a receiver. This scheme is called Hidden Pair Awareness (HiPA).
- By utilizing HiPA, we propose a Relaying UE (R-UE) selection scheme and a CAM (to be relayed) selection algorithm. The proposed method evaluates the priority based on which broadcast messages are not properly received by other neighboring UEs.
- We evaluate the performance via realistic simulation, which adopts realistic vehicle mobility and road situations, such as the operation of traffic lights.

1.4 Organization of the Dissertation

The rest of the dissertation is organized as follows.

Chapter 2 presents FAGA, feedback-aided greedy algorithm for periodic messages in LTE-V2X communications. First, we provide the preliminaries and related work, and describe our proposed solution regarding a feedback mechanism design and a resource change trigger algorithm. Then, we provide the performance evaluation of

the proposed scheme with other existing scheme. Finally, we summarize the chapter with conclusion.

Chapter 3 presents RA-eV2V, RSU relaying scheme for enhancement of LTE-V2V for periodic messages. First, we provide the preliminaries and related work, and explain our proposed RSU relaying system regarding a resource occupation scheme and standard-compliant operation of UE. Then, we provide the performance evaluation of the proposed scheme with other existing scheme. Finally, we summarize the chapter with conclusion.

Chapter 4 presents HiPA, UE relaying scheme for cooperative relaying operations of vehicles. First, we provide the preliminaries and related work, and explain our proposed UE relaying system regarding a V2V connectivity prediction mechanism and relaying UE operation algorithms. Then, we provide the performance evaluation of the proposed scheme with other existing scheme. Finally, we summarize the chapter with conclusion.

In Chapter 5, we concludes the dissertation with the summary of contributions and discussion on the future work.

Chapter 2

FAGA: Feedback-Aided Greedy Algorithm for Periodic Messages in LTE-V2V Communications

2.1 Introduction

Every year, thousands of people are killed or injured in car accidents. One way to alleviate this problem is to use vehicular communication. In vehicular communication, dangerous situations can be inferred if vehicles exchange their status messages with nearby vehicles. Since the performance of wireless communications is hardly affected by weather changes such as fog, rain, and snow, the introduction of vehicular communication is considered a cheap and efficient solution.

Dedicated Short-Range Communication (DSRC) is a representative example of vehicular communication, and a lot of research and development have been conducted for decades [40]. DSRC relies on IEEE 802.11p for its Medium Access Control (MAC) and Physical (PHY) layers and IEEE 1609 for the upper layers. IEEE 802.11p employs Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) operation.

Meanwhile, 3GPP has recently developed Long Term Evolution-Vehicle-to-Vehicle (LTE-V2V) communication technology as part of 3GPP Release 14 [41, 42]. LTE-V2V communication reuses a lot of LTE Device-to-Device (LTE-D2D) communi-

cation technologies developed as part of 3GPP Release 12. In addition, some parts have been developed in accordance with the vehicular communication environment as well. For example, when Vehicular User Equipments (V-UEs) choose resource in a distributed way, a new algorithm, called greedy algorithm, choosing resource based on received energy levels has been introduced. While greedy algorithm is known to have decent performance, it lacks collision-detection mechanism, which limits the performance.

In this chapter, we mathematically analyze the performance of greedy algorithm to prove that the performance is limited due to the lack of collision-detection mechanism. We use well-known properties of Spatial Poisson Point Process (SPPP) to analyze the performance of greedy algorithm [43]. Moreover, to complement the drawback of greedy algorithm, we propose *Feedback-Aided Greedy Algorithm (FAGA)*. V-UE using FAGA can recognize resource collisions by using feedback mechanism.

The main contributions of this chapter are as follows.

- To our best knowledge, it is the very first study that mathematically analyzes the performance of greedy algorithm in the context of LTE-V2V.
- We propose a noble feedback mechanism to enhance the message reception performance. By utilizing residual bits of every transmission, it can achieve zero-overhead property.
- We evaluate the performance via realistic simulation, which adopts realistic vehicle mobility and road situations, such as real city map layout and the operation of traffic lights.

The rest of this chapter is organized as follows. We first present the preliminaries and related work in Section 2.2, and the performance analysis is presented in Section 2.3. Then, our proposed algorithm is presented in Section 2.4 and the proposed algorithm is evaluated via system-level simulations in Section 2.5. Finally, we conclude the chapter in Section 2.6.

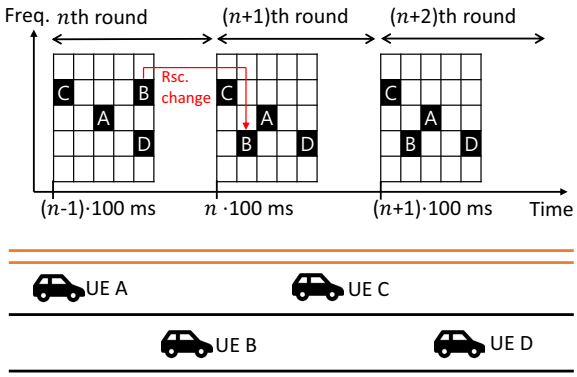


Figure 2.1: Periodic CAM transmission using RU in a resource pool.

2.2 Preliminaries and Related Work

2.2.1 LTE V2V Communication

As mentioned earlier briefly, the current state-of-the-art V2V communication is based on LTE systems, called LTE-V2V. Unlike LTE-D2D communication systems where some of the LTE uplink resources are used for D2D communication, LTE-V2V communication systems use independent resources. A typical option is to use the 5.9 GHz band already specified for vehicular communications in many countries [44].

The very first priority in LTE-V2V is the transmission of safety-related messages. For safety-related messages, vehicle sends two types of broadcast message [45]. First, Cooperative Awareness Message (CAM) that informs the vehicle's current status (e.g., ID, position, speed, and direction) periodically. The typical CAM generation period is 100 ms and the latency requirement is also 100 ms [46]. By receiving CAMs, vehicles can infer specific situations (e.g., slow/fast vehicle warning). Second, Decentralized Environmental Notification Message (DENM) that is transmitted in an event-driven manner to inform specific situation such as an internal component failure. Since DENM is not generated in a general situation, in this chapter, it is assumed that vehicles transmit only CAM.

The general CAM transmission model is described in Fig. 2.1. We define a *re-*

source unit (RU) as a set of Resource Block (RB) pairs, which can contain a single CAM. A RB pair is the minimum transmission unit in LTE and it consists of 14 time slots (= 1 ms) and 12 subcarriers (= 180 kHz) in frequency. We call a *resource pool* a set of RUs and it is periodically dedicated every round according to the CAM generation period (100 ms). In Fig. 2.1, each small box represents RU and V-UE selects its own RU for transmission of CAM (CAM RU), marked in black, in a distributed manner. We refer to the event that UE changes its CAM RU, e.g., UE B at the $(n+1)$th round in Fig. 2.1, as *resource change.*

2.2.2 Greedy Algorithm in LTE-V2V

In 3GPP standard, greedy algorithm [1] is adopted as a CAM RU selection method. In greedy algorithm, UE selects an RU based on sensing results of energy level on each RU in the previous round. Basically, UE selects the RU which has the lowest received energy. In such a case, resource collision, i.e., two or more UEs selecting the same RU, may frequently occur since multiple UEs might trigger resource change simultaneously. To prevent such problem, greedy algorithm can be enhanced by making UE select an RU out of a group of RUs which have the lowest $X\%$ received energy level. Please note that UEs close to each other have similar sensing results, thus meaning that they have high possibility of collision, if they intend to choose only the RU with lowest received energy. Therefore, increasing X reduces the possibility of collision by making the number of candidate RUs larger.

When it comes to resource change, in each round, only $Y\%$ of UEs trigger resource change while the other $(100-Y)\%$ UEs maintain the RU as in the previous round.[1] Obviously, such operation is not wise because it enforces resource change even on well-selected RUs as well. However, it is inevitable because UE is incapable of detecting resource collisions by itself in greedy algorithm.

[1]Please note that in our simulation, X and Y are set to 20% and 20%, respectively, as stated in [1].

2.2.3 Performance Analysis of Greedy Algorithm

The resource selection problem can be interpreted as K-coloring problem, where M nodes select their own colors from K colors. The most common objective in K-coloring problem is to maximize distance between nodes of the same color. However, finding the optimal solution is known as NP-hard problem [4]. Meanwhile, greedy algorithm has been proven to have decent performance and low complexity.

Although many papers have analyzed the performance of greedy algorithm, none has presented a way to predict the exact performance, i.e., the distance between nodes of the same color. In [2, 3], the authors analytically show that the performance of greedy algorithm is bounded to a certain level and prove their claim by both proof and simulation. In [4], the authors derive the performance of greedy algorithm asymptotically (i.e., when the number of nodes goes to infinity). Thus, it is still inaccurate to use in practice. In [5], the authors use the number of collisions as performance metric, and show that it is bounded to a certain level.

However, the techniques used in the above-mentioned papers can not be applied to our work. In those papers, only asynchronous greedy algorithm has been considered, which changes the color of only one node at a particular moment and recognizes the changed color immediately by all other nodes. However, as explained above, greedy algorithm in LTE-V2V operates in a synchronous manner, i.e., multiple nodes change their colors simultaneously and the change is not recognized by other nodes until the transmission of CAM. To our best knowledge, the performance analysis of synchronous greedy algorithm has never been addressed in the literature.

2.2.4 Performance Enhancement in LTE-V2V Communication

There have been studies that try to improve the performance of V2V communications on top of D2D communication or LTE network. The papers [47–49] aim at maximizing the performance (throughput or link capacity) of cellular UEs while guaranteeing the performance of vehicular UEs. The authors try to optimize the performance based

on unicast communications for both cellular and D2D links. The authors of [50] also consider mobile D2D communication, but the work also targets the same objective (i.e., coexistence of cellular and D2D users).

Our work can be distinguished from the above-mentioned papers with respect to the following aspects: 1) *We consider broadcast communications* for the delivery of safety messages. 2) In particular, CAM should be shared with neighboring vehicles with high probability. Thus, *this work is oriented to maximizing not throughput but Message Reception Ratio (MRR)*. 3) *We consider a fully distributed algorithm* so that V-UEs can work well even without a base station.

2.3 Analysis of Greedy Algorithm

2.3.1 Assumption

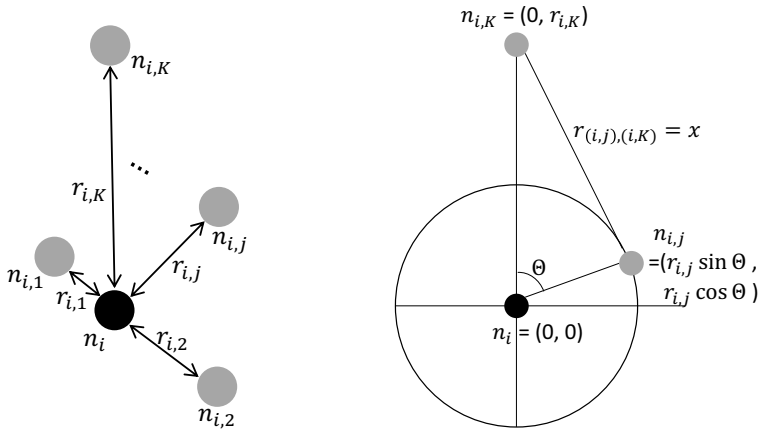
The resource selection problem in LTE-V2V communication can be interpreted as K-coloring problem. The notations in K-coloring problem are summarized as follows. There are K colors, $c_1, \cdots, c_K$, and M nodes, $n_1, \cdots, n_M$. We assume SPPP for node placement and M is larger than K. Each node chooses a color from K colors. Let $C(n_i)$ be the color selected by n_i. Distance of n_i to color c_l, $d(n_i, c_l)$, is defined as follows.

$$d(n_i, c_l) = \min_{1 \leq j \leq M} \{d(n_i, n_j) : C(n_j) = c_l\}, \tag{2.1}$$

where $d(n_i, n_j)$ is the distance between n_i and n_j. Please note that $d(n_i, C(n_i)) = 0$. Then, the distance between node n_i and the nearest other node of the same color, $\delta(n_i)$, is defined as follows.

$$\delta(n_i) = \min_{1 \leq j \leq M} \{d(n_i, n_j) : C(n_j) = C(n_i), j \neq i\}. \tag{2.2}$$

The jth nearest node from n_i is denoted as $n_{i,j}$ and the distance between them is denoted as $r_{i,j}$.



(a) K nearest nodes from n_i (b) (x, y) coordinate system

Figure 2.2: Example of node placement.

We use the concept of *Super Optimal State (SOS)*. A given node, n_i, is considered to be in SOS if the following conditions are satisfied. 1) Nearest K nodes from the given node, $n_{i,1}, \cdots, n_{i,K}$, have different colors. 2) Nearest K nodes from each node, $n_{i,j}$ $(1 \leq j \leq K)$, also have different colors. Please note that $C(n_i)$ does not affect the condition of SOS. Even though SOS is non-realistic state in many cases, the performance of greedy algorithm in SOS is highly related to the performance of greedy algorithm in normal state, where nearest K nodes from a given node do not necessarily have different colors. That is because, even though SOS makes the situation simpler, it still analyzes the behavior of greedy algorithm at a certain situation. In addition, it is proven that the performance of greedy algorithm in SOS offers tight bound for the performance of greedy algorithm in normal state [2, 3]. Thus, it is meaningful to analyze the performance of greedy algorithm in LTE-V2V assuming SOS.

2.3.2 Expectation of Delta $(\delta(n))$

Let us assume that a given node in SOS, n_i, intends to change its color as shown in Fig. 2.2(a).[2] To maximize $\delta(n_i)$, n_i should select $C(n_{i,K})$ so that $\delta(n_i)$ becomes $r_{i,K}$.[3] However, due to the synchronous behavior of greedy algorithm in LTE-V2V, there is a possibility that one (or more) of $K-1$ nearest nodes from n_i, $n_{i,j}$ $(1 \leq j \leq K-1)$, may change its color to $C(n_{i,K})$. This happens only when both n_i and $n_{i,j}$ change their colors simultaneously and $n_{i,K}$ is also the Kth nearest node from $n_{i,j}$. Let us define $n_{(i,j),k}$ as the kth nearest node from $n_{i,j}$. Then, the above-described case can be expressed as $n_{i,K} = n_{(i,j),K}$. Thus, the expectation of $\delta(n_i)$ is as follows.

$$
\begin{aligned}
&E[\delta(n_i))] \\
&= E\big[P(C(n_{i,1}) = C(n_{i,K})|r_{i,1}, r_{i,K}) \cdot r_{i,1} \\
&+ P(C(n_{i,1}) \neq C(n_{i,K})|r_{i,1}, r_{i,K}) \\
&\quad \cdot P(C(n_{i,2}) = C(n_{i,K})|r_{i,2}, r_{i,K}) \cdot r_{i,2} + \cdots \\
&+ P(C(n_{i,1}) \neq C(n_{i,K})|r_{i,1}, r_{i,K}) \\
&\quad \cdot P(C(n_{i,2}) \neq C(n_{i,K})|r_{i,2}, r_{i,K}) \\
&\quad \cdots P(C(n_{i,K-1}) \neq C(n_{i,K})|r_{i,K-1}, r_{i,K}) \cdot r_{i,K}\big],
\end{aligned} \tag{2.3}
$$

where $P(C(n_{i,j}) = C(n_{i,K})|r_{i,j}, r_{i,K}) = P_c \cdot P(n_{(i,j),K} = n_{i,K}|r_{i,j}, r_{i,K})$ and $P(C(n_{i,j}) \neq C(n_{i,K})|r_{i,j}, r_{i,K}) = 1 - P(C(n_{i,j}) = C(n_{i,K})|r_{i,j}, r_{i,K})$, and P_c is color change probability of a node, which is equivalent to $Y/100$ in Section 2.2.2. Here, we assume that $C(n_{i,K})$ does not change during the change of $C(n_i)$. This assumption does not affect the performance much since we are only interested in region

[2]Please note that n_i is not self-aware of whether it is in SOS or not because n_i can only sense the color of its own neighboring nodes. In addition, it is not sure how long SOS will persist because neighboring nodes may change color. Therefore, greedy algorithm in LTE-V2V stipulates changing color on a random basis, which causes nodes in SOS to change colors.

[3]Please note that the randomness induced by X in Section 2.2.2 is not considered here for simplicity. If it is considered, the resulting equation covered by this paper will be much more complicated. However, the principle to derive the resulting equation is the exactly same as that in this paper.

of small P_c. In addition, the variation of distance between nodes, $\sigma^2(r_{i,j})$, generally becomes extremely small in SPPP if we consider a large number of nodes [51]. It means that $P(C(n_{i,j}) = C(n_{i,K})|r_{i,j}, r_{i,K})$ has a relatively static value at a certain $r_{i,j}$ and $r_{i,K}$. Thus, (2.3) can be approximated as follows.

$$\begin{aligned}
&E[\delta(n_i))] \\
&= P(C(n_{i,1}) = C(n_{i,K}))E[r_{i,1}] \\
&+ P(C(n_{i,1}) \neq C(n_{i,K}))P(C(n_{i,2})) = C(n_{i,K}))E[r_{i,2}] \\
&+ \cdots \\
&+ P(C(n_{i,1}) \neq C(n_{i,K}))P(C(n_{i,2}) \neq C(n_{i,K}))\cdot \\
&\quad \cdots P(C(n_{i,K-1}) \neq C(n_{i,K}))E[r_{i,K}],
\end{aligned} \tag{2.4}$$

where $P(C(n_{i,j}) = C(n_{i,K})) = P_c \cdot P(n_{(i,j),K} = n_{i,K})$ and $P(C(n_{i,j}) \neq C(n_{i,K})) = 1 - P(C(n_{i,j}) = C(n_{i,K}))$. If we can derive a general expression for $P(n_{(i,j),K} = n_{i,K})$ and $E[r_{i,j}]$, the value of $E[\delta(n_i)]$ can be obtained. $E[r_{i,j}]$ can be obtained as follows [43].

$$\begin{aligned}
E[r_{i,j}] &= \int_0^\infty r_{i,j} f(r_{i,j}) dr_{i,j} \\
&= \int_0^\infty r_{i,j} \frac{2(\pi\lambda)^K}{(K-1)!} r_{i,j}^{2K-1} \exp(-\pi\lambda r_{i,j}^2) dr_{i,j},
\end{aligned} \tag{2.5}$$

where $f(\cdot)$ is (joint) Probability Density Function (PDF) of input(s) and λ is the mean density of nodes ($\#/m^2$). By replacing $\lambda\pi r_{i,j}^2$ with t and using Gamma function, $\Gamma(x) = \int_0^\infty t^{s-1} \exp(-t) dt$, (2.5) can be formulated as follows.

$$E[r_{i,j}] = \frac{1}{\sqrt{\pi\lambda}(K-1)!}\Gamma(K + 0.5). \tag{2.6}$$

$P(n_{(i,j),K} = n_{i,K})$ can be obtained by integrating $P(n_{(i,j),K} = n_{i,K}|r_{i,j}, r_{i,K})$ for possible values of $r_{i,j}$ and $r_{i,K}$.

$$\begin{aligned} &P(n_{(i,j),K} = n_{i,K}) \\ &= \int_0^{\infty}\int_0^{r_{i,K}} P(n_{(i,j),K} = n_{i,K}|r_{i,j}, r_{i,K}) f(r_{i,j}, r_{i,K}) dr_{i,j} dr_{i,K}. \end{aligned} \tag{2.7}$$

To obtain $P(n_{(i,j),K} = n_{i,K}|r_{i,j}, r_{i,K})$, we use well-known properties in SPPP. The probability that R is the distance to the kth neighbor of a point is as follows [43].

$$P(k, \pi R^2) = \frac{(\lambda \pi R^2)^k \exp{(-\lambda \pi R^2)}}{k!}. \tag{2.8}$$

Then,

$$P(n_{(i,j),K} = n_{i,K}|r_{i,j}, r_{i,K}) = \int_{r_{i,K}-r_{i,j}}^{r_{i,K}+r_{i,j}} P(K, \pi x^2) f(x) dx, \tag{2.9}$$

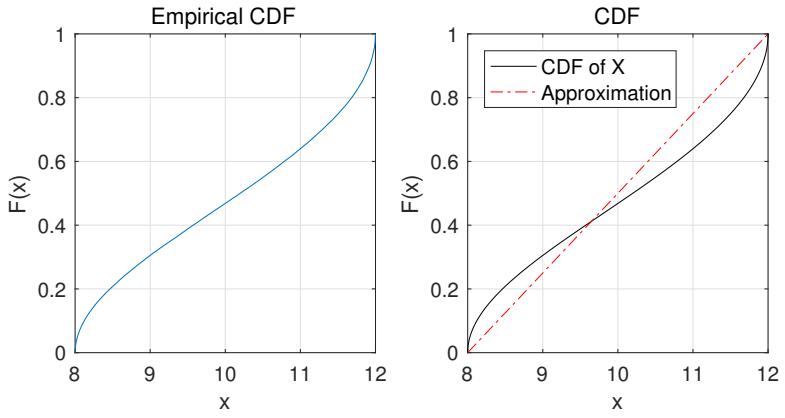
where $x = r_{(i,j),(i,K)}$, defined as the distance between $n_{i,j}$ and $n_{i,K}$ as shown in Fig. 2.2(b). By making (x, y) coordinates of n_i and $n_{i,K}$ be (0, 0) and (0, $r_{i,K}$), the coordinate of $n_{i,j}$ can be expressed as ($r_{i,j}$sin(θ), $r_{i,j}$cos(θ)), where θ is a uniform random variable within $[0, 2\pi)$. Then, x is formulated as follows.

$$x = \sqrt{(r_{i,j} \sin\theta)^2 + (r_{i,K} - r_{i,j} \cos\theta)^2}. \tag{2.10}$$

The Cumulative Distribution Function (CDF) of random variable X, where $F_X(x) = P(X \leq x)$, can be derived as follows.

$$\begin{aligned} F_X(x) &= P\Big(\sqrt{(r_{i,j} \sin\theta)^2 + (r_{i,K} - r_{i,j} \cos\theta)^2} \leq x\Big) \\ &= P\Big(\arccos\Big(\frac{r_{i,j}^2 + r_{i,K}^2 - x^2}{2 r_{i,j} r_{i,K}}\Big) \geq \theta\Big) \\ &= F_\theta\Big(\arccos\Big(\frac{r_{i,j}^2 + r_{i,K}^2 - x^2}{2 r_{i,j} r_{i,K}}\Big)\Big) \\ &= \frac{1}{\pi} \arccos\Big(\frac{1 + r_{i,K}^2 - x^2}{2 r_{i,j} r_{i,K}}\Big), \end{aligned} \tag{2.11}$$

where $F_\theta(\cdot)$ is CDF of θ.



