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電信工程研究所

碩士論文

在裝置對裝置通訊網路下鄰近搜尋及自我連結建立
之設計與分析

Proximity Discovery and Autonomous Link Setup
in D2D Communication Networks

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摘 要

在傳統的蜂巢式網路底下，連結的建立必須經由基地台和核心網路的幫助。假如裝置對裝置(D2D)具有相對近距離的情況下，蜂巢式網路在多節點跳躍、路由、網路負載或延遲及功率的效能上可能會比D2D連結不具效率。對於在蜂巢式網路底下自動的D2D通訊可以減輕基地台和核心網路的負載並且藉由好的直接連結，可以增強頻譜使用效率和網路吞吐量。

對有效率的 D2D 通訊來說，裝置必須可以追蹤它的周遭環境和尋找適合可以做連結的裝置，在論文中，我們提出了一個裝置對裝置連結建立的流程可以促使裝置建立可靠 D2D 的連結並且在傳送訊號時不能對蜂巢式網路造成過大的干擾。基於提出的流程及相關的訊號品質要求，假設裝置分別由泊松點過程 (PPPs)模型下產生，我們分析成功的 D2D 連結建立(SDLS)機率。一個精確的干擾表示式是非常複雜的，因此我們分別利用近似和上限的情況，用 PPP 去描述對蜂巢式使用者所造成的干擾源位置並計算相對應蜂巢式使用者的訊號與干擾加雜訊比，在這兩種情況下，SDLS 機率對於傳送功率是一擬凹 (quasiconcave)函數，同時也提出二分法搜尋的上下界，這可以使我們加快演算法的收斂速度並證明在我們所搜尋的區間存在著唯一的最佳探詢訊號的功率。

Proximity Discovery and Autonomous Link Setup in D2D Communication Networks

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Abstract

Conventional cellular networks require that a link be setup through the aids of base stations and the associated core network. It is very inefficient either in terms of required multi-hop link setup, routing and other network overheads or from the viewpoint of delay and power performance if the associated physical device-to-device (D2D) link is in relatively good condition. Autonomous D2D communication as an underlay to an existing cellular network reduces the base stations (eNBs) and core network's loadings while enhancing the spectral efficiency and network throughput by taking the advantage of good direct link qualities.

For efficient D2D communications, a device must be able to track its local environment and discover suitable connecting devices within a short time span. In this thesis, we propose a D2D link setup protocol that enables a device to establish a reliable D2D link using proper radio resources while causing only tolerable interference to the underlaid cellular network. We analyze the success D2D link setup (SDLS) probability based on the proposed protocol and related signal quality requirements, assuming devices are distributed according to some two dimensional Poisson point processes (PPPs). As the exact expression for the sum interference is very complicated, we use an approximation model and an upper bound to describe the active devices' location distribution in evaluating the signal-to-noise-plus-interference ratio of a macrocellular terminal. Using either

one in computing the SDLS probability, we show that it is a quasiconcave function of the device' transmit power. We apply a bisection search with the help of the derived upper and lower search bounds to accelerate the search and prove that the existence of the optimal solution.

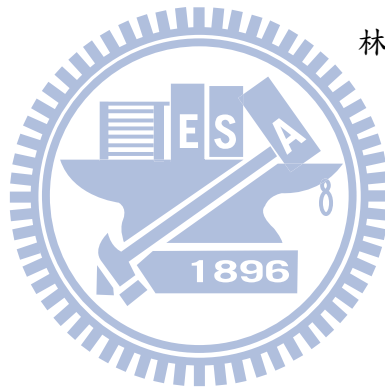


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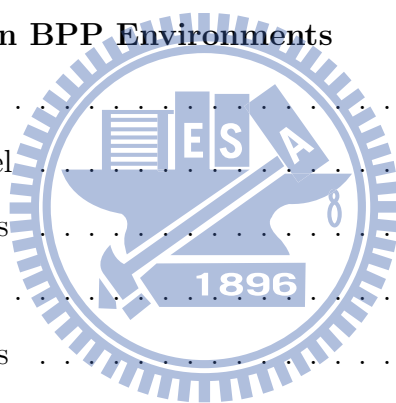
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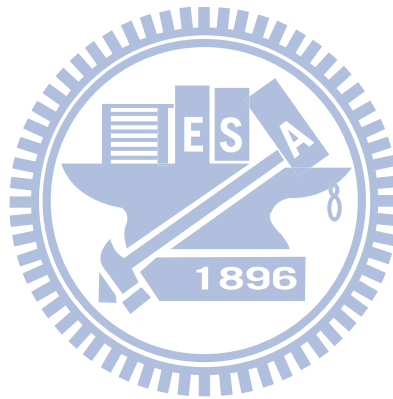
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Chapter 1

Introduction

The ever increasing demands for multimedia services have made the shortage of the radio resources a very challenge problem in the cellular network (CN) design and deployments. Device-to-device (D2D) communications as an underlay coexistence with CN has been proposed to overcome the resource shortage problem and improve the network throughput. It is a proximity-based technology enabling the cellular devices to communicate with each other directly. Because D2D devices share the same resources with CN, the resulting devices-to-CUs interference is of paramount concern. Therefore, the devices need to limit the interference causing to CN.

1.1 Concept of D2D Communications

In early 2006, Qualcomm began a project that wanted to exploit D2D communications. The idea was that devices would communicate directly with each other without the need for intermediary infrastructure. The motivation of this idea was quite simple. It is evidently resource inefficient for two proximate devices to communicate via evolved NodeB (eNB). One obvious way to serve some of this demand is to enable direct communications between proximate devices. There is an ongoing discussion on proximity-based services (ProSe) in Long term Evolution-Advanced (LTE-A).

