공학박사 학위논문

Performance Enhancement in LTE-based D2D Networks

LTE 기반 기기간 통신 성능 향상 연구

2016년 2월

서울대학교 대학원

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이 논문을 공학박사 학위논문으로 제출함

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2015년 12월

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Abstract

Performance Enhancement in LTE-based D2D Networks

Recently, Device-to-Device (D2D) communication has attracted much attention as an emerging solution to cope with heavy cellular traffic caused by the proliferation of mobile devices such as smartphones and tablet PCs along with the increased demands for high data rate services. D2D communication is a promising technique which is introduced to one of the technology in Fifth Generation (5G) mobile network. In this scenario, allowing User Equipments (UEs) to reuse cellular resources can boost up the network performance in terms of the system capacity. In addition, reduced number of hops and shorter communication distance via direct communication between proximity UEs implies reduced energy consumption and communication delay. Moreover, D2D communications can help offload cellular traffic and avoid congestion in cellular network.

This dissertation dealt with various aspects of problems under D2D network. For performance enhancement, various schemes and algorithms for D2D discovery and communication are proposed and evaluated via simulation.

First of all, we investigate the interference problem occurring during D2D discovery. Every D2D-UE (D-UE) chooses the discovery resource randomly. Therefore, if the same resource is selected by more than one D-UE, mutual interference by collision is inevitable. Moreover, the collided D-UEs can not recognize the collision event in

distributed D2D network. To reduce such mutual interference, interference mitigation technique is necessary. This study proposes two schemes to improve the discovery performance by alleviating the mutual interference. Since the proposed schemes are considered to operate in distributed manner, additional signaling or resources are not needed. In addition, performance evaluation of the proposed schemes and algorithm are conducted by incorporating in recent specification.

Secondly, this study proposes the D2D discovery and link setup protocol model working in an LTE network. In addition, propose discovery synchronization, beacon resource and energy efficient RRC_IDLE state discovery. These proposed model and discovery design in LTE-based is the first study in academia. Even though, the demand for D2D communication has increased, energy consumption is a growing concern as well. A device has to support both cellular and D2D communication, meaning that additional energy is required. Due to the energy concerns, we comparatively analyze the performance of the D2D discovery and link setup in RRC_CONNECTED and RRC_IDLE states. The performance analysis is conducted by utilizing the real measurement results with commercialized LTE smartphones.

Lastly, we design a spatial reuse scheme which is well-known as one of the advantages in proximity D2D communication. The spatial reuse scheme is allowed to reuse one resource by sharing multiple transmitters. However, sharing the spectrum is carefully allowed due to the generating interference mutually. Especially, when two (or more than) devices reuse in proximity. This study investigate the spatial reuse problem under D2D multicast transmission and solve it with distributed manner. Moreover, this study proposes novel resource reusing schemes by multiple transmitters to increase spectrum efficiency. The performance evaluation of the proposed schemes are conducted by incorporating in recent specification, thus the simulation results demonstrate that proposed schemes outperform the baseline scheme.

Keywords: Device-to-Device (D2D), D2D discovery, D2D communication, resource collision, interference, spatial reuse, LTE-A networks

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Chapter 1

Introduction

Recently, Device-to-Device (D2D) communication has attracted much attention as an emerging solution to cope with heavy cellular traffic caused by the proliferation of mobile devices such as smartphones and tablets along with the increased demands for high data rate services. From a technical perspective, using D2D communication in cellular network can offer several benefits.

First, allowing User Equipments (UEs) to reuse cellular resources can boost up the performance of the network in terms of the system capacity. Second, reduced number of hops and shorter distance via proximity communication implies reduced energy consumption and delay. Third, to increase spectrum efficiency, reusing a same resource between D2D UEs is also feasible. Fourth, D2D communication can help offload network traffic and avoid congestion in cellular networks.

In the past, direct D2D communications did not consider the help of external entities (e.g., Wi-Fi Direct, Bluetooth) [1, 2]. However, recently D2D communication via network-assistance has been considered and studied in many articles [3–6]. In general, the resource of D2D communication can reuse cellular uplink spectrum in underly or overlay mode [6–9].

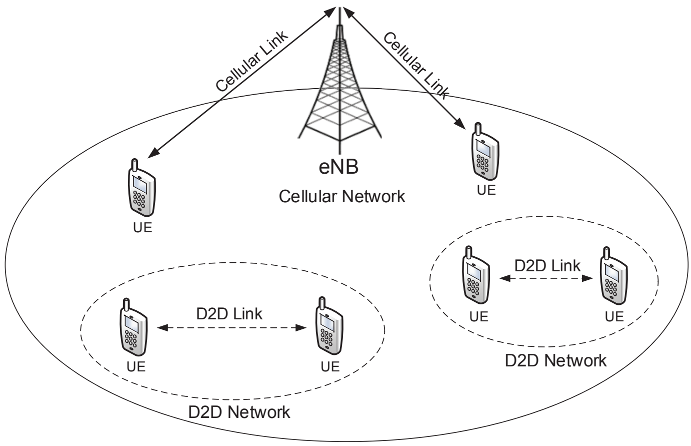

Figure 1.1: An example of D2D communication in LTE networks.

1.1 Device-to-Device (D2D) Network

1.1.1 D2D Discovery

D2D discovery is a procedure used to detect proximity devices or be detected by neighboring devices. In this phase, D2D-UEs (D-UEs) can discover the existence of other D-UEs. For the purpose, D-UEs have to exchange predefined signals, referred to as *beacons* in this work. Inside beacon, D-UEs can contain useful information, e.g., UE ID (identity), required service, and friends. Since the discovery procedure is performed under blind circumstance, essential information of the receiver (e.g., location, channel status, number of receivers) is unknown before the discovery phase. Therefore, transmitter D-UE will broadcast its own beacon signal to neighboring D-UE receivers.

D2D discovery is categorized into two types: centralized and distributed [10]. In the centralized scheme, optimal resource and transmission power are allocated by evolved Node B (eNB). However, this method considers higher signaling overhead and complexity for multiple transmitters to be coordinated. For this reason, this dissertation focuses on the distributed scheme which is considered a suitable under large and dense D2D networks. Moreover, due to the mobility of D-UEs, associated eNB will be changed continuously as well. Fig. 1.2 illustrates the concept of D2D network.

1.1.2 D2D Communication

Compared with the D2D discovery procedure, D2D communication is a procedure in which D-UEs can transmit (receive) required data over a direct link. For the D2D communication, D2D discovery phase is not prerequisite. Under D2D communication, a D-UE can establish multiple D2D links directly without infrastructure. This work defines a group which can be composed of multiple D-UE transmitters and receivers. The transmission type is group-based multicast transmission.

As a special scenario, if only one receiver belongs to only one group, the scenario becomes unicast transmission. Therefore, multicast transmission includes unicast transmission as well. The group formation is provisioned by network before D2D communication started or a D-UE can request and formate a group via network. This group provisioning is essential since prerequisite parameters for its own group formation will be configured to all of the group receivers (e.g., group ID, group IP multicast address, security content) [11].

In this dissertation, we limit our scope only to a synchronous communication. That is, all D-UEs are assumed to be in-coverage and time synchronization reference can be obtained from eNB.

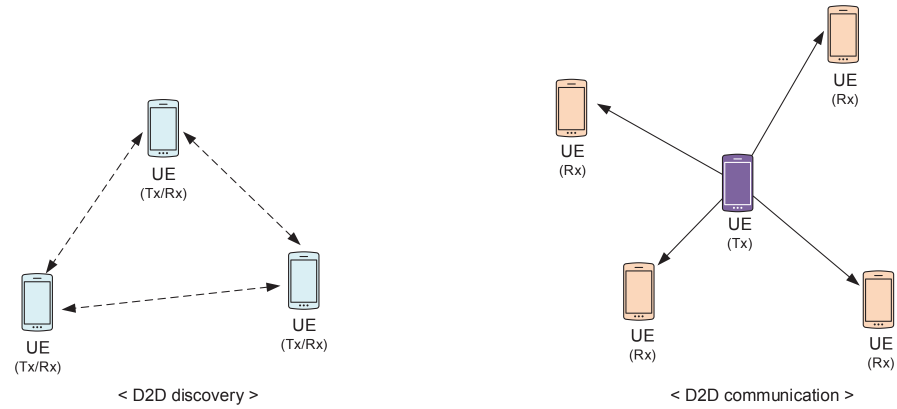

Figure 1.2: D2D discovery and communication.

1.2 Overview of Existing Approaches

1.2.1 LTE in 3GPP Standard

Long Term Evolution (LTE), commonly marketed as 4G, is a standard for wireless communication of high-speed data for mobile phones. The LTE standard has been proposed and standardized by the Third Generation Partnership Project (3GPP). LTE-Advanced (LTE-A) has opened the true fourth generation (4G) cellular technology era. The main goals of LTE are to support reduced latency, higher user data rate, improved system capacity, and increased spectral efficiency. The above mentioned potential benefits of the D2D communication has led the 3GPP community to start the standardization of D2D communication in LTE-A networks [12, 13].

1.2.2 D2D in 3GPP Standard

D2D discovery and communication have recently emerged as the state-of-the-art technologies exploited in future 5G technology [14]. Currently, LTE-A technology includes D2D discovery and communication under the name, Proximity Service (ProSe) in Release 12/13. Since an initial use case of release 12 of D2D communication has been considered public safety context only, transmission mode is mainly focused on multicast transmission. In the case of the D2D discovery, primary use case has been considered commercial advertisement. For that reason, D2D discovery is widely assumed not to be delay-sensitive.

The D2D discovery and communication in LTE networks are promising technologies that are expected to fulfill future service requirements or needs in various use cases and scenarios, e.g., public safety, content sharing, social networking, gaming, and advertising. Moreover, not only in coverage case, but also out-of-coverage case is considered for disaster environment. D2D technologies will be utilized in current LTE-A networks or 5G networks, while guaranteeing various future requirements [12, 15, 16].

As further issues, relay transmission, guarantee the QoS (Quality-of-Service), high data rate transmission, discovery in out-of coverage are considered [17].

1.2.3 Approaches for D2D Communication

Even with the above mentioned potential gains, the co-existence of multiple D-UEs reusing the same resource with cellular network is a challenging issue due to the difficulty of interference management. As the demand for D2D communication increases, the interference concern naturally grows. Therefore, interference management is essential to ensure successful D2D communication.

There has been growing interest about the D2D interference problem in cellular networks [18, 19]. Compared to legacy cellular system, D2D network has to control the transmission power due to the lack of controller. Therefore, proper power control schemes for D-UEs and (Cellular-UE) C-UEs are very important and have been studied in [20–22]. The resource allocation technique for D-UEs is also critical and various schemes have been addressed in [23–27]. Moreover, optimal power control with mode switching concurrently has been studied [28, 29].

1.2.4 Approaches for D2D Discovery

The main objective of D2D discovery is how to detect as many D-UEs as possible. For that reason, there has been increasing interest in investigating D2D discovery problem in D2D network. However, most recent researches have focused on the D2D communication issues assuming that discovery procedure has been done in advance. As a consequence, there have been only a few studies [30] investigating the D2D discovery problem.

The interference management for D2D discovery is dealt in [19]. The system simulation of D2D discovery is discussed in [31]. The research [32] has been firstly done to address discovery protocol and measurement-based modeling under LTE network. The collision resolution scheme for mitigating interference has been done in [33]. Moreover, efficient power control and collision resolution schemes and algorithms have been studied in [34].

1.2.5 Approaches for D2D Spatial Reuse

The objective of D2D spatial reuse is that a resource is shared by multiple transmitter D-UEs to increase the spectrum efficiency. Existing approaches [35–37] for spatial reuse are based on cellular or D2D unicast transmission. Therefore, one cellular resource allocated for C-UE is reused by other D2D links (i.e., transmitter D-UE and receiver D-UE) or vice versa. Therefore, for a spatial reuse access, maximum tolerable interference of the reusing D2D link can be estimated that the transmitter D-UE is allowed to reuse spatially. In addition, the concept of existing spatial reuse is for the cognitive technology, not recent D2D communication.

In [37], the authors propose distance-based spatial reuse scheme which is multiple

D2D pairs reuse the cellular resource. However, the reusing pairs are focused on the unicast transmission which is only focused on one receiver. However, in multicast transmission, there may coexist multiple receiver D-UEs where maximum tolerable interference can not be measured by selecting a D-UE. Therefore, the transmitter D-UE can not decide whether to reuse it or not. For a coordination, essential information (e.g., channel gain, interference level) of every D2D link can be exchanged with a central coordinator (e.g., eNB). However, such centralized method requires high signaling overhead and complexity for multiple D2D links to be coordinated. To the best of our knowledge, even though previous work has studied spatial reuse scheme in D2D scenario, none of them has considered in the context of D2D multicast transmission, which has been considered in recent 3GPP standard. In [38], the authors dealt with the concept of D2D multicast transmission. However, the problem is focused on how to share the cellular resources. Moreover, reusing one D2D group is considered, which is not practical in dense D2D network.

Even with the above mentioned potential gains, coexistence of multiple D-UEs reusing the same resource with cellular network is a challenging issue due to the difficulty of interference management and resource allocation. As the demand for D2D communication increases, the concern of interference and resource allocation naturally grows.

1.3 Main Contributions

1.3.1 Interference Mitigation

One of the serious challenges for D2D discovery in cellular networks is the interference between D-UEs. Therefore, we study the interference problem occurring during D2D discovery and propose two different schemes to improve the performance by alleviating this interference problem. Specifically, we propose a novel distributed power control scheme with an effective algorithm which aims to improve the performance of overall D2D discovery. In addition, we propose a novel distributed collision resolution scheme which can solve the D2D interference problem occurring during the discovery phase. These two proposed schemes do not require resource or signaling overhead. We evaluate the performance of the proposed schemes and algorithms by incorporating the assumptions in recent 3GPP ProSe technical documents.

1.3.2 Discovery Protocol Design

We have firstly proposed a novel D2D discovery and link setup protocol and procedure working in LTE-based networks. In addition, a beacon resource, synchronization method, and periodic D2D discovery are proposed as well. The power and delay consumption comparison for the proposed procedure is conducted as well. We have also analyzed the energy consumption of D2D discovery in RRC_IDLE and RRC_CONNECTED states, using an analytic evaluation. For the analysis, parameters are measured with commercialized smartphones. We prove that there is a trade-off relationship between energy consumption and delay. That is, the energy consumption of D2D discovery in RRC_IDLE state is smaller than that in RRC_CONNECTED (cDRX), but after the device is detected, the D2D link setup delay in RRC_IDLE state is longer than that in RRC_CONNECTED.

1.3.3 Spatial Reuse Operation

Spatial reuse is one of the techniques, which can enhance the spectrum efficiency. However, it is widely known impractical due to high signaling or resource overhead, especially, under D2D network. We design a novel spatial reuse access protocol and simple distributed scheme which aim to improve the D2D system performance. We approach a spatial reuse problem involving D2D multicast communication by exploiting proposed scheme and algorithm. We design simple and low complexity operation which can be utilized in LTE D2D networks. We evaluate the performance of the proposed scheme and algorithm by incorporating in recent 3GPP ProSe specification. We propose an effective spatial reuse scheme, while performing under D2D multicast transmission. Due to the drawback of centralized approach, this study focuses on the distributed operation which is considered a suitable strategy under large and dense D2D networks.

1.4 Organization of the Dissertation

The rest of the dissertation is organized as follows. In Chapter 2, we propose the interference problem occurring in D2D discovery operation. To reduce mutual interference by collisions, this study proposes two effective schemes to improve the performance by alleviating the interference.

Chapter 3 presents the D2D discovery protocol model and procedure working in LTE network. In addition, we propose an energy efficient RRC_IDLE state discovery. We then comparatively analyze the performance of the D2D discovery in RRC_IDLE state by utilizing the real measurement results with commercialized LTE smartphones.

Chapter 4 introduces spatial reuse problem as well as complexity and mutual interference issues. We propose a distributed spatial reuse scheme with low complexity. After that, we present the performance evaluation of the our proposed scheme.

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

Chapter 2

Interference Mitigation for D2D Discovery

2.1 Introduction

Long Term Evolution (LTE) standard, which has been proposed by the 3rd Generation Partnership Project (3GPP), has opened the true fourth generation (4G) cellular technology era. The main goals of LTE are to support reduced latency, higher user data rate, improved system capacity, and increased spectral efficiency. The above mentioned potential benefits of the D2D communication has led the 3GPP community to start the standardization of D2D communication in LTE-Advanced (LTE-A) networks.

LTE-A will include D2D under the name, Proximity Service (ProSe) in Release 12. The D2D communication in LTE networks is a promising technology that is expected to fulfill future service requirements or needs, e.g., public safety, social networking, and proximity-based advertising in various use cases and scenarios [12].

Even with the above mentioned potential gains, the co-existence of multiple D2D UEs reusing the same resource with cellular network is a challenging issue due to the difficulty of interference management. As the demand for D2D communication increases, the interference concern naturally grows. Therefore, interference management is essential to ensure successful D2D discovery. There is a growing interest in academia about D2D communication in cellular networks [18–20]. However, most of the recent research has focused on the D2D communication issues assuming that discovery procedure has been done in some way. As a consequence, there have been only a few studies [30, 32, 33] investigating the D2D discovery problem.