(a) Simulation (b) Analysis

Figure 2.3: CDF of x when $r_{i,K} = 10$ and $r_{i,j} = 2$.

As shown in Figs. 2.3(a) and 2.3(b), the analysis result of (2.11) is consistent with the simulation result. For simplicity of next steps, the shape of CDF is approximated as a straight line. Thus, PDF of x can be expressed as follows.

$$f(x) \approx \frac{1}{2r_{i,j}} \quad \text{for} \quad r_{i,K} - r_{i,j} \leq x \leq r_{i,K} + r_{i,j}. \tag{2.12}$$

By combining (2.8) and (2.12), (2.9) becomes

$$\begin{aligned} &P(n_{(i,j),K} = n_{i,K} | r_{i,j}, r_{i,K}) \\ &= \int_{r_{i,K}-r_{i,j}}^{r_{i,K}+r_{i,j}} \frac{(\lambda\pi x^2)^K}{K!} \exp\left(-\lambda\pi x^2\right) \frac{1}{2r_{i,j}} dx. \end{aligned} \tag{2.13}$$

By replacing $\lambda\pi x^2$ with t and using Gamma function, $\Gamma(s,x) = \int_x^\infty t^{s-1} \exp(-t) dt$, (2.13) can be formulated as follows.

$$\begin{aligned} &P(n_{(i,j),K} = n_{i,K} | r_{i,j}, r_{i,K}) \\ =&A \int_{\lambda\pi(r_{i,K}-r_{i,j})^2}^{\lambda\pi(r_{i,K}+r_{i,j})^2} t^{K-0.5} \exp(-t) dt \\ =&A \Big[\Gamma(K + \frac{1}{2}, \lambda\pi(r_{i,K} - r_{i,j})^2) \\ &- \Gamma(K + \frac{1}{2}, \lambda\pi(r_{i,K} + r_{i,j})^2) \Big], \end{aligned} \tag{2.14}$$

where $A = (4r_{i,j}K!\sqrt{\lambda\pi})^{-1}$. In addition, $f(r_{i,j}, r_{i,K})$ in (2.7) can be obtained from [43] as follows.

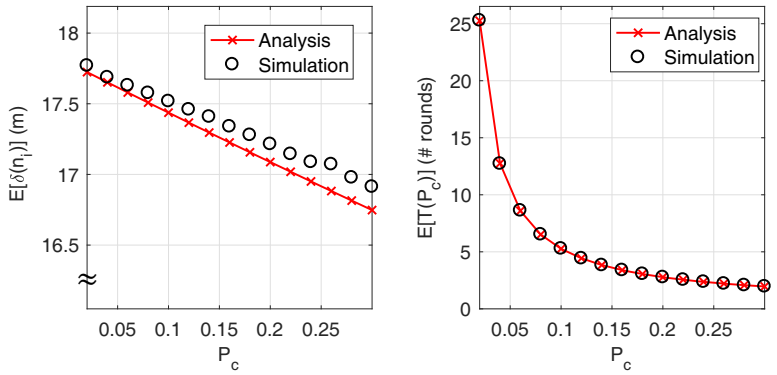
$$\begin{aligned} & f(r_{i,j}, r_{i,K}) \\ & = \exp\left(-\lambda\pi r_{i,K}^2\right)(2\pi\lambda)^K \left[\frac{r_{i,j}^{2j-1} r_{i,K} (r_{i,K}^2 - r_{i,j}^2)^{K-j-1}}{2^K (j-1)!(K-j-1)!}\right]. \end{aligned} \tag{2.15}$$

By using (2.14) and (2.15), we can obtain the value of $P(n_{(i,j),K} = n_{i,K})$ in (2.7). Please note that 2-dimensional integral can be computed by well-known techniques such as Riemann integral. Then, (2.4) is obtained.

2.3.3 Expectation of Collision Resolution Time (T)

Let us define *collision* as the event that two given nodes within a target range choose the same color. Since nodes are aware of colors of neighboring nodes, collision only happens when they re-choose their colors at the same time. Then, the collision lasts until one (or both) of them changes its (their) color(s). We do not consider the case where both of the nodes change their colors and collision happens again because the possibility of such case is extremely small if K is large enough. Please note that collision resolution time, T, is a function of P_c, which determines how often node reselects its own color. In addition, node can change color every round, therefore, the collision resolution time can be expressed as the number of rounds, N. The probability that $T(P_c) = N$ is as follows.

$$\begin{aligned} P(T(P_c) = 1) &= 1 - (1 - P_c)^2 \\ P(T(P_c) = 2) &= (1 - P_c)^2 \cdot (1 - (1 - P_c)^2) \\ &\cdots \\ P(T(P_c) = N) &= \underbrace{(1 - P_c)^{2(N-1)}}_{\text{No change until (N-1)th round}} \cdot \underbrace{(1 - (1 - P_c)^2)}_{\text{Change after this round}} \end{aligned} \tag{2.16}$$



(a) Expected delta (b) Collision resolution time

Figure 2.4: Results of analysis when K = 50 and $\lambda = 500/100^2$ $(\#/m^2)$.

Therefore, the expected collision resolution time, $E[T(P_c)]$ can be expressed as follows.

$$E[T(P_c)] = (1-(1-P_c)^2)\sum_{i=0}^{\infty}(1-P_c)^{2i}(i+1)$$
$$= \frac{1}{1-(1-P_c)^2}. \tag{2.17}$$

Here, we use the property of power series, $\sum_{x=0}^{\infty} a^x(x+1) = (1-a)^{-2}$.

2.3.4 Analysis results

In Fig. 2.4, our analysis results are shown with simulation results. In the simulation, each result point is obtained by averaging 100,000 attempts. In both δ and T analysis results, we observe that the accuracy of our analysis is high enough to predict performance trend according to the change of P_c. $P_c = 0.2$, which is adopted by greedy algorithm in LTE-V2V, is reasonable in that the collision resolution time is reduced to prevent a long collision time. However, it is inevitable to sacrifice the performance of δ.

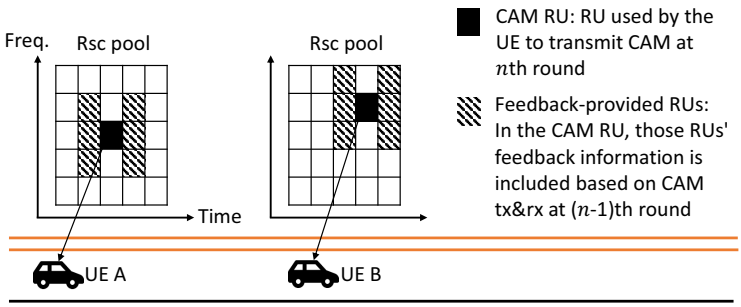


Figure 2.5: Example of CAM and feedback transmission.

2.4 Proposed Feedback-Aided Greedy Algorithm

In the previous section, we verify that the performance of greedy algorithm is not optimal in terms of δ. In this section, we propose a new resource selection algorithm, called Feedback-Aided Greedy Algorithm (FAGA), which makes UEs capable of detecting resource collision to achieve more intelligent resource selection.

2.4.1 Feedback Protocol Design

Basically, CAM is extended to contain feedback about RUs, which the CAM transmitter UE listened to in the previous round. Since UE cannot listen to its own CAM RU,[4] the UE has to acquire the feedback of its own CAM RU from neighboring UEs. Therefore, UEs help each other by exchanging feedback. Since the size of CAM may increase proportional to the number of additional bits for feedback, it is necessary to make the system such that UEs are able to adjust the number of feedback-provided RUs. For example, Fig. 2.5 shows that each UE gives feedback about only six RUs.

We design the pattern of feedback-provided RUs. The basic set of feedback-provided RUs from the location of CAM RU k, $S_{BS}(k)$, is fixed once the number of feedback-provided RUs is determined by the system. However, if the location of feedback-

[4]It is called half duplex problem, where UEs transmitting signal at a certain time cannot receive signals transmitted by itself and other UEs at the same time.

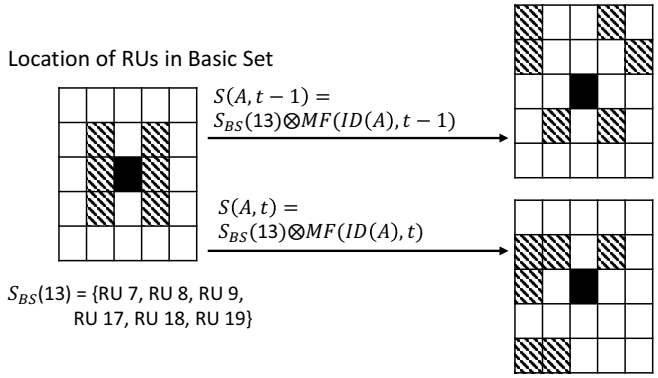


Figure 2.6: Relation between basic set and physical locations of feedback-provided RUs.

provided RUs does not change over rounds, unlucky UE might not obtain feedback for its CAM RU from neighboring UEs in succession.[5] To prevent such case, the actual locations of feedback-provided RUs change every round according to a mapping function, $MF(ID(j), t)$, by using CAM transmitter j' ID, $ID(j)$, and round index t. A typical example for mapping function is circular shifting function, which makes RU index from k to $(k + ID(j) + t)$ mod N_{RU}. The mapping function is globally unique information according to $ID(j)$ and t. The pattern derived from the mapping function is expressed as follows.

$$S(j, t) = S_{BS}(k) \otimes MF(ID(j), t). \tag{2.18}$$

For example, Fig. 2.6 is the case where RU 13 (i.e., $k = 13$) is selected by UE A (i.e., $j = A$). If neighboring UEs around UE A can successfully receive CAM from UE A on RU 13, they can acquire ID of UE A. Then, they can also acquire the location of feedback-provided RUs by UE A.

[5]Of course, it is neither desirable nor frequent case. By adjusting system parameter, it should be guaranteed that every UE normally obtains at least multiple numbers of feedback from different UEs.

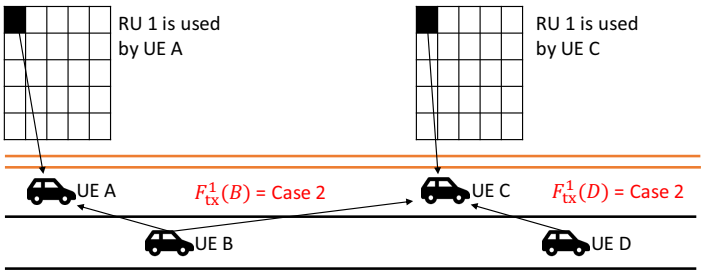


Figure 2.7: Example of hidden collision problem.

2.4.2 Feedback Content Design

In the previous section, we explained that the location of feedback-provided RUs of feedback-transmitting UE can be acquired by feedback-receiving UEs. Now, we explain the feedback information of each feedback-provided RU. We assume there is feedback-transmitting UE j. Then, the feedback information on RU k, $F_{\text{tx}}^{k}(j)$, can be classified into three cases. Please note that RU $k \in S(j,t)$.

- $F_{\text{tx}}^{k}(j)$ = Case 1: RU k is not used by any UE. This can be inferred when the energy level of the RU is lower than a threshold.
- $F_{\text{tx}}^{k}(j)$ = Case 2: RU k is used by a single UE. This can be inferred when the CAM on the RU is decoded successfully.
- $F_{\text{tx}}^{k}(j)$ = Case 3: RU k is used by two or more UEs. This can be inferred when the energy level of the RU is higher than a threshold while no message on the RU is decoded successfully.

However, categorizing only the three cases may not work well because of hidden collision problems. Fig. 2.7 exemplifies the hidden collision problem where UEs A and C use the same RU (i.e., RU 1) and neighboring UEs B and D give feedback about RU 1. Please note that the distance between UEs A and C is less than a target range, thus meaning that UEs A and C have to exchange CAM from each other.

UE B could successfully receive the CAM on RU 1 since the signal strength of UE A is much higher than that of UE C. Similarly, UE D could successfully receive the CAM on RU 1 since the signal strength of UE C is much higher than that of UE A. Therefore, $F_{\text{tx}}^{1}(B)$ = Case 2 and $F_{\text{tx}}^{1}(D)$ = Case 2 as shown in Fig. 2.7. Accordingly, UEs A and C misunderstand the situation that they do not need to change their RUs. However, in this example, UEs A and B do not even recognize the existence of UE C while they need to receive UE C's CAM as well. In a nut shell, Case 2 can be further divided into two subcases from the perspective of a feedback-receiving UE, UE i, as follows.

- Case 2-1: UE j successfully decoded UE i's CAM.
- Case 2-2: UE j successfully decoded another UE's CAM while UE i's signal was treated as interference.

The very easy solution to differentiate the two subcases is including information of CAM transmitter. In the previous example, if UE B could inform that UE B receives CAM on RU 1 from UE A, UE C could notice that RU 1 is experiencing collision. However, including the exact information of CAM transmitter for feedback of each RU requires much overhead. Instead, we come up with a novel solution. When UE j announces Case 2, it uses two different integer values[6] according to the result of an arithmetic operation using $ID^{k}(j)$ and $ID(j)$. Here, $ID^{k}(j)$ is ID of UE discovered by UE j on RU k and $ID(j)$ is ID of UE j. Then, the arithmetic operation is a modular operation as follows.

$$\text{Modular operation: } (ID^{k}(j) + ID(j)) \bmod 2. \tag{2.19}$$

Then, the feedback information generated by UE j on each RU k can be summarized as follows.

[6]The number of integer values can be easily extended to M. We set M = 2 as a representative value, achieving the goal with the minimum overhead.

Bit info.	Situation
00	$F_{\text{tx}}^k(j)$ = Case 1
01	$F_{\text{tx}}^k(j)$ = Case 2 and if $(ID^k(j) + ID(j)) \mod 2 = 0$
10	$F_{\text{tx}}^k(j)$ = Case 2 and if $(ID^k(j) + ID(j)) \mod 2 = 1$
11	$F_{\text{tx}}^k(j)$ = Case 3

2.4.3 Utilization of Feedback

Now, we explain how feedback-receiving UE i utilizes the feedback information. We want to express the average number of UEs using RU k at UE i side, $N_{\text{UE}}^k(i)$, by using the feedback information. Since there can be two (or more) UEs, giving feedback on RU k, $N_{\text{UE}}(k)$ can be obtained by averaging feedback from each UE, i.e., $N_{\text{UE}}^k(i) = \sum_j F_{\text{rx}}^k(i,j) / \sum_j 1$.

First of all, the feedback information can be classified into two based on whether RU k is UE i's CAM RU or not. If RU k is not UE i's CAM RU, then the feedback information on RU k from UE j to UE i, $F_{\text{rx}}^k(i,j)$ is as follows.

Assigned value	Situation
$F_{\text{rx}}^k(i,j) = 0$	Bit info. = 00
$F_{\text{rx}}^k(i,j) = 1$	Bit info. = 01 or 10
$F_{\text{rx}}^k(i,j) = 2$	Bit info. = 11

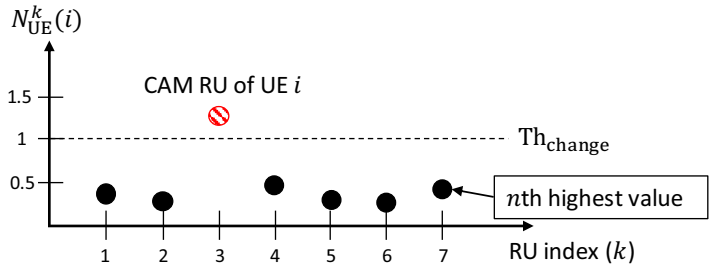
If RU k is UE i's CAM RU, then $F_{\text{rx}}^k(i,j)$ is as follows.

Assigned value	Situation
$F_{\text{rx}}^k(i,j) = 0$	Bit info. = 00
$F_{\text{rx}}^k(i,j) = 1$	(Bit info. = 01 and $(ID(i) + ID(j))$ mod 2 = 0) or (Bit info. = 10 and $(ID(i) + ID(j))$ mod 2 = 1)
$F_{\text{rx}}^k(i,j) = 2$	Bit info. = 11
$F_{\text{rx}}^k(i,j) = 3$	(Bit info. = 01 and $(ID(i) + ID(j))$ mod 2 $\neq$ 0) or (Bit info. = 10 and $(ID(i) + ID(j))$ mod 2 $\neq$ 1)

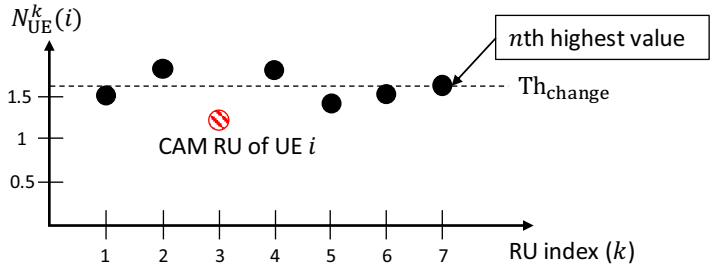
Let us assume that there is UE i using RU k as its own CAM RU and UE i receives feedback from UE j. In this case, $ID^k(j) \neq ID(i)$. Please note that only when UE j successfully received CAM on RU k (i.e., Case 2), UE j can discover $ID^k(j)$. Therefore, the bit information of feedback about RU k will be either '01' or '10' based on whether $((ID^k(j) + ID(j))$ mod 2) is '0' or '1'. Then, UE i needs to detect $ID(i) \neq ID^k(j)$. However, $((ID^k(j) + ID(j))$ mod 2) coincides with $((ID^k(j) + ID(j))$ mod 2) with probability of 0.5. Since N_{UE}^k is calculated by averaging feedback from multiple UEs, we want to make $N_{UE}^k = 2$ in the average sense. To do so, UE i assigns '3' to $F_{\text{rx}}^k(i,j)$ when $((ID^k(j) + ID(j))$ mod 2) does not coincide with $((ID^k(j) + ID(j))$ mod 2).