The concept of D2D communications as an underlay to a CN is illustrated in Fig. 1.1. It operates on the same radio resources with CN. Besides cellular operation, where user

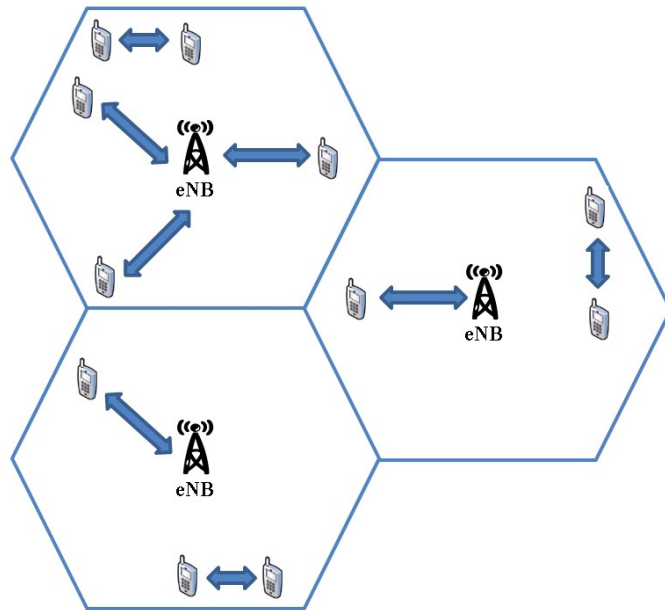


Figure 1.1: D2D communications are an underlay to a cellular network.

is served by eNB in the LTE architecture, device may want to communicate with each other over D2D link. The device in D2D link remains controlled by eNB and cellular operation user. The eNB can control the resources used for D2D link and cellular operation. The eNB also can set up the constraints on the maximum transmit power of D2D transmitters to limit the interference experienced at the cellular user (CU). In the case of a high loading LTE-A network, resources may also be assigned to D2D links. However, cognitive radio (CR) with a CN as the primary service would not have ability to detect locally unused spectrum perfectly.

D2D communications have three types of gains.

1. Proximity of device: provide for relatively high transmission rates, low propagation delays and low transmit power consumption [1].
2. Reuse gain: because the radio resources may be simultaneously used by CN and D2D links, tightening the reuse factor even in a reuse-1 system [2].
3. Hopping gain: D2D mode is used by a single communication link. However, in

the cellular mode, the both an uplink and a downlink resource are used when communicating via eNB.

But D2D communications still have some disadvantages, it would cause much overhead and interference to CN when the number of devices is very large. It would decrease the CUs' performance.

The applications of D2D communications lie mainly in three categories: commercial/social use, network offloading, and public safety. Some details can be seen in [3].

1.2 Other Communication Standards

In this section, we describe some existing local (short distance) communication standards which have some features and encounter problems similar to what D2D communications might have. Wireless local area network (WLAN) and Bluetooth both operate in the license-free industrial, scientific and medical (ISM) bands, so they maybe meet severe interference and no hard quality of service (QoS) guarantees. D2D communication operates in the licensed bands, so it can support interference-controllable and reliable communication. Nevertheless, when users utilize D2D communication service, they need be charged.

A wireless ad-hoc network is a self-configuring wireless network. Namely it does not rely on a preexisting infrastructure. But D2D communication can be controlled by eNB. CR technology is seen as the solution to the problem of low usage of the licensed spectrum. It has been proposed to exploit the spectrum holes—the frequency bands which are not used at some time or space—for license-exempt usages [4]. It has the same goal with D2D communication: to increase spectral efficiency. D2D device transmits data signals directly to each other by reusing the cellular network resources, similar to the secondary user (SU) scenario introduced in CR systems. However, with D2D communication can be controlled in cooperation with CNs, whereas the SU in CR systems is not controlled by the primary user (PU) networks [5, 6].

Machine-to-Machine (M2M) and D2D communication are two important technology trends. M2M is the communication that devices communicate without direct human interaction. D2D communication is the direct link communication between devices which use the cellular spectrum.

Wi-Fi Direct is an application of D2D communications. It allows Wi-Fi devices that can connect to each other without the help of a wireless access point (AP).

1.3 Overhead

Before the two devices can communicate over D2D link, they need to discovery each other which is close. In this section, we study why we consider an autonomous D2D link setup scheme. Supporting a massive number of D2D communications is an unavoidable trend. When establishing an air interface, a device needs to execute random access at random access channel (RACH). But there are few RACHs, supporting a massive random access requests will cause many collisions. Access class barring (ACB) is one of the solutions to combat this problem of RACH [7]. According to the idea of ACB, eNB control u (u is the probability that the device can execute random access at RACH) to let average simultaneous accesses at a common channel to be one. When the number of device is very large, u is relatively small. There will be an unacceptable waiting time for devices. If the device is located at cell edge, the aid of eNB is seen impossible in this case. There may exist a blind vision between eNB and device. Even if the two device are close to each other, they can not communicate with each other directly due to the limitation of eNB. In order to reduce the overhead of eNB and avoid problems as mentioned above, we discuss the autonomous D2D link setup scheme. The eNB will broadcast the message to devices if some RBs are interfered. The devices need to stop transmission. But how to charge the device which uses the D2D communication is a important commercial problem. Here, we don't discuss this issue. There is also an example to motivate us to consider D2D link setup automatically. FlashLinQ [8] is a proximity-aware technology

which has been proposed by Qualcomm. The device discovery protocol is a synchronous OFDM-based physical layer. It allows the device to discover other FlashLinQ enabled devices automatically. More details about FlashLinQ are described in the next chapter.

1.4 Literatures Review and Motivation

There exists a problem in D2D communication. Before the two devices can directly communicate with each other, they must discovery that they are close to each other. Most of works on D2D communication have mainly focus on the resource allocation, power control, and mode selection schemes [9-17]. However these works have an unreasonable assumption, D2D link has been already set up and most of them only consider a single D2D pair which coexists with CN. Only few works focus on link discovery [18-20]. Therefore, we need to consider multiple D2D pairs, focus on D2D link setup procedure, and how to find the usable radio resources such that the interference cause to CN is acceptable.

There are three common technologies that have proximity discovery. There are Bluetooth, FlashLinQ and Wi-Fi Direct. Because the proximity discovery in Bluetooth is a low-level radio channel to discovery, we apply the concept of proximity discovery in Bluetooth. The environment that we consider is a multi-devices system. The traditional proximity discovery in Bluetooth seems to be very weak. Therefore, we need to consider a adequate proximity discovery scheme to make multi-devices communications possible. In our thesis, we consider that there is a single probing channel to support proximity discovery. There will be a very high collision probability. In order to achieve high D2D link setup performance, a multiple probing channels scheme is necessary in future work.