The main contributions of this chapter can be summarized as follows. We first introduce D2D link discovery as well as the definition of a new metric for D2D discovery. Second, we propose a novel distributed power control scheme for mitigating interference. Third, we evaluate the performance of the proposed algorithm conforming to 3GPP specification.

The rest of the chapter is organized as follows. We first introduce the background in Section 3.2, and present our system model in Section 2.3. Then, we describe the proposed power control scheme in Section 2.5, and evaluate the performance of our scheme in Section 4.7. Finally, the chapter concludes in Section 4.9.

2.2 Background

2.2.1 Resource Selection

In general, UEs may exploit both downlink and/or uplink cellular resource for communication. In this work, we assume that D2D-UE (D-UE) utilizes uplink resources because of several reasons as discussed in [39]. To guarantee the performance of the discovery, dedicated discovery period is introduced periodically (e.g., every 10 sec) with reserved resources (e.g., N_f $(= 44)$ Resource Blocks (RBs)[1] and N_t $(= 64)$ subframes in 10 MHz LTE system) [40, 41].

Therefore, a D-UE participating in discovery will select one discovery resource

[1] One RB consists of 12 subcarriers in the frequency domain.

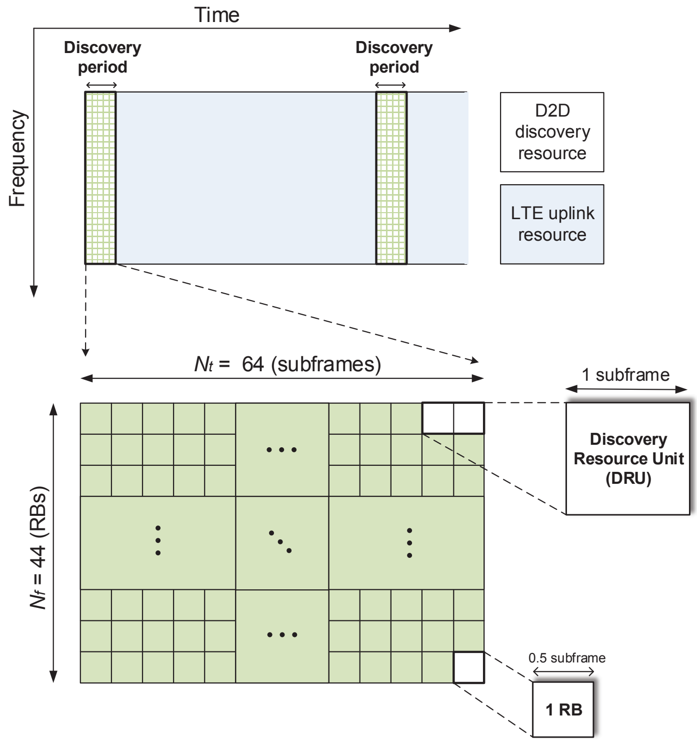

Figure 2.1: D2D discovery resources in LTE networks.

unit (DRU) among the periodic discovery resources, where a DRU consists of two RBs. An example of discovery period and DRU resource is presented in Fig. 2.1. The D-UE can transmit its discovery signal on its selected DRU one time and listen to discovery signals from other D-UEs during the rest of the discovery period. During the discovery phase, every D-UE participates only in the discovery process, while other types of communication (e.g., D2D or cellular) are not allowed. The UE conducting infrastructure-based communication is denoted by Cellular UE (C-UE) in this article.

D2D resource selection is also categorized into two types: sensing-based and random selection. In sensing-based selection, D-UEs select a DRU resource based on the sensing results of the available discovery resources. Every D-UE assesses all DRU's received energy level and selects the DRU which has the lowest energy level. Accordingly, multiple D-UEs located far away might choose the same resource. One the other hand, according to the random selection, each D-UE randomly selects a DRU resource for discovery signal transmission. This work focuses on a random selection for the following reasons.

The sensing-based selection is inefficient when the sensing results are outdated quickly, such as under high UE mobility scenario. Furthermore, the sensing results of D-UEs in proximity may be similar, and hence, these results might lead to a collision in the resource usage. For these reasons, most vendors participating in 3GPP propose a simple random selection scheme as a distributed resource selection method in recent 3GPP standardization [40, 42, 43].

2.2.2 Resource Collision

Since the resource is randomly selected by each D-UE, it has to be chosen carefully. When more than one D-UE reuse the same resource in proximity, a collision may occur due to the simultaneous transmission. Moreover, since there is no centralized coordination or signaling during the discovery procedure, those involved with collision event cannot be recognized by D-UEs.

Therefore, these neighboring D-UEs can neither detect each other nor be detected because of the mutual interference. Moreover, different from cellular network, there coexist multiple receivers (D-UEs) under D2D network topology which are potentially exposed to suffer high interference. Due to the interference, the performance of D2D discovery will be severely degraded.

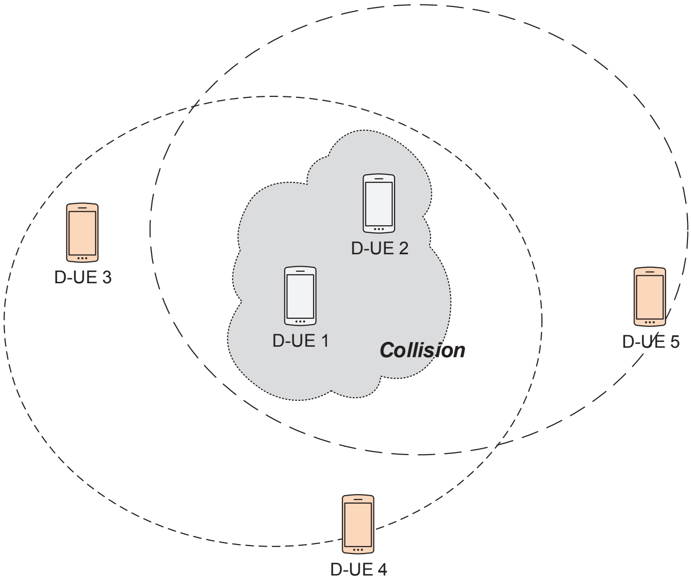

Figure 2.2: The collision.

2.2.3 Motivation

Despite the advantages of the distributed scheme, the following challenges might arise due to the lack of a central controller (i.e., eNB): interference management, resource allocation, and collision resolution. The collision will happen easily due to random selection. Moreover, RRC (Radio Resource Control) idle state which is no connection can participate D2D discovery. The scenario of D2D discovery is assumed to be exploited in high-density environments which a D-UE can collide easily. As seen in Fig. 2.2, when two D-UEs (D-UE1 and D-UE2) occur a collision. Both D-UEs can not recognize the collision and generate interference to proximity D-UEs (D-UE3, D-UE4 and D-UE5) as well.

In order to achieve enhanced discovery performance, mutual interference caused by collisions should be reduced or avoided. In this regard, there are two main approaches for mitigating interference between D-UEs, namely, power control and collision resolution scheme.

In general, power control is a useful solution in energy saving and interference reduction. The main focus of the power control is to mitigate D2D interference, not to reduce energy consumption in this article. The received interference can be efficiently reduced by transmitter power control. On the other hand, collision resolution scheme for avoiding interference is another approach. To avoid collision, the resource which is being reused by multiple proximity D-UEs has to be changed. Note that the motivation of this study is to mitigate interference between D-UEs with power control and collision detection scheme in a distributed system to improve the overall performance of the D2D discovery as well.

2.3 System Model

2.3.1 D2D System

In this section, we give a brief introduction to the system model of D2D discovery. In our study, we limit our scope to synchronous D2D discovery, i.e., all D-UEs are in-coverage and time synchronization reference can be obtained from the eNB downlink transmission. This obviously consumes much less energy and discovery time compared with asynchronous discovery. For the synchronous discovery, every D-UE can be active during predefined discovery time, which appear periodically, i.e., D-UE wakes up periodically to perform discovery procedure (e.g., beacon transmission and reception) using the DRU. After finishing the periodic discovery, D-UEs begin sleeping until the next discovery period. When a D-UE has discovered a desired target D-UE by receiving a beacon, it can establish a D2D link for direct communication.

In a cellular network topology, the receiver of C-UEs' transmission is always an eNB. Accordingly, if multiple C-UEs belonging to different cells reuse a common resource in cell edge, a C-UE's signal interferes with a neighboring eNB. On the other hand, in D2D networks, there coexist multiple D-UEs which can be both transmitter and receiver. Under this topology, emitted signals from different transmitting D-UEs will arrive at proximity receiving D-UEs. Note that multiple receivers are potentially exposed to suffer high interference by multiple D2D links. Assuming the number of K D-UEs in D2D networks, the maximum number of D2D links is $K^2 - K$, which has a polynomial growth rate.

2.3.2 Criteria of Discovery Success

For the D2D discovery, a D-UE has to choose a DRU. Then, the D-UE can transmit and receive predefined signals, referred to as *beacons*. Only one beacon will be transmitted by each D-UE during the discovery period. By receiving beacons periodically, a D-UE maintains a list of neighboring D-UEs in order to establish direct communication link when it is needed after discovery process.

The minimum unit of a beacon consist of two RBs, which carry 168 (with normal cyclic prefix) OFDM Resource Elements (REs) [44]. Within the beacon, each D-UE can convey such information as its own identity, requesting service, and interest.

Since D-UE k can be either transmitter or receiver at a given time, a D-UE is denoted by t (r) when transmitting (receiving), where $t, r \in \{1, ..., K\}$. For the successful decoding of a beacon, the signal-to-interference-plus-noise ratio (SINR) of the received beacon signal should be above a certain level. The SINR of beacon b from D-UE t at D-UE r is given by

$$\gamma_r^{(b)} = \frac{P_t h_{t,r}}{\sum_{j \neq t} P_j h_{j,r} + \sigma^2}. \tag{2.1}$$

where P_t is the transmission power of D-UE t and $h_{t,r}$ denotes the channel gain between transmitter D-UE t and receiver D-UE r. The cumulative received interference from the other D-UEs is defined as $\sum_{j \neq t}^{J} P_j h_{j,r}$ and the power of Additive White Gaussian Noise (AWGN) is denoted by σ^2.

A device is assumed to be successfully discovered only if the SINR of a received beacon signal exceeds decoding threshold γ_{thd}. We define $\delta_b \in \{0, 1\}$ as a detection indicator of beacon $b \in \{1, ..., B\}$. That is, $\delta_b = 1$ if beacon b is successfully detected, and $\delta_b = 0$, otherwise. Therefore,

$$\delta_b = \begin{cases} 0, & \gamma_r^{(b)} < \gamma_{thd} \,, \\ 1, & \gamma_r^{(b)} \geq \gamma_{thd} \,. \end{cases} \tag{2.2}$$

In order for D-UE t to be successfully discovered by D-UE r, the transmission power of D-UE t should satisfy

$$P_t \geq \gamma_{thd} \left(\sum\nolimits_{j \neq t} \frac{P_j h_{j,r}}{h_{t,r}} + \frac{\sigma^2}{h_{t,r}} \right). \tag{2.3}$$

2.4 Problem Formulation

The objective of conventional communication has been to achieve the maximum link capacity between transmitter and receiver, assuming a communication link is already established. Different from the previous approach, the aim of discovery may not be related to transmission rate or link throughput since a target link is not established. Therefore, the objective of D-UEs should be how to detect and to be detected by as many devices as possible during the discovery period.

To deal with this problem, we propose a new metric, called *discovery success ratio* $S_k \in [0, 1]$, which is defined as the ratio of discovered D-UEs to the total number of D-UEs participating (except itself) in discovery.

The discovery success ratio of D-UE k is given by

$$S_k = \left\{ \frac{1}{K-1} \sum\nolimits_{b=1, b \neq k}^{K} \delta_b \right\}. \tag{2.4}$$

The higher this ratio is, the more D-UEs have been discovered during the discovery period. To maximize the D2D discovery success ratio, each D-UE has to select its proper transmit power considering mutual interference, and select beacon resource without collision.

However, due to an initial step, most essential information for discovery is unknown (e.g., distance of transmitter and receiver, channel gain, number of receivers and reusing resource). Moreover, since more than one proximity receiver may coexist, the optimal power level of transmitter cannot be determined for a specific receiver.

Therefore, considering such constraints, the primary goal of D2D discovery is to achieve the maximum discovery success ratio during the discovery period, denoted by t_d.

The objective of D2D discovery problem can be formulated as follows:

$$\max \sum_{t_d=1}^{\infty} \sum_{k=1}^{K} S_k \tag{2.5}$$

subject to

$$0 < P_t^{(b)} \leq P_{\max}. \tag{2.6}$$

2.5 Power Control Scheme

2.5.1 Power Control Performance

Different from cellular transmission between C-UE and eNB, D2D discovery transmission is broadcast. Due to the broadcast topology, a transmitter D-UE will periodically send the beacon to every neighboring D-UEs. Under this scenario, transmitted signal might be a desired signal for some D-UEs, while it might be undesirable interference to other D-UEs due to the collision. By adopting power control scheme, the transmitted interference among D-UEs can be reduced.

For the purpose of the verification of power control operation, we consider two simulation scenarios as shown in Fig. 2.3 and Fig. 2.4. This article conducts the following simulation as an example. We assume that there are two D-UEs which reuse discovery resource in a cell center region. The distance between two D-UEs is 200 m (which are marked by red dots) and beacon detection threshold is set to 4.5 dB [45]. 10,000 D-UEs are placed uniformly within a cell (radius = 1000 m). The path loss exponent is assumed to be 4 in this simulation.

In Scenario 1, the two D-UEs transmit with the same maximum power (23 dBm). In Scenario 2, the two D-UEs transmit the maximum and one-third of the maximum (18 dBm) alternately. That is, D-UE1 transmits with 23 dBm and D-UE2 transmits with 18 dBm at the first discovery period, then D-UE1 transmits with 18 dBm and D-UE2 transmits with 23 dBm in the next discovery period to alternate over time.

As shown in Fig. 2.3, if the two D-UEs transmit with the same maximum power, the region which is able to receive beacons (which are marked by dark blue dots) is limited due to proximal strong interference. In contrast, as illustrated in Fig. 2.4, with power control, the number of discoverable D-UEs can be greatly increased and the possible range of beacon detection can be immensely extended as well.

2.5.2 Proposed Power Control Algorithm

In this section, we propose a novel power control algorithm which is described in Algorithm 1. Firstly, the D-UEs transmit and receive beacons during the D2D discovery period with maximum power. Then, all D-UEs measure $\psi_k^{(b)}$, which represents

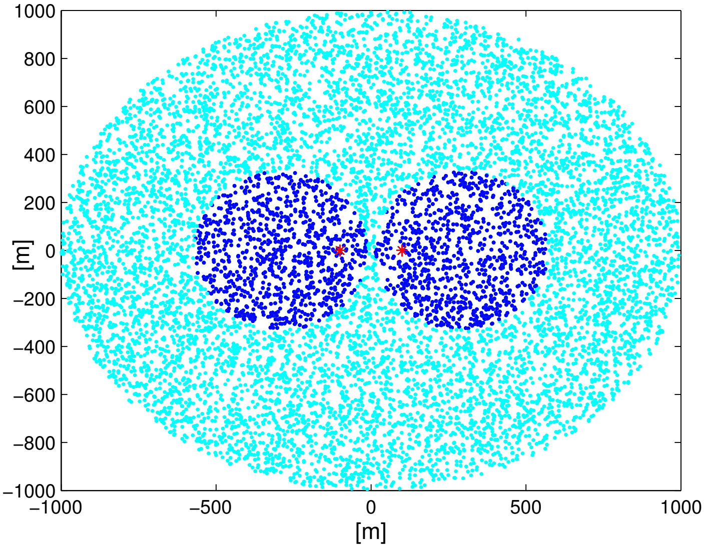

Figure 2.3: Performance of maximum power transmission.

the Received-Signal-Strength-Indicator (RSSI) of proximal beacons. Since the measurement of RSSI can be simply conducted in parallel with receiving beacons from neighboring D-UEs as part of the usual D2D discovery procedure, this measurement does not consume additional resources or processing overhead. Then, every D-UE figures out the sum of RSSI values with received multiple beacons. In the distributed scheme, as mentioned above, the D-UEs may not recognize whether a mutual collision has occurred or not.