In summary, UE i considers only three cases (i.e., Case 1, Case 2, Case 3) for RUs other than UE i's CAM RU. However, if UE i's CAM RU belongs to Case 2, then UE i attempts to differentiate Case 2-1 and Case 2-2. Since Case 2-2 means resource collision from the perspective of UE i. $N_{\text{UE}}^k(i)$ is desired to be 2. Since the detection probability of Case 2-2 is 0.5, we compensate it by assigning a higher value (i.e., 3) more than 2 when Case 2-2 is detected.

Once UE i obtains $N_{\text{UE}}^k(i)$ for all possible RUs, UE i decides whether to change the current CAM RU or not. Basically, CAM RU is desired to be changed when $N_{\text{UE}}^k(i) > 1$. However, there might be a lot of UEs trying to change their RUs at the same time because of sudden environmental changes (e.g., introduction of a lot of new vehicles).



(a) RU change



(b) RU hold

Figure 2.8: Example of RU change.

Therefore, to prevent such case, the threshold to trigger RU change is determined as follows.

$$\mathrm{Th}_{\mathrm{change}} = \max\left(1, n\text{th highest } N^k_{UE}(i) \text{ value}\right). \tag{2.20}$$

Here, n is set to a value corresponding to about 20% of the total number of RUs, $0.2 \times N_{RU}$. Please note that 20% is selected to prevent too many simultaneous changes. Then, UE i triggers RU change when $N^k_{\mathrm{UE}}(i) > \mathrm{Th}_{\mathrm{change}}$. As shown in Fig. 2.8(a), if $N^k_{UE}(i)$ values for RUs other than UE i's CAM RU are less than 1, then $\mathrm{Th}_{\mathrm{change}}$ is set to 1. In this case, UE i decides to change CAM RU. However, in Fig. 2.8(b), UE i does not decide to change CAM RU even though $N^k_{\mathrm{UE}}(i) > 1$ because $N^k_{UE}(i)$ values for RUs other than UE i's CAM RU are generally high. It means that there are other UEs which also want to change their CAM RUs.

If UE i decides to change its own CAM RU, a new RU is selected by greedy

algorithm, explained in Section 2.2.2. Greedy algorithm has decent performance in terms of selecting a good resource.

2.4.4 Properties of FAGA

Since LTE is a synchronous system, the smallest resource allocation unit, RB-pair, is fixed in terms of both time and frequency. RU is composed of RB-pairs and the size of CAM is not exactly the same as the capacity of RU. Thus, we can utilize the residual bits of RU for containing feedback. As long as the number of feedback bits is less than the number of residual bits in RU, FAGA can maintain zero-overhead property.

The proposed scheme has advantages in that it is simple to implement. The proposed scheme does not depend on other entities such as base stations, so only UE needs to be modified. To do so, UE needs to include feedback in CAM and utilize the feedback information in resource selection, which does not require hardware modification.

2.5 Performance Evaluation

In this section, the performances of *FAGA* algorithm and the other comparison schemes are evaluated following the evaluation methodology of 3GPP V2V in Annex A of [54]. We use a system level simulation developed reflecting the 3GPP methodology in MATLAB while employing mobility traces obtained using Simulation of Urban Mobility (SUMO), a well-known open-source vehicle mobility simulator [52].

2.5.1 Simulation Environments

The overview of simulation environments is presented in Table 2.1. Please note that carrier frequency is 5.9 GHz and system bandwidth is 10 MHz, which are typical options of 3GPP V2V communication as well as 802.11p [54, 55].

Topology: We conduct real city map-based simulation. We use OpenStreetMap (OSM) Web Wizard provided by SUMO [52] to link the actual map information provided

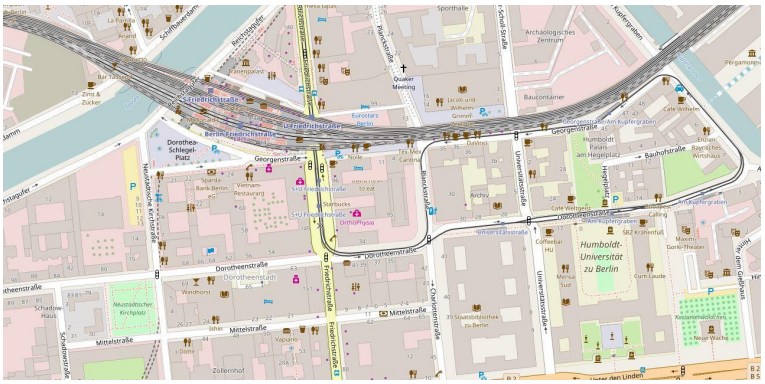
Table 2.1: Simulation environments.

Carrier frequency	5.9 GHz
System bandwidth	10 MHz (50 RBs)
Topology	Berlin, Germany
Vehicle mobility model	SUMO [52]
Link performance model	ns-3 [53]
Channel model	Fast fading + shadowing + pathloss + in-band emission [54]
Tx power of UE	23 dBm
Noise figure	9 dB
Noise power	-174 dBm/Hz
CAM size	800 B
CAM generation period	100 ms
No. RUs in a resource pool	144
Simulation time	200,000 subframes (200 s)

in [56] to our simulator. Fig. 2.9 shows the center of Berlin, Germany (1,200 m by 800 m), which is a target area in the simulation.

Vehicle mobility model: SUMO is used to describe realistic vehicle movements. We create a random route for each vehicle, and use the SUMO default model (which includes car following, lane changing, and intersection models) to control the vehicle movements and traffic light. To reflect heterogeneous vehicle types in the real world, we consider 91% of cars, 3% of trucks, and 6% of buses, where each type of vehicle has different size and mobility model. The number of total V-UEs is 119.

Channel model: Fast fading is generated by using ITU-R IMT UMi model in [57]. We create shadowing according to log-normal distribution with standard deviation of 3 dB and 4 dB for Line-Of-Sight (LOS) and Non-LOS (NLOS), respectively, and



(a) Berlin captured in OSM

(b) Berlin layout in SUMO, converted from OSM

Figure 2.9: Simulation area: Berlin, Germany.

decorrelation distance of 10 m as indicated in Clause A.1.4 of [54]. As for pathloss, it is calculated by using WINNER+ B1 model [58]. In-band emission, which is unwanted emission to neighboring resources in the same time slot, is generated according to the model in Clause A.2.1.5 of [59].

Link performance model: In order to use a proven link performance model, we use the implementation in the LTE model of ns-3 [53], a well-known open-source simulator in the field of network and communications. SINR determined based on channel model is converted to Transmission BLock Error Rate (TBLER).

Resource pool: One Resource Block (RB) pair of LTE carries up to 430 bits in 1 ms if

16-Quadrature Amplitude Modulation (16-QAM) and 0.64 code rate, the modulation and coding combination which will be used for 3GPP V2V [54], are applied. Therefore, 15 RB pairs in frequency are required to transmit a single CAM of 800 B in 1 ms. Accordingly, an RU, used for transmission of a single CAM as explained in the previous sections, is equivalent to a group of 15 RB pairs. Please note that, in this case, there are 50 $(= 430 \times 15 - 6400)$ residual bits, which can make feedback of 25 RUs while maintaining zero-overhead property. In LTE network, 10 MHz of bandwidth can accommodate up to 50 RBs in frequency domain. Therefore, the number of RUs in frequency becomes 3 $(= \lfloor 50/15 \rfloor)$. The number of RUs in time is set to 48 in this evaluation, thus making the number of RUs in a resource pool 144.

2.5.2 Simulation Result

Fig. 2.10 shows the MRR performance over ranges which are divided every 20 m. For a transmitted message, MRR is calculated by M/N, where N is the number of V-UEs located in the target range,[7] and M is the number of V-UEs with successful reception of the message among N. In addition, the MRR performance can be distinguished by whether the channel between transmitter and receiver is LOS or NLOS. Accordingly, Fig. 2.10(b) (Fig. 2.10(c)) shows LOS (NLOS) MRR performance while Fig. 2.10(a) shows total MRR performance. In vehicular communications, the reception performance is limited by channel and there is no way to improve NLOS performance without being helped by other entities (e.g., relay).

The black line with a circle marker represents the performance of greedy algorithm explained in Section 2.2.2. The blue line with a diamond marker represents the performance of a centralized scheduling assuming there is a base station allocating RUs to V-UEs. In this simulation, the number of V-UEs (119) is less than the number of RUs (144), and hence, it is possible to allocate RUs to V-UEs without resource collision.

[7] Typical target range for CAM transmission is 320 m and 150 m for freeway and urban environments, respectively [45].

The red lines represent the MRR performance of FAGA with a different amount of feedback, defined as follows.

$$\rho = \frac{\text{No. feedback-provided RUs}}{\text{No. total RUs}}. \tag{2.21}$$

Please note that the maximum ρ is not 1 but $\frac{141}{144}$ due to half duplex problem. In fact, there is no noticeable change in performance depending on ρ. The main idea of FAGA is to inform V-UE experiencing resource collision that the V-UE's RU needs to be changed. The probability of being informed of the resource collision by other feedback-providing UEs is determined by ρ. However, since there are many neighboring V-UEs that can provide feedback, FAGA operates well even with small ρ. Also, once V-UE resolves resource collision, the stable status lasts until drastic environmental change occurs (e.g., introduction of new vehicles).

Compared with comparison schemes, the advantages of FAGA can be summarized as follows. 1) *The performance of FAGA is almost optimal.* This can be inferred from the fact that the performance of 'scheduled', in which there is no resource collision, and the performance of FAGA are very similar to each other. Also, as shown in Fig. 2.10(b), the LOS performance converges to almost 1. 2) *FAGA is efficient.* Please note that V-UEs using FAGA select their RUs in a distributed manner. Centralized resource scheduling imposes a large overhead on the network. In particular, vehicles are required to have frequent handovers between base stations because of their mobility. Greedy algorithm, which is a representative method of distributed resource selection, is not as good as FAGA. FAGA can operate without using additional overhead by utilizing residual bits.

Fig. 2.11 shows the relative MRR gain of FAGA (with 20 bits of feedback) over greedy algorithm for various traffic density values. Here, the traffic density, η, is defined as follows.

$$\eta = \frac{\text{No. UEs}}{\text{No. total RUs}} \ \text{(per square kilometer)}. \tag{2.22}$$

First, we observe that the MRR gain increases as R increases in Fig. 2.11(a). As the

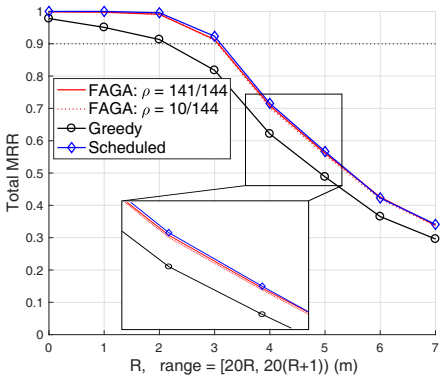
distance between transmitter and receiver increases, the received signal strength of target signal decreases, thus making the reception performance vulnerable to interference. Therefore, the collision-aware mechanism in FAGA is more effective when R is high. However, if we separate Fig. 2.11(a) into two figures (Figs. 2.11(b) and 2.11(c)) based on whether the channel between transmitter and receiver is LOS or NLOS, we can notice that Figs. 2.11(b) and 2.11(c) have different tendency. As we present in Fig. 2.10(c), the NLOS MRR performance severely decreases as R increases. Thus, it means that the NLOS MRR performance is highly dependent on channel error when R is large. Accordingly, it is difficult to predict the performance gain in NLOS cases due to the impact of channel error.

Second, we observe that the performance gain increases as η increases. It is similar to that FAGA has higher gain when R is high in LOS cases. Since the chance of encountering strong interference is high when η is large, the collision-aware mechanism in FAGA is more effective in such a case.

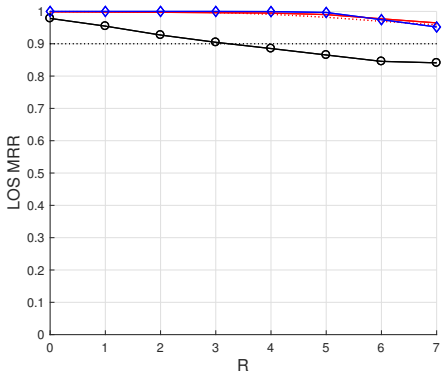
Fig. 2.12 is a graph showing the results of a transmission where a CAM is (not) received successfully at receiving UE on the left (right) when two or more UEs transmit a CAM using the same RU. The x axis (y axis) means the distance between a transmitting UE (interfering UE) and a receiving UE. The UE that has transmitted the signal with the largest received power (the second largest signal) at the receiving UE becomes the transmitting UE (the interfering UE). In case of greedy algorithm as shown in Fig. 2.12(a), there are a number of cases where two or more UEs transmit a CAM using the same RU even with low x and y values (less than 150 m). While the proposed scheme as shown in Fig. 2.12(b) effectively removes those cases by utilizing the feedback mechanism.

2.6 Summary

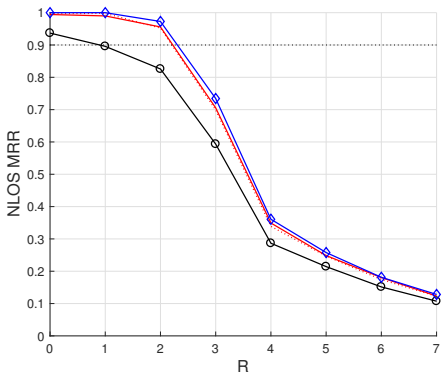
In this chapter, we claim that greedy algorithm adopted by LTE V2V for distributed resource selection does not work efficiently because unnecessary resource reselection occurs too frequently and greedy algorithm cannot be aware of resource collisions. To enhance the performance of greedy algorithm, we propose a novel resource selection algorithm, named *FAGA*. We aim at making UEs aware of resource collisions to trigger resource change wisely. The objective is achieved by utilizing well-designed feedback mechanism. In the design, we propose smart solutions to make the algorithm operate well even without additional overhead. To verify the performance of the proposed scheme, we conduct realistic simulation in vehicular environments by utilizing a well-known simulator SUMO. In the simulation, it is shown that FAGA operates well even with small amount of feedback and its performance is close to the performance of centralized scheduling method. Moreover, FAGA outperforms greedy algorithm by up to 23.7% in terms of MRR performance.



(a) Total MRR

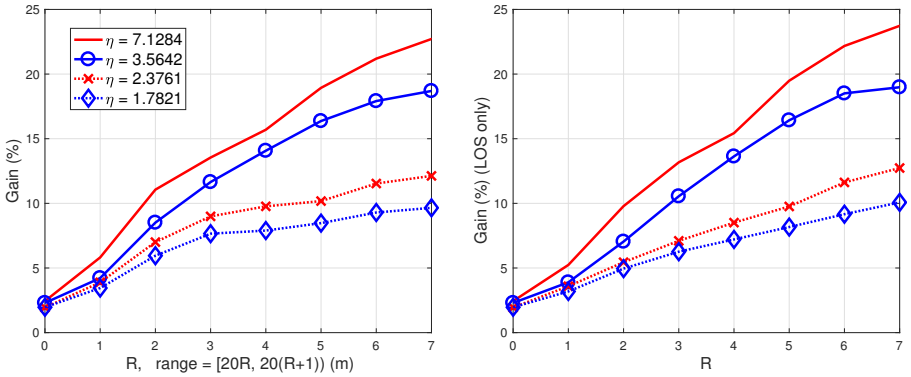


(b) LOS MRR



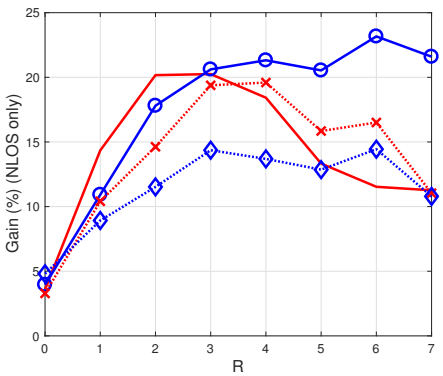
(c) NLOS MRR

Figure 2.10: Average MRR performance according to the range.



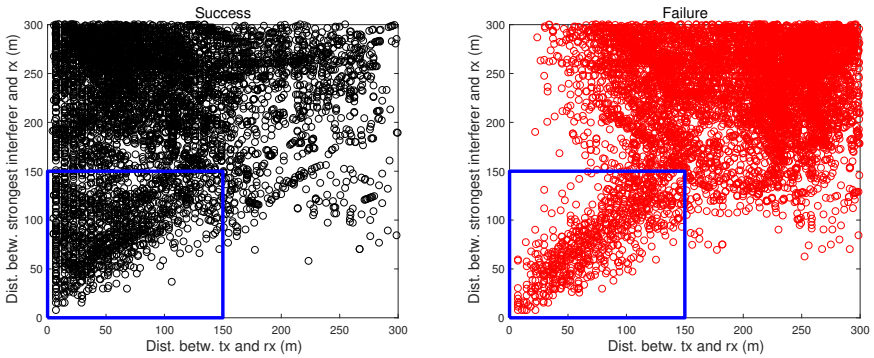
(a) All cases

(b) LOS cases only

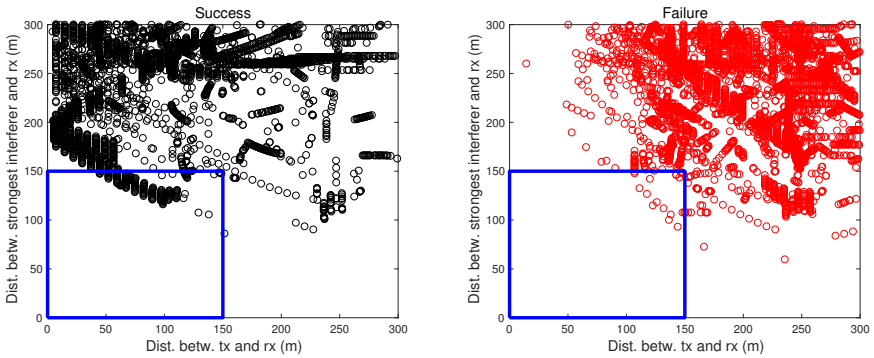


(c) NLOS cases only

Figure 2.11: MRR gain over greedy algorithm for various traffic density values (η).



(a) Greedy



(b) FAGA

Figure 2.12: Collision events according to distance.

Chapter 3

RA-eV2V: Relaying Systems for LTE-V2X Communications

3.1 Introduction

In this chapter, we propose a relay-based V2V system, called Relay-Assisted enhanced V2V (RA-eV2V), to improve the Message Reception Ratio (MRR) in LTE-V2V communication, where V-UEs select their own resources in a distributed manner. In general, the MRR performance drops sharply as communication distance increases if the communication channel is in a Non-Line-of-Sight (NLOS) situation. In order to solve this problem, we propose a scheme for relaying V2V messages by using Road Side Units (RSUs) installed on the road, especially, near road intersections. Note that traffic light post at intersection is a good place to install RSU because the channel conditions with nearby vehicles are normally Line-Of-Sight (LOS) conditions.

The main contributions of our chapter are as follows.

- To our best knowledge, it is the very first framework that proposes relaying system and RSU resource control algorithm in LTE-V2V communications.
- We closely examine whether RA-eV2V is compatible with current standard operation. In particular, it has been shown that the performance of V-UEs can be greatly

improved even when the standard-compliant operation is maintained by V-UEs.