1.5 Contributions

We analyze the success D2D link setup (SDLS) probability under two different point processes describing the locations of communication terminals, namely, the Binomial

point process (BPP) and the Poisson point process (PPP). The point process is used to model the locations of CU and devices. We propose a D2D link setup scheme. Based on this scheme, we analyze the SDLS probability with the help by some mathematical functions and stochastic geometry. Under BPP model, we consider a quite simple case here. The deterministic and stochastic also covered in our analysis. We obtained the close-form of SDLS probability without channel fading effect. But in stochastic scenario, the performance is evaluated by numerical method. Under PPP model, we respectively use an approximate scenario and a upper bound scenario to model the interference sources which are generated by PPP and let the SDLS probability as an optimization problem in upper bound scenario. The goal is to find the optimal transmit power P_D of active device to maximize the SDLS probability. We prove that the objective function is quasiconcave and use the bisection method to find the only optimal solution. We also find a scheme to set up the upper limit of this method. However, the optimal transmit power P_D^* is based the parameters of wireless environment. Therefore, the power control is needed in active devices to make the SDLS probability larger.

1.6 Thesis Structure

The rest of this thesis is organized as follows. In chapter 2, we review the point process, some mathematical tools, and connection setup procedure for some existing wireless communication standards. The following chapter 3 introduces system model and the procedures to set up a D2D communication link. SDLS analysis and analytical results under Binomial point process and Poisson point process models are described respectively in chapter 4 and chapter 5. Finally, we draw our conclusion and future work in chapter 6. In the table 1.1, we give some symbol descriptions of our thesis.

Table 1.1: Summary of Notations

Symbol	Description
\mathbb{R}^d	d -dimensional space
\mathbb{R}^+	positive real numbers
$A \cap B$	the intersection of set A and set B
$\mathbb{P}(A)$	probability of event A
$\mathbb{E}(X)$	expectation of random variable X
α	path loss exponent
d	number of dimensions of the network
$ A $	Lebesgue measure of set A . For $d = 1, 2$, or 3 , it consists with the standard measure of length, area, or volume.
$\ \cdot\ $	Euclidean norm
c_d	volume of the d -dim. unit ball
$\mathcal{L}_X(s) = \mathbb{E}(e^{-sX})$	Laplace transform of random variable X
$\Phi = \{X_i\} \subset \mathbb{R}^d$	point process
$F_X(x) = \mathbb{P}(X \leq x)$	cumulative distribution function of random variable X
P_D	common transmit power of active devices
N_0	noise power

Chapter 2

Preliminaries

The signal-to-interference-plus-noise-ratio (SINR) is the primary signal quality metric that must be satisfied by a communication link. The interference is an important term in wireless network. However, it is a function of network topology, path loss, and channel fading effect. There are two main tools to help us analyze the interference: stochastic geometry [21] and random geometric graphs [23]. Because the nodes appearing in the wireless network may follow some spatial distribution, stochastic geometry is useful in modeling the network topology, and analyzing the average behavior over many spatial realizations of a network. Then, we will introduce some concepts about stochastic geometry. They called it point process (PP). Later, there will be some mathematical tools and functions to help us compute some properties that we are interested in of wireless communication systems. Finally, the connection procedure of some wireless communication standards such as FlashLinQ, Bluetooth, WLAN, and ZigBee are introduced.

2.1 Point Process

In the stochastic geometry, the basic objects are point processes. A PP can be described as a stochastic collection of points in the space. For a detailed concept and analysis of PP, readers can refer to [21-22, 24]. Why do we consider the PP? When we describe the locations of nodes, a PP can be used to model these nodes on the space

that we are interested in. It can help us do some mathematical analysis of the wireless network.

$\phi(B)$ denotes the number of points of ϕ in $B \subset \mathbb{R}^d$. \mathcal{N} denotes the smallest sigma algebra such that the mappings $\phi \rightarrow \phi(B)$ are measurable for all Borel sets $B \subset \mathbb{R}^d$.

Definition 1 (Point process, [24]) *It is a measurable mapping function Φ on \mathbb{R}^d from the probability space $(\Omega, \mathcal{A}, \mathbb{P})$ to $(\mathbf{N}, \mathcal{N})$.*

$$\Phi : \Omega \rightarrow \mathbf{N} \quad (2.1)$$

A point process is a stochastic variable which takes the values in the set of the sequences \mathbf{N} . There are some terminologies about PP Φ in the following.

1. If a PP is said to be simple \Rightarrow no two points with the same location (at most one point at a location).

$$\lim_{|A| \rightarrow 0} \frac{\mathbb{P}(\Phi(A) \geq 1)}{\mathbb{P}(\Phi(A) = 1)} = 1 \quad (2.2)$$

where $\Phi(A)$ is the number of points in set A .

2. If a PP is said to be stationary \Rightarrow the regulation of the PP is invariant by translation.

$$\Phi + s = \{u + s | u \in \Phi\} \sim \Phi, \quad s \in \mathbb{R}^d \quad (2.3)$$

3. If a PP is said to be isotropic \Rightarrow the regulation of the PP is invariant by rotation.

$$R\Phi = \{Ru | u \in \Phi\} \sim \Phi \quad \forall R \in \mathcal{M}_{d \times d} = \{d \times d \text{ Orthogonal Matrix}\} \quad (2.4)$$

where R denotes the rotation around the origin.

If the PP is both stationary and isotropic, it is also called a *motion-invariant* PP.