Therefore, without distinguishing the D-UEs which involved in collision, we need to approach a probabilistic method that a relationship can be defined between the sum of high RSSI energy level and D-UE collision probability. Intuitively, we can assume that the sum of high energy level can be regarded as high probability of collision occurrence because it indicates that the number of proximal D-UEs may be large. Specifically, when the discovery resources are predefined as a system configuration,

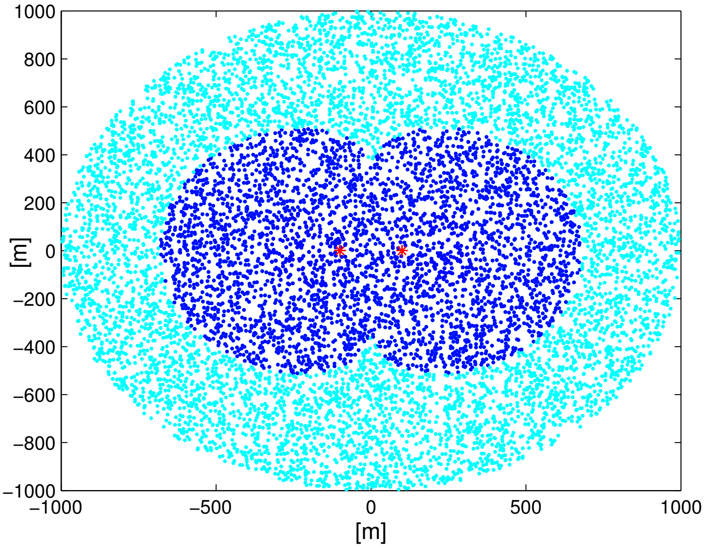

Figure 2.4: Performance of power control transmission.

the collision probability depends only on the number of D-UEs participating in D2D discovery procedure.

By checking E^* which is defined as the aggregation of received beacons. If E^* of D-UE is higher than E_{thd}, which is a predefined energy threshold, the D-UE will follow the proposed power control scheme. For the proposed scheme, we define α as a random variable coefficient, where $\alpha \in [0, 1]$. The D-UE multiplies the maximum power level by α, when the power control works. If E^* of D-UE is lower than E_{thd}, the D-UE transmits with the maximum power because of low density in the vicinity of D-UEs. To determine a proper E_{thd}, infrastructure can help in D2D networks. Note that the eNB can also receive multiple beacons during the reserved D2D discovery period. Therefore, infrastructure can decide variable E_{thd} according to the density and topology of D-UEs and it can be periodically broadcast through the system information.

Algorithm 1 Distributed Power Control Algorithm

for all t_d **do**
  for all $k \in K$ **do**
    if $t_d = 1$ **then**
      $P_t^{(b)} \leftarrow P_{\text{max}}$
    end if
    $E^* \leftarrow \sum_{b=1}^{\mathbf{B}} \psi_k^{(b)}$
    if $E^* > E_{\text{thd}}$ **then**
      $P_t^{(b)} \leftarrow \alpha P_{\max}\ \alpha \in [0, 1]$
    else
      $P_t^{(b)} \leftarrow P_{\text{max}}$
    end if
  end for
end for

2.6 Collision Resolution Scheme

2.6.1 Beacon Design

For the collision resolution, collision detection and notification should be conducted in a way. Under a distributed D2D networks, due to the absence of a central controller, such operation can be performed by neighboring D-UEs. The proposed collision detection scheme will be explained in Section 2.6.2. For the collision notification, a new approach without any signaling or resource overhead will be required. We propose a novel beacon design which aims at notifying the index of colliding beacon. As mentioned in the previous section, a beacon consists of two RBs, where each beacon carries 168 OFDM REs (12 subcarriers $\times$ 14 symbols, normal cyclic prefix). Therefore, within one beacon, up to 168 bits can be conveyed using QPSK modulation and 1/2-rate code.

As shown in Fig. 2.5, one OFDM symbol (12 bits) is dedicated (in blue color)

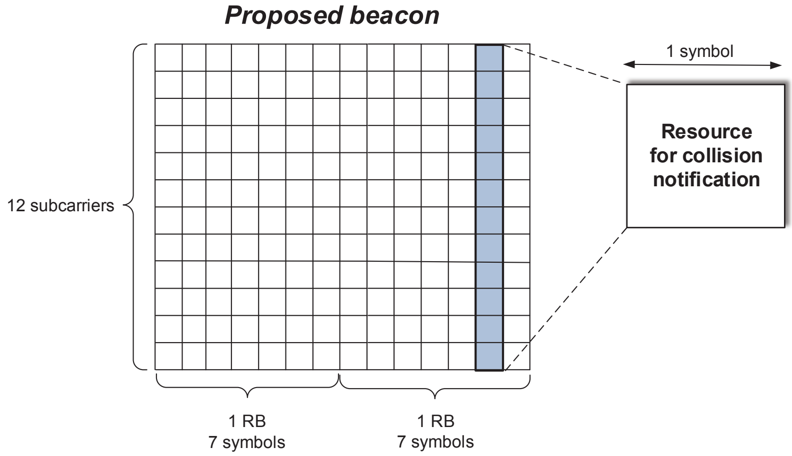

Figure 2.5: Proposed beacon design.

for the purpose of collision notification. With 12 bits, 4096 (2^{12}) beacons can be expressed, and hence, 2816 discovery resources (44 RBs $\times$ 64 subframes = 2816) can be handled.

2.6.2 Collision Resolution Scheme

For collision resolution, the occurrence of a collision will be determined by neighboring D-UEs based on the received signal and interference. The signal strength of D-UE can be measured by RSSI value of a received beacon, thus the interference level can also be estimated by received SINR value of the beacon.

The main idea is that if the RSSI value of the received beacon is high, whereas its SINR is low, this can be regarded as the occurrence of a collision in proximity. The procedure of the proposed approach is illustrated in Fig. 2.6. First of all, assuming that D-UE2 and D-UE3 reuse the same beacon in proximity, where they are not aware of the collision event. Under this scenario, D-UE1 receives high RSSI from nearby D-UE2, while D-UE3 is generating strong interference signal to neighboring D-UE1.

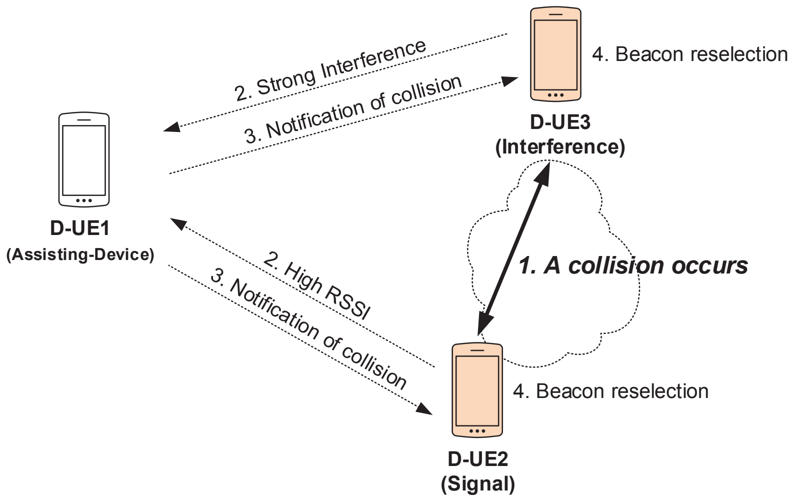

Figure 2.6: Collision resolution scheme.

Therefore, D-UE1 (assisting device) can detect a beacon collision by measuring RSSI and SINR values with thresholds -85 dBm and -1 dB, respectively. In our work, assisting D-UE informs proximity D-UEs of their collisions. To determine whether other D-UEs are located in the proximity or not, D-UE utilizes RSSI. We set RSSI threshold as -85 dBm, which corresponds to about 100 m with path-loss exponent of 4 and transmit power of 23 dBm. In other words, assisting D-UE regards D-UEs, which are located within 100 m from itself, as proximity D-UEs. In addition, we set an SINR threshold to be below zero (e.g., -1 dB). If SINR value is negative, aggregated interference plus noise is larger than desired signal, which means there might be a collision event.

Since all D-UEs transmit or receive beacons periodically, every D-UE can estimate RSSI and SINR level of beacons. Therefore, any D-UE can operate as an assisting device when a collision is detected. When the collision is detected, the index of colliding beacon can be notified using the proposed beacon format. After the reception of the

Table 2.1: System parameters

Parameter	Values
Cell layout	7 cell-site (21 cells)
Inter Site Distance (ISD)	500 m (cell radius = 167 m)
Number of UEs	100 UEs per cell
UE dropping	Uniform distribution
UE mobility	3 km/h (pedestrian)
System bandwidth	10 MHz (N_f = 44)
Number of subframes	64 ms (N_t = 64)
Carrier frequency	2 GHz
Maximum power of UE	23 dBm
Beacon threshold	4.5 dB
Beacon threshold for CR	6 dB
Path Loss exponent	4
Noise power per RB	-121.44 dBm
Channel model	Path loss+Shadowing+Multipath
Shadowing	Log normal with 7 dB std
Modulation for beacon	QPSK and 1/2 code rate

notification, the index of transmitted beacons by D-UE2 and D-UE3 will be randomly changed in the next discovery period for the collision resolution. This study assumes that no priority will be given to the resources since beacon status (e.g., frequency selectivity, channel gain, and interference) is unknown during the discovery phase.

2.7 Performance Evaluation

In this section, we present the performance evaluation of our proposed schemes. We have implemented a system level simulator using MATLAB in accordance with the LTE system simulation. The main parameters are summarized in Table 2.1. In this work, we compare our proposed Power Control (PC) and Contention Resolution (CR) schemes with a baseline scheme. In the baseline scheme, all D-UEs use the same transmission power (23 dBm [40]) and do not report any collision to their proximity

D-UEs. The iteration of discovery period is set to 40 that is also represented as one of the simulation assumptions [40].

Since the received interference highly depends on the D-UE density or location, we assume that the locations of D-UEs are modelled by a Poisson Point Process (PPP) model. With such a process, the D-UEs are independently and uniformly distributed in a two dimensional space. We also assume that the D-UEs move within the deployed area according to a pedestrian mobility model, where the direction of a D-UE is randomly determined between $[0, 2\pi]$.

Fig. 2.7 shows the average discovery success ratio according to the number of discovery periods. The proposed schemes outperform the baseline scheme by mitigating D2D interference. Compared with PC scheme, CR scheme achieves better performance since the collision resolution with maximum power transmission can be more effective than PC scheme. When a D-UE reduces transmission power under PC operation, both interference and desired signal for proximity D-UEs will be reduced. Note that the CR scheme requires higher SINR decoding threshold of beacon detection. Since one symbol is allocated for colliding beacon notification, the proposed beacon consists of fewer symbols. For that reason, the beacon with CR scheme has to use higher-order modulation and code rate compared with other schemes.

The delay of average discovery success ratio is shown in Fig. 2.8. We present initial 5 discovery periods for clear observation of the performance cross-point. By controlling transmission power and selecting beacons, the proposed schemes take some delay to satisfy the average of success ratio in early stage. However, after two discovery periods in the case of CR and four discovery periods in the case of PC are passed respectively, the proposed schemes outperform the baseline scheme due to the power control and contention resolution gains.

Fig. 2.9 shows that a Cumulative Density Function (CDF) of discovery success ratio, and we observe that the proposed schemes outperform the baseline scheme. The mutual D2D interference will be reduced by PC scheme. In addition, the interference by collisions will be resolved by the proposed CR scheme. These results prove that our proposed schemes achieve to detect and be detected by larger number of D-UEs than baseline scheme does, thus improving overall D2D system performance.

The CDF of the maximum distance of detected D-UEs is presented in Fig. 2.10. We observe that the proposed schemes outperform the baseline scheme by detecting farther D-UEs. As presented in Fig. 2.10, PC achieves higher gain than CR, regarding the average distance between the discovered D-UEs. Although the D-UEs change beacons in the CR scheme, due to the maximum power transmission, the interference will affect multiple receivers under D2D networks. In contrast, the D-UEs control the transmission power, the reachable interference range will dynamically change according to the power level. Therefore, when the D-UE reduces the power, the detectable region by other proximity D-UEs will be greatly extended.

2.8 Summary

In this chapter, we propose novel distributed power control and contention resolution schemes for D2D discovery. We have investigated the performance of the proposed schemes compared with the baseline scheme. The simulation results demonstrate that the discovery success ratio is remarkably improved such that the average distance of detected devices is increased as well. The CR scheme can simply overcome the D2D interference by collisions without a signaling or resource overhead, while the PC scheme can mitigate D2D interference by transmitter power control method. Moreover, the results reveal that there is a trade-off relationship between gain and delay. We conclude that the proposed schemes can be exploited for various D2D discovery sce-

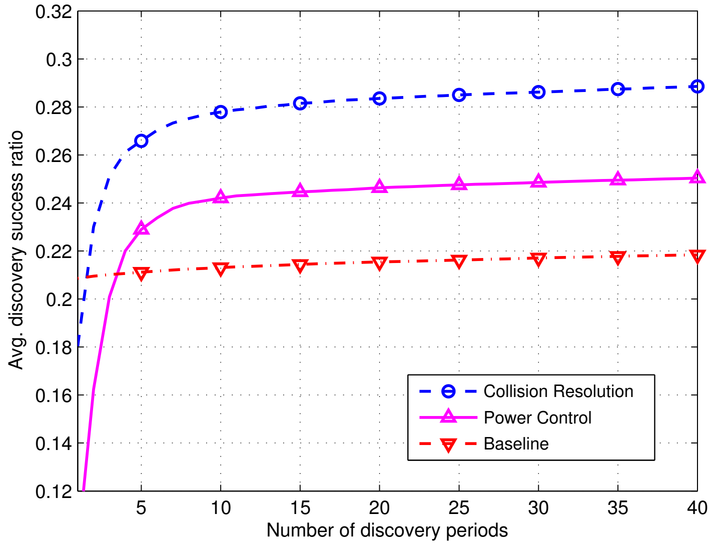

Figure 2.7: Average discovery success ratio.

narios and applications in future LTE-A/5G networks, while guaranteeing the different delay requirements.

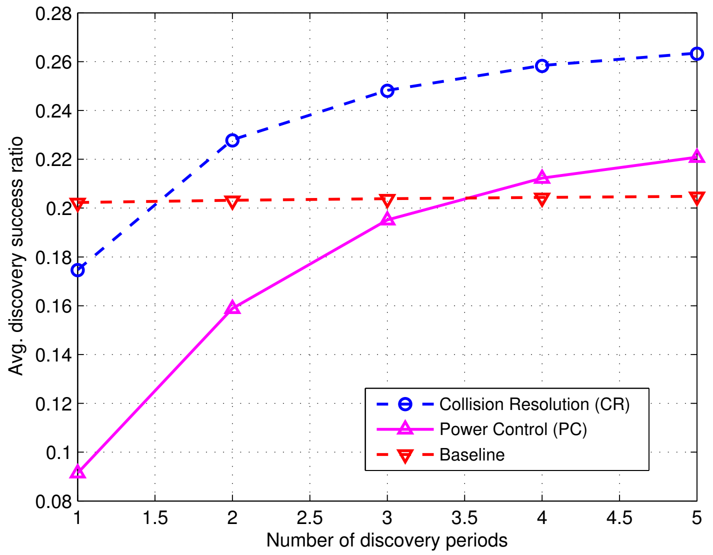

Figure 2.8: Delay of average discovery success ratio.

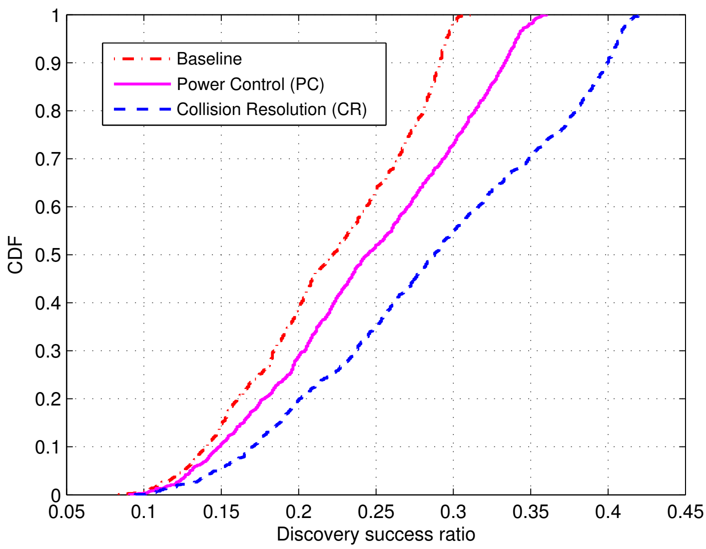

Figure 2.9: CDF of discovery success ratio of D-UEs.

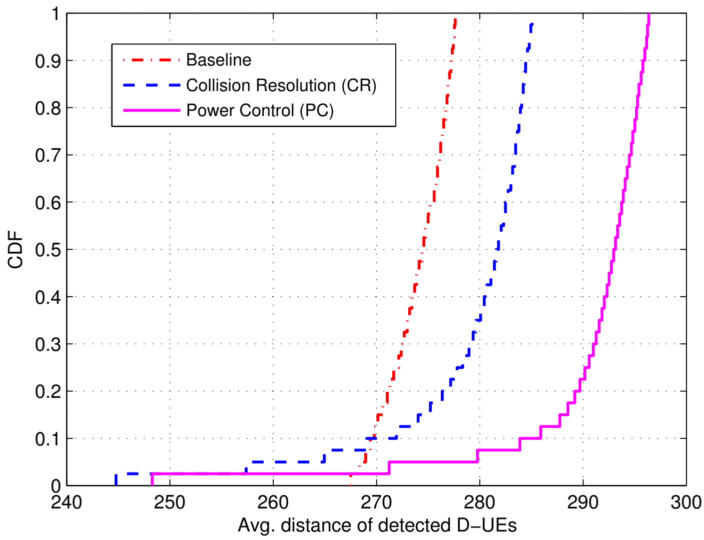

Figure 2.10: CDF of average distance of discovered D-UEs.