- Adaptive resource control algorithm of RSU has been proposed so that the RSU can operate independently without having to communicate with enhanced Node B's (eNBs) or other entities.
- Through realistic simulation, the characteristics of the proposed algorithm have been studied thoroughly and the MRR performance is hugely improved by up to 36.5% in NLOS situations.

The rest of the chapter is organized as follows. Related work and system model are presented in Section 3.2 and Section 3.3, respectively. Then, our proposed algorithm is presented in Section 3.4. The proposed algorithm is evaluated via realistic, high-fidelity system-level simulations in Section 3.5. Finally, we conclude the chapter in Section 3.6.

3.2 Related Work

In vehicular communication, many studies propose to use relay for enhancing performance, where there are two main approaches. In the first approach, V-UE can be a relay, and hence, selecting proper V-UEs as relays to maximize system performance is a very important problem. In [60,61], it is assumed that V-UEs use IEEE 802.11p, where usually one of V-UEs occupies the channel at a certain time while the other V-UEs listen because of Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) operation. However, there can be simultaneous transmissions of multiple V-UEs at a certain time in LTE-V2V, meaning that V-UE misses concurrently transmitted CAMs while operating as relay. This aggravates the reception performance of V-UE, selected as relay. Therefore, it is not a good solution in LTE-V2V. In the second approach, RSU or fixed object (e.g., parked car) operates as relay [6–9]. These studies also assume to use IEEE 802.11p. In addition, the operation band of relay is set to be different

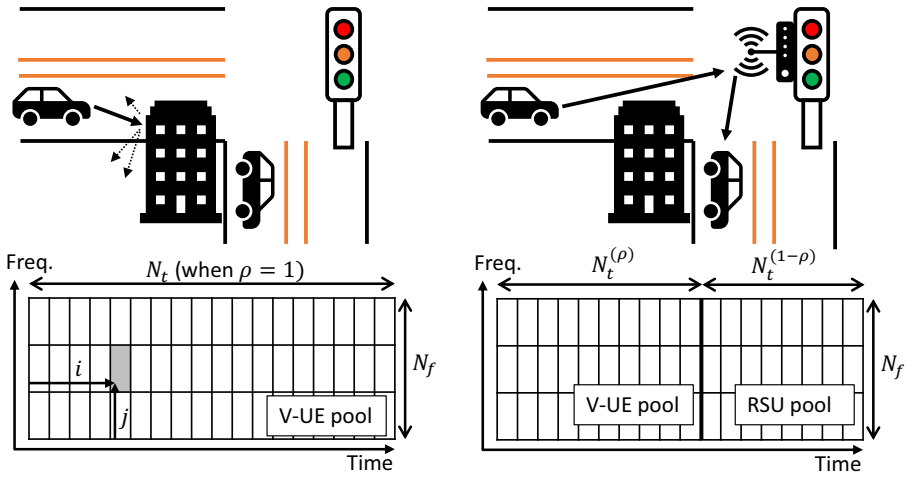
from that of V-UEs. Even though it is difficult to make a fair comparison with LTE-V2V, it has been shown that using RSU in 802.11p V2V has an advantage. To our best knowledge, there is no study proposing a relay system in the context of LTE-V2V.

Meanwhile, efficient RSU deployment strategies [13–17] motivate us when we conduct simulations. In [13, 14], the authors study cost-efficient RSU deployment to maximize their own performance metric, e.g., spatio-coverage. The authors of [15] propose an RSU deployment scheme which aims at minimizing cost while satisfying an objective. In [16, 17], the authors focus on overlapped area covered by different RSUs such that RSU coverage area is maximized by minimizing overlapped area.

In addition, there have been efforts to utilize D2D communication for vehicular communication instead of using 802.11p. The authors of [18] analytically predict the performance of LTE-D2D based vehicular communication, showing that LTE systems are suitable for vehicular communication. The authors of [19, 20] propose resource management policies, satisfying given latency and reliability constraints for D2D based vehicular communication. The authors of [21] consider optimizing performance when different types of links (i.e., V2V and V2I links) exist in the same resource pool. However, in these studies, the performance is optimized in terms of unicast communication, which is out of scope of this work. The authors of [22] consider broadcast communication of vehicular communication, yet the approach is based on 3GPP Release 12, where the resource pool structure is different from that of 3GPP Release 14. Accordingly, it is difficult to be applied to our work.

3.3 System Model

In this section, we explain our system model. Since we already explained the basic system model regarding LTE-V2V in Section 2.2, we explain additional concepts regarding RSUs. In RA-eV2V, RSU relays CAMs received from neighboring V-UEs and all neighboring V-UEs intend to receive the relayed messages again. As shown



(a) Without RSU (b) With RSU

Figure 3.1: Resource pool configuration.

in Fig. 3.1, V-UE and RSU use the same frequency band since we design the system so that V-UE does not need to distinguish whether a CAM is transmitted from V-UE or RSU. In fact, V-UE does not even need to notice the existence of RSU as long as CAM contains the information of the original transmitter (i.e., V-UE). From the perspective of RSU, as shown in Fig. 3.1b, RSU uses V-UE pool and RSU pool separately by determining ρ, which is the ratio of resources for V-UE pool to the total resources, but ρ is not necessarily recognized by V-UE. Here, RSU can relay only the received CAMs in the same round, to meet the stringent latency requirement. By using RA-eV2V, it is expected that when a V-UE fails to receive a CAM due to low Signal-to-Interference-plus-Noise Ratio (SINR), SINR of the CAM relayed by RSU is likely to be higher. This is because RSU usually has good channel condition (i.e., LOS channel) with nearby vehicles. Moreover, the communication distance may be increased in case of the relayed CAM transmission.

For notation, there are total $N_f \cdot N_t$ RUs every round, where N_f and N_t are the numbers of RUs in frequency and time, respectively. The numbers of RUs in V-UE

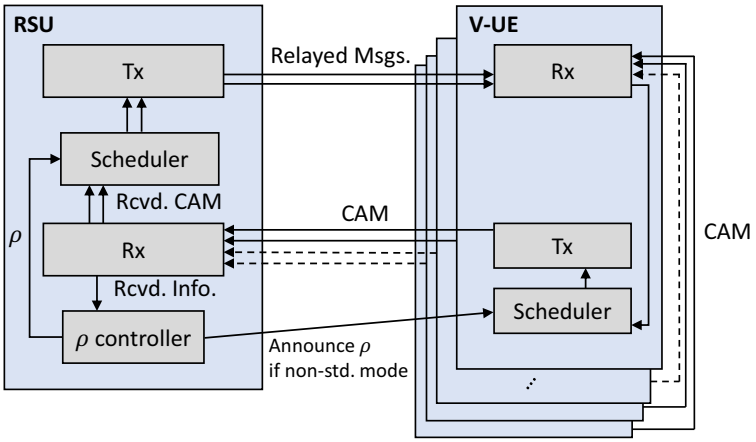


Figure 3.2: Overview of relaying systems.

pool and RSU pool are expressed as $N_f \cdot N_t^{(\rho)}$ and $N_f \cdot N_t^{(1-\rho)}$, respectively, where $N_t^{(\rho)} = \rho N_t$ and $N_t^{(1-\rho)} = (1-\rho)N_t$. In addition, $RU(i,j)$ denotes the RU located at the ith and jth positions in time and frequency, as shown in Fig. 3.1a.

3.4 Proposed Scheme

In this section, we explain the proposed relaying systems in detail and propose resource pool control algorithms, which determine ρ in real-time in a distributed manner.

3.4.1 Overview

The overall relaying system is presented in Fig. 3.2. Please note that CAM with solid (dotted) line represents success (failure) of reception. Apparently, RSU can relay only successfully received CAMs. Basically, ρ is adjusted by ρ controller based on received information. RSU scheduler is in charge of determining the frequency and time locations of RUs to transmit relayed messages. V-UE scheduler also determines the frequency and time location of its own CAM, as defined in [41, 42].

In this chapter, we consider two operation modes based on whether the operation of V-UE is standard-compliant or not.

- **Standard mode:** V-UEs strictly follow the current standard, 3GPP Release 14. In this mode, it is assumed that V-UEs cannot recognize the change of ρ. Therefore, resource collisions, i.e., the same RU is selected by two or more transmitters, between V-UEs and RSUs can happen.

- **Non-standard mode:** V-UEs are aware of the change of ρ by announcement from RSU. Therefore, the 3GPP standard should be modified to support signaling and protocol. In this case, resource collision between V-UE and RSU never happens while there can still be resource collisions among V-UEs or among RSUs.

3.4.2 Scheduler in V-UE

In 3GPP standard, greedy algorithm [1] is adopted as an autonomous RU selection method. Using greedy algorithm, the scheduler in V-UE selects an RU based on energy level sensing results on each RU in the previous round. Basically, UE selects the RU which has the lowest received energy. In such a case, resource collision may frequently occur since multiple UEs might trigger resource change simultaneously. In the standard, to prevent such problem, greedy algorithm is enhanced by making UE randomly select an RU out of a group of RUs which have the lowest $X\%$ received energy level. When it comes to resource change, in each round, only $Y\%$ of UEs trigger resource change while the other $(100 - Y)\%$ UEs maintain the RU as in the previous round.[1]

Following the standard, in this work, we also adopt greedy algorithm for V-UE scheduler. Please note that, in standard mode, even though V-UEs are not aware of the change of ρ, they always try to find RUs with lower energy level based on greedy algorithm. Thus, V-UEs are not likely to select the RU used by RSU due to high received energy level.

In case of non-standard mode, there is an additional case to trigger resource change. If V-UE finds out that its own CAM RU will belong to RSU pool due to ρ change in

[1]Please note that in our simulation, X and Y are set to 20% and 20%, respectively, as stated in [1].

Algorithm 1 ρ control based on SiRA.

When system starts:

1: $n = 1$ {Current round index is set to 1}

2: $\rho = 1$ {ρ is set to 1}

The nth round begins:

3: $N_{\text{CAM}}^{(n)} = 0$ {No. of successfully received CAMs at round n}

CAM reception and CAM relay

The nth round ends: $i \leftarrow 1, \cdots, N_t^{(\rho)}$ $j \leftarrow 1, \cdots, N_f$ Msg. on $RU(i, j)$ is received successfully

4: $N_{\text{CAM}}^{(n)} \leftarrow N_{\text{CAM}}^{(n)} + 1$

5: $N_t^{(1-\rho)} \leftarrow \left\lceil N_{CAM}^{(n)} / N_f \right\rceil$ and $N_t^{(\rho)} \leftarrow N_t - N_t^{(1-\rho)}$

6: $\rho \leftarrow N_t^{(\rho)} / N_t$

7: $n \leftarrow n + 1$

8: Go back to line 3

the following round, V-UE reselects an RU within the newly announced V-UE pool.

3.4.3 ρ controller in RSU

Let us analyze the relaying system first. If RSU reduces ρ, the number of RUs in V-UE pool will decrease (the number of RUs in RSU pool increases), thus resulting in more resource collisions among V-UE. As the number of the resource collisions increases, the number of successfully received CAMs on the RSU side decreases. Thus, RSU will increase ρ again because RSU does not need to maintain the currently available RUs in RSU pool. On the other hand, if RSU increases ρ, the number of resource collisions among V-UEs is reduced, but the number of RUs to relay the successfully received CAMs will be insufficient. In other words, $1 - \rho$ is inversely proportional to the number of CAMs successfully received on the RSU side. Therefore, if we do this negative feedback operation several times, ρ will converge to an appropriate level.

In addition, considering that the transmission period of CAM is very short, when RSU changes ρ, RSU can immediately recognize a change in the number of success-

fully received CAMs. By utilizing these points, we propose Simple Resource pool Adaptation algorithm (SiRA), which adapts ρ depending on the number of successfully received CAMs at the previous round, as described in Algorithm 1.

When the algorithm runs first, all variable parameters are set to their default values (lines 1–2). Then, when the nth round begins, it initializes $N_{\text{CAM}}^{(n)}$ as well (line 3). After then, RSU listens to CAMs during V-UE pool and updates $N_{\text{CAM}}^{(n)}$ (lines 4–10). Please note that RSU relays CAM only when $\rho < 1$. By using the updated $N_{\text{CAM}}^{(n)}$, RSU reserves RSU pool for the next round as many as the number of successfully received CAMs. ρ mapped by $N_t^{(\rho)}$ value has a discrete value.

However, if the situation changes significantly, the change in ρ will be severe. In particular, V-UEs operating in standard mode are more sensitive to the change of ρ. This is because V-UEs in standard mode are not aware of the change of ρ. Therefore, V-UE might experience resource collision with RSU in standard mode. Of course, this situation may not be a big problem, considering the unexpected resource collisions also frequently occur due to a stochastic resource change among V-UEs. To confirm this, we propose a new algorithm, called Less-changing Resource pool Adaptation (LeRA), to make the changing ratio of ρ (η), defined as the ratio of ρ change events over the last S_{fixed} rounds, be a target value, η_{target}.

As described in Algorithm 2, LeRA computes new ρ every S_{CAM} rounds using a counter, T_{CAM} (lines 16–17). If $S_{\text{CAM}} = T_{\text{CAM}}$, new ρ is determined based on averaged N_{CAM} over the last S_{CAM} rounds (line 19). Moreover, we use ρ change history, stored as IsChange(n) (lines 23 and 26), to adaptively adjust S_{CAM}. If η is larger than η_{target}, S_{CAM} is increased to lower η (lines 28–29). If not, S_{CAM} is decreased to raise η (lines 30–31). Based on the operation, η converges to η_{target}.

3.4.4 Scheduler in RSU

Recall that we have allocated as many RUs in RSU pool as the number of CAMs successfully received by ρ controller. However, since the current ρ is determined based on

Algorithm 2 ρ control based on LeRA.

When system starts:

1: $n = 1$

2: $\rho = 1$

3: $S_{\text{CAM}} = 1$ {Adaptive N_{CAM} average window size}

4: $T_{\text{CAM}} = 0$ {Adaptive N_{CAM} average window timer}

5: $S_{\text{fixed}} = 50$ {Moving average size for η control}

6: $\eta_{\text{target}} = 0.05$ {Target changing ratio}

7: MAX WIND = 8 {Maximum S_{CAM}}

The nth round begins:

8: $N_{\text{CAM}}^{(n)} = 0$

CAM reception and CAM relay

The nth round ends: $i \leftarrow 1, \cdots, N_t^{(\rho)}$ $j \leftarrow 1, \cdots, N_f$ Msg. on $RU(i, j)$ is received successfully

9: $N_{\text{CAM}}^{(n)} \leftarrow N_{\text{CAM}}^{(n)} + 1$

10: $T_{\text{CAM}} \leftarrow T_{\text{CAM}} + 1$ $S_{\text{CAM}} = T_{\text{CAM}}$

11: $\rho_{\text{old}} \leftarrow \rho$

12: $\overline{N}_{CAM} \leftarrow \sum_{i=0}^{S_{\text{CAM}}-1} N_{\text{CAM}}^{(n-i)} / S_{\text{CAM}}$

13: $N_t^{(1-\rho)} \leftarrow \lceil \overline{N}_{CAM} / N_f \rceil$ and $N_t^{(\rho)} \leftarrow N_t - N_t^{(1-\rho)}$

14: $\rho \leftarrow N_t^{(\rho)} / N_t$

$\rho \neq \rho_{\text{old}}$

15: IsChanged$(n) = 1$

16: $S_{\text{CAM}} \leftarrow 1$

17: IsChanged$(n) = 0$

18: $\eta \leftarrow \sum_{i=0}^{S_{\text{fixed}}-1}$ IsChanged$(n - i)/S_{\text{fixed}}$ $\eta > \eta_{\text{target}}$

19: $S_{\text{CAM}} \leftarrow \min(2S_{\text{CAM}}, \text{MAX WIND})$

20: $S_{\text{CAM}} \leftarrow \max(S_{\text{CAM}}/2, 1)$

21: $T_{\text{CAM}} \leftarrow 0$

22: $n \leftarrow n + 1$

23: Go back to line 8

the results of the previous rounds, the number of RUs available in RSU pool is not always the same as the number of CAMs successfully received currently. Therefore, the RSU may need to select the CAMs to be relayed (although it does not happen often). Considering that CAM is a broadcast message and V-UEs are randomly distributed around the RSU, we cannot give priority to specific CAMs. Thus, RSU randomly selects CAMs for relaying if RUs in RSU pool are insufficient.

In fact, there might be an issue with processing time of RSU. Thus, it is more desirable that the time interval between a CAM RU and the corresponding relayed CAM RU should be larger than the processing time of RSU. However, the processing time is usually assumed to be less than 4 ms [62]. This is a practical issue, which barely affects the overall performance. Therefore, we ignore this effect in performance evaluation.

3.4.5 RSU Deployment

We may not be able to install RSUs in all the candidate locations where RSU can be installed. Thus, it is natural to consider a cost-effective deployment strategy. However, our main objective in this chapter is not studying RSU deployment scheme, thus we study existing work and borrow an efficient RSU deployment scheme. In [13], it is proven that finding the optimal RSU deployment in terms of maximizing utility is NP-hard. Therefore, many papers [13, 16, 17] claim that designing a utility function of a location which can represent the performance well and selecting RSU candidate locations in the order of utility can provide near-optimal performance.

In this chapter, we design our own utility function $U(i)$ of candidate location i and a utility maximization problem under the constraint of the number of RSUs, K, as

follows.

$$\text{Maximize } S = \sum_i I(i)U(i)$$

$$\text{s. t. } U(i) = N(i)V(i) - \alpha \sum_j I(j)N(i,j)V(j)$$

$$\sum_i I(i) \leq K, \tag{3.1}$$

where $I(i)$ is an indicator function to represent whether location i is selected as an RSU location or not, $V(i)$ is a long-term vehicle traffic volume, and $N(i)$ is the probability that an RSU at location i changes the channel between UEs within its coverage from NLOS to LOS. $N(i,j)$ is the probability that an RSU at location j changes the channel between UE in the overlapping coverage of RSUs at locations i and j and UE in the coverage of the RSU at location j, from NLOS to LOS.[2] The parameter, α ($0 < \alpha \leq 1$), controls how much $U(i)$ is affected by neighboring RSUs where each influence is expressed as $N(i,j)V(j)$.[3] Please note that $N(i)$, $N(i,j)$, and $V(i)$ are available before installing RSUs. The value of utility function $U(i)$ changes whenever a location is selected. Therefore, we repeat a procedure selecting the location with the highest utility (among locations with $I(i) = 0$) up to K times as long as S increases.

3.5 Performance Evaluation

In this section, the performance of the proposed relaying system is evaluated following the evaluation methodology of 3GPP LTE-V2V in Annex A of [54]. The simulation environments are the same as those in Section 2.5, except for that we adopt Manhattan grid as the target simulation area. As shown in Fig. 3.3, there exist nine grids

[2]Please note that $N(i)$ and $N(i,j)$ can be derived from a simple geometric calculation by using road layout (such as buildings) assuming that V-UEs are uniform randomly distributed on the road, but the derivation is omitted in this chapter.

[3]In this chapter, α is set to 0.5 so that the performance improvement of UEs in the overlapping coverage is the same as that of UEs in the non-overlapping coverage when both RSUs at locations i and j are installed

Table 3.1: Simulation environments.

Carrier frequency	5.9 GHz
System bandwidth	10 MHz (50 RBs)
Topology	Manhattan grid [54]
Vehicle mobility model	SUMO [52]
Link performance model	ns-3 [53]
Channel model	Fast fading + shadowing + pathloss + in-band emission [54]
Tx power of UE	23 dBm
Noise figure	9 dB
Noise power	-174 dBm/Hz
CAM size	800 B
CAM generation period	100 ms
No. RUs in a resource pool	$N_f \cdot N_t$
Simulation time	100,000 subframes (100 s)

where each grid consists of two lanes outside of a building area. The size of a grid is 433 m $\times$ 250 m. We install an RSU at each intersection. For more realistic simulation, an actual layout of Berlin, Germany is also considered in Section 3.5.4. The overview of simulation environments is presented in Table 3.1. The detailed explanations for simulation environments are omitted since it is already explained in Chapter 2.