Definition 2 (Intensity Measure, [24]) *The intensity measure of the PP Φ is equal to the average number of points in the set $B \subset \mathbb{R}^d$.*

$$\Lambda(B) = \mathbb{E}[\Phi(B)] \quad (2.5)$$

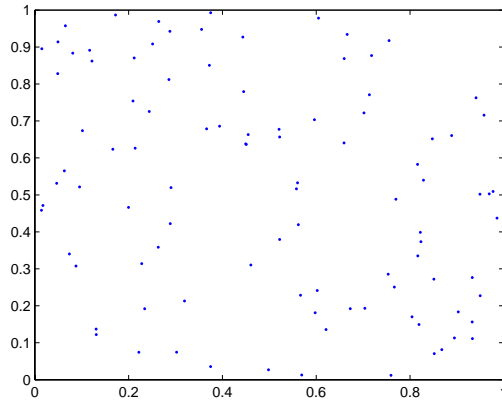


Figure 2.1: BPP with bounded set $S = [0, 1] \times [0, 1]$, $n = 100$.

If Φ is a stationary PP, then $\Lambda(B) = \lambda|B|$ where λ is called the intensity of Φ .

Definition 3 (Probability Generating Functional, [24]) Let $\psi(x) : \mathbb{R}^d \rightarrow [0, \infty)$ be measurable. The probability generating functional (PGFL) of the PP can be defined.

$$G(\psi) = \mathbb{E} \left[\prod_{x \in \Phi} \psi(x) \right] \quad (2.6)$$

The subsequent subsections will introduce two types of PP, namely Binomial point process (BPP) and Poisson point process (PPP).

2.1.1 Binomial Point Process

In a bounded domain, the BPP is generally used to construct the location of wireless nodes with a fixed number n . It is a quite simple point process. The n points are independently and uniformly distributed in a bounded and closed set $B \subset \mathbb{R}^d$ (d -dimensional space). The BPP can be illustrated in Fig. 2.1. The probability that there are k points in $A \subset B$ is given by

$$\mathbb{P}(\Phi(A) = k) = \binom{n}{k} \left(\frac{|A|}{|B|} \right)^k \left(1 - \frac{|A|}{|B|} \right)^{n-k} \quad (2.7)$$

where $\Phi(A)$ is defined as the number of points in set A and $|A|$ stands for the Lebesgue measure of the set A .

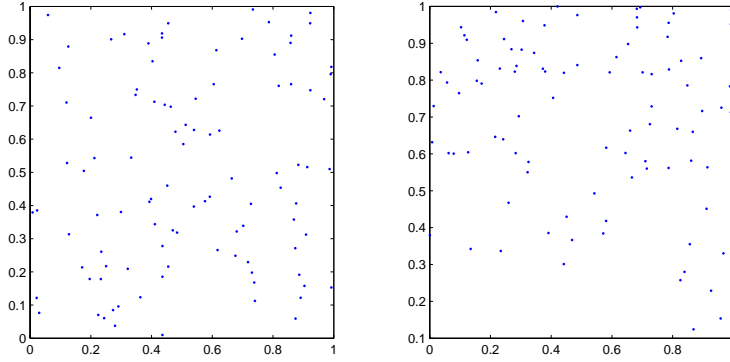


Figure 2.2: PPP with set $S = [0, 1] \times [0, 1]$; left side: homogeneous, $\lambda=100$; right side: inhomogeneous, $\lambda(x, y) = 200y$.

Note that the $\Phi(A)$ and $\Phi(B)$ are not independent even if $A \cap B = \emptyset$. This property makes the analysis of the received interference in the wireless network more difficult.

The PGFL of BPP Φ is equal to

$$G(\psi) = \left(\frac{1}{|A|} \int_A \psi(x) dx \right)^n \quad (2.8)$$

2.1.2 Poisson Point Process

The PPP is a most well-studied point process. Its importance comes from its ease to analyze. Therefore, the PPP provides a handy computational framework for different performance metric of interest.

1. If a PP is said to be a homogeneous PPP \Rightarrow the value of intensity keeps the same across space. It is isotropic and stationary process. It may be the simplest point process. It can be illustrated on the left side in Fig. 2.2.
2. If a PP is said to be an inhomogeneous PPP \Rightarrow the value of intensity doesn't keep the same across space, and it can be used to model the distribution with non-uniform type across space. Like in a city, the intensity is not the constant everywhere. It can be illustrated on the right side in Fig. 2.2.

The homogeneous PPP Φ with intensity (or density) λ is characterized by the below properties:

1. For all the disjoint sets A_1, \dots, A_k , the random variables $\Phi(A_i)$ are independent.
2. All the random variables $\Phi(A_i)$ are Poisson random variables with mean $\lambda|A_i|$.

$$\mathbb{P}(\Phi(A) = k) = e^{-\lambda|A|} \frac{(\lambda|A|)^k}{k!} \quad (2.9)$$

Conditioned on the fact that there are n points in set A , the n points are independently and uniformly distributed in set A , namely BPP. There are some important properties of the PPP as the following.

1. The superposition of two or more independent PPPs with intensities $\lambda_1, \dots, \lambda_k$ is also a PPP with intensity $\sum_{i=1}^k \lambda_i$
2. The independent thinning of the PPP with intensity λ results in independent PPPs with intensity $\kappa_i \lambda$ such that $\sum_{i=1}^K \kappa_i = 1$.
3. If Φ is a homogeneous PPP with unit intensity ($\lambda=1$), then $\lambda^{-1/d} \Phi$ is a homogeneous PPP with intensity λ .
4. The PGFL of PPP Φ is equal to

$$G(\psi) = \exp \left(- \int_{\mathbb{R}^d} (1 - \psi(x)) \Lambda(dx) \right) \quad (2.10)$$

2.2 Mathematical Tools

2.2.1 Gamma Function

The definition of Gamma function is given by

$$\Gamma(a) \triangleq \int_0^{\infty} t^{a-1} e^{-t} dt \quad (2.11)$$

Corollary 1 (Convex, [24]) When X is a exponential random variable with unit mean, then the m -th moment of X is given by

$$\mathbb{E}[X^m] = \Gamma(1 + m) \quad (2.12)$$

Proof:

$$\mathbb{E}[X^m] = \int_0^{\infty} x^m e^{-x} dx = \int_0^{\infty} x^{(m+1)-1} e^{-x} dx = \Gamma(1 + m)$$

■

There is an important functional equation: Euler's reflection formula.

$$\Gamma(1 - a)\Gamma(a) = \frac{\pi}{\sin(\pi a)} \quad (2.13)$$

2.2.2 Other Function

Definition 4 (Convex, [25]) A function f is convex if and only if $\mathbf{dom} f$ is convex and for any $x, y \in \mathbf{dom} f$ and $0 \leq \theta \leq 1$,

$$f(\theta x + (1 - \theta)y) \leq \theta f(x) + (1 - \theta)f(y) \quad (2.14)$$

If f is convex, $-f$ is concave.