Chapter 3

Protocol Design for D2D Discovery

3.1 Introduction

Long Term Evolution (LTE) technology brings cellular communication to the fourth generation (4G) era. LTE standard specification has been proposed by the 3rd Generation Partnership Project (3GPP). The aim of LTE is to support reduced latency, higher user data rate, improved system capacity and increased spectral efficiency [46]. Currently, LTE is studied and labeled as LTE-Advanced (LTE-A) technology. LTE-A technology includes Proximity Service (ProSe) which is the same concept of D2D communication as a new study item in Release 12. It is expected to be a promising technology that serves future services or needs, e.g., public safety, social networking, and proximity-based advertising in various use cases and scenarios [12].

Even though the demand for D2D communication has increased, energy consumption is a growing concern. A device has to support both cellular and D2D communication, meaning that additional energy is required. Meanwhile, recent device supports multiple Radio Access Technologies (RATs), i.e., multiple modems, RF chains and antennas are implemented in one device. Furthermore, LTE shows the highest UE energy consumption compared with Wi-Fi or WCDMA (3G) [47].

There is a growing interest in D2D communication underlaying cellular networks. However, most of the previous D2D works have focused on the D2D communication issues assuming discovery procedure is completed, and as a result, few have investigated on the D2D discovery [30]. The contributions of this chapter are summarized as follows. We firstly propose the D2D discovery and link setup model working in an LTE network. Second, we comparatively analyze the performance of the D2D discovery and link setup in RRC_CONNECTED and RRC_IDLE state by utilizing the real measurement results with LTE smartphones.

The rest of the chapter is organized as follows. We first introduce background in Section 3.2, and present our system model in Section 3.3. After that, we describe the analysis model in Section 3.4, and evaluate the performance in Section 3.5. Finally, we conclude the chapter in Section 4.9.

3.2 Background

3.2.1 Radio Resource Control (RRC)

The main function of the RRC protocol is to manage the connection between UE and network. The RRC state in LTE system is simplified to only two states: RRC_IDLE and RRC_CONNECTED. There is no connection between UE and evolved NodeB (eNB) in RRC_IDLE state, i.e., the location of UE is not known at the eNB level. In this case, it can be traced by an Mobile Management Entity (MME). We define the UE in RRC_IDLE as an idle-UE and the UE in RRC_CONNECTED state as a connected-UE, respectively [48].

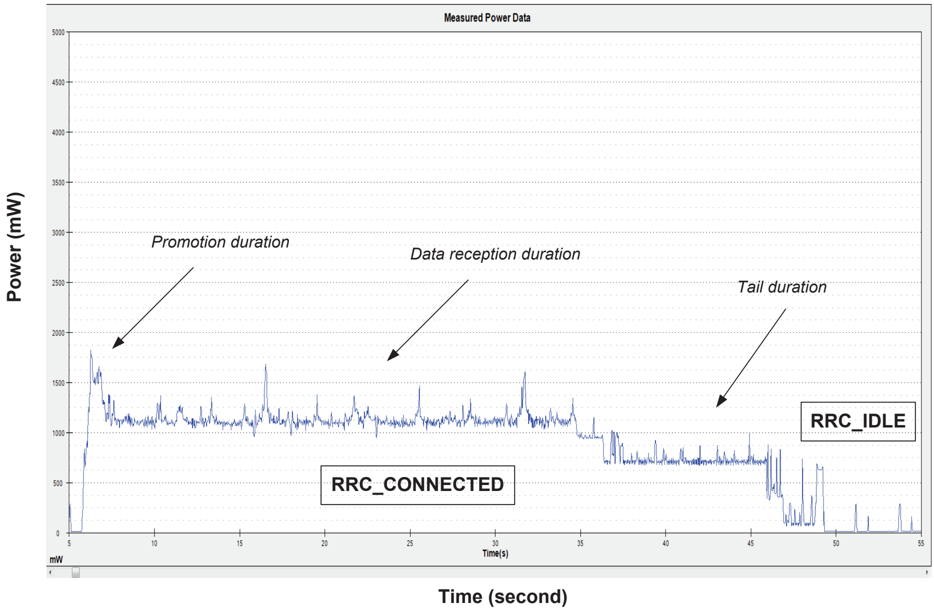

Figure 3.1: UE power measurement.

3.2.2 Discontinuous Reception (DRX)

In DRX mode, the UE powers down when there is no packet activity. In LTE system, DRX mode can be enabled in both RRC_IDLE and RRC_CONNECTED states. DRX operation in RRC_CONNECTED state is defined as connected mode DRX (cDRX). When no data is sent or received during a specified time, the connected-UE performs DRX operation with a short DRX cycle, where the UE wakes up only periodically and sleeps for the remaining time to save energy. If there is no data activity until the short DRX cycle timer is expired, the connected-UE switches to long DRX mode which operates with a longer DRX cycle. All the parameter values related to DRX are defined by RRC configuration [49–51].

3.2.3 Motivation

Fig. 3.1 shows the power trace of User Datagram Protocol (UDP) packet received at 6 Mbps for 30 seconds by iperf.[1] It is measured with Samsung Galaxy Note 2 LTE phone (SHV-E250L). Our experiment is conducted with Monsoon power monitor.[2] Because the UE screen is off, most of the energy is consumed by the radio connection and interface.

The procedures for packet reception are as follows. First, an idle-UE has to perform the promotion procedure for initial random access [49]. After the promotion procedure is completed, the connected-UE can receive packets. After completing the reception of packets, there is some amount of energy consumption although there is no packet activity during tail duration (which is the RRC inactivity time). Then, the connected-UE releases the RRC connection to switch to RRC_IDLE state. Through the measurement results, we observe that there is some amount of base power in RRC_CONNECTED state. However, if cDRX is activated in LTE system, energy consumption will be reduced in tail duration [52].

In this chapter, we introduce the *chip-on-duration*, T_c, which depends on the modem chipset implementation. When the UE wakes up according to the DRX cycle, it has to remain in active state during T_c. In Fig. 3.1, if cDRX cycle is long enough when cDRX is enabled, the connected-UE may reduce tail energy. However, if T_c is longer than the cDRX cycle when cDRX is activated, energy consumption is not reduced in tail duration as shown in Fig. 3.1.

Based on these observations, the motivation of our study is to reduce the energy consumption in the D2D discovery and D2D link setup. In order to verify the relationship between energy and delay, we analyze energy consumption of the D2D discov-

[1] Iperf is a network testing tool that can create TCP and UDP data streams.

[2] http://www.msoon.com/LabEquipment/PowerMonitor.

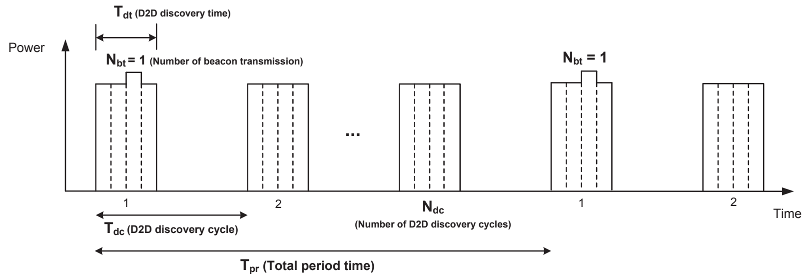

Figure 3.2: D2D discovery operation using uplink.

ery and delay of the D2D link setup in RRC_CONNECTED (cDRX) and RRC_IDLE state respectively. If the D2D discovery occurs only in RRC_CONNECTED state, the idle-UE always has to switch to RRC_CONNECTED state regardless of cellular communication. This will increase energy consumption due to the promotion procedure.

3.3 System Model

3.3.1 D2D Beacon

D2D discovery is a procedure that D-UEs find each other periodically before the communication link is set up. For the purpose, D-UEs have to exchange predefined signals, referred to as *beacons*. By checking beacons periodically, a D-UE maintains a list of proximity D-UEs in order to establish communication link when it is needed. Beacons should be detected reliably, even in low Signal-to-Noise Ratio (SNR) environments [30]. To allow beacons transmitted periodically, resources for beacons should be assigned. For guaranteeing the performance of C-UEs, we assign some dedicated resources for beacons. The minimum unit of beacon is Resource Block (RB) which carries 72 OFDM symbols [44]. Therefore, we can fill the beacon with some useful information such as D-UE identity and offered/required service list.

3.3.2 D2D Discovery

Table 3.1 summarizes a list of important parameters for the D2D discovery and LTE system. Fig. 3.2 shows the D2D discovery operation by using LTE uplink resources [9]. It presents an example of a D-UE beacon transmission and reception. Discovery time T_{dt} is the sum of beacon transmission and reception time. We design that a D-UE transmits one beacon (N_{bt} =1) during T_{pr} and receives beacons during the remaining period of T_{pr}. The energy consumption of beacon transmission is higher than beacon reception. We also design that the D2D discovery and cellular downlink operation occurs simultaneously with periodic cycle. During D2D operation, an idle-UE wakes up periodically during $T_{I,on}$ according to paging cycle, T_{pa}. Within each periodic interval, the idle-UE monitors Physical Downlink Control Channel (PDCCH) and checks whether a paging message is delivered. A connected-UE also monitors a PDCCH during $T_{C,on}$ according to T_{ld} cycle.

$$T_{pr} = N_{dc}T_{dc} \tag{3.1}$$

$$T_{dt} = N_{bt}T_{bt} + N_{br}T_{br}$$

$$N_{dc} = \left\lfloor \frac{T_{pr}}{T_{dc}} \right\rfloor, N_{pa} = \left\lfloor \frac{T_{pr}}{T_{pa}} \right\rfloor, N_{ld} = \left\lfloor \frac{T_{pr}}{T_{ld}} \right\rfloor \tag{3.2}$$

3.3.3 Synchronization

In our work, we limit our scope to synchronous discovery, which means that all D-UEs are synchronized with external timing information. Compared to asynchronous discovery, synchronous discovery has many advantages over asynchronous discovery such as fast detection, low energy consumption, and the large number of discoverable D-UEs [45]. All D-UEs are able to synchronize using signals from an eNB which are transmitted in downlink. Those are broadcasted periodically by an eNB through

Table 3.1: Important parameters.

Parameters	Definition
T_{pr}	Total period time
T_{pa}	Paging cycle
T_{ld}	Long DRX cycle
T_{dc}	D2D discovery cycle
T_{dt}	D2D discovery time in a T_{dc}
T_{bt}	Beacon transmission time
T_{br}	Beacon reception time
T_{on}	On duration time
T_{pt}	Promotion time
T_c	Chip on duration time
N_{dc}	Number of D2D discovery cycles
N_{bt}	Number of beacon transmissions
N_{br}	Number of beacon receptions
N_{pa}	Number of paging cycles
N_{ld}	Number of long DRX cycles
P_{bt}	Beacon transmission power
P_{pt}	Power during promotion
P_{on}	Power during on duration time

dedicated channel [44,53]. Even though D-UEs are synchronized with external source, the exact synchronization between D-UEs cannot be achieved. However, we assume that the maximum range of D2D communication is shorter than the range of cellular communication. Thus, we assume that propagation delay is negligible and delay spread is smaller than the normal cyclic prefix duration in 3GPP [30].

3.3.4 D2D Link Setup

In this section, we illustrate a call flow for the D2D discovery and link setup in Fig. 3.3. The D2D link setup procedure is composed of three parts: D2D link setup request/response, resource allocation and D2D link establishment. Dtx is the D-UE which transmits a beacon and Drx is the D-UE which receives a beacon. After a device is detected, the D2D devices perform the D2D link setup procedure. We assume that D-UE1 and D-UE2 are already registered so that their eNB is aware of D2D candidates (D-UE1 and D-UE2) when a D2D link setup request is received.

1) D2D link setup request/response: After receiving a beacon, D-UE2 (Drx) transmits (in RRC_CONNECTED state), a D2D link setup request message to its eNB. If the D-UE2 is in RRC_IDLE state, the D-UE2 has to switch to RRC_CONNECTED state through the promotion procedure. Then, the eNB sends a request to D-UE1 (Dtx) for a D2D link setup. After that, D-UE1 responds (in RRC_CONNECTED state) to its eNB for a D2D link setup. If the D-UE1 is in RRC_IDLE state, D-UE1 also has to switch to RRC_CONNECTED state through a promotion procedure.

2) Resource allocation: The eNB allocates the temporal link setup resources to both D-UE1 and D-UE2 through RRC connections. The resources are appropriately allocated in a centralized manner.

3) D2D link establishment: After each D-UE is assigned to a dedicated resource, they can transmit and receive messages each other. After a D2D link is established,

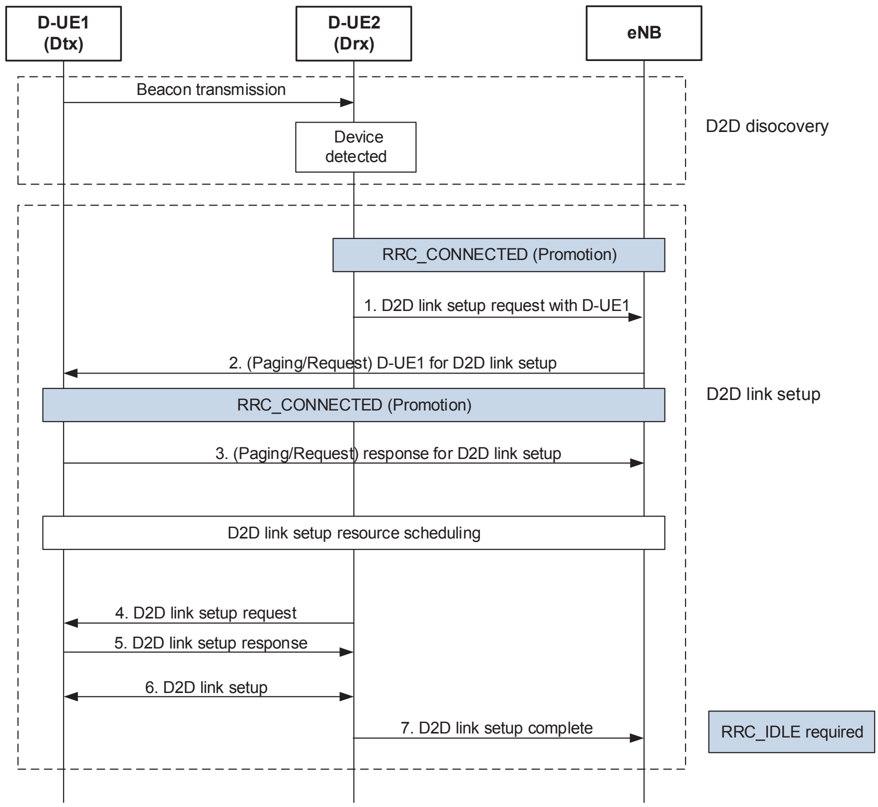

Figure 3.3: D2D link setup procedure.

D-UE2 will notify eNB that the D2D link setup is completed.

3.4 Numerical Analysis

3.4.1 Average Power Model

In this section, we analyze the average power. The average power of the connected-UE is the sum of uplink $E[P_{C,ul}]$, downlink $E[P_{C,dl}]$, base $E[P_{C,base}]$ and promotion

$E[P_{C,pt}]$:

$$E[P_C] = E[P_{C,ul}] + E[P_{C,dl}] + E[P_{C,base}] + E[P_{C,pt}] \tag{3.3}$$

where

$$E[P_{C,ul}] = \frac{N_{dc}(P_{bt}N_{bt}T_{bt} + P_{br}(T_{dt} - N_{bt}T_{bt}))}{T_{pr}}, \tag{3.4}$$

$$E[P_{C,dl}] = \frac{P_{C,on}T_{C,on}}{T_{ld}},\ E[P_{C,pt}] = \frac{P_{pt}T_{pt}}{T_{pr}}, \tag{3.5}$$

and $E[P_{C,base}]$ is derived below. Similarly, the average power of the idle-UE is the sum of uplink $E[P_{I,ul}]$, downlink $E[P_{I,dl}]$ and $E[P_{I,base}]$:

$$E[P_I] = E[P_{I,ul}] + E[P_{I,dl}] + E[P_{I,base}] \tag{3.6}$$

where

$$E[P_{I,ul}] = \frac{N_{dc}(P_{bt}N_{bt}T_{bt} + P_{br}(T_{dt} - N_{bt}T_{bt}))}{T_{pr}}, \tag{3.7}$$

$$E[P_{I,dl}] = \frac{P_{I,on}T_{I,on}}{T_{pa}}, \tag{3.8}$$

and $E[P_{I,base}]$ is derived below.