3.5.1 3GPP Baseline Scheme

First, we analyze the MRR performance of the 3GPP baseline scheme. Multiple transmissions of a single CAM in the same round are allowed to enhance the decoding performance. Fig. 3.4 shows the MRR performance based on the number of V-UE CAM transmissions per round. Here, various density options are controlled by the number of V-UEs and the number of RUs in resource pool. As shown in the figure, the use of retransmissions, when the density is high, rather degrades the performance. Moreover, even when the performance can be improved, it is difficult to judge the optimal number of retransmissions from the perspective of V-UE or network entity. Furthermore, the performance gain is marginal compared to the gain in RA-eV2V, which will be shown

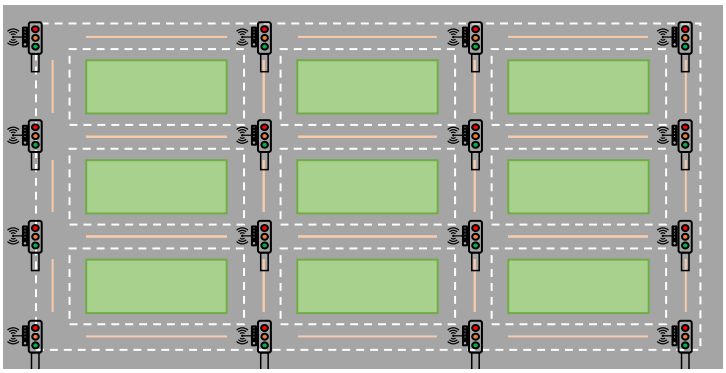


Figure 3.3: Simulation layout: Manhattan grid.

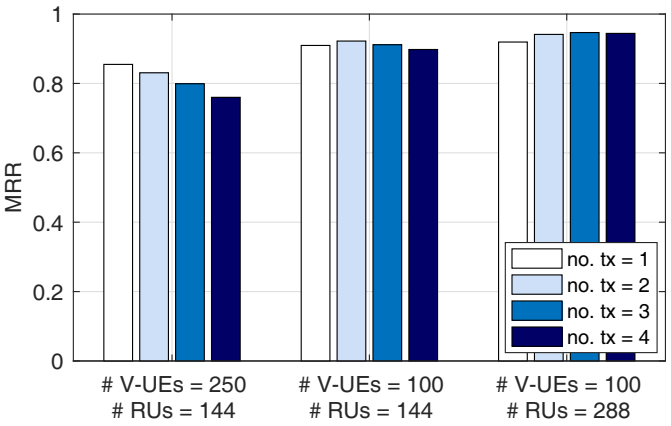
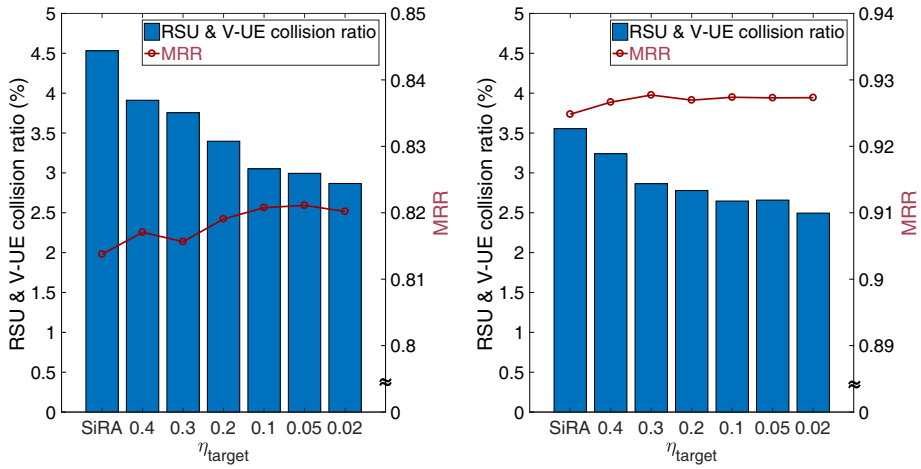


Figure 3.4: MRR performance in 3GPP baseline scheme when target range = [0, 150) m.



(a) # V-UEs = 250 and # RUs = 72

(b) # V-UEs = 250 and # RUs = 144

Figure 3.5: Performance comparison of LeRA with SiRA for varying η_{target} in standard mode.

in Section 3.5.3. For simplicity of comparison, from now on, we limit the number of V-UE CAM transmissions per round to one.

3.5.2 Analysis of Proposed Algorithms

We now compare the proposed algorithms, in particular, SiRA and LeRA in standard mode. As explained earlier, LeRA adjusts S_{CAM} to make the changing ratio of ρ (η) be as much as η_{target}. In Fig. 3.5, the collision ratio between RSU and V-UE is shown, which is defined as the ratio of the number of collisions between RSU and V-UE to the total number of collisions (i.e., including collisions among V-UEs). Here, collision is defined as the event that more than two transmitters within 300 m select the same RU.[4] The MRR performance is also shown as red line.

In the figure, it is shown that the collision ratio between RSU and V-UE decreases

[4]In such a case, there is a chance that a receiver is located within the target range of both transmitters. The receiver is likely to fail to receive one or two CAMs due to interference, while it is required to receive both CAMs.

and the MRR performance increases as η_{target} decreases, while it is saturated at some point. Please note that the ρ changing ratio in SiRA is 0.6–0.7 in our simulation. In fact, the collision ratio between RSU and V-UE accounts for a small portion overall so that the performance gain, obtained by reducing the collision ratio between RSU and V-UE, is marginal in average sense. Nevertheless, considering that we cannot control the number of collisions among V-UEs without proposing new resource selection algorithm in V-UE scheduler, it is meaningful to lower the number of collisions between V-UE and RSU.

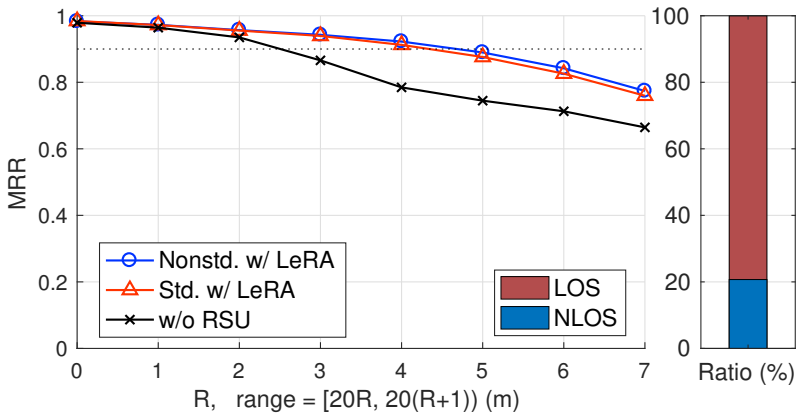
Here, we regard LeRA in standard mode as the representative scheme in RA-eV2V since it is easily applicable to the real world in that it only requires a deployment of RSUs without changing the current standard or V-UE implementation. However, by comparing standard mode with non-standard mode, we can predict the performance improvement in less constrained situations. Considering the simulations results at various densities, η_{target} is set to 0.05 unless otherwise stated.

3.5.3 Overall Performance Comparison

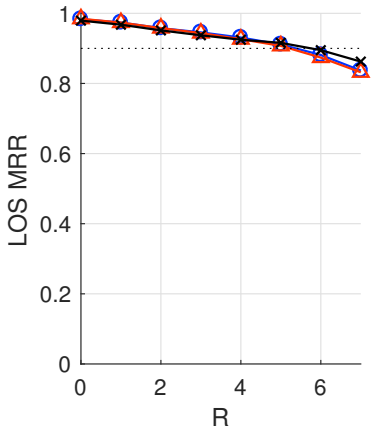
We compare the MRR performances of RA-eV2V with the 3GPP baseline method without the relaying system. The number of V-UEs and the number of RUs are set to 250 and 144, respectively, to mimic the medium traffic case in [54].

Fig. 3.6 presents MRR performance over ranges, which are divided every 20 m, based on the distance between transmitter and receiver. The entire samples can be divided according to the LOS or NLOS channel conditions between transmitter and receiver. It is shown that about 20.7% of the samples are from NLOS channel, and they basically limit the overall performance.

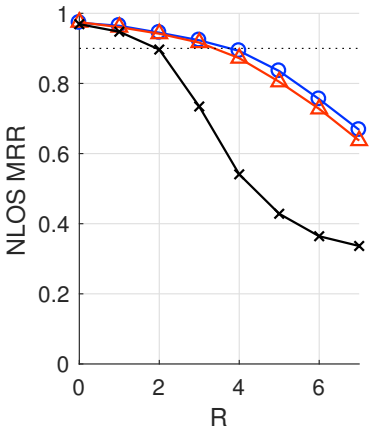
When it comes to 3GPP baseline scheme operating without RSU, the overall performance decreases as the distance increases, while the performance drop is more drastic in NLOS cases as shown in Fig. 3.6c. If RA-eV2V is used, the performance drop can be much alleviated especially in NLOS cases. Please note that the perfor-



(a) All cases



(b) LOS cases only



(c) NLOS cases only

Figure 3.6: MRR performance over distance when # V-UEs = 250 and # RUs = 144.

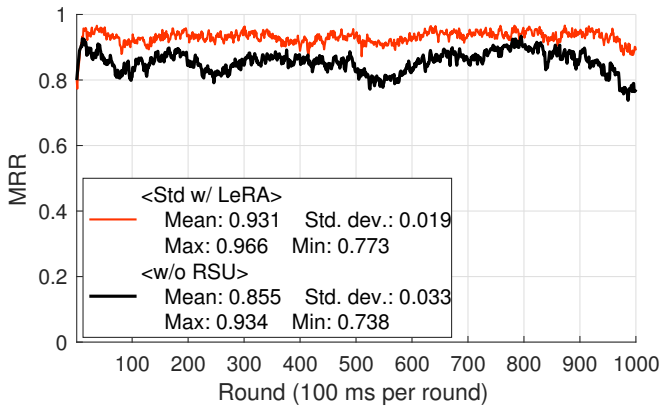
mance in NLOS cases is more important for communication-based vehicle safety applications considering that it compensates for the fact that sensor-based vehicle safety applications can not cope with the NLOS cases. Considering the fact that the typical MRR requirement is 0.9 according to [45], the communication range is almost doubled in NLOS cases, which can be interpreted by comparing maximum R satisfying MRR > 0.9.

Non-standard mode improves the performance further because there is no resource collision between RSU and V-UE in non-standard mode However, performance improvement is not significant compared with the performance gain over 3GPP baseline scheme. As explained in Fig. 3.5, the resource collisions between RSU and V-UE account for only a small portion compared with the total collisions, thus achieving marginal performance gain.

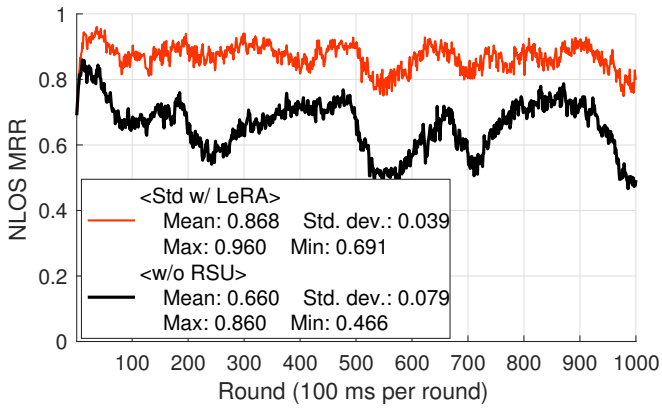
As shown in Fig. 3.7, the MRR performance changes sensitively with time change since the mobility of vehicles is high. For simplicity, only the performances of relaying scheme with LeRA in standard mode and 3GPP baseline scheme are shown. It is shown that RA-eV2V always improves the performance. Moreover, the variance of RA-eV2V is much less than that of the 3GPP baseline scheme especially in NLOS cases, which proves that the performance of RA-eV2V is much more stable.

Fig. 3.8 shows the Empirical Cumulative Distribution Function (ECDF) of MRR performance per transmission. Considering that the MRR requirement is 0.9, it is shown in Fig. 3.8a that 40% of transmissions do not satisfy the MRR requirement in 3GPP baseline scheme while only 14% of transmissions do not satisfy the MRR requirement in RA-eV2V. For various density options as shown in Fig. 3.8b, it is shown that the performance in terms of the transmission ratio satisfying the requirement is greatly improved.

Fig. 3.9 shows the ECDF of Message Inter-Reception (MIR) performance, defined as the time elapsed between two successive successfully-received CAMs from the same V-UE. As shown in Fig. 3.9a, there are many MIR samples close to 100 ms

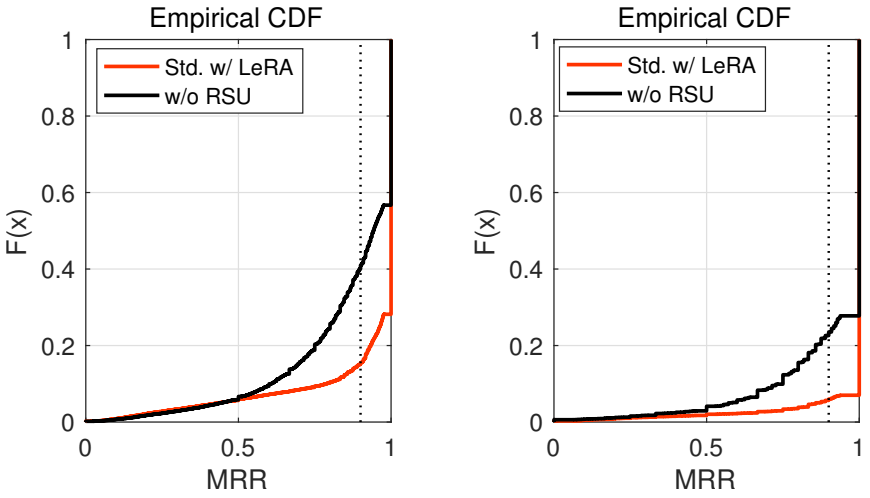


(a) All cases



(b) NLOS cases only

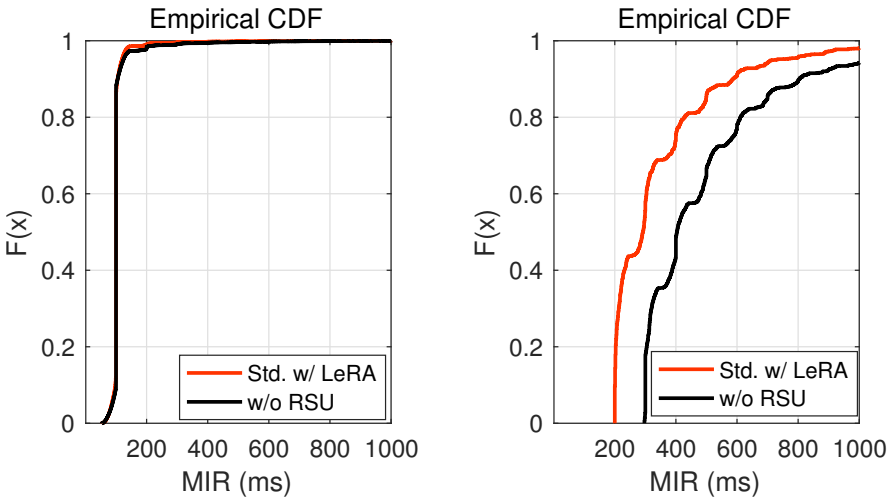
Figure 3.7: Instantaneous MRR performance over rounds when target range = [0, 150) m (# V-UEs = 250 and # RUs = 144).



(a) # V-UEs = 250 and # RUs = 144

(b) # V-UEs = 100 and # RUs = 144

Figure 3.8: ECDF of MRR.



(a) All samples

(b) Bottom 1% samples

Figure 3.9: Empirical CDF of MIR (# V-UEs = 100 and # RUs = 144).

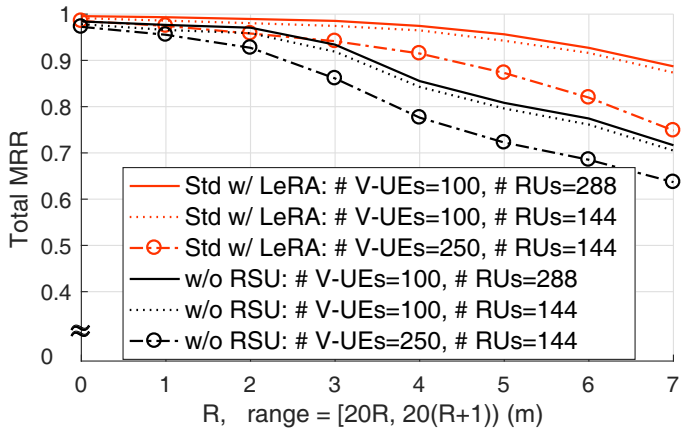


Figure 3.10: MRR performance over distance with various density options.

overall. On the other hand, Fig. 3.9b shows MIR samples corresponding to bottom 1% of the MIR values in the entire samples. In those bottom 1% of the MIR values, at least two rounds are needed to transmit CAM once in RA-eV2V, while at least three rounds are needed to transmit CAM once in 3GPP baseline scheme. Thus, the performance gap between the two schemes in terms of V-UEs with poor performance is remarkable.

Fig. 3.10 shows the MRR performance for various densities. We find that the proposed relaying system outperforms 3GPP baseline scheme with substantial gain for all the considered densities. Especially, we observe that the gap between the black solid line (w/o RSU: # V-UEs=100, # RUs=288) and the black dashed line (w/o RSU: # V-UEs=100, # RUs=144) is small even though the difference in the number of RUs is large. Therefore, the performance difference caused by resource collisions appear to be marginal in this case. It is interpreted that simply increasing the resource cannot solve the fundamental problem if the amount of resource is large enough. By comparing the red dotted line (Std w/ LeRA: # V-UEs=100, # RUs=144) and the black solid line (w/o RSU: # V-UEs=100, # RUs=288), we find that RA-eV2V effectively enhances the performance since RA-eV2V outperforms the baseline scheme even with smaller number of RUs.