Definition 5 (Quasiconvex, [25]) A function f is quasiconvex if and only if $\mathbf{dom} f$ is convex and for any $x, y \in \mathbf{dom} f$ and $0 \leq \theta \leq 1$,

$$f(\theta x + (1 - \theta)y) \leq \max\{f(x), f(y)\} \quad (2.15)$$

If f is quasiconvex, $-f$ is quasiconcave.

Consider a d -dimensional homogeneous PPP with intensity λ . Let's determine the distance D between the device k and its nearest neighbor. The cumulative distribution function (CDF) of random variable D :

$$\begin{aligned} F_D(x) &= \mathbb{P}(D \leq x) = 1 - \mathbb{P}(D > x) \\ &= 1 - \mathbb{P}(\text{there exist no other devices in ball centered at the device } k \text{ with volume } c_d x^d) \\ &= 1 - \exp(-\lambda c_d x^d) \end{aligned} \quad (2.16)$$

where c_d is the volume of the d -dimensional unit ball and defined in the following.

$$c_d \triangleq \begin{cases} \frac{\pi^{\frac{m}{2}}}{(\frac{m}{2})!}, & \text{for even } d \\ \frac{\pi^{\frac{d-1}{2}} 2^d (\frac{d-1}{2})!}{d!}, & \text{for odd } d \end{cases} \quad (2.17)$$

Therefore, the probability density function (PDF) of D :

$$f_D(x) = \frac{d}{dx} F_D(x) = \lambda c_d d x^{d-1} \exp(-\lambda c_d x^d) \quad (2.18)$$

For example, by letting $d=2$, then $f_D(x) = 2\lambda\pi x \exp(-\lambda\pi x^2)$ and $F_D(x) = 1 - \exp(-\lambda\pi x^2)$.

2.3 Connection Setup Procedure

In this section, we describe how these local wireless communication standards (FlashLinQ, Bluetooth, WLAN, and ZigBee) perform connection setup respectively.

2.3.1 FlashLinQ

It is a synchronized device discovery operation [26, 27]. All devices are synchronized to an external time resource. The device uses a small fraction of time-slots to discover the existence of other nodes in the neighborhood. Every device sends its own discovery signal and listens to other discovery signals from other devices to detect the device of interest in the proximity periodically. All devices are required to play a part in device discovery even if they are not active.

There are 5600 logical channels for device discovery and repeats every 8 seconds. The question is how to pick the logical channel in a distributed way. Carrier sensing is a way to pick the logical channel.

2.3.2 Bluetooth

Bluetooth is a short-range technology which operates in the 2.4 GHz ISM band. The transmission range of Bluetooth is about 10 meters, and its signals do not require line-of-sight (LOS) which can pass through most physical barriers. The procedures of

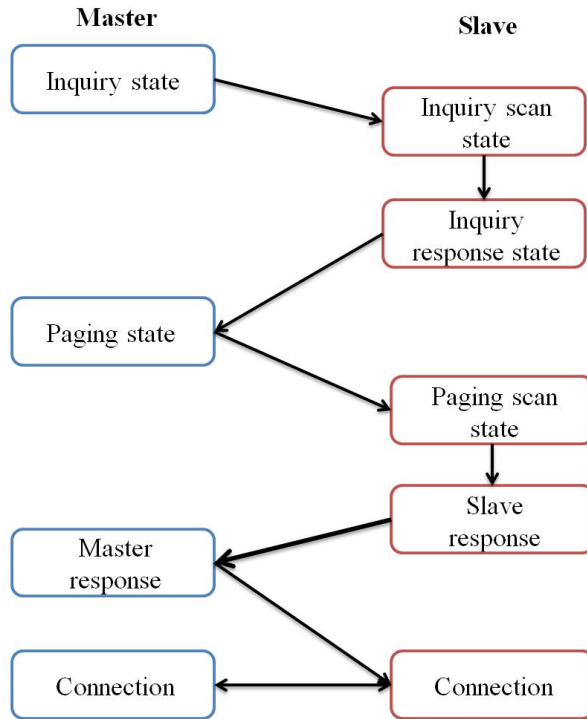


Figure 2.3: The connection setup procedure of Bluetooth devices.

Bluetooth connection setup can be divided into two steps: Bluetooth device discovery and connection setup. In Fig. 2.3, the procedures of connecting with other Bluetooth device is illustrated. When a Bluetooth device wants to setup a connection with other Bluetooth devices, it enters the inquiry state to discover other devices. During inquiry state, the device generates an inquiry hopping sequence and broadcasts inquiry messages so that it sequentially changes to each channel according to the hopping sequence.

Discoverable devices periodically enter the inquiry scan state. If the device executes the inquiry scan and receives an inquiry message, it will enter the inquiry response state and feedback an inquiry response message. This response contains the remote (slave) device's address and clock. All the discoverable devices that are within the range of the broadcaster will reply to the inquiry device. A list of all discovered devices will be shown in the broadcaster. The user needs to manually choose the desired Bluetooth device.

After obtaining and choosing a Bluetooth device, the local (master) device enters

paging state to setup a connection with remote device. In this state, the local device generates a hopping sequence. A device periodically enters the page scan state if it allows other devices to connect. When the remote device receives the page packet, it will reply a page response packet to the local device. Upon receiving the response, the local device sends a Frequency Hopping Synchronization (FHS) packet to the remote device. Once the remote device receives the FHS packet, it sends an acknowledgement (ACK) to the local device. If the paging procedure is complete, the devices enter the connection state. The local device will send a poll packet to the remote device to confirm that the transition of hopping sequence is successful. Then, they will communicate with each other. Some technical details can refer to [28].