3.4.2 Base Power Model

$E[P_{C,base}]$ and $E[P_{I,base}]$ are the average base power in D-UE. We define P_{active} as base power when the UE is active and P_{idle} as base power when the D-UE is idle. Fig. 3.4 shows the base energy consumption according to the DRX cycle. Before cDRX is enabled, the connected-UE has to operate a promotion procedure to switch to RRC_CONNECTED state. While the connected-UE enters cDRX mode, optionally a short DRX cycle is applied before enabling a long DRX cycle. In this chapter, short DRX mode (e.g., 40 msec) energy consumption is added up to the energy consumption of promotion. If T_{ld} is longer than T_c, energy consumption will be reduced to P_{idle}

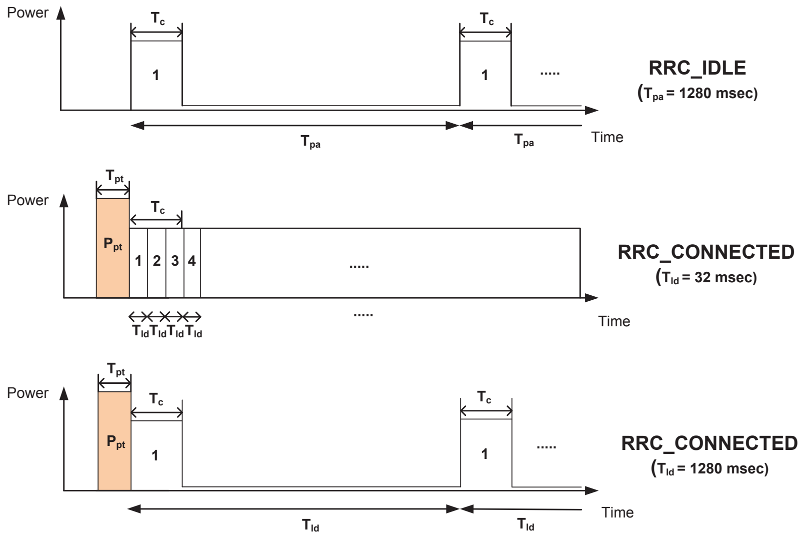

Figure 3.4: Base power comparison under various DRX cycles ($T_c = 100$).

with cDRX operation. However, if T_{ld} is shorter (e.g., 32 msec) than T_c, high power level P_{active} is maintained. $u(t)$ is the unit step function.

$$E[P_{C,base}] = P_{active} \min\left(\frac{T_c}{T_{ld}}, 1\right) + P_{idle}\frac{u(T_{ld} - T_c)}{T_{ld}} \tag{3.9}$$

$$E[P_{I,base}] = P_{active} \min\left(\frac{T_c}{T_{pa}}, 1\right) + P_{idle}\frac{u(T_{pa} - T_c)}{T_{pa}} \tag{3.10}$$

3.4.3 D2D Link Setup Delay

We analyze the D2D link setup delay based on our proposed D2D link setup procedure in Fig. 3.3. T_{pa} indicates the average of paging time which depends on the paging cycle. T_{sc} represents the scheduling time for D2D link setup. T_{ue} is the time for signal transmission from D-UE to eNB and T_{link} represents the time for D2D link setup between D-UEs. In addition, processing delays in both eNB and D-UE are also considered [54]. The average delay of D2D link setup can be given as follows:

$$E[T_{C,link}] = E[T_{ld}] + E[T_{sc}] + 2E[T_{link}] + 3E[T_{ue}] \tag{3.11}$$

$$E[T_{I,link}] = E[T_{pa}] + 2E[T_{pt}] + E[T_{sc}] + 2E[T_{link}] + 3E[T_{ue}] \tag{3.12}$$

3.5 Performance Evaluation

In this section, we compare the performance of RRC_CONNECTED and RRC_IDLE through numerical analysis. Detailed parameters are shown in Table 3.2. We utilize D2D parameters which are based on our power measurement with Samsung Galaxy Note 2 LTE smartphone. Fig. 3.5 shows that the average power as a function of T_c. As T_c increases, the average power also increases due to the time that a D-UE is active. RRC_CONNECTED state shows more average power because of the promotion procedure and short DRX mode operation. Fig. 3.6 represents that the average power is varied according to T_{ld} and T_{pa}. If T_{ld} is longer than T_c, the energy consumption is decreased because the D-UE can reduce P_{idle} after T_c duration. The average delay of D2D link setup is shown in Fig. 3.7. The D2D link setup delay in RRC_IDLE state is longer than that in RRC_CONNECTED state because of the promotion procedure. The delay increases according to the length of T_{ld} and T_{pa}, which are related with how frequently the D-UE wakes up.

3.6 Summary

In this chapter, we have analyzed the energy consumption of D2D discovery in RRC_IDLE and CONNECTED states, and have proposed a novel D2D link setup procedure for delay comparison. Using the analytic evaluation, we prove that there is a trade-off relationship between energy consumption and delay. That is, the energy consumption

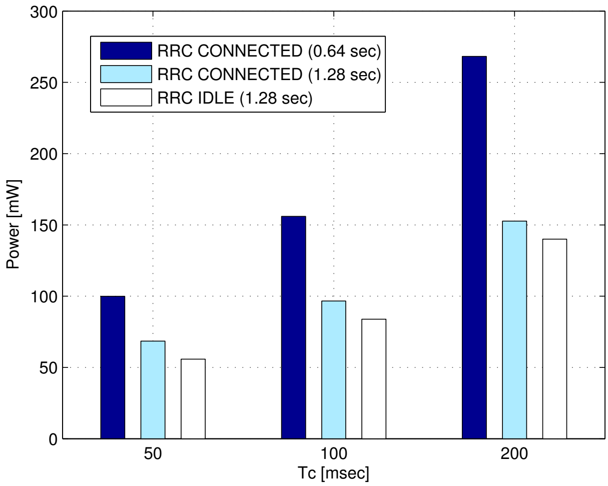

Figure 3.5: Average power under various T_c configurations.

of D2D discovery in RRC_IDLE state is smaller than that in RRC_CONNECTED (cDRX), but after the device is detected, the D2D link setup delay in RRC_IDLE state is longer than that in RRC_CONNECTED.

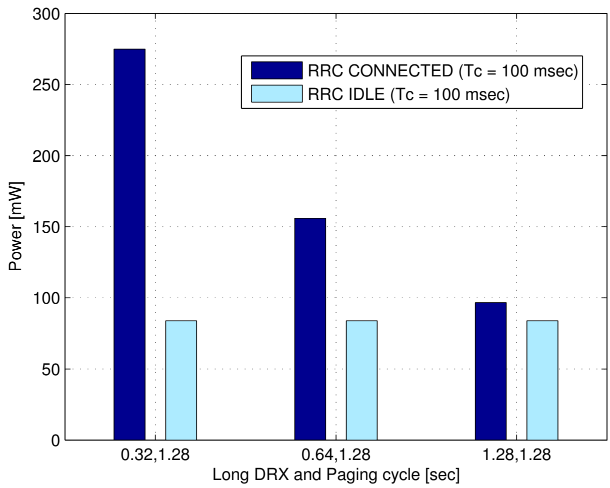

Figure 3.6: Average power under various DRX cycles.

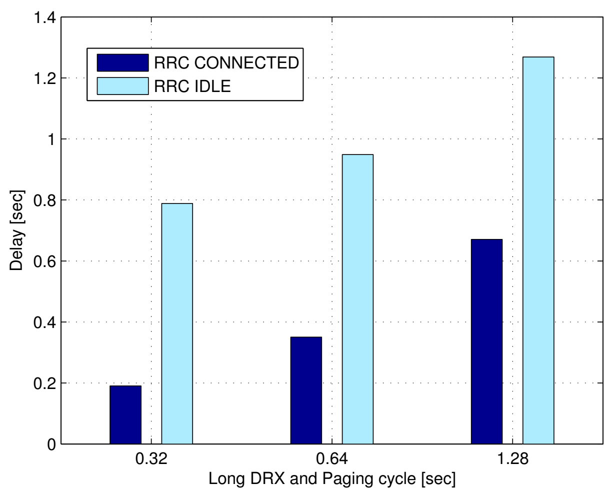

Figure 3.7: Average D2D link setup delay under various DRX cycles.

Table 3.2: System parameters for analysis

Parameters	Values
System bandwidth	10 MHz
Cell size	1 km
Number of eNBs	1
Number of D-UEs	2 (Dtx/Drx)
Distance between D-UEs	500 m
Paging cycle/Long DRX cycle	0.32/0.64/1.28 sec
On duration time in RRC_CONNECTED	5 msec
On duration time in RRC_IDLE	76 msec
RRC connection delay	40 msec
Promotion time	279 msec
Power during promotion	703 mW
Device transmission power	125 mW
Path loss (dB)	128.1+37.6$\log_{10}$(d), d[km]
Parameters for D2D	**Values**
Total period time	10.24 sec
D2D discovery cycle	1.28 sec
D2D discovery time in a cycle	5 msec
Base power in D-UE active	727.9±11.8 mW
Base power in D-UE idle	9.83±0.5 mW
Beacon transmission/reception time	0.5 msec
Beacon transmission power in D-UE	1362±31.25 mW
Beacon reception power in D-UE	1240±18.55 mW

Chapter 4

Spatial Reuse for D2D Communication

4.1 Introduction

Recently, there have been ongoing efforts to incorporate D2D technology in cellular network. Although such D2D scheme under cellular network promises various gains, available resources for D2D communication is always limited since the D2D spectrum will be allocated within the cellular resource (i.e., dedicated or shared). While the D2D network is congested with large number of devices, a lack of resource allocation issue will be raised. Therefore, one of the challenging issues is how to share resources efficiently between D2D transmitters.

In this chapter, we focus on resource sharing scheme, in which one or multiple D2D-UEs (D-UE) can share one resource to increase the spectrum efficiency. Through the spatial reuse operation, multiple transmitter D-UEs can transmit data simultaneously. Existing approaches for spatial reuse in D2D communication are based on unicast D2D transmission with an allocated resource. Under such unicast topology, the target is only one receiver such that transmitter can easily adjust its transmission power for better resource sharing. However, a recent scenario for D2D communication has been focused on multicast transmission which can not adjust its transmission power for only one receiver. Therefore, the transmission power control for resource sharing is difficult under a multicast topology.

Moreover, one of the serious challenges in spatial reuse scheme is resource overhead. From a practical perspective, reusing the same resource will spend lots of signaling to estimate distances for measuring interference whether to reuse or not. Moreover, how to select a proper resource out of the reusable resource candidates is another issue. For this reason, the spatial reuse operation incurs resource overhead problem (e.g., signaling, procedure, and protocol).

In legacy cellular network, fortunately, such complicated spatial reuse operation can be coordinated by a central controller (e.g., eNB). For such a coordination, essential information (e.g., SINR, channel gain, interference level) of every D2D link (i.e., transmitter and receiver) can be exchanged with a central coordinator. However, under D2D network, resource allocation issue for spatial reuse operation will occur due to the lack of central controller, especially, it will be more serious, when the D2D network is congested with large number of D-UEs.

In [37], the authors propose a distance-based spatial reuse scheme in which multiple D2D links reusing a cellular resource exist. However, the reusing D2D links communicate via unicast transmission, thus focusing on only one receiver. Under multicast transmission, there may exist multiple receiver D-UEs such that interference should be measured from the multiple receiver D-UEs. After that, a transmitter D-UE can decide whether to reuse the resource or not. In [38] the authors deal with the concept of D2D multicast transmission. However, only the problem of how to share the cellular resources using a centralized method is considered. Moreover, only one reusing D2D group is considered, which is not practical in large and dense D2D networks.

To the best of our knowledge, none of the previous studies has considered spatial reuse scheme under D2D scenario in the context of D2D multicast transmission, which has been the focus of the recent 3GPP standard. In addition, previous studies consider only centralized spatial reuse schemes, which are not suitable in dense D2D networks.

The rest of the chapter is organized as follows. We first introduce the background in Section 4.2, and present spatial reuse problem in Section 4.3. Then, we describe the proposed spatial reuse scheme in Section 4.4, and a spatial reuse operation is presented in Section 4.5. After presenting the performance evaluation of our scheme in Section 4.7, this chapter concludes in Section 4.9.

4.2 Background

4.2.1 D2D Communication

In general, D-UEs may exploit both the downlink and/or uplink cellular resource for communication. In this work, we assume that D-UE utilizes uplink resources for several good reasons as discussed in [39]. D2D techniques are categorized into two types: D2D discovery and D2D communication. D2D discovery is a procedure to discover neighboring D-UEs. During this phase, a D-UE can detect existence of proximate D-UEs, as well as can be detected by announcing its own identity.

On the other hand, D2D communication is a procedure to communicate directly between neighboring D-UEs. Since an initial use case in release 12 has been considered public safety service only, transmission mode is focused on multicast (one-to-many) D2D communication. Therefore, a transmitter D-UE can selectively establish multiple D2D links with multiple receivers as a group [11].

For the group communication, every D-UE that desires to participate in D2D communication needs to be provisioned to a group. This provisioning is essential since prerequisite parameters for its own group formation will be configured to all of the group receivers [11]. This provisioning procedure can be done by the network or a D-UE can be pre-provisioned for out-of-coverage scenario.

In this study, we limit our scope only to a synchronous communication. All D-UEs are assumed to be in-coverage and time synchronization reference can be obtained from eNB. This obviously consumes much less energy and time compared with asynchronous communication. For the synchronous communication, every receiver D-UE will be active during the time which is allocated for D2D communication. In addition, a resource for every transmitter D-UE will be allocated by eNB.

The resource for D2D communication (e.g., SA, D2D data) is shown in Fig. 4.1. While statically partitioning spectrum between cellular and D2D communication is a simple method to mitigate mutual interference, this study assumes that the resources are allocated in a Time Division Multiplexing (TDM) manner. Therefore, only D2D communication is allowed and conducted during the D2D communication period.

4.2.2 D2D Group Communication

Based on the provisioning procedure, every D-UE can be configured to be part of at least one group, where a group transmitter D-UE can transmit data to proximity group receivers. The resource allocation for D2D communication categorized into two types: centralized and distributed. The centralized method by eNB can allocate a resource without collision. In contrast, in a distributed scheme, transmitter D-UE will select a resource randomly. Therefore, a collision between D-UE transmitters is unavoidable. In this work, the resource allocation for D2D communication is performed in a centralized manner within in-coverage scenario.

For the group-based transmission, a radio resource can be scheduled by network. After the transmission is granted, a transmitter D-UE can send data in multicast transmission. For the D2D multicast transmission, the control information for the group

Table 4.1: SA format

Parameter	Values
Modulation and Coding Scheme (MCS)	5 bits
Time-Resource Pattern	7 bits
Time Advance Indication	11 bits
Group Destination ID	8 bits
Resource Block Assignment and Hopping flag	5–13 bits
Frequency Hopping flag	8 bits
Total	37–45 bits

receivers will be transmitted in advance, and then, data will be transmitted sequentially. Detailed resource structure and configuration are shown in Fig 4.1.

The control information can be conveyed through a format in accordance with Scheduling Assignment (SA) [55] (or Physical Sidelink Control Channel (PSCCH)). An SA message is made of two Resource Blocks (RB) and occupied with useful information for target group D-UE receivers. The detailed information is presented in Table 4.1 [11, 56]. The configuration of SA pool (i.e., subframe duration, SA period, SA bandwidth) will be configured by the network with system information [57].

The detailed operation of the D2D communication works as follows. For a transmission, a transmitter D-UE can be scheduled to use a resource by network. Then, the transmitter D-UE broadcasts SA and data periodically for group receivers. For a reception, a receiver D-UE can check all of the SAs in SA resource pool since an SA mapping for the receiver's group is unknown. While performing the SA monitoring, if it detects any group ID which matches with its provisioned group, then the D-UE can receive data packets selectively. Therefore, the receiver D-UE can skip to receive data packets from other groups.

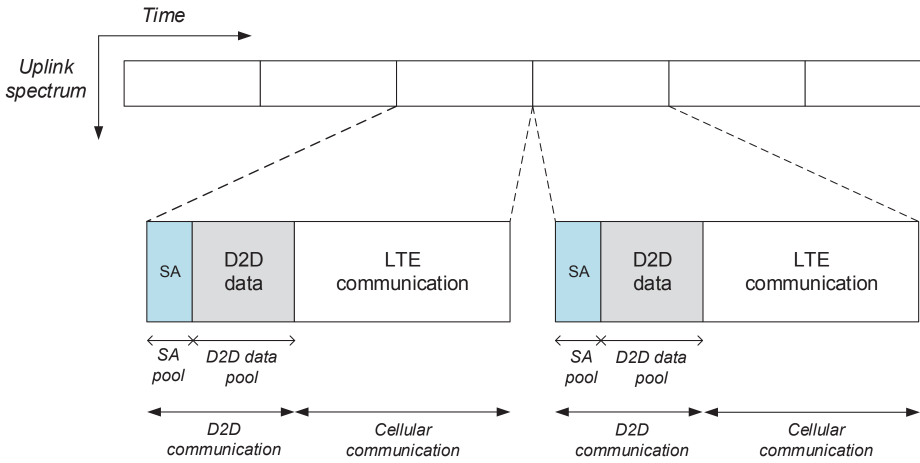

Figure 4.1: Resource configuration.

4.2.3 Motivation

The resource allocation scheme for D2D communication is considered to an overlay strategy, which a different resource will be allocated to each D-UE. Therefore, there will be no interference between the allocated D-UEs. However, this allocation leads to limited spectrum utilization. On the other hand, a spatial reuse scheme with sharing can allow D-UEs to transmit concurrently. Therefore, such reuse scheme can significantly enhance a limited spectrum utilization.