Fig. 3.11 shows a comparison of the proposed method and relaying methods that

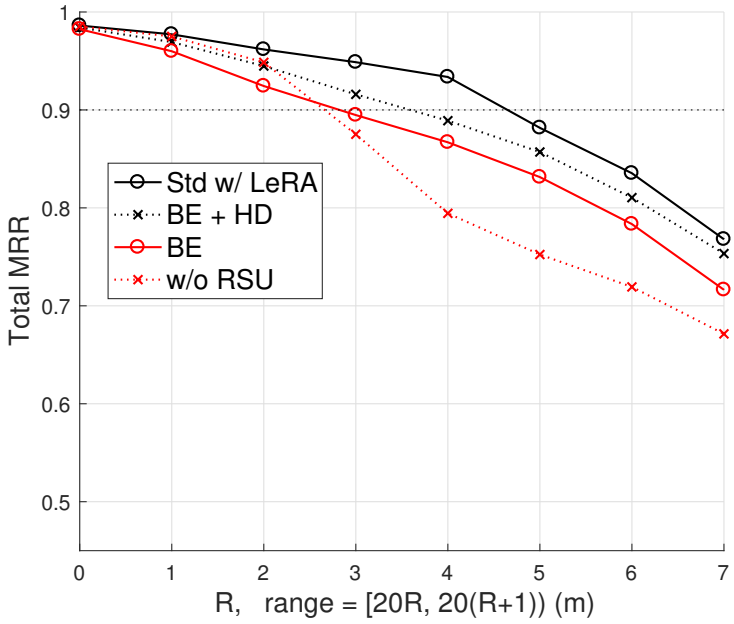
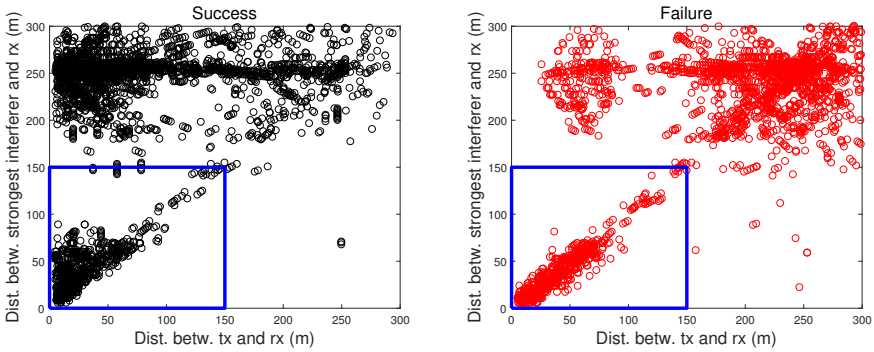
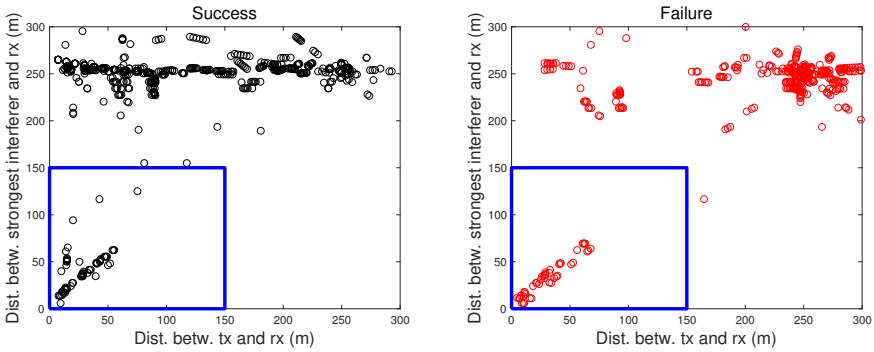


Figure 3.11: MRR performance comparisons with other relaying schemes.



(a) BE



(b) LeRA

Figure 3.12: Inter-collision events (between a UE and an RSU) according to distance.

operate in a best effort (BE) manner in terms of time to transmit relaying messages. In order to minimize the half duplex problem, a method of transmitting three relaying messages in one time slot (HD) is considered, i.e., it operates in a best effort manner for every three relaying messages. As shown in Fig. 3.11, the performance of BE is not as good as our proposed scheme since the resource occupation of RSU in a best effort manner occurs a lot of resource collisions with other UEs. There is a slight gain for using BE+HD in order to reduce the half duplex problem, still the gain is not significant. However, our proposed scheme has higher gain than the comparison scheme since the resource occupation of RSU is much stable thanks to LeRA.

Fig. 3.12 is a graph showing the results of a transmission where a CAM is (not) received successfully at a receiving UE or an RSU (call it an object to mean either a UE or an RSU) on the left (right) when an RSU and a UE transmit CAMs using the same RU (call it an inter-collision event). The x axis (y axis) means the distance between a transmitting object (an interfering object) and a receiving object. The object that has transmitted the signal with the largest received power (the second largest signal) at the receiving object becomes the transmitting object (the interfering object). In case of BE as shown in Fig. 3.12(a), there are a number of inter-collision events even with low x and y values (less than 150 m). In case of LeRA, the number of inter-collision events is much reduced since it utilizes resources in a more stable manner.

Here, we verify how efficient the RSU deployment scheme, explained in Section 3.4.5, is. Fig. 3.13 shows the MRR performance gain compared to 3GPP baseline scheme according to the number of available RSUs, K. In the figure, different colors represent different available numbers of RSUs and dotted bar represents the performance gain of NLOS samples while solid bar includes that of all samples. It is shown that the gain increases as K increases, but it gradually converges. Thus, it means that RSUs installed at locations with high utility can improve the performance efficiently even when K is small.

3.5.4 Feasibility Test via Real City Map-based Simulation

For more realistic performance validation, we conduct real city map-based simulation. We use OpenStreetMap (OSM) Web Wizard provided by SUMO [52] to link the actual map information provided in [56] to our simulator. Fig. 3.14 shows the center of Berlin, Germany (1,200 m by 800 m), which is a target area in the simulation. Note that the size of simulation area in the Berlin case is similar to that in the Manhattan case (1,299 m by 750 m). The blue boxes with number indicate installed RSUs. It is easily shown that the number of RSUs is increased compared to the above-used Manhattan grid case. The deployment pattern is irregular as well. To reflect heterogeneous vehicle

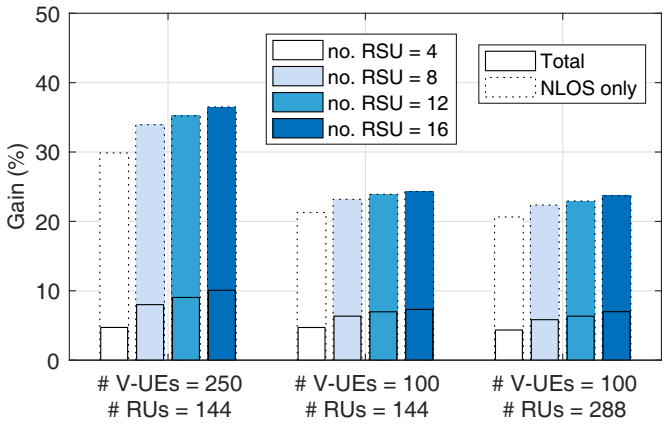


Figure 3.13: MRR performance gain compared to 3GPP baseline scheme according to the number of available RSUs.

types in the real world, we consider 91% of cars, 3% of trucks, and 6% of buses, where each type of vehicle has different size and mobility model.

Fig. 3.15 shows the MRR performance over distance in the Berlin case when # V-UEs = 119 and # RUs = 144. We first observe that the MRR performance of RA-eV2V is better than that of baseline scheme as expected. Please note that it is more crowded with vehicles than in the Manhattan case (when # V-UEs = 250 and # RUs = 144) because the vehicles are concentrated in a smaller area.[5] That can be clearly understood by comparing Fig. 3.15b with Fig. 3.6b. In Fig. 3.6b, the MRR performance of 3GPP baseline scheme is quite good even when R is large, meaning that resource collisions with nearby V-UEs rarely happen. However, in Fig. 3.15b, the MRR performance of 3GPP baseline drops sharply as R increases, meaning that resource collisions with nearby V-UEs frequently happen. In case of LOS, the MRR performance of baseline scheme is over 0.9 when $R \leq 2$ (i.e., range is less than 60 m). This implies that RUs are well-reused among V-UEs within this range.

[5]In case of the Manhattan case, the lane exists up to the simulation border area, so vehicles are distributed over a wider area compared to the Berlin case. In addition, in the Berlin case, the actual area is also reduced since vehicles cannot exist on rivers, train lines, and parks.

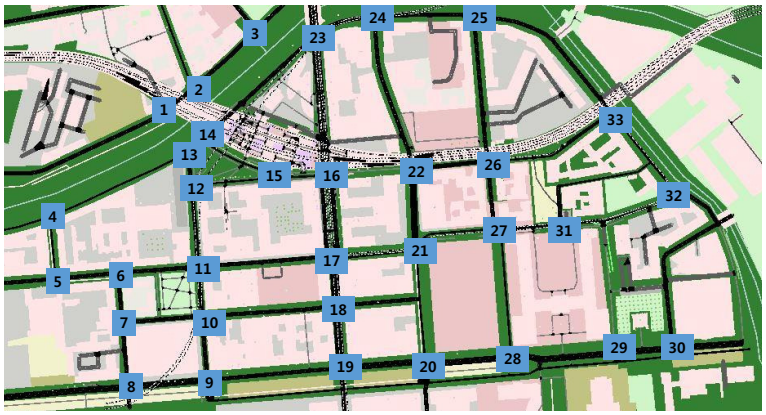
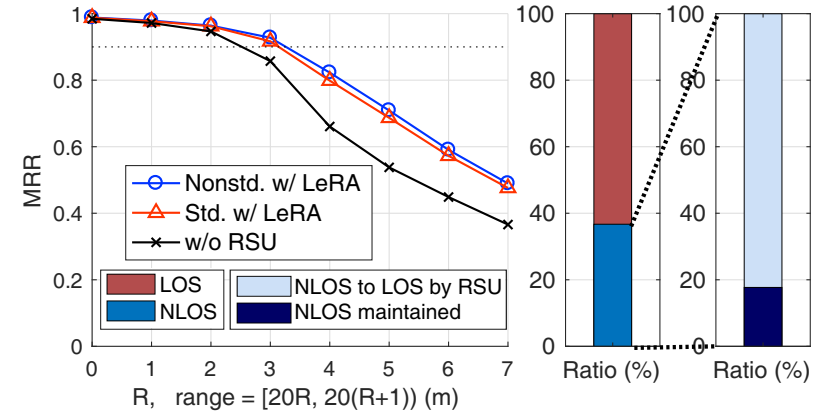


Figure 3.14: Berlin layout and RSU deployment in real map-based simulation.

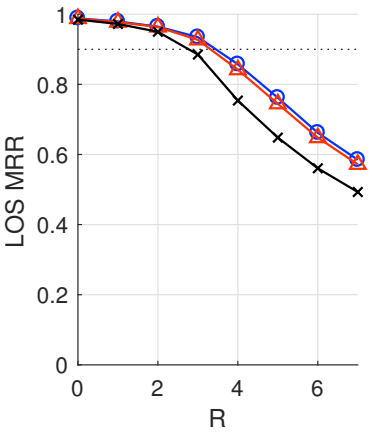
On the other hand, in case of NLOS, the range is reduced to 40 m, meaning that the MRR performance is more sensitive to interference in NLOS cases. As shown in Fig. 3.15c, there is slight performance loss[6] of RA-eV2V in standard mode in NLOS case when $R = 0$ (i.e., range is less than 20 m). This is because V-UEs are very close to each other so that they can exchange their CAMs without the help of RSU, while interference among V-UEs is intensified due to the reduced number of RUs by RSU operation. However, except for that single range, RA-eV2V outperforms the baseline scheme hugely since RSU effectively increases communication distance by utilizing two-hop communication.

In the Berlin case, the ratio of NLOS cases over the entire cases is 36.7%, which is larger compared to that in the Manhattan case (20.7%) due to the existence of small blocks and winding roads. In such circumstances, RSU occasionally fails to relay CAM because RSU might not have LOS channel with transmitter and/or receiver. For example, if a transmitter is on the east side of a square block and a receiver is on the west side of the block, there is no RSU having LOS channel with both of them. If the size of the block is small, the distance between the transmitter and the receiver may be less than the target range. This is a problematic situation where RSU cannot resolve

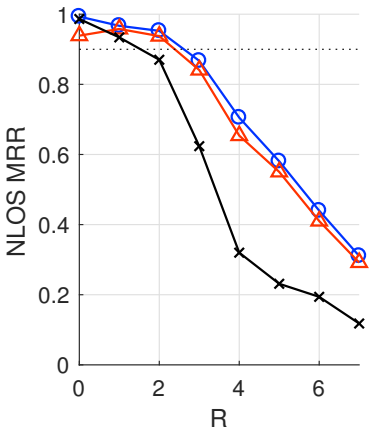
[6]The performance loss is not severe in that the MRR requirement is still satisfied.



(a) All cases



(b) LOS cases only



(c) NLOS cases only

Figure 3.15: MRR performance over distance in the Berlin case when # V-UEs = 119 and # RUs = 144.

the NLOS case between them. However, this never happens in the Manhattan case, since only large blocks are considered. The cases, where NLOS channel cannot be resolved by RSU, accounts for 17% in the entire NLOS cases as shown in Fig. 3.15a. Still, 83% of CAM transmissions in NLOS situations are aided by RSU, thus making huge improvement in overall performance.

3.6 Summary

In this chapter, we aim at enhancing the MRR performance while developing realistically applicable technologies. As a result, we proposed a relaying system, called RA-eV2V, designed for easy installation and operation according to the newest V2V communication system in 3GPP. Through extensive simulation, we prove that RSU harmoniously coexists with V-UEs while providing significant gain to V-UEs in various aspects. In particular, the longer distance between a transmitter and a receiver, the more performance gain, which implies RA-eV2V effectively increases the communication distance. We hope that more V2V communication-based applications will be developed with performance improvements in V2V communications.

Chapter 4

HiPA: Hidden Pair Awareness for Efficient UE Relaying Algorithms in LTE-V2X Communications

4.1 Introduction

One major reason to CAM reception failure is the presence of large obstacles such as buildings between a transmitter and a receiver so that the channel between them becomes Non-Line-Of-Sight (NLOS). However, it is difficult to confirm whether a CAM is successfully received at neighboring vehicles from the perspective of a transmitter. That is because there is no feedback about CAM transmission, which is broadcast transmission.

Therefore, in this chapter, we aims to recover CAM reception failure by proposing a distributed relaying system where any UE can operate as an relay. In the proposed relaying system, we focus on finding a hidden pair (i.e, a transmitter and receiver pair with failure of CAM exchange) and recovering the reception performance of the pair with relaying operation by being helped by other vehicles. The main contribution of the chapter is as follows.

- We propose a way called Hidden Pair Awareness (HiPA) to predict the connectivity of any V2V pair, which is challenging in case of broadcasting messages due to

absence of response to the result of transmission from a receiver.

- By utilizing HiPA, we propose a Relaying UE (R-UE) selection scheme and a CAM (to be relayed) selection algorithm. The proposed method evaluates the priority based on which broadcast messages are not properly received by other neighboring UEs.
- We evaluate the performance via realistic simulation, which incorporates the models of realistic vehicle mobility and road situations, such as the operation of traffic lights.

The rest of this chapter is organized as follows. We first present related work and the motivation of this chapter in Section 4.2. Then, our proposed scheme is presented in Section 4.3 and the proposed algorithm is evaluated via system-level simulations in Section 4.4. Finally, we conclude the chapter in Section 4.5.

4.2 Related Work and Motivation

The previous research on relaying in V2V communications has been mainly based on IEEE 802.11p systems, where resources are used in an asynchronous manner. The objective is mainly to minimize the number of retransmissions within the target range by imposing a stochastic relaying opportunity on each UE. Authors in [10] propose to assign different rebroadcast probability values to UEs according to distance between a message transmitter and a message receiver. Authors in [23,24] consider traffic density of vehicles to assign rebroadcast probability values. Authors in [25] consider both distance and traffic density for probability values.

In order to use a more deterministic approach than the probabilistic approach, a method of imposing a different waiting delay before retransmission is also considered [11,12,26–33]. The common idea is to assign a shorter waiting delay to a specific UE considering distance, traffic density, and message generation time as described

above. However, adjusting the waiting delay to give priority to UE is suitable for 802.11p where slot time is relatively short, but it is not good for LTE systems with relatively long slot time (1 ms).

The above-mentioned papers have been proposed through the general assumptions such that the wireless communication performance decreases with distance, and the retransmitted message will have a high success rate. However, since wireless communication between vehicles is affected by the existence of buildings, it is difficult to assume that the performance is constantly decreased according to the distance. In addition, actual performance is difficult to predict depending on the number of users using the same resource pool, the MCS level, and the existence of interfering UEs. Also, since the retransmission efficiency of a UE that is largely hidden in a building is lowered, it is more advantageous to adjust the retransmission opportunity according to the expected transmission performance of the UE. However, unlike the relaying schemes of unicasting messages [34–39], which can determine the success of the actual transmission with ACK, it is difficult to determine whether the transmission is successful in relaying schemes of broadcasting messages.

Being motivated by the challenges, we propose a scheme of predicting transmission success based on previous data. Because we use repeatedly collected data in the same situation, we can make a more accurate prediction about the expected transmission performance of each (potential) relaying UE. In order to efficiently accumulate data, we use a broadcasting-based feedback scheme and UE can operate with low overhead in LTE-V2V system.

4.3 Proposed Hidden Pair Awareness

In this chapter, we consider an UE relaying scheme, where UE relays CAMs transmitted by other UEs as shown in Fig. 4.1. Since the detailed system models are already explained in the previous chapters, we omit the details. Please note that the resources

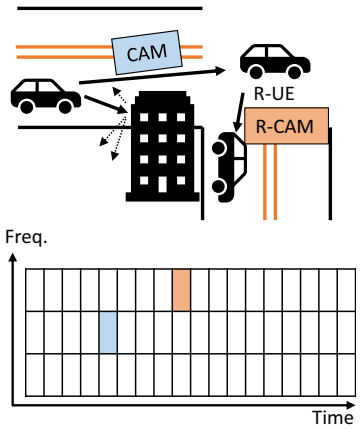


Figure 4.1: System model.

for relayed messages are also selected in the same resource pool as the original UE resource pool. For efficient relaying operation, the selection of Relaying UE (R-UE) is important. Also, the selection of proper CAMs to relay is important from the perspective of R-UEs. However, since CAM is a broadcast message, there is no ACK. Therefore, it is difficult to know whether a UE is proper to be a R-UE and whether a CAM is proper to be relayed.

To deal with such challenges, we consider an efficient feedback protocol. Since the performance of wireless link is highly dependent on distance if channel environments are similar, it is important to know the distance at which the success and failure of the transmission changes. Let us call this distance *criterion distance*. Based on previous studies, the performance of NLOS link is much worse than that of LOS link and it is enough to satisfy the general requirement of CAM reception in case of LOS links at target range. However, it is challenging to satisfy the general requirement of CAM reception in case of NLOS links at target range. Even though the performance of NLOS links at target range is bad, the performance of NLOS links within shorter ranges than the target range becomes difficult to be predicted. Therefore, in this paper, we refer

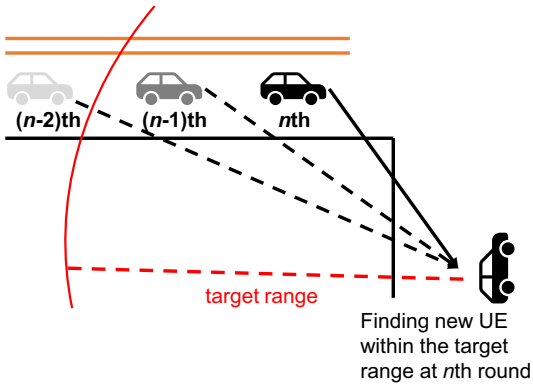


Figure 4.2: Example of finding a new UE based on CAM transmissions and receptions.

to the relationship between the CAM transmitting UE and the CAM receiving UE as an exposed pair (hidden pair) when CAM can (not) be transmitted successfully in the target range. To put it simply, without regard to random elements such as channels, if the distance of a pair is greater than the criterion distance, the two are hidden and if not, two are exposed. Please note that the criterion distance is obtained differently for each location of CAM transmitting UE and CAM receiving UE.

First, let us explain how to find and report the criterion distance. Since the period of CAM transmission is short, the location variation is little between the consecutive CAMs of the same transmitter. In addition, the location variation of any receiver is little as well. Please note that the location variation may be zero if a vehicle stops in front of a traffic light. As shown in Fig. 4.2, a vehicle is moving to the right while transmitting CAMs every round. At the nth round, the CAM receiving UE first successfully receives the CAM. Please note that a solid (dotted) arrow means the success (failure) of CAM reception. The CAM receiving UE finds out that the distance between the UEs is close to criterion distance. Let us call the CAM transmitting UE *newly found UE (nf-UE)*. Finding nf-UE can be defined when UE finds a CAM transmitting UE, which has never been found last M rounds. In the simulation, we normally set M to be 10. Since collecting the information of finding nf-UE locally within a UE requires tremendous

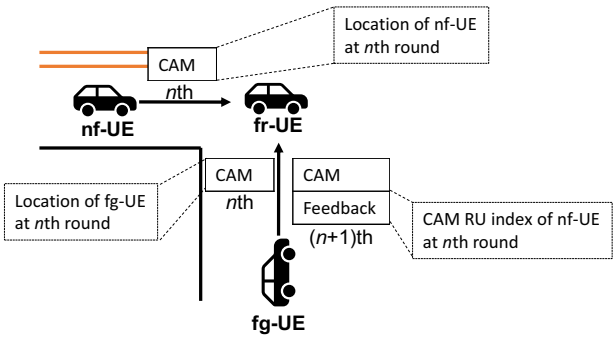
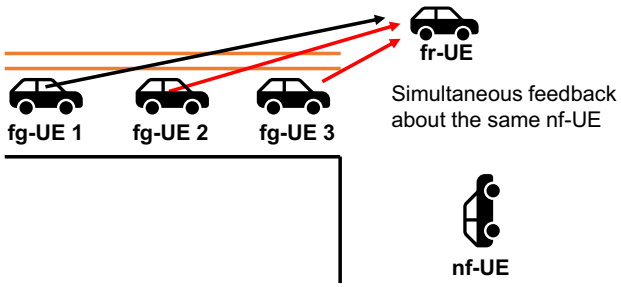


Figure 4.3: Example of receiving feedback.