2.3.3 WLAN

IEEE 802.11 is the set of standards for executing wireless local area network (WLAN). It is a local area network which doesn't depend on wired connections. It provides short-range wireless connections between mobile devices and nearby APs. Because the wireless signal is broadcast in the wireless environment, every device which is nearby to the broadcaster can share it. Therefore, several security protections are necessary. The range of WLAN can cover from a small office to a large campus. The procedures of establishing a connection with WLAN can be classified into two scanning modes. [29].

1. **Passive scanning mode:** a device listens to the WLAN traffic for detecting APs and measures the noise level and signal strength.
2. **Active scanning mode:** a device transmits a request frame which contains the broadcast address and waits for responses from APs.

2.3.4 ZigBee

An application of ZigBee is in wireless sensor networks. The device in the ZigBee

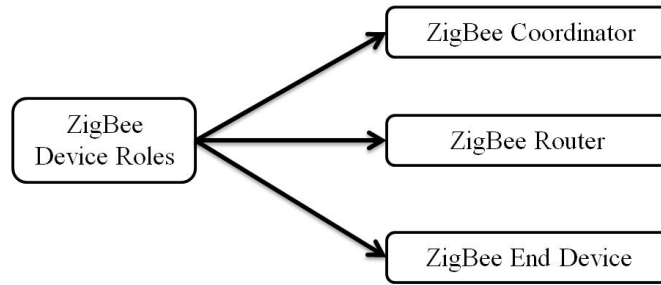


Figure 2.4: Device roles in the ZigBee standard.

standard can be classified into three roles as shown in Fig. 2.4. Note that a ZigBee end device is neither a router nor a coordinator.

A ZigBee network constructs its topology when devices become active. Like in a mesh network, the first full-function device (FFD) that begins communicating can setup itself as the ZigBee coordinator. By sending association requests, other devices can join the network. There is no additional regulator required to setup a network, so the ZigBee networks are called as self-forming networks. When a mesh network is setup, there may exist more than one transmission path to relay the message from the source to the destination. There will exist one path to route the message efficiently. If the network condition changes, the change of the routing path in the network is necessary. In contrast to other networking technologies, ZigBee networks have no infrastructure. For example, in WLAN, there is a wireless AP. More details of the ZigBee standard can refer to [30].

Chapter 3

System Model and Link Setup Procedure

We present in this chapter the system model and related D2D link setup procedure. The system model is the environment that we consider. Some detailed settings are described respectively in chapters 4 and 5. In the next section, we will introduce the procedure to set up a D2D communication link.

3.1 System Model

The structure of system that we consider is a two-dimensional (plane) single cell orthogonal frequency-division multiple access (OFDMA) system. The whole spectrum is divided into equal and consecutive orthogonal sub-channels. We assume that all the radio resources are assigned to CUs. Therefore, D2D transmitter needs to share the same resources with CUs without causing harmful interference (we assume that the D2D device reuses the downlink resources of the CN). There are three types of users in our scenario:

1. Cellular user: the user who uses the orthogonal resource units assigned by the eNB.
2. Active device: the device which wants to communicate with a received device over D2D link. It has a common transmit power P_D . It does not need a specific received

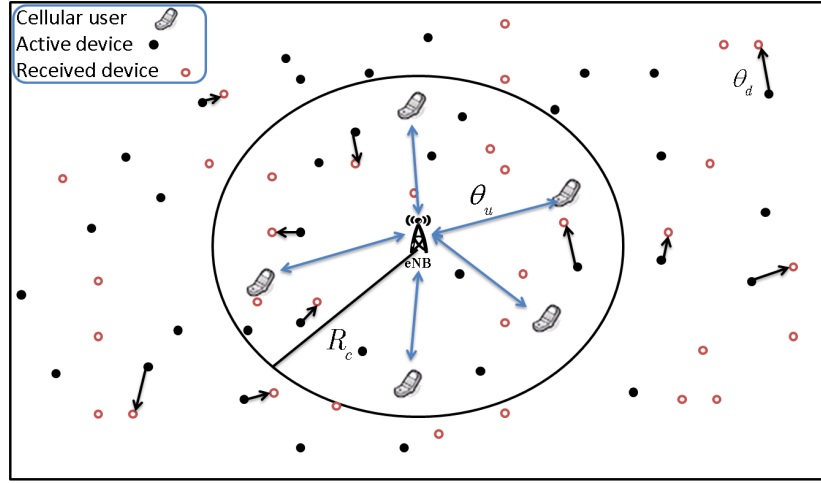


Figure 3.1: System model of D2D communications underlies a cellular network.

device. Every device which is idle can connect with it.

3. Received device: the device which wants to receive the data from an active device over D2D link.

Fig. 3.1 depicts a scenario which includes active CUs, active devices, received devices, and an eNB. Both CUs and devices are equipped with single antenna. The coverage range of the eNB is defined as R . The radius of cell coverage range is R_c . Without loss of generality, the location of eNB is defined as origin $(0,0)$. There are M resource blocks (RBs) per (sub)frame. Each active CU is given average amount of all the RBs orthogonally. Namely, if there are N_u active CUs, every CU obtains M/N_u RBs. Due to the exhaustion of battery, the received device which is power off or not in discoverable mode, we define busy probability of received device as β . As there is no inter-cell interference, no inter-CU interference exists. However, as multiple active devices share the same OFDMA RBs with CUs, the resulting devices-to-CUs interference is of paramount concern. The CUs' locations are modeled by BPP in the bounded domain R . Namely, CUs are uniformly distributed within the coverage range R of the eNB. The active and received devices' locations follow two point processes, BPP and PPP. In the next two chapters, the D2D link setup analysis based on BPP and PPP models will be shown.

1. BPP: the numbers of active and received devices are given with two fixed numbers N_a and N_d respectively in the bounded domain R . These devices are uniformly distributed in R .
2. PPP: the locations of active and received devices are modeled by two independent homogeneous PPPs Φ_a and Φ_d with intensity λ_a and λ_d (over an area much larger than a cell).

To have a reliable link between the active and received devices, and an acceptable interference to CUs, we define the following two primary parameters: θ_d and θ_u .

1. θ_d : the minimum signal-to-noise-ratio (SNR) requirement of the received device.
2. θ_u : the minimum SINR requirement of the CU.