In spite of the advantage, the Spatial Reuse (SR) access has to be applied carefully due to mutual interference. Simultaneous transmission by multiple D2D links on the same resource may cause the interference to proximity D-UE receivers. When suffering from such interference, D2D links could lead to failure in the delivery of data. After all, the performance of D2D system will be severely degraded. For that reason, the SR access should be exploited under an opportunistic policy as long as proximity D2D links should not be affected by SR D2D links.

Existing approaches for the SR access are based on sharing cellular resource.

Moreover, most related work is focused on D2D unicast transmission. Therefore, one cellular resource allocated for Cellular-UE (C-UE) is reused by other D2D links (i.e., transmitter D-UE and receiver D-UE) or vice versa. Under the multicast, there may coexist multiple receiver D-UEs such that an allowable interference can not be measured by a selection. Therefore, the transmitter D-UE can not decide whether to reuse it or not.

For a SR coordination, essential information (e.g., SINR, channel gain, interference level) of every D2D link can be exchanged with a central coordinator (e.g., eNB). However, such centralized method requires high signaling overhead and complexity for multiple D2D links to be coordinated.

To the best of our knowledge, even though previous work has studied SR scheme in D2D scenario, none of them has considered in the context of the D2D multicast transmission, which has been considered in recent 3GPP standard. In addition, most SR studies do not consider signaling or resource overhead as well, which is a significant and practical issue under D2D network. Moreover, none of them studies such complicated SR protocol and procedure under cellular network.

We proposes an SR scheme to gain spectral efficiency, while performing under multicast D2D transmission. The transmitter D-UE considers multiple receivers to receive data successfully. In addition, considering the drawbacks of the centralized SR, this study focuses on the distributed method for the SR operation which has been considered a suitable solution under large and dense D2D networks.

4.3 Problem Statement

4.3.1 Criteria of Successful D2D link

The conventional objective of the cellular communication has been to achieve the maximum channel capacity (e.g., throughput) between a transmitter and a receiver. Different from the previous approaches, the goal of multicast D2D communication may not be related to one channel capacity since there coexist multiple receivers.

Therefore, the goal of D2D multicast transmission will be how to transmit data successfully to as many D2D links as possible. D2D link can be defined as a logical connection between a D-UE transmitter and receiver in this study. For a successful delivery of D2D communication, the SINR of the target D2D link should be above a certain level. The SINR of D2D link k is given by

$$\gamma_k = \frac{P_t h_{t,r}}{\sum_{j \neq t} P_j h_{j,r} + \sigma^2}. \tag{4.1}$$

where P_t is the power of transmitter D-UE t and $h_{t,r}$ denotes the channel gain between transmitter t and receiver r. The cumulative received interference from other D-UEs is defined as $\sum_{j \neq t}^{J} P_j h_{j,r}$ and the power of Additive White Gaussian Noise (AWGN) is denoted as σ^2.

The performance of the D2D multicast transmission can be expressed as the number of successful D2D links during the D2D communication period. When a decoding threshold of SINR is defined as γ_{thd}, a transmission of D2D link k can be assumed to be successful if the SINR of a D2D link γ_k exceeds the γ_{thd}. Therefore, the criteria of a successful D2D link is given by

$$\gamma_k \geq \gamma_{thd}. \tag{4.2}$$

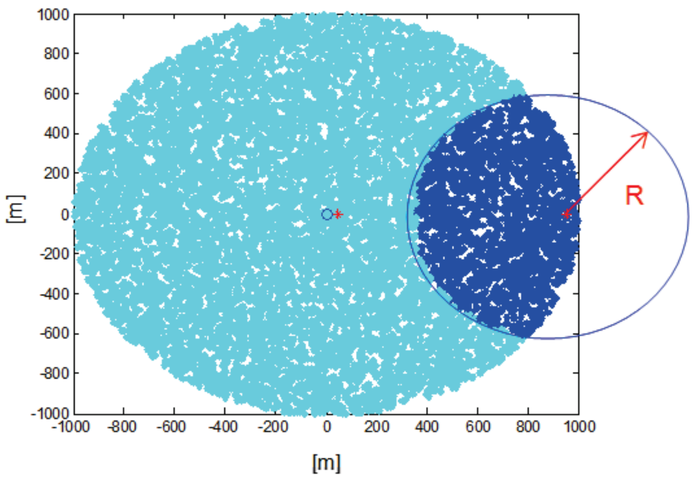

Figure 4.2: Without spatial reuse transmission.

4.3.2 Spatial Reuse Interference

For the purpose of the SR interference verification, we conduct the following simulations as shown in Figs. 4.2 and 4.3. We assume that there are two D-UEs in a center and edge region. The distance between two D-UEs (which are marked by red dots) is 900 m. 10,000 D-UEs are placed uniformly within a cell (radius = 1000 m). The path loss exponent is assumed to be 4.

In these simulations, the D-UE in an edge region transmits with maximum power level (23 dBm), while the D-UE in a center region transmits one-third of the maximum (18 dBm). If the SINR of D2D link is above threshold (e.g., 4.5 dB [45]), then they are marked by blue dots which can be assumed to be successful D2D links.

In Fig. 4.2, both D-UEs do not share a same resource such that interference will not exist between them. In contrast, as shown in Fig. 4.3, if the both D-UEs transmits with the same resource, mutual interference will be generated. For that reason, the number of successful D2D links located near edge D-UE will decrease while an achievable

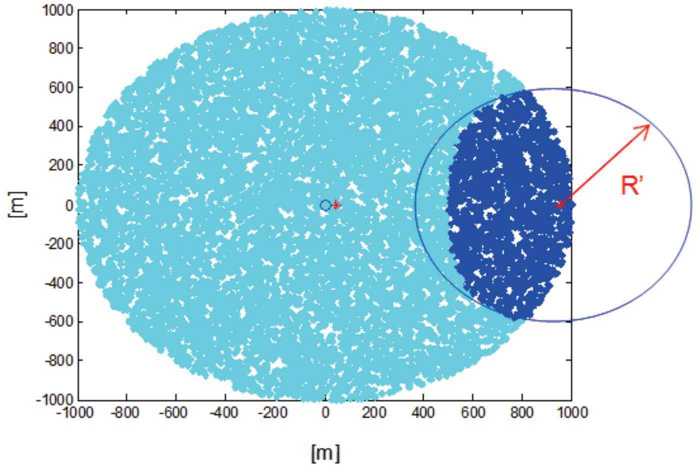

Figure 4.3: With spatial reuse transmission.

multicast D2D communication range R will be reduced to R'.

4.4 Proposed Spatial Reuse Scheme

4.4.1 Range-Based Approach

Based on the previous simulations, even though the reusing transmitter D-UEs are located far away within a large cell (i.e., from edge to center), incurring mutual interference is not negligible when multicast transmission is considered. If one of the D2D link fails to deliver multicast data due to the interference, it certainly can not be allowed to share the resource considering the performance of the group using the resource.

To address such interference problem, this work proposes a target range-based group communication. The SR access scheme is allowed only if target ranges are satisfied by both a resource allocated group and a resource sharing group. Considering the different ranges for D2D communication [12,15,16], a target range-based approach for

D2D communication will be exploited in various locations and scenarios (e.g., conference room, shopping mall, stadium, and enterprise network). Under these scenarios, the transmitter wishes direct communication within a target range. Consequently, appropriate transmission power with sharing resource will be required to guarantee the group's target range.

4.4.2 Spatial Reuse Scenario

In this section, we give an example of spatial reuse access in Fig. 4.4. One D-UE (t_1) in group 1 multicasts data to the multiple group receivers, while anoother transmitter D-UE (t_2) in group 2 desires to share the resource of t_1.

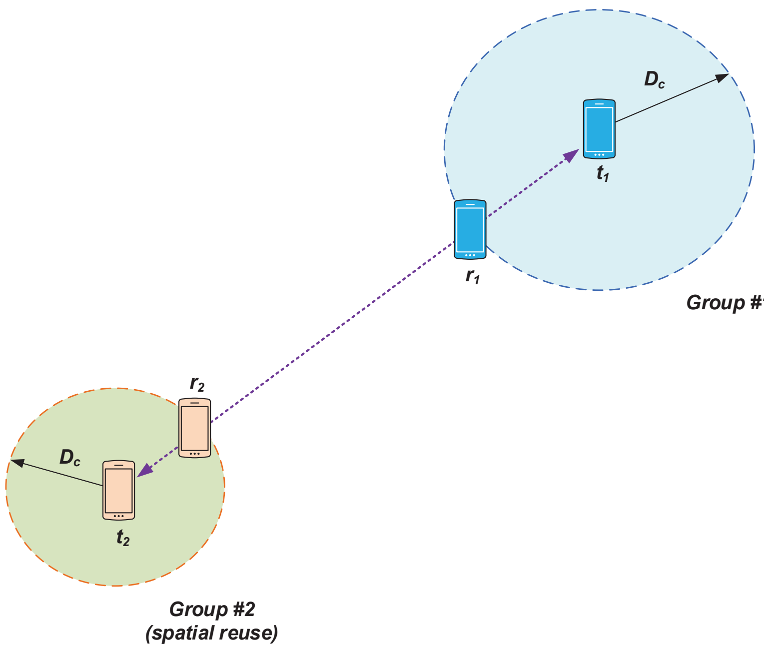

Figure 4.4: An example of spatial reuse scenario.

When t_2 is reusing the resource of t_1, t_2 will generate interference to r_1 as well as receivers in group 1, while t_1 will incur interference to r_2 as well as receivers in group 2. Therefore, in order to achieve a certain level of SINR at all the receivers, an appropriate transmission power is necessary for the reusing transmitter t_2. However, under the multicast topology, there may coexist multiple receivers including r_1 and r_2. Therefore, the reusing transmitter can not set a proper power level for only one receiver.

To tackle this problem, we propose a concept of *reference receiver*, which is assumed to exist virtually and will receive maximum interference from the SR transmitter. Moreover, the reference receiver will receive minimum desired signal due to the radius distance. Therefore, if the target SINR of the reference receiver is satisfied, all other group receivers' target SINR will be satisfied as well. In Fig. 4.4, considering the D-UE t_2, the reference receiver of group 1 is assumed to be r_1, which will receive maximum interference from t_2 and minimum received signal power from t_1 due to the distance. For the same reason, the reference receiver of group 2 is assumed to be r_2. In this study, to guarantee the performance of a group, the guarantee of the group's reference receiver will be considered.

P_{t_n} is the transmission power of D-UE t_n and D_{t_n,r_n} denotes the distance between transmitter and receiver. D_c is defined to be a target range for group communication. In addition, α is path-loss exponent and Additive White Gaussian Noise (AWGN) is denoted by N_0. Considering the mutual interference, achievable SINR of the both reference receivers (r_1, r_2) are derived as follows.

$$SINR_{r_1} = \frac{P_{t_1} D_{t_1,r_1}^{-\alpha}}{(P_{r_2} D_{t_2,r_1}^{-\alpha}) + N_0}. \tag{4.3}$$

$$SINR_{r_2} = \frac{P_{t_2} D_{t_2,r_2}^{-\alpha}}{(P_{t_1} D_{t_1,r_2}^{-\alpha}) + N_0}. \tag{4.4}$$

4.4.3 Upper Bound and Lower Bound

To determine the appropriate transmission power of SR D-UEs, we introduce a concept of Upper Bound (UB) and Lower Bound (LB). Every receiver has an Interference margin I_m, which means that a tolerable interference level with maintaining a target SINR. All receivers have a different I_m depending on the received signal or interference level. Considering I_m of receivers, the transmission power level should be determined properly by SR transmitter. Consider an example of SR scenario in 4.4, the resource of transmitter (t_1) is allocated and the transmitter will send data. Meanwhile, another transmitter (t_2) desires to reuse the resource of t_1.

In this study, we assume a Primary Transmitter (PT) is a transmitter D-UE for which a resource is already allocated by eNB. The group of PT is defined to be a primary group. On the other hand, Secondary Transmitter (ST) is another transmitter D-UE, which wishes to reuse PT's resource. The group of ST can be regarded as a secondary group. In Fig. 4.4, group 1 is a primary group and group 2 is a secondary group, respectively. When a D-UE (t_2) reuses the resource of another D-UE (t_1), mutual interference will be certainly generated. t_2 has an allowed transmission power. That is, the SINR of all receivers in group 1 will be satisfied as long as t_2's transmission power is under this allowed transmission power.

This work also assumes that the transmission power of PT is maximum (e.g., 23 dBm). That is, the PT with an allocated resource is not required to control power in consideration of other primary group or secondary groups. In this SR scenario, r_1 is the reference receiver of group 1, and hence, if the SINR of r_1 is guaranteed, all receivers in group 1 will be satisfied.

The $P_{t_2}^U$ is the upper bound of t_2, i.e., the maximum allowed transmission power as an ST. As seen (4.9), the upper bound of power increases with the distance between the SR transmitters and the reference receiver.

$$\frac{P_{t_1} D_{t_1,r_1}^{-\alpha}}{I_m + N_0} \geq \gamma_{thd} \tag{4.5}$$

$$I_m + N_0 \leq \frac{P_{t_1} D_{t_1,r_1}^{-\alpha}}{\gamma_{thd}} \tag{4.6}$$

$$I_m = P_{t_2} D_{t_2,r_1}^{-\alpha} \tag{4.7}$$

$$P_{t_2} D_{t_2,r_1}^{-\alpha} \leq \frac{P_{t_1} D_{t_1,r_1}^{-\alpha}}{\gamma_{thd}} - N_0 \tag{4.8}$$

$$P_{t_2}^{U} = D_{t_2,r_1}^{\alpha} \left(\frac{P_{t_1} D_{t_1,r_1}^{-\alpha}}{\gamma_{thd}} - N_0 \right) \tag{4.9}$$

In contrast, every receiver of SR group 2 will receive interference from PT (t_1). Therefore, the SINR guarantee of all secondary group's receivers within the target range is considered as well. If the transmission power satisfies a target SINR of receivers in secondary group, it can be Lower Bound in this work. The Lower Bound is a required minimum transmission power for the secondary group.

In this study, we set an upper bound to the maximum transmission power of the ST, guaranteeing the SINR of primary group's receiver. In contrast, the lower bound is set to the minimum transmission power, satisfying the secondary group's receivers. The lower bound of power is described as follows (4.13). The $P_{t_2}^{L}$ is the lower bound of t_2, which is the minimum transmission power.

$$\frac{P_{t_2} D_{t_2,r_2}^{-\alpha}}{I_m + N_0} \geq \gamma_{thd} \tag{4.10}$$

$$P_{t_2} D_{t_2,r_2}^{-\alpha} \geq \gamma_{thd} \left(I_m + N_0 \right) \tag{4.11}$$

$$I_m = P_{t_1} D_{t_1,r_2}^{-\alpha} \tag{4.12}$$

$$P_{t_2}^{L} = D_{t_2,r_2}^{\alpha} \gamma_{thd} (D_{t_1,r_2}^{-\alpha} + N_0) \tag{4.13}$$

4.5 Spatial Reuse Operation

4.5.1 Spatial Reuse Procedure

In this section, we propose SR procedure and signaling which are described in Fig. 4.5. Every transmitter is assumed to be allocated a resource by eNB and transmit its data. The SR operation candidates can be assumed to be every PT. e.g., when PT in group 1 transmits a data, except the PT of group 1, the other PTs can operate as ST with reusing manner. Therefore, the aim of SR operation is to obtain additional SR gain with reusing a resource.

Firstly, resources of SA and data for a PT will be allocated before D2D communication. All PTs transmit SA and data for its group receivers during D2D communication period. Therefore, during SA period, other PTs can receive SAs from other PTs. Through SA information, other PTs can measure a distance (e.g., D_{t_2,r_2}) from the PT transmitting SA.

In Fig. 4.5, an example of D-UE of group 2 work as a ST. The PT of group 2, receive an SA from the PT of group 1. Then the PT of group 2 can measure the distance, and calculate upper bound and lower bound. To estimate I_m of receivers, the distance information is needed from (4.7). Through the SA signal, required distance from the transmitter to the receiver can be measured.

The proposed algorithm will operate during cellular communication period, which is shown in grey box. If one of PTs satisfies the criteria of SR, the PT receives a SR grant from the eNB. Then, an SA resource for ST are allocated by eNB. After receiving the grant and SA, the ST can reuse the resource of PT. The detail criteria of the SR grant is discussed later.