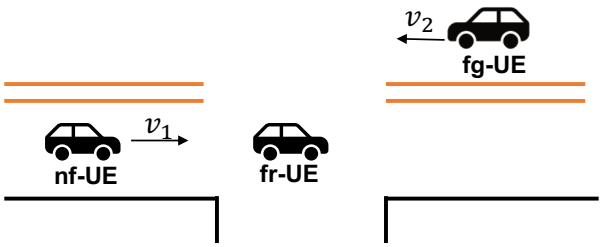
time until the UE collects enough data to utilize it, it needs to be shared with other UEs for efficient data collection. One of solutions is giving feedback about the event that a UE finds a nf-UE. Let us call the CAM receiving UE which finds nf-UE, *feedback-giving UE (fg-UE)*.

The required information to report a criterion distance is the location of nf-UE and fg-UE because the criterion distance is location specific information. However, it is not efficient to allocate a large number of bits to load location information on every feedback in terms of network overhead. Here, we note that CAM contains the location information of each CAM transmitter and CAM is a broadcast message, thus meaning that neighboring UEs are also receiving the CAM. In addition, from the perspective of fg-UE, it does not need to inform the location of fg-UE once fg-UE contains the feedback on top of its own CAM. As shown in Fig. 4.3, fg-UE transmits CAM RU index information for nf-UE found at the n round as feedback, included in CAM of the $(n+1)$ round. Then, any fr-UE, which successfully decodes three CAMs (nf-UE's CAM at the nth round, fg-UE's CAM at the nth round, and fg-UE's CAM at the $(n+1)$th round), can obtain the feedback of *new UE found event*.

However, in a distributed CAM resource selection, there might be a resource collision where two or more UEs located close to each other select the same CAM RU for their transmission. Then, unwanted situations may be reported in feedback. We share



(a) After resource collision



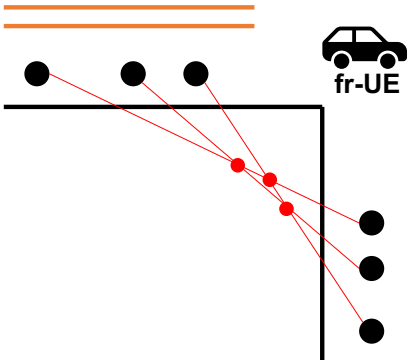
(b) On the same line

Figure 4.4: Common problems in reporting feedback

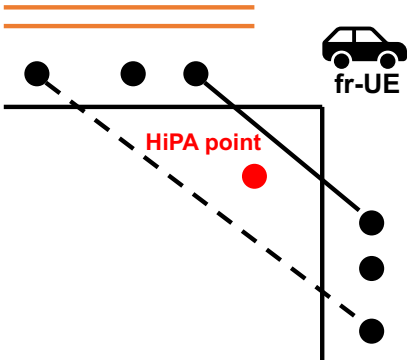
two misleading situations that are likely to occur as shown in Fig. 4.4. The first is that multiple fg-UEs (closely located to each other) find the same nf-UE in the same round and give feedback about the nf-UE at the same time as shown in Fig. 4.4(a). During having a resource collision with other UE, the existence of nf-UE cannot be found at fg-UEs. After resolving the resource collision, multiple UEs can suddenly find the nf-UE. When this situation occurs, it can be inferred that the longest distance of a pair (fg-UE 1 and nf-UE in Fig. 4.4(a)) is the closest to the criterion distance. Therefore, in this case, the report excluding the pair can be ignored. The second situation is that fg-UE reports that it has discovered nf-UE, and fg-UE and nf-UE are on the same straight line. In this case, the nf-UE and the fg-UE generally communicate well, but the performance becomes bad temporarily due to a resource collision. This case can be inferred by using the direction of vehicles, and it is judged that the feedback is not valid.

Fig. 4.5 shows an example of reported pairs (fg-UE and nf-UE) at a given fr-UE after removing reports of invalid feedback. Since the number of reported pairs is large, we propose a way to efficiently process this data and predict the actual performance of any pair. The proposed method is as follows. 1) Find the intersection points of the reported pairs as shown in Fig. 4.5(a). 2) We use the obtained intersection points to define a HiPA point, where we use the average of the intersections points as shown in Fig. 4.5(b). Then, we use this HiPA point to determine whether any pair is hidden or exposed. However, please note that the number of HiPA points can be changed according to the number of buildings (or any large obstacles). Fig. (c) shows that we find HiPA points through simulation, obtained by a single UE during 10 s, where the intersection of a road is surrounded by buildings. Thus, in this case, we confirm that the intersection points of reported pairs form four clusters according to buildings.

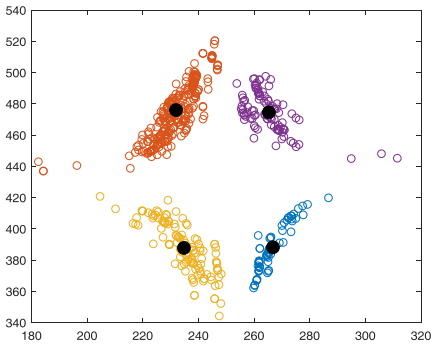
Obtaining a HiPA point at a given UE takes a few seconds when there are enough vehicles in the vicinity. In addition, when there are not many vehicles in the vicinity, the required time to get a HiPA point can increase or the accuracy of the HiPA point can



(a) Valid reported pairs



(b) Prediction of pair using a HiPA point



(c) HiPA points in simulations

Figure 4.5: Obtaining HiPA points.

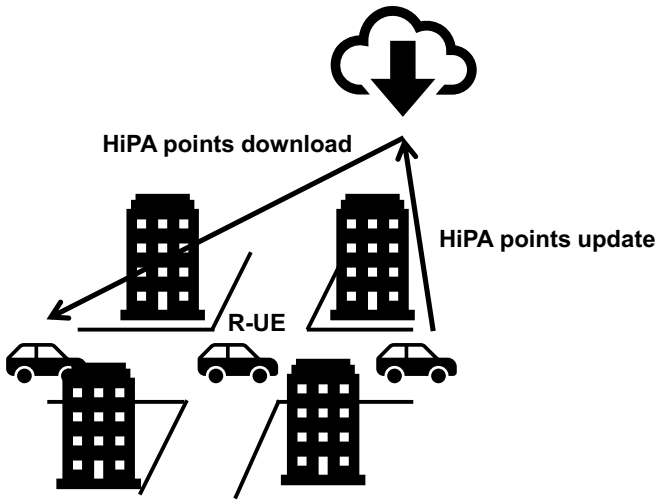
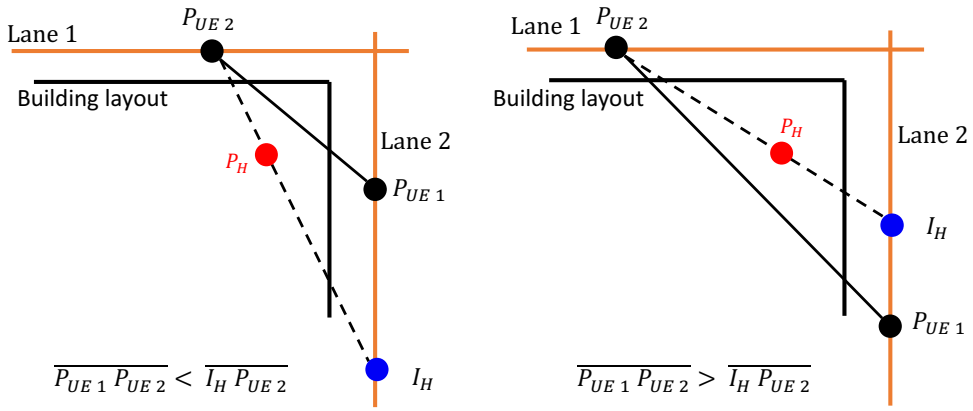


Figure 4.6: Crowdsourcing-based HiPA point management.

be low. When the mobility of a vehicle is high, there might be a change that the vehicle passes the proper relaying region before obtaining a HiPA point. For an efficient HiPA point management, we propose a crowdsourcing-based HiPA point management as shown in Fig. 4.6. Before passing through each intersection area, UE can download the HiPA point information of the corresponding area from the server. Based on the HiPA point information, the R-UE performs a relay operation and obtains a new HiPA point. Then, when leaving the intersection area, the R-UE uploads the newly obtained HiPA point to the server. Based on the newly uploaded HiPA information, the server can correct the HiPA point based on recent information.

The detailed procedure to determine whether a pair is hidden is as follows. If the following conditions are satisfied all, the pair is hidden, and if not, the pair is considered exposed. 1) First of all, the line segment connecting the positions of two UEs should have at least one intersection point with building layout as shown in Fig. 4.7. We assume that the building layout information can also be provided through the server. 2) Let us choose the nearest HiPA point (P_H) to the line segment ($\overline{P_{UE1}P_{UE2}}$) in the building. Also, let us find an intersection point (I_H) between the lane 2 (which UE 1



(a) Exposed pair (b) Hidden pair

Figure 4.7: Example of determining whether a pair is hidden or not.

belongs to) and the straight line connecting P_{UE2} and P_H. Then, the pair is hidden if $\overline{P_{UE1}P_{UE2}}$ ¿ $\overline{I_H P_{UE2}}$. According to the procedure, the pair in Fig. 4.7(a) is considered exposed and the pair in Fig. 4.7(b) is considered hidden.

R-UE also needs to transmit its CAM and receive CAMs from neighboring UEs. Therefore, if only a few R-UEs relay a large number of CAMs, R-UEs becomes vulnerable to a half-duplex problem due to an increased number of transmissions, thus R-UEs can not receive CAMs from neighboring UEs well. Therefore, we propose to select R-UEs as many as possible based on HiPA points. Fig. 4.8 is an example of four HiPA points (red points) obtained at an intersection where it is surrounded by buildings. Black points mean the edges of building. Without obtaining a HiPA point, we may consider selecting R-UEs based on the edges of the building as the simplest way. However, in this case, the vehicle with good communication performance with vehicles located on both the horizontal and vertical roads as shown in Fig. 4.8 cannot be selected as R-UE, thus the total number of R-UEs decreases accordingly. On the other hand, if we select R-UE based on HiPA points, the corresponding vehicle can be selected as R-UE as well. Therefore, we choose R-UE as the vehicle with good

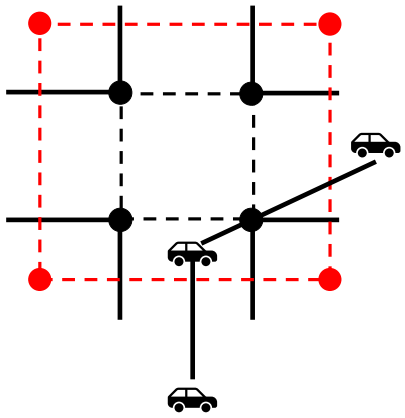


Figure 4.8: HiPA point based R-UE selection.

communication performance with vehicles located on both the horizontal and vertical roads based on the obtained HiPA points.

The detailed procedure to select an R-UE is as follows. First of all, considering that the two-dimensional space is divided by each lane, we consider only the HiPA points in the same space as the location of UE as shown in Fig. 4.9. For each HiPA point P_H, we can find an intersection point (I_H) between the lane (which UE belongs to) and the straight line connecting P_{UE} and P_H. Then, UE is considered to be R-UE if $\overline{P_{UE}I_H}$ ¡ $\overline{I_H P_H}$. For example, the location of the UE is tested to determine whether the UE is proper to be R-UE or not with respect to Lane 1 in Fig. 4.9. Since there are two HiPA points, there can be two intersection points as we explained above. In this case, the UE can be R-UE since the conditions are met. Please note that if there are multiple lanes, this procedure should be repeated as many as the number of lanes.

Since multiple R-UEs operates at the same time, there might be a chance that the same CAMs are relayed several times unnecessarily by R-UEs. Therefore, it is important for each R-UE to select CAMs to avoid such collisions. In this chapter, we consider a priority-based CAM selection algorithm as shown in Fig. 4.10. Each R-UE selects priority for its received CAMs and relays it in order from the CAM with

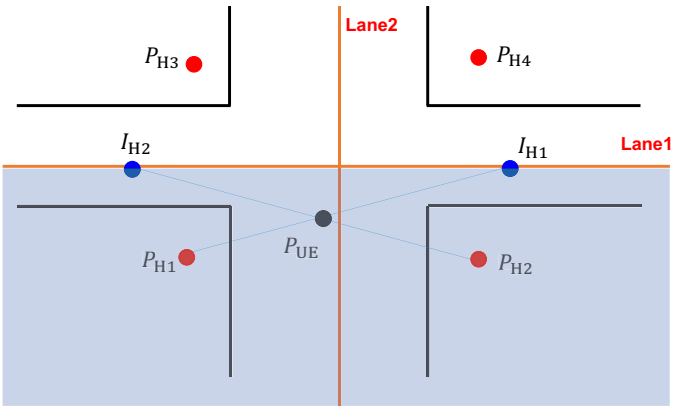


Figure 4.9: Example of determining R-UE.

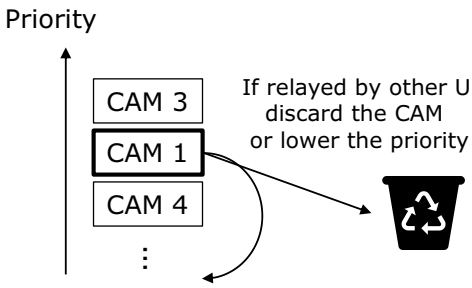


Figure 4.10: Example of CAM pool for relaying at a given R-UE.

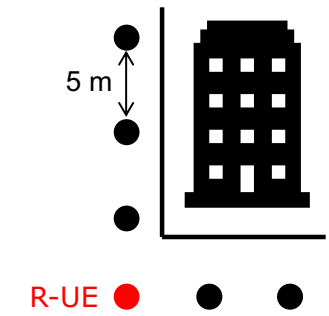
Table 4.1: Simulation environments.

Carrier frequency	5.9 GHz
System bandwidth	10 MHz (50 RBs)
Vehicle mobility model	SUMO [52]
Link performance model	ns-3 [53]
Channel model	Fast fading + shadowing + pathloss + in-band emission [54]
Tx power of UE	23 dBm
Noise figure	9 dB
Noise power	-174 dBm/Hz
CAM size	800 B
CAM generation period	100 ms
Simulation time	100,000 subframes (100 s)

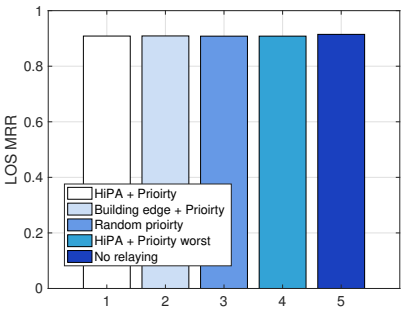
higher priority each time there is a transmission opportunity. The priority is designed to be influenced by two factors as follows. 1) To consider cooperative operation among other R-UEs, the priority should be decreases when a R-UE detects that one of CAMs in its own CAM pool is relayed by other R-UE. 2) Based on the received CAMs, the position of each CAM transmitter UE can be grasped. Based on the proposed HiPA point, it is possible to know whether or not each pair is hidden. In selecting CAM, it is desirable to relay the CAM of the terminal with the highest weight of the hidden pair first. Finally, the priority of CAM i can be formulated as follows.

$$P_i = \begin{cases} \frac{H_i}{2^{N_i}}, & \text{if } N_i < N_{th}, \\ 0, & \text{otherwise}, \end{cases} \tag{4.1}$$

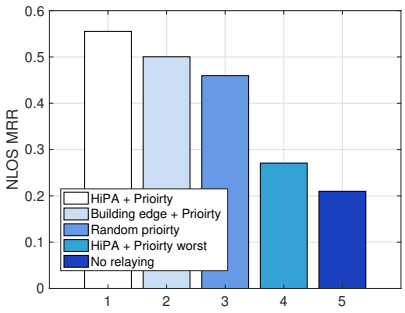
where H_i is the ratio of hidden pairs of CAM i in all pairs of CAM i within the target range and N_i is the number of retransmissions (transmitted by itself and by other UEs) of CAM i. Also, we set N_{th} to 4 in the simulations. When P_i becomes zero or lifetime of CAM i is over, CAM i is removed from the CAM pool.



(a) All cases



(b) LOS cases only



(c) NLOS cases only

Figure 4.11: MRR performance when target range is 150 m and # UEs = 250 and # RUs = 300.

4.4 Performance Evaluation

The overview of simulation environments is presented in Table 4.1. The detailed explanations for simulation environments are omitted since it is already explained in Chapter 2.

First, we confirm how efficiently the proposed priority-based CAM selection algorithm works. As shown in Fig. 4.11(a), R-UE is placed in the center and 125 UEs are arranged at intervals of 5 m to the north and 125 UEs are arranged at intervals of 5 m to the east. Here, we compare the proposed algorithm with other algorithms as follows.

- **Building edge + Priority**: When we can not obtain HiPA points as proposed in this chapter, we use the map information to run the algorithm assuming that the building edge is a HiPA point.
- **Random priority**: R-UE randomly selects and relays CAMs.
- **HiPA + Priority worst**: HiPA points are obtained by the proposed scheme, and the priority is set, but CAMs are relayed in the order of low priority.
- **No relaying**: R-UE does not relay CAMs.

Since the proposed scheme is designed to overcome NLOS channels by relaying, the LOS MRR performance is not enhanced as shown in Fig. 4.11(b). Even though R-UE uses additional resources for relaying, it can be seen that there is almost no difference in performance compared to 'No relaying' which does not use additional resources for relaying. However, from the viewpoint of NLOS MRR performance as shown in Fig. 4.11(c), it can be seen that the proposed scheme outperforms the scheme, 'No relaying' hugely. Compared with 'Building edge + Priority', the gain of the proposed method is about 10%. Even though 'Building edge + Priority' is not as efficient as the proposed scheme but it achieves gain over 'No relaying' because it selects the CAM by determining whether or not there is a building between the pair have. In addition, the performance of 'HiPA + Priority worst' is similar to that of 'No relaying', which means that the proposed CAM selection algorithm works well. Also the performance of 'Random priority' is halfway between the performances of 'HiPA + Priority' and 'HiPA + Priority worst'.

Next, we verify the performance of the proposed scheme in the Manhattan scenario using SUMO. Here, we compare the proposed algorithm with other algorithms as follows.

- **RA-eV2V**: By installing RSUs as introduced in Chapter 3, RSU is responsible for relaying CAMs.