Definition 6 (Outage Probability, [31]) *The outage is the event that capacity is smaller than the information rate R . The outage probability is defined as*

$$\nu \triangleq \mathbb{P}(\log_2(1 + SINR) < R) \quad (3.1)$$

For a given information rate R , θ_u is obtained.

$$\theta_u \triangleq 2^R - 1$$

The goal is that there are active devices which want to communicate with other received device over D2D link which has a reliable link condition and shares the spectral resources with CUs, but they can not cause much interference to make CU outage. Therefore, the distance between two devices needs to be close enough and the interference from devices to CUs needs to be small enough. According to these two requirements, the SDLS condition is defined in the following.

Definition 7 (Conditions for SDLS) *The SDLS includes two conditions. There is at least one idle received device which received the SNR larger than pre-determined threshold*

θ_d . There are also existing Q usable RBs that the active device can share with CUs and satisfy the CU's SINR requirement θ_u (non-outage).

The transmitted signal suffers from a deterministic path loss in the deterministic channel or channel fading effect (including path loss) in the stochastic channel, i.e., the received signal power is a deterministic or random function of the transmitted power, the transmission distance, or channel fading effect.

3.2 SDLS Procedure

From the existing connection setup procedure of some wireless communication standards introduced in chapter 2, we propose a link setup procedure for D2D communication. The SDLS procedure includes four steps: access the probing channel, device discovery, resource discovery, and D2D link setup. The flowchart will be shown in Fig. 3.2.

1. **Access the probing channel:** A probing channel (resource block, RB) is reserved for devices' initial link discovery application. When the active device wants to probe other received devices at a probing channel, it needs to check the probing channel whether it is being used or not. It uses carrier sense multiple access (CSMA)-type MAC scheme. If there are active devices using the probing channel, it re-senses the probing channel after a random nonzero delay.
2. **Device discovery:** If the active device senses that there are no other active devices using the probing channel, it emits a probing signal with power P_D at the probing channel to check if any idle received devices are within its probing range. An idle received device which received the SNR larger than pre-determined threshold will respond with a consent-to-send message along with a preferred RB list. If there exists more than one received device responses, the active device will choose one amongst all the devices which have responded. If no received devices

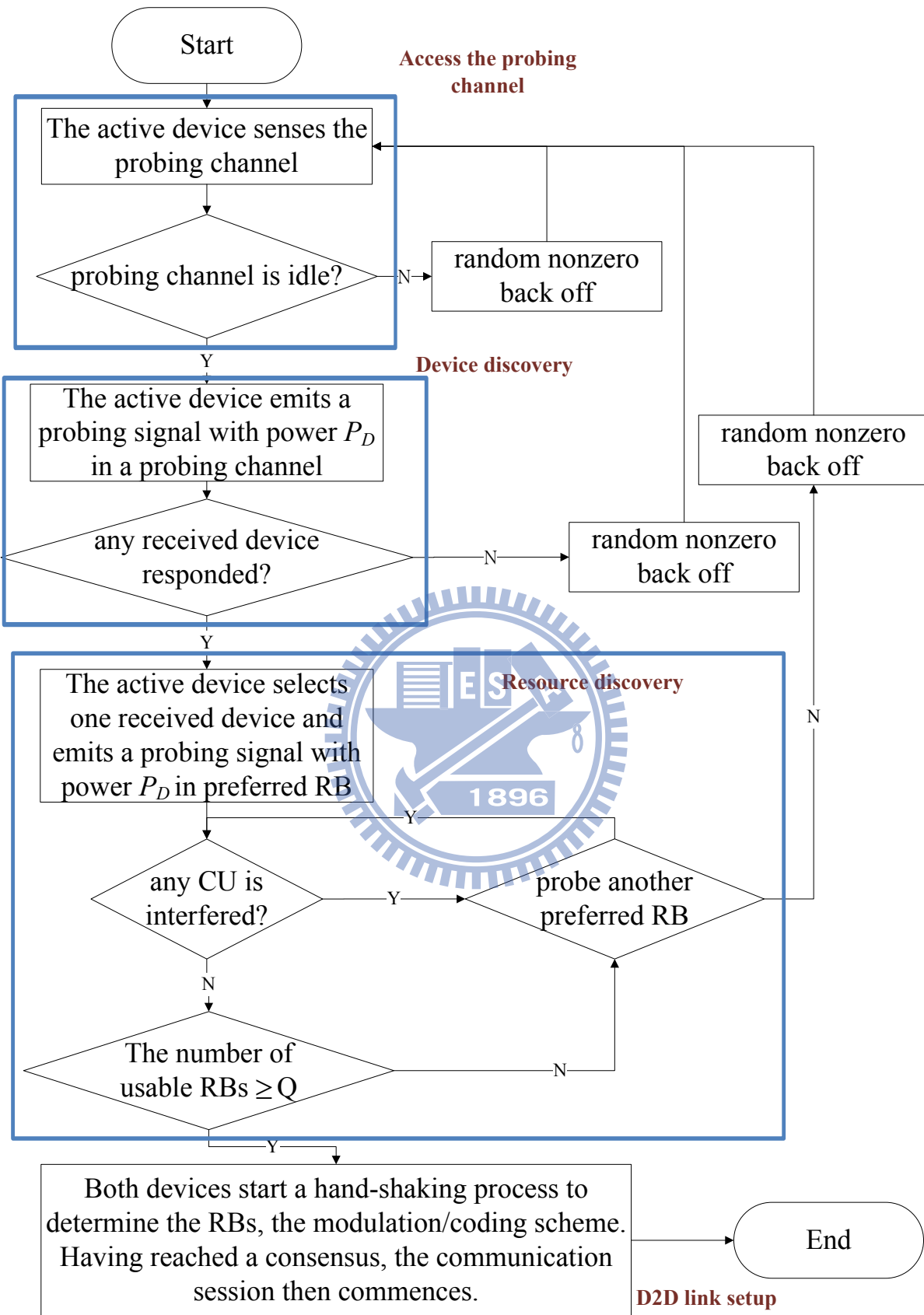


Figure 3.2: The flow chart of SDLS procedure.

respond for a pre-defined period (this period depends on the round-trip time which is based on coverage radius), the active device re-executes step-1 after a random nonzero delay.