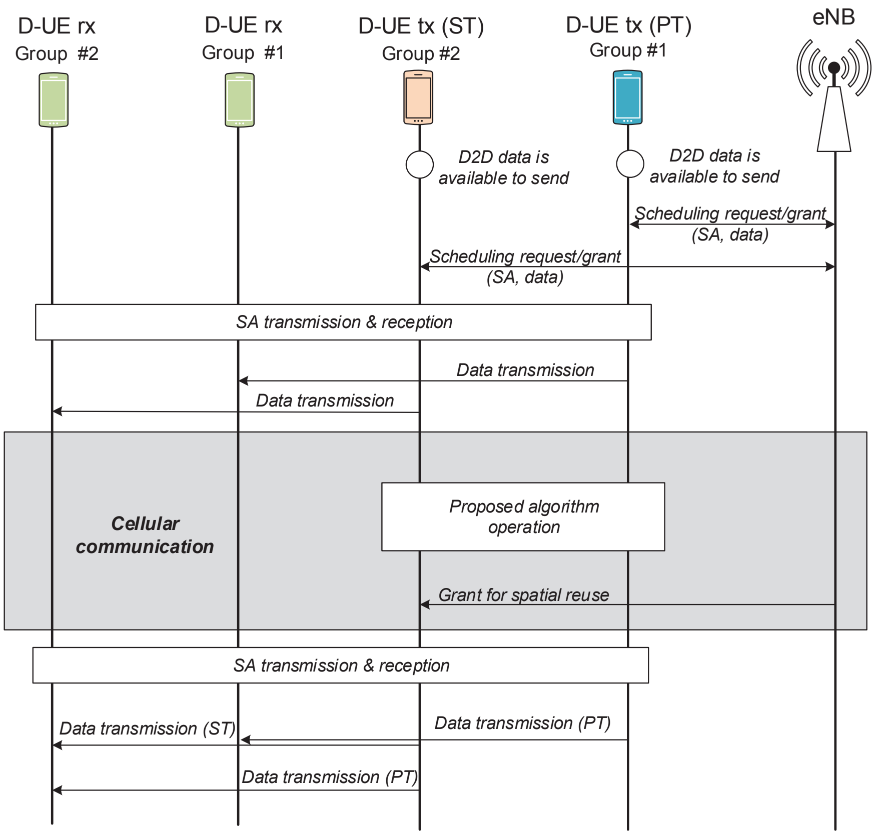

Figure 4.5: Signaling for proposed SR scheme.

4.5.2 Spatial Reuse Grant

The SR grant is presented in Fig. 4.6. Every PT transmits SA and data for group receivers, while other STs can estimate power. The transmission power of ST will be determined between upper bound and lower bound, certainly, the measured upper bound must be higher than the lower bound to protect the primary group. The k D-UE reports its power P_k with a medium of the upper bound and lower bound. The reason for a reporting the average value is explained as below.

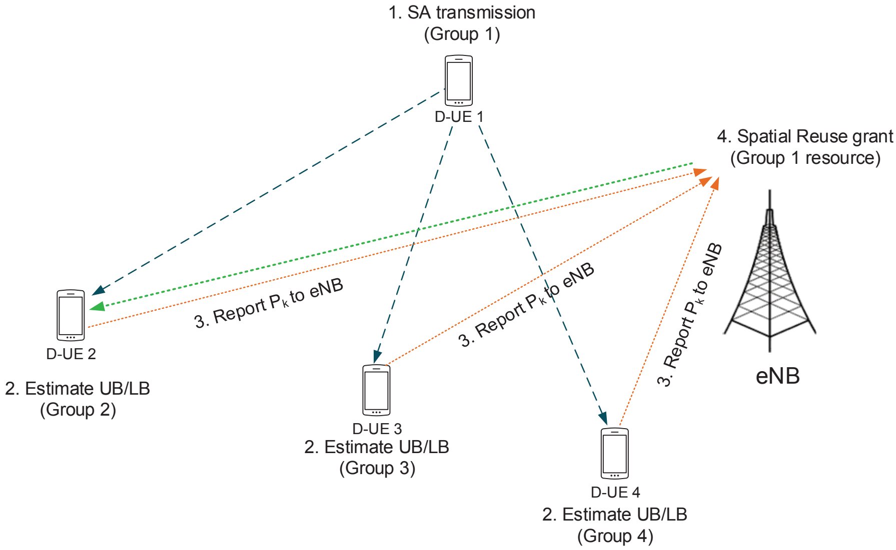

Figure 4.6: Grant for spatial reuse.

When a ST transmits with the upper bound, there may not exist an interference margin for the primary group's resource. Therefore, the resource of primary group can not reuse any more. In contrast, in case of the transmission with lower bound, due to the same reason, the resource of secondary group can not obtain spatial reuse gain any more. Therefore, an average of upper bound and lower bound is reasonable value to obtain interference margins and reuse gains for both the primary and secondary group fairly.

$$P_k = \frac{P^U + P^L}{2} \tag{4.14}$$

After received all the estimated the average power level from STs, the eNB can determine and notify which ST can share the resource. Without the help of eNB, a decision for SR will be another resource overhead issue. In this study, therefore, the decision which a transmitter can be a ST will be conducted by eNB. In Fig. 4.6, D-UE2

Algorithm 2 Spatial Reuse Algorithm

for $s = 1$ to N_s **do**
    for $k = 1$ to $|K|$ **do**
        Estimate P^U by using (4.9)
        Estimate P^L by using (4.13)
        if $P_{\mathrm{l}} < P_{\mathrm{u}}$ **then**
            $P_k^{(s)} \leftarrow \frac{P^U + P^L}{2}$
        else
            $P_k^{(s)} \leftarrow \infty$
        end if
    end for
    $r = \underset{k}{\operatorname{argmin}}(P_k^{(s)})$ $\{r$: ST transmitter$\}$
end for

can reuse the resource of D-UE1 due to the lowest power. The criteria of SR is power level, which can assume that it will generate minimum interference with a minimum transmission power. This work proposes a novel SR algorithm which is described in Algorithm 2. Every ST measure the P_k based on the received SA s. Then the eNB selects one ST for reusing which can transmit with the minimum P_k.

4.6 SR with Multiple Transmitters

In the previous sections, the SR operation is considered assuming one resource is shared by one ST. Due to the limited number of SR access transmitters, the gain of SR is limited by one transmitter. To boost up the gain of SR operation, we now extend our proposed SR operation by considering resource sharing by multiple STs.

However, to increase the gain of SR, the mutual interference will be increased as

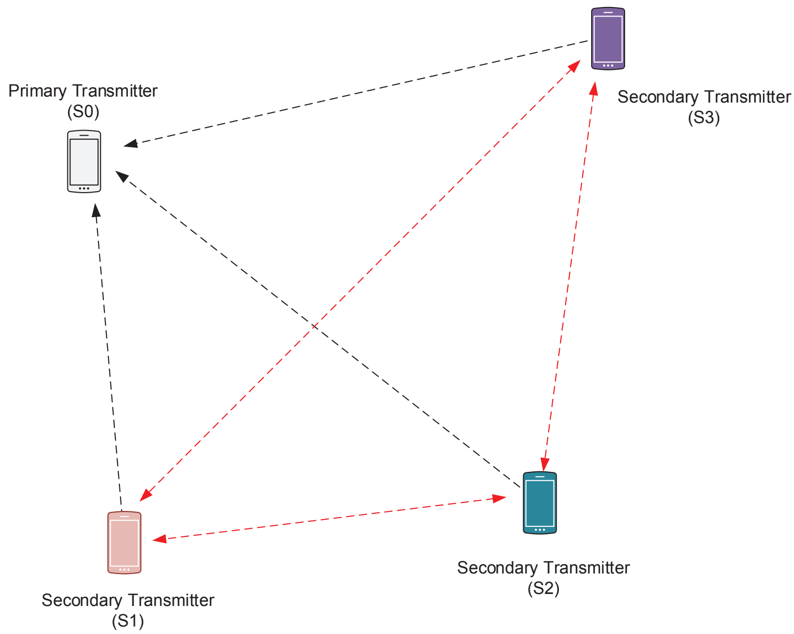

Figure 4.7: Mutual interference between the SR groups.

well. When the resource of PT is reused by multiple STs, the generated interference level will be aggregated as well. As shown in Fig. 4.7, there may be two kinds of mutual interference will be generated when there coexist 3 groups (e.g., 1 primary and 2 secondary groups). Consider $S1$ in secondary group 1, the PT will generate mutual interference to the secondary group 1 receivers. In addition, other STs (e.g., $S2$, $S3$) will make mutual interference to the secondary group's receivers concurrently. Therefore, receivers of secondary group 1 will be affected by multiple interference from PT and STs. We denote the primary group as $S0$ for consistency.

4.6.1 PS-SR Scheme

PS-SR (Primary and Secondary - Spatial Reuse) scheme considers the primary group and the secondary group as well. As shown in Fig. 4.8, the PT ($S0$) and ST ($S1$) are

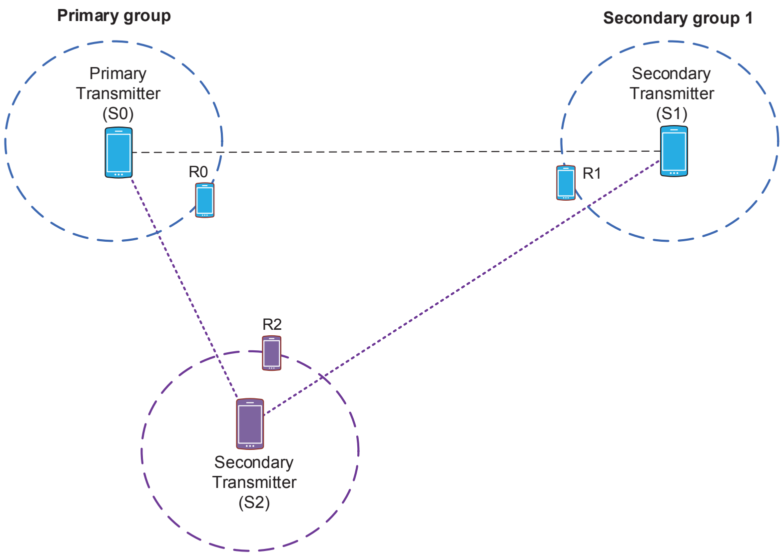

Figure 4.8: PS-SR scheme.

reusing the same resource. Meanwhile another ST ($S2$) desire to share the resource, so the ST ($S2$) determines a proper transmission power for an upper bound considering the primary group and secondary group 1, as well.

Assuming that if there estimated two available powers $P0$ for primary group, $P1$ for secondary group 1, respectively. In that case, $min(P0, P1)$ power is selected for upper bound. When the number of secondary transmitters will be increased, the minimum power value will be selected as $min(P0, Pn)$. If the minimum power is transmitted, the SINR of target group will be satisfied and other groups will be also guaranteed.

4.6.2 P-SR Scheme

P-SR (Primary - Spatial Reuse) scheme considers transmission power with only the primary group. The criteria of the SR is determined by s distance between the primary group and reuse secondary transmitter. As shown in Fig. 4.9, if the distance between

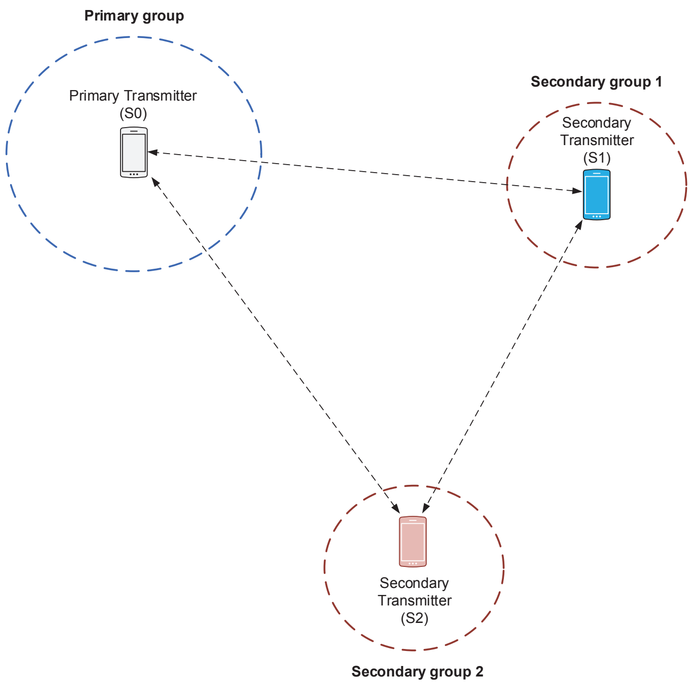

Figure 4.9: P-SR scheme.

$S0$ and $S1$ (i.e., a reuse distance in this study) is longer than the distance between $S0$ and $S2$, the generated interference from $S2$ will be smaller than $S1$ when assuming that $S1$ and $S2$ will transmit with equal power.

Therefore, there exist n secondary groups with a reuse distance, the transmission upper bound for the secondary transmitters will be equally reduced by n. In Fig. 4.9, the $S2$ transmits reduced half of power of $S1$ due to n is two. P-SR scheme has a benefit for a simple design which reduces transmission power according the number of SR transmitters. The estmation of the secondary groups for the upper bound is not required in this scheme.

However, the P-SR scheme can guarantee only the performance of primary group and performance of the its secondary groups can not be guaranteed. Moreover, the performance of secondary groups will be degraded while the secondary transmitters are located in proximity.

4.7 Performance Evaluation

In this section, we present the performance evaluation of our proposed schemes. We have implemented a system level simulator using MATLAB in accordance with the LTE system simulation. The main parameters are summarized in Table 4.2. In this work, we compare our proposed schemes with a baseline scheme. In the baseline scheme, every transmitter D-UE does not share the resource. The number of groups is set to 10 which is represented as one of the simulation assumptions [40]. In this evaluation, two primary transmitters (PT) are allocated per a group. Therefore, each transmitter is allocated an orthogonal data slot (resource) by eNB. In each data slot, each group transmitter transmits the data (e.g., 1 data slot, 1 group transmitter), respectively.

Table 4.2: System parameters

Parameter	Values
Cell layout	7 cell-site (21 cells)
Inter Site Distance (ISD)	500 m (cell radius = 167 m)
Number of UEs	100 UEs per cell
UE dropping	Uniform distribution
UE mobility	3 km/h (pedestrian)
System bandwidth	10 MHz (N_f = 44)
Number of D2D groups	10
Communication range (D_c)	150 m
Carrier frequency	2 GHz
Maximum power of UE	23 dBm
Minimum association RSRP	-107 dBm [40]
Path Loss exponent	4
Noise power	-174 dBm/Hz
Channel model	Path loss+Shadowing+Multipath
Shadowing	Log normal with 7 dB std

Since the received interference highly depends on the D-UE density or location, we assume that the locations of D-UEs are modelled by a Poisson Point Process (PPP) model. With such a process, the D-UEs are independently and uniformly distributed in a two dimensional space. We also assume that the D-UEs move within the deployed area according to a pedestrian mobility model, where the direction of a D-UE is randomly determined between [0, 2π].

In this section, we present the performance evaluation of our proposed schemes. We have implemented a system level simulator using MATLAB in accordance with the LTE system simulation. The main parameters are summarized in Table 2.1. In this work, we compare our proposed schemes of the PS-SR and P-SR schemes with a baseline scheme. The baseline scheme allocate a resource for every transmitter which does not share a resource.

Fig. 4.10 shows the number of successful D2D links during data transmission.

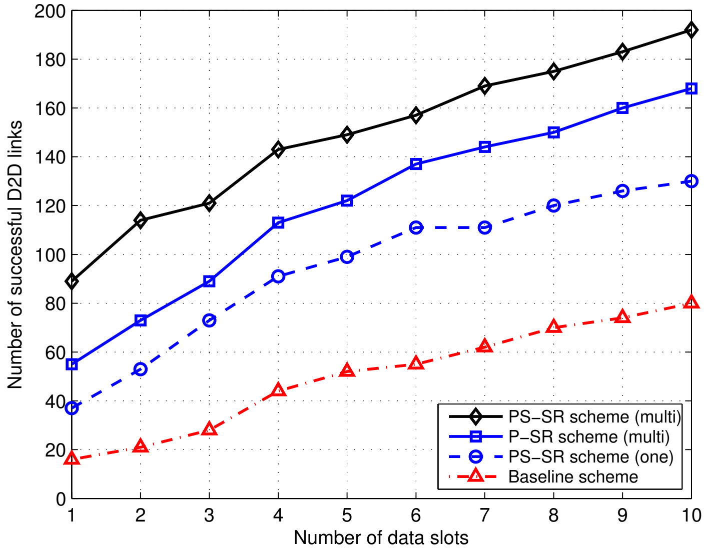

Figure 4.10: Successful D2D links.

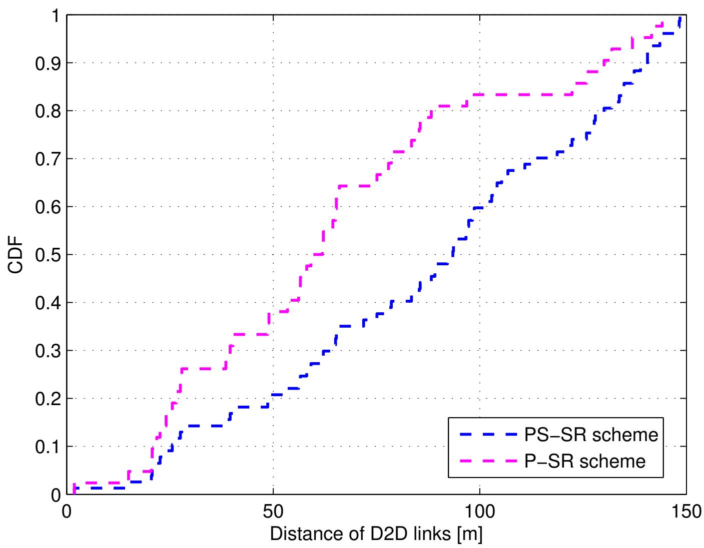

Figure 4.11: Coverage comparison.