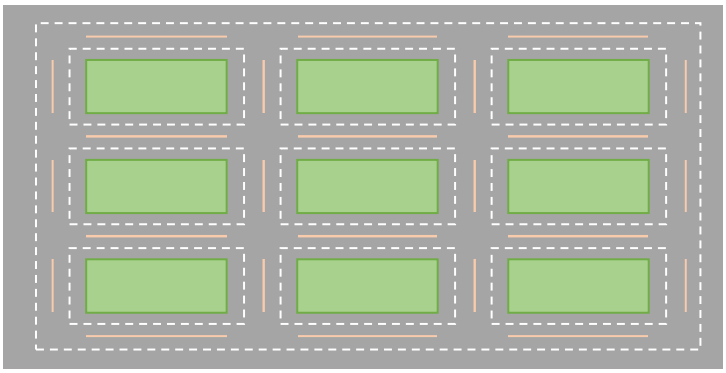
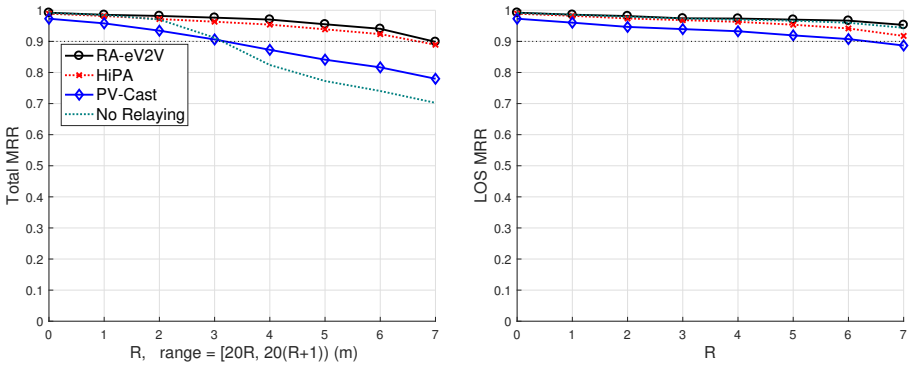


Figure 4.12: Simulation layout: Manhattan grid.

- **PV-Cast**: A relaying system based on 802.11p, proposed in [33], allocates the priority to occupy the resources considering the distance between the transmitter of a message and the R-UE in order to prevent redundant message relaying. However, it does not determine whether a particular message is experiencing an NLOS channel with surrounding receiving UEs or not.
- **No relaying**: CAM is not relayed by UE or RSU.

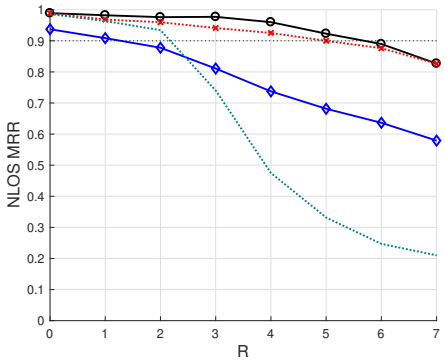
Fig. 4.13 shows the total MRR performance, LOS MRR performance and NLOS MRR performance, respectively. Since the target situation that we aim to overcome is a NLOS case, the performance gap is huge in cases of NLOS while the performance gap is marginal in LOS cases. As we can see in Fig. 4.13(c), the performance severely decreases as the distance between the transmitter and receiver increases in case of NLOS if we do not consider relaying. Even though 'PV-Cast' enhances the NLOS performance compared to 'No relaying', the performance is still quite lower than 'HiPA'. That is because 'PV-Cast' does not consider whether a particular message is experiencing an NLOS channel with surrounding receiving UEs or not as explained above. On the other hand, 'HiPA' achieves a huge gain over 'No relaying' and 'PV-Cast'. Also the performance is close to 'RA-eV2V', where RSU operates as relay.

Obtaining a HiPA point can be inaccurate due to various influences. Typical exam-



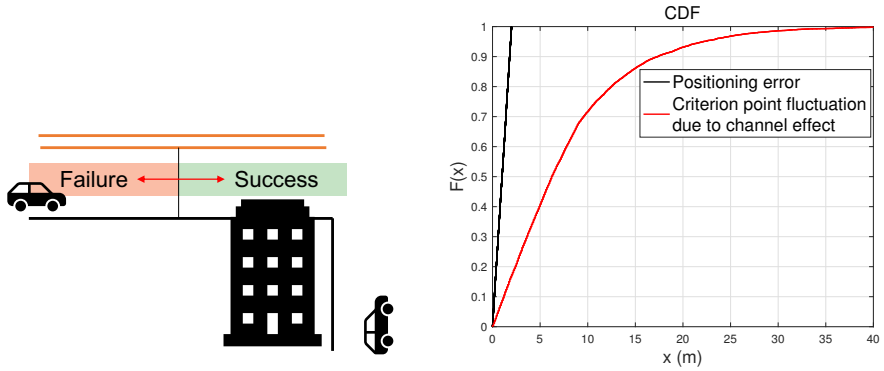
(a) All cases

(b) LOS cases only



(c) NLOS cases only

Figure 4.13: MRR performance in Manhattan Scenarios with # UEs = 250 and # RUs = 300.



(a) Criterion point fluctuation

(b) CDF result

Figure 4.14: Impact of positioning error and channel effect.

ples are positioning accuracy of a vehicle and various channel effects (fading, shadowing, etc.). The criterion point, estimated by a vehicle with such effects, can be changed compared to the point estimated without such effects as shown in Fig. 4.14(a). We call the difference a criterion point fluctuation in this chapter. In Fig. 4.14(b), the criterion point fluctuation due to positioning error and channel effects are shown separately. Since LTE-V2X chip sets require relatively high positioning accuracy, it is assumed that the maximum error is 2 m in our simulations. In fact, the criterion point fluctuation due to channel effects is more influential in our simulations. However, in our proposed scheme, UEs use many reports in feedback to obtain a HiPA point. We also consider methods to remove outlier points in the process of obtaining HiPA points. Also, since the HiPA point obtained by a UE is uploaded to the server, the server uses the average value of multiple HiPA points, so that it is confirmed that those effects are negligible.

4.5 Summary

In this chapter, we have proposed a way to predict the connectivity of a V2V pair. Connectivity is predicted on the basis of actual communication result, so it can reflect the

communication situation that can be changed according to the surrounding environment. It also manages data based on crowdsourcing for more efficient data collection. We propose a relaying UE selection scheme and a CAM selection algorithm for relaying UEs using HiPA. Simulation results show that the proposed method achieves high performance by efficiently relaying the CAM which is experiencing much NLOS situation than the existing method.

Chapter 5

Concluding Remarks

5.1 Research Contributions

In this dissertation, we have addressed the performance enhancement schemes in LTE-V2X.

In Chapter 2, we have proposed FAGA, an interference-aware resource change algorithm, which can be used with the current resource selection algorithm in 3GPP Release 14. By proposing an efficient feedback mechanism, UEs can be aware of the current status of their CAM RUs with low overhead. Through realistic simulations using SUMO and OSM, we verify that the proposed algorithm outperforms the conventional scheme and the proposed algorithm is more effective when the reception performance is vulnerable to interference.

In Chapter 3, we have proposed RA-eV2V, an RSU relaying scheme in LTE-V2X systems. In the proposed scheme, RSU reuses the resource of UEs while minimizing the potential problems to UEs. Since our proposed scheme does not require any modifications to a UE side, UE maintains the current standard-compliant operation in 3GPP Release 14. Through extensive simulations, we verify that our model uses resources more efficiently than when RSU relaying is not supported. In addition, the proposed scheme outperforms the conventional relaying schemes in terms of MRR performance.

In Chapter 4, we have proposed HiPA, a UE relaying scheme in LTE-V2X systems. We propose an inventive method to predict the connectivity of any V2V pair by utilizing HiPA. Then, we propose a cooperative relaying operation of UE and a priority-based CAM selection algorithm. Through realistic simulations, we demonstrate that the proposed scheme outperforms the conventional scheme and the proposed connectivity prediction has high accuracy.

5.2 Future Work

As future work, there are several research items as follows.

First, the distributed resource selection algorithm can be extended to consider various types of messages while the current algorithm considers only a single type of message, i.e., CAM.

Second, regarding relaying schemes, we need to study whether the underlying idea of the proposed relaying schemes can be applied to other types of vehicular networks (e.g., 802.11p).

Lastly, we need to consider more realistic situations such as the coexistence of heterogeneous vehicular networks (e.g., LTE-V2X and 802.11p) and study ways to deal with them.

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초 록

차량 통신은 지난 수십 년 동안 802.11p라고 불리는 Wi-Fi 기술 기반으로 연구되어 왔습니다. 그러나, 2017년 3GPP에서 발표한 LTE-V2X의 출현으로 새로운 시스템 기반의 차량 통신 기술 연구에 대한 필요성이 대두되었습니다. LTE-V2X는 비동기식으로 동작하는 802.11p와는 다르게 동기식으로 동작하므로 많은 기술적 차이가 있습니다. 또한, 차량 간 안전 관련 메시지의 교환은 매우 높은 수신 성능을 필요로 하는데, 이는 차량 통신이 상용화되기 위해 필수적으로 해결되어야 할 문제입니다.

본 논문에서는 방송 기반 주기적인 안전 메시지가 교환되는 LTE-V2X의 성능을 향상시키기 위해 다음과 같은 세 가지 전략을 고려합니다. (i) 효율적인 피드백 메커니즘을 이용하는 간섭 인식 자원 선택 알고리즘, (ii) UE의 3GPP 표준 동작을 준수하는 RSU 보조 중계 시스템, (iii) V2V 연결성 예측 기법 및 UE 중계 알고리즘.

먼저, 우리는 간섭 인식 자원 선택 알고리즘을 제시하였습니다. 이 방식은 종래 방식의 UE가 자신이 전송하는 자원의 상태 및 같은 시간에 전송되는 다른 주파수 자원의 상태를 알 수 없는 점을 개선합니다. 이 문제를 해결하기 위해 잘 효율적인 피드백 메커니즘을 제안합니다. 특히 피드백은 기존 주기적인 안전 메시지에 포함되어 전송되므로 피드백을 전송하기 위한 추가 리소스가 필요하지 않습니다. 피드백을 활용하여 제안된 알고리즘은 간섭이 있는 경우에만 이를 파악하여 자원을 변경하도록 제안되었기 때문에, 자원을 변경할 때 확률적인 방식을 취하는 기존 방식에 비해 효율적입니다. 우리는 제안된 방식이 기존 방식보다 MRR 성능이 우수함을 확인하였으며, 수신 성능이 간섭에 취약한 환경에서 더욱 효과적임을 밝혔습니다.

두 번째로, 우리는 UE의 자원이 RSU에 의해 재사용되는 LTE-V2X 시스템에서 RSU 중계 방식을 제안합니다. LTE-V2X의 분산 자원 선택 기법에서는 UE는 자원을 자주 변경하므로 감지 기반 자원 선택의 정확성이 낮아집니다. 우리는 RSU가 사용하는 자원이 UE들의 감지 기반 자원 선택에 미칠 수 있는 잠재적인 문제들을 최소화하는 기법을 제안하였습니다. 제안하는 방식에서 기존 UE의 동작의 변경을 요구하지 않기 때문에, UE는 3GPP Release 14의 표준 동작을 유지할 수 있습니다. 다양한 시뮬레이션을 통해 RSU 릴레이 기법이 릴레이가 지원되지 않는 경우보다 자원을 더 효율적으로 사용하는 것을 확인하였습니다. 또한 기존의 802.11p 기반 중계 방식보다 MRR 성능이 더 우수함을 확인하였습니다.

마지막으로, 우리는 UE들이 협동적으로 메시지를 릴레이해주는 LTE-V2X 시스템 기반 UE 릴레이 방식을 제안합니다. HiPA라고 불리는 제안된 방식에서, 피드백 메커니즘을 이용하여 V2V 쌍의 연결성을 예측하는 기법을 제안합니다. 또한, HiPA를 활용하여 릴레이 UE 결정 및 우선순위 기반 릴레이 메시지 결정 기법을 제안합니다. 현실적인 상황을 반영한 시뮬레이션을 통해 제안된 기법이 기존의 기법보다 성능이 우수함을 증명하였고, V2V 쌍의 연결성 예측이 높은 정확도를 갖는 것을 검증하였습니다.

요약하자면, 방송 기반 주기적인 안전 메시지가 교환되는 LTE-V2X 시스템에서 성능을 저하시킬 수 있는 두 가지 주요 문제를 해결하였습니다. 첫 번째로, 간섭을 인지할 수 있는 자원 선택 기법을 제안하여 자원 선택의 효율성을 개선하였습니다. 두 번째로, 차량 간의 NLOS 채널을 극복하는 두 가지 릴레이 방식을 제안하였습니다. 제안된 기법의 성능은 현실적인 차량 통신 시뮬레이션을 통해 검증되었습니다.

주요어: 차량 통신, LTE-V2X, 릴레이 기법, 링크 성능 예측 기법, RSU.

학번: 2014-30297

감사의 글

7년의 연구실 생활을 마무리 하며 지난 날을 돌아보니, 많은 기억이 떠오릅니다. 조마조마한 마음으로 최성현 교수님께 연구실 지원 메일을 작성하던 일, 석사 시절에 랩세미나, 코랩세미나, 팀미팅 등 처음으로 겪어보는 수 많은 발표에 힘들어하며 또 성장했던 경험, 박사 시절에 학회 논문을 작성해보고, 팀장이 되어 팀을 이끌었던 경험 등등 다양한 경험을 통해 성장할 수 있었던 귀중한 시간이었습니다. 학위과정 동안 많은 어려움과 좌절도 겪었지만, 그 때마다 도움과 격려를 주신 분들이 있었기에 학위과정을 마칠 수 있었습니다. 도움을 준 많은 분들께 짧지만 진심을 담아 감사의 글을 올리고자 합니다.

먼저, 부족한 저에게 끊임없는 관심과 가르침을 주신 최성현 교수님께 깊은 감사의 말씀을 올립니다. 항상 올바른 연구자, 지도자로서의 모습을 보여주시는 교수님께 학위과정 동안 많은 내용을 배우며 성장할 수 있어 영광이었습니다. 또한, 인간적으로 따뜻하여 늘 학생들의 생활과 복지에 관심을 가져주시는 모습에서 교수님의 사랑을 느낄 수 있었습니다. 앞으로도 교수님의 모습을 본받아 항상 노력하는 자세로 더욱 성장해 나가며 좋은 모습을 많이 보여드릴 수 있도록 하겠습니다.

학위 논문을 작성할 수 있게 도움을 주신 심사위원 분들께도 깊은 감사의 말씀을 드립니다. 찾아뵐 때마다 늘 온화한 미소로 반겨주시는 박세웅 교수님께 감사의 말씀을 올립니다. 교수님의 인자하고 배려심 깊은 행동을 보며, 인간적으로 더욱 성숙해질 수 있는 기회가 되었습니다. 바쁘신 와중에도 논문 지도를 해주신 심병효 교수님께도 감사의 말씀을 올립니다. 항상 위트가 넘치시며 긍정적인 분위기를 만드시는 교수님의 여유로운 모습을 보며 많은 것을 배웠습니다. 연구 내용에 큰 관심을 갖고 논문의 완성도를 올리는데 도움을 주신 김선우 교수님과 바쁘신 와중에도

논문 심사를 위해 멀리서 와주신 김재현 교수님께도 큰 감사의 말씀을 올립니다. 심사위원 분들의 깊은 통찰로 완성도 있는 논문을 작성할 수 있었습니다.

긴 시간동안 같이 생활한 연구실 선후배분들과 동기들에게 감사의 말씀을 드립니다. 비록 같이 생활은 하지 못하였지만, 후배들을 위해 연구실의 기반을 닦아주신 진성근, 김영수, 김성관, 최영규, 유정균, 한광훈, 장재혁, 김태현, 최기환, 나민수, 우승민, 여창연, 김서욱, 이종희, 로찬, 키란, 강두호, 최승현 선배들께 감사의 말씀을 전합니다. 또한, 연구실에서 같이 생활하며 많은 가르침을 주신 김동명, 최문한, 에드윈, 이혜원, 이원보, 이옥환, 홍종우, 유승민, 손위평, 신연철 선배에게 감사의 말씀을 드립니다. 먼저 사회로 나가 열심히 일하고 있는 곽규환, 김병진, 김현우, 조병갑, 알폰소, 박천우, 서지훈, 가순원 선후배에게도 감사의 말씀을 드립니다. 같은 시기에 입학하여 동고동락한 김성원, 구종회, 변성호에게 감사의 말씀을 전합니다. 늘 우수한 모습으로 주변 사람에게 많은 귀감이 된 동기들과 같이 생활할 수 있어서 참 다행이었습니다. 모두 각자의 자리에서 더욱 빛나는 사람이 될 수 있으면 좋겠습니다.

제가 졸업한 후에도 연구실 생활을 하며 노력하고 있을 서경주 누님, 윤강진 형, 이규진, 양창목, 김선도, 손영욱, 김지훈, 이재홍, 김준석 형, 윤호영, 최준영, 이기택, 곽철영, 황선욱, 이지환, 이강현, 허재원, 권휘재, 장민석, 김병준, 임수훈, 이경진에게도 감사의 말씀을 전합니다. 여러분과 함께 즐거운 연구실 생활을 하였기에 많은 추억을 만들 수 있었습니다. 또한, 이번에 같이 졸업하는 박태준, 이주헌에게도 감사와 축하의 말씀을 드립니다. 특히, V2X 팀에서 고생했던 윤호영, 김병준, 황선욱에게 다시 한 번 큰 감사의 말씀을 드립니다. 부족한 것이 많은 저를 잘 따라주었고 또한 많은 도움을 주었기 때문에 늘 큰 힘이 되었습니다. 택타일 팀의 김성원, 김선도, 김준석 형, 이기택, 임수훈에게도 다시 한번 큰 감사의 말씀을 드립니다. 연구실 구성원 모두 계획하고 있는 일이 잘 풀리길 바라며, 자주 연락하며 지내면 좋겠습니다.

학위과정동안 취미 생활을 공유하며 즐거운 추억을 만들어주신, 스누민턴, FC 몬유, PSZ, 나래울 배드민턴클럽 구성원께도 감사의 말씀을 드립니다. 연구 스트레스도 풀며, 건강을 유지할 수 있었기에 더욱 의미있던 시간들 이었습니다.

자주 연락하는 친구들 박기현, 김도윤, 장윤식, 유병준, 이정석에게도 특별히 감

사의 말을 전합니다. 각자 바쁜 와중에서도 늘 격려의 말을 해줘서 많은 위로를 받았습니다.

연락 드릴 때마다 늘 힘이 되는 말씀을 해주시는 이찬용, 현혜정 은사님께도 감사의 말씀을 올립니다. 벌써 졸업한지 15년이 지난 지금에도 늘 한결 같으시고, 아직도 저에게 많은 가르침을 주셔서 감사합니다.

부족한 사위를 믿고 기다려주신 장인어른, 장모님께도 큰 감사의 말씀을 올립니다. 항상 열정적으로 일하시는 장인어른을 보면서 많은 것을 배웁니다. 또한 인자한 모습으로 저를 대해주시는 장모님께도 늘 감사드립니다. 공부를 마치고 사회에 진출한 처남 성창우에게도 감사한 마음을 전합니다.

멀리서 늘 응원해주시는 고모, 큰아버지를 비롯한 친가 친척들과 큰외삼촌을 비롯한 외가 친척들에게도 감사의 말씀을 드립니다. 자주 연락하여 응원해주신 서현이 누나에게 다시 한 번 큰 감사의 말씀을 드립니다.

늘 사랑으로 저를 격려해주시고 기나긴 공부를 끝마칠 수 있게 도와주신 부모님께 큰 감사의 말씀을 올립니다. 성실하게 일하시는 아버지의 모습을 보며 근면하게 살아야겠다고 항상 다짐하며, 긍정적으로 주변에 밝은 분위기를 전해주시는 어머니의 모습을 보면서 그 모습을 닮아야겠다고 생각합니다. 또한, 친형에게도 감사의 말씀을 드립니다.

마지막으로 사랑하는 아내 성향기에게 감사의 말을 전합니다. 누구보다 이 과정의 어려움을 잘 이해하며 묵묵히 믿고 기다려준 아내가 있었기에 졸업을 할 수 있었습니다. 앞으로 좀 더 가정적인 남편이 되어 화목한 가정을 만들 것을 다짐합니다.

모든 분들께 다시 한 번 감사의 말씀을 올리며 글을 마칩니다.

2018 년 7월

박승일 올림