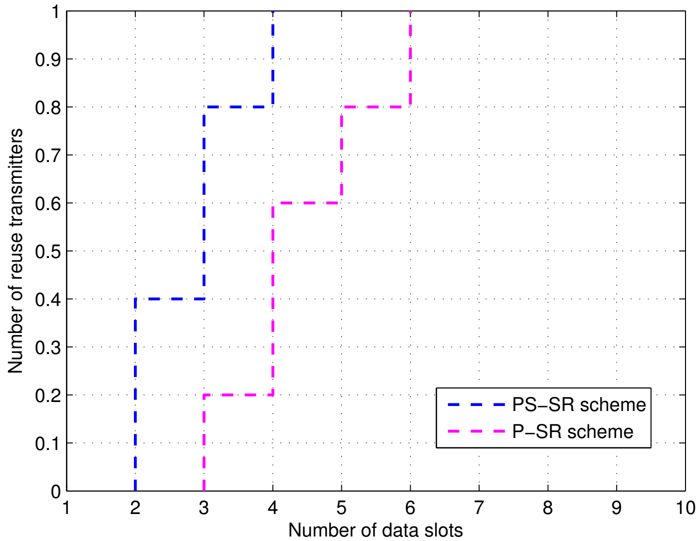

Figure 4.12: Number of reuse transmitters.

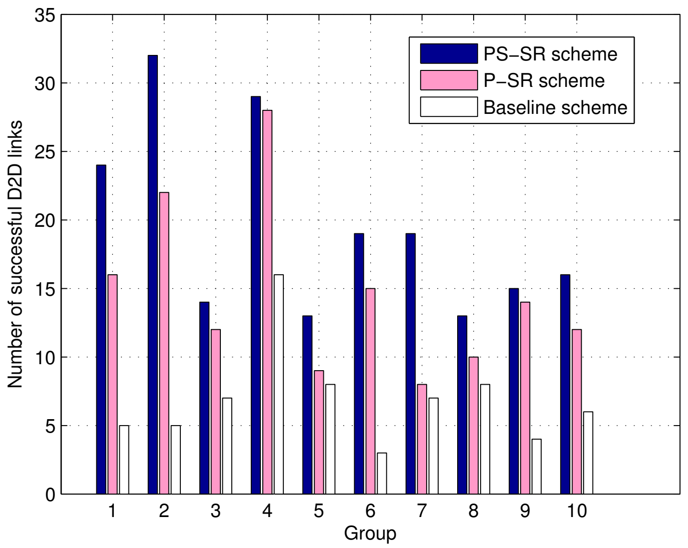

Figure 4.13: Successful D2D links per group.

The proposed PS-SR schemes outperforms the P-SR scheme by reusing the resource spatially. The PS-SR scheme considers the upper bound all the secondary groups and a primary group as well. In case of the P-SR scheme, considering the only primary group, the system performance will be degraded when the secondary transmitters are located in proximity. In the PS-SR scheme (one), a resource is reused by only one secondary group. Therefore, the performance gain is lower than other proposed multiple reusing schemes.

The CDF of reusing transmitter is presented in Fig. 4.12. In case of the P-SR scheme, more transmitters will be reused for a each data slot, only if the reuse distance is guaranteed, the secondary transmitters can reuse it. Therefore, more secondary group transmitters can share it. The number of successful D2D links per a group is shown in Fig. 4.13. We observe that the proposed schemes i.e., PS-SR, P-SR outperform the baseline scheme. In addition, the PS-SR scheme represents better performance than the P-SR scheme in every group. This is because that the performance between secondary groups will be guaranteed, when the secondary transmitters are in proximity (e.g., group 5 and 8).

The comparison of the two schemes are shown in Fig. 4.11. We observe that the coverage of the PS-SR scheme outperform the P-SR scheme. Since the transmitters will reduce the transmission power according to the number of transmitters in the P-SR scheme. While the number of secondary transmitters are increased, transmission power will be reduced linearly.

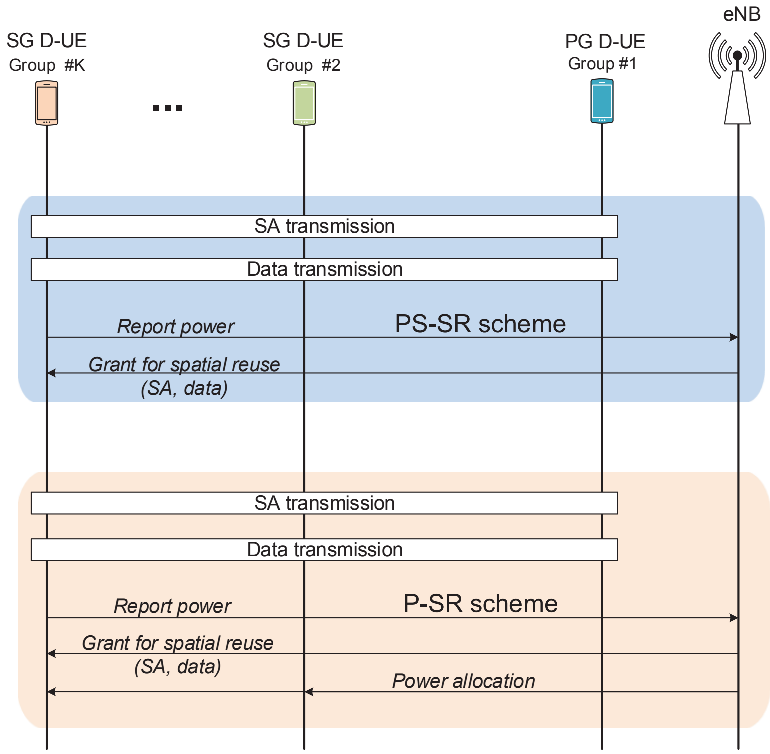

Figure 4.14: Overhead comparison.

4.8 Comparison of PS-SR and P-SR Schemes

4.8.1 Overhead Comparison

In this section, we compare required resources of the PS-SR and P-SR schemes. The operation procedure of the PS-SR and P-SR scheme are described in Fig. 4.14. Both schemes require a procedure to transmit SA and data for the group's receivers in the same way. However, for the reusing, the required information and signaling will be quite different.

The overall overhead comparison is summarized in Table 4.3. Let us define the

Table 4.3: Resource overhead comparison

	PS-SR scheme	P-SR scheme
Required SA	K	2
Required information	Power (K-1) Interference margin (K)	Reuse distance (1) Power (1)
Estimation overhead	Upper Bound Lower Bound	N/A
Signaling (D-UE)	1	1
Signaling (eNB)	1	2

number of secondary transmitters is as K. When $K = 1$, the signaling procedure and overhead of the two schemes are equal. For the first secondary transmitter, both schemes needed to estimate the upper bound and lower bound. However, when the $K \geq 2$, the required resource overhead will be different. Therefore, the resource overhead comparison is conducted, when the $K \geq 2$ in this section.

In the PS-SR scheme, if the number of secondary group is K, the required number of SAs will be K. The number K comes from all the secondary group (except itself) and primary group. Every secondary transmitter has to estimate upper bound for all the groups. To estimate the upper bound with interference margin, every group's reference receiver has to be considered. In addition, for the lower bound estimation, transmission power from every secondary transmitter will be needed except itself i.e., $(K - 1)$.

On the other hand, in the P-SR scheme, a reuse distance and power of the first reusing transmitter (e.g., $S0$) are required information to reuse. Other secondary transmitters will divide the power of $S0$ according to the number of K. However, in case of the eNB signaling, P-SR scheme operation includes a signaling to power allocation for the secondary group's transmitter. Therefore, additional a signal is required, compared to P-SR scheme.

4.9 Summary

In this chapter, we propose novel spatial reuse schemes for D2D communication. We have investigated the performance of the proposed schemes compared with the baseline scheme. The simulation results demonstrate that the number of successful D2D links are remarkably improved by sharing the resources. The PS-SR and P-SR schemes can overcome the mutual interference in a distributed manner. The PS-SR outperforms the P-SR scheme. However, required resource overhead of the PS-SR is larger than that of the P-SR scheme. We conclude that the proposed SR schemes can be exploited for various D2D communication scenarios and applications to increase spectrum efficiency, while guaranteeing the SINR requirement.

Chapter 5

Conclusion

5.1 Summary

In this dissertation, we propose a couple of compelling algorithms, mitigation interference, increase the successful D2D links, to improve the performance of LTE based D2D networks. We also present a new energy efficient discovery and protocols to minimize energy consumption. Furthermore, we design the proposed schemes based on recent standards, i.e, protocol, resource, parameters and scenarios. Therefore, operation of the proposed schemes complies with the current 3GPP standard (release 12).

More into detail, the research contributions of each chapter in the dissertation are summarized as follows.

In Chapter 2, we propose novel power control and contention resolution schemes for improving the performance of D2D discovery. Those the proposed schemes operate in distributed manner which is a suitable solution scalable D2D network. We have investigated the performance of the proposed schemes compared with the baseline scheme. The simulation results demonstrate that the discovery success ratio is remarkably improved such that the average distance of detected devices is increased as well.

This means that enhanced the discovery success ratio will indicate more devices are detected.

The CR scheme can simply overcome the D2D interference by detecting the collisions without a signaling or resource overhead. Moreover, the PC scheme can mitigate D2D interference by controlling the power of transmitters. In results, the performance evaluation reveals that there is a trade-off relationship between gain and delay.

In Chapter 3, we have firstly proposed a novel D2D discovery and link setup procedure working in LTE-based networks. In addition, a beacon resource, synchronization method, and periodic D2D discovery is proposed as well. The power and delay consumption comparison for proposed procedure is conducted as well. We also have analyzed the energy consumption of D2D discovery in RRC_IDLE and CONNECTED states, using the analytic evaluation.

For the analysis parameters are measured with a commercialized recent smartphones. We prove that there is a trade-off relationship between energy consumption and delay. That is, the energy consumption of D2D discovery in RRC_IDLE state is smaller than that in RRC_CONNECTED (cDRX), but after the device is detected, the D2D link setup delay in RRC_IDLE state is longer than that in RRC_CONNECTED.

In Chapter 4, we propose a spatial reuse schemes for D2D communication. We have investigated the performance of the proposed schemes compared with the legacy baseline scheme which does not allow a reuse of resource. The proposed schemes can operate in distributed manner with low signaling or resource overhead. Compared the existing approach, this work focuses the multicast transmission with novel concept of reference receiver.

Moreover, the PS-SR and P-SR schemes which one resource is reusing by multiple transmitters are proposed. The comparison of signaling and procedure overhead of the two proposed schemes is also conducted. The simulation results demonstrate that the number of successful D2D links are remarkably improved with sharing the resources. The PS-SR and P-SR scheme can work under multicast transmission with the reference receiver. The PS-SR scheme shows better performance than P-SR scheme due to considering all the secondary groups. However, more resources are required to operate the PS-SR scheme. Our proposed schemes have a trade-off which can be utilized in various D2D communication scenarios.

5.2 Future Work

We conclude the dissertation with a brief discussion of ongoing study in further improving and expanding our contributions.

Firstly, novel distributed power control and contention resolution schemes are discussed. We have investigated the performance of the proposed schemes compared with the baseline scheme. The simulation results demonstrate that the discovery success ratio is remarkably improved such that the average distance of detected devices is increased as well. The CR scheme can simply overcome the D2D interference by collisions without a signaling or resource overhead, while the PC scheme can mitigate D2D interference by transmitter power control method. Moreover, the results reveal that there is a trade-off relationship between gain and delay.

Secondly, analysis of the energy consumption of D2D discovery in RRC_IDLE and RRC_CONNECTED state is conducted. Also, we have proposed a novel D2D link setup procedure for delay comparison. Using the analytic evaluation, we prove that there is a trade-off relationship between energy consumption and delay. That is, the energy consumption of D2D discovery in RRC_IDLE state is smaller than that in CONNECTED, but after the device is detected, the D2D link setup delay in RRC_IDLE state is longer than that in RRC_CONNECTED.

Finally, a novel spatial reuse schemes for D2D communication is introduced. The performance of the proposed schemes compared with the baseline scheme. The simulation results demonstrate that the number of successful D2D links are remarkably improved with sharing the resources. The PS-SR and P-SR scheme can simply overcome the mutual interference by sharing the resource without a signaling or resource overhead.

As a future work, a priority of spatial reuse access can be considered. So far, the secondary transmitters can share the resource without a priority, the fairness issue which only some transmitters can reuse it. Considering the required traffic or a target application scenario (e.g., delay-sensitive or not), the priority of spatial reuse operation should be considered as well.

Moreover, the D2D discovery in out-of-coverage can be a further study item. Compared the cellular network, D2D network can work under a out-of-coverage environment. This work has considered only a synchronous system which the D-UEs can synchronize through the eNB. Under a disaster scenario, the D-UEs can form a cluster or group. On the other hand, one of the D-UEs can operate as an eNB.

We expect that our proposed schemes can be exploited for various D2D communication and applications. moreover, this dissertation can be a milestone for future LTE-A/5G networks.

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초 록

최근 몇 년간 스마트폰과 태블릿 기기의 급격한 보급으로 고용량 멀티미디어 통신이 활성화되면서 모바일 인터넷 트래픽이 매년 급격히 증가하고 있으며 이로 인해 셀룰러 통신망의 과부하가 심해지고 있다. 기지국의 과부하를 줄이는 또 다른 방법으로 네트워크 인프라를 거치지 않고 단말기 간에 직접 트래픽을 주고 받는 단말 간 직접 통신이 부각되고 있다. 기기간 통신은 가까운 거리에서 단말 간 직접 데이터를 주고 받는 방식으로 기존 셀룰라 통신과 비교하여 전력소모, 주파수 자원, 기지국 부하 등의 측면에서 매우 효율적이다. 또한 하나의 기지국 범위 내에서도 여러 링크가 동일한 주파수에서 통신이 가능하여 주파수 재 사용률을 높일 수 있다는 장점이 있다. 본 논문에서는 셀룰라 네트워크에서 기기간 탐색 및 통신을 위하여 성능을 개선 하는 것을 목표로 한다.

첫째, 현재 셀룰라 네트워크 기반 기기간 탐색과정은 복잡도와 시그널 오버헤드를 고려하여 분산적인 방법으로 단말들이 진행한다. 이러한 경우, 서로 다른 단말이 같은 자원을 선택했을 경우(자원 충돌)에 서로 간 간섭이 발생하여 기기간 탐색 성능이 저하된다. 또한 분산적인 방법의 경우 모든 단말들은 근처 단말들이 어떠한 자원을 선택하고 어떠한 단말들이 간섭을 발생하는지 판단하지 못한다. 이러한 문제를 해결하기 위해서 기기들의 전송 파워를 간섭을 줄이기 위해서 효율적인 알고리즘으로 동작하여 성능을 개선한다. 또한 자원 충돌이 난 경우에 근처 단말들이 수신 신호와 간섭세기를 기반으로 자원 충돌이 발생했음을 인지하고 이를 해당 단말에

게 알려서 자원 충돌을 해결한다. 이러한 간섭 제어 방식들을 통해서 기기간 탐색의 성능을 높일수 있다.

둘째, 에너지 효율적인 기기간 탐색기술의 프로토콜을 제안하고 이를 측정 기반으로 모델링 한다. 셀룰라 네트워크에서 단말은 기지국의 자원을 할당 받은 Connected 상태와 할당 받지 않은 Idle 상태인 두가지가 존재한다. 이러한 기기간 탐색을 위해서는 높은 에너지가 소모가 문제인데 이러한 문제를 해결하기 위해서 이러한 Idle인 상태에서 즉, 기지국과 연결이 없는 상태에서도 단말 탐색이 가능하도록 프로토콜 및 프로시져를 제안한다. 제안한 프로토콜과 프로시져를 기반으로 각각의 상태에 따른 기기 탐색 시 장단점(에너지, 지연)을 분석한다. 실제적인 분석을 위해서, 현재 상용중인 LTE 네트워크 단말의 측정 데이터를 활용하여 모델링 하고 분석한다.

셋째, 주파수 재사용(Spatial Reuse)은 기기간 통신의 큰 장점중의 하나이며 이는 서로 같은 자원을 사용하여 주파수 재 사용률을 높일 수 있다. 그러나 주파수 재사용 시 같은 자원을 근처의 단말들이 사용한다면 상호 간에 간섭이 발생하므로 간섭이 없는 경우에만 기회적으로 재사용이 가능하다. 본 연구에서는 주파수 재사용을 위한 자원선택 프로토콜 및 알고리즘을 제안한다. 또한 기존의 문제인 주파수 재사용을 위해서 발생하는 복잡도와 시그널링 오버헤드를 고려하여 분산적인 정보를 기반으로 단말들 간에 주파수 재사용이 가능하도록 고려한다. 또한 한개의 자원을 여러명의 단말들이 동시에 사용하는 다양한 방식도 제안하고 제안한 방식들을 시스템 레벨 시뮬레이션 성능 분석을 통하여 현재 표준에서 규정되어 있는 방식보다 성능이 개선됨을 증명한다.

주요어: 기기간 탐색, 기기간 통신, 셀룰라 네트워크, 간섭제어, 프로토콜, 주파수 재사용

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