3. **Resource discovery:** Then, the active device emits a probing signal with power P_D in the first preferred RB to check if any CU is interfered. If there are no CUs interfered (the device does not receive any negative-acknowledgement (NACK) from CUs), the active device can reuse this RB and check whether the number of usable RBs satisfy the constraint (at least Q usable RBs) or not. If the number of usable RBs $\leq Q$, the active device probes another preferred RB. On the contrary, if the CU is interfered (the device receives a NACK from the CU), the active device re-broadcasts the probing signal in next preferred RB. It repeats this setup until the number of usable RBs $\geq Q$ or all the preferred RBs are testing over. If there exists at least Q usable RBs that the active device can share with CUs without causing harmful interference, the active device executes step 4. On the contrary, the active device re-executes step-1 after a random nonzero delay.
4. **D2D link setup:** Both devices start a hand-shaking process to determine the modulation/coding scheme. Having reached a consensus, the communication session then commences.

The analysis under BPP and PPP models which are described respectively in chapters 4 and 5 are based on an example case, we assume that the received device responds one preferred RB and $Q = 1$ which means the active device uses one preferred RB to communicate over D2D link. Note that in the transmission of D2D communication, if some CUs are interfered, the eNB has the right to forbid the active devices' transmission.

Chapter 4

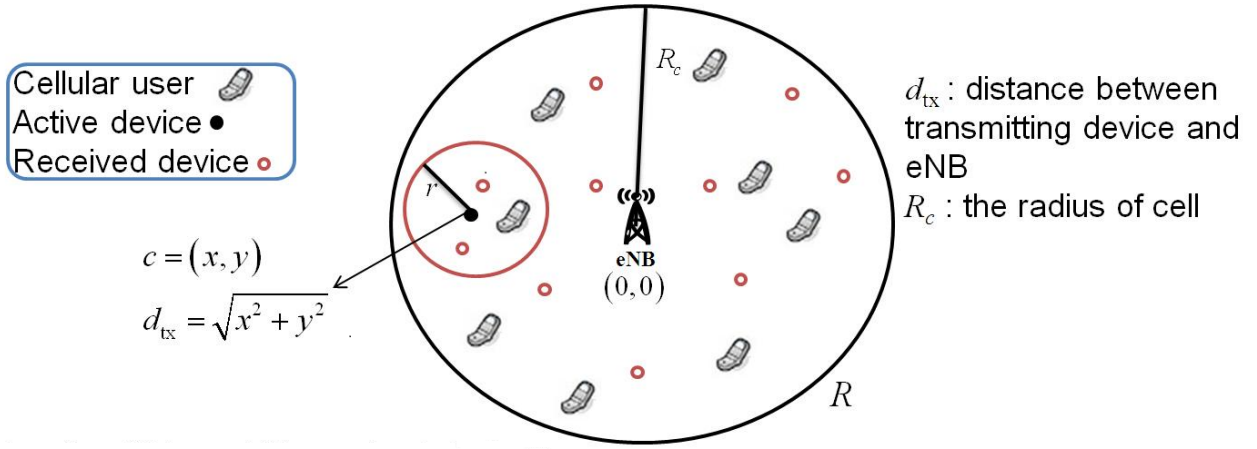
Performance Analysis in BPP Environments

In this chapter, we consider the scenario that an active device wants to setup a D2D link (a reliable link between the active device and received device) using the same spectrum with CUs without causing intolerable interference. Therefore, the link range has to be close enough and the interference from the active device to CUs has to be small enough. According to *Definition 7*, we analyze the SDLS performance using the BPP model with deterministic and stochastic channels respectively. Closed-form expressions of the SDLS performance are derived and related numerical results are given.

4.1 System Model

To begin with, we consider the special case that there is only a single active device so that there is no need for accessing the probing channel. The system architecture under BPP model is shown in Fig. 4.1. To establish a D2D link this device has to find an idle device without causing too much interference to CUs. We assume that a proper power control scheme is in place to ensure that the same average power P_{CU} is received for every CU and each CU within the coverage region has the same tolerable interference $I_{\min}^{(CU)}(\frac{P_{CU}}{\theta_u} - N_0)$.

Given the active device location $c=(x,y)$ and its distance $d_{tx}=\sqrt{x^2 + y^2}$ in a reference coordinate within R , we have to evaluate its distance to the eNB. We assume that both



N_d active CUs, N_r received devices and an single active device

Figure 4.1: BPP model of D2D communications underlays cellular network.

CUs and the potential receiving devices are uniformly distributed within the coverage range R of the eNB and denote by $\mu_d^{(k)}(r_d|d_{tx})$, the probability that the active device finds k received devices within a radius- r_d circle (centered at c).

Because we skip the accessing the probing channel step, SDLS procedure includes three steps:

1. Received device discovery.
2. Resource discovery: find the spectral resources to share with CUs without causing harmful interference.
3. D2D link setup.

In the next two sections, we analyze the SDLS performance in the deterministic and stochastic channels respectively.

4.2 Deterministic Channel

The received signal power $P_{D_i}^{(d)}$ at the i th received device terminal and the corresponding SNR $\gamma_{D_i}^{(d)}$ in deterministic channel are given respectively by

$$P_{D_i}^{(d)} = \frac{P_D}{d_{\text{tx},D_i}^\alpha}, \quad i = 1, \dots, N_d \quad (4.1)$$

and

$$\gamma_{D_i}^{(d)} = \frac{P_{D_i}^{(d)}}{N_0}, \quad i = 1, \dots, N_d \quad (4.2)$$

where d_{tx,D_i} is the distance between the active device and the i th received device.

The received interference power $I_{\text{CU}_i}^{(d)}$ at the i th CU in deterministic channel is given by

$$I_{\text{CU}_i}^{(d)} = \frac{P_D}{d_{\text{tx},\text{CU}_i}^\alpha}, \quad i = 1, \dots, N_u \quad (4.3)$$

where $d_{\text{tx},\text{CU}_i}$ is the distance between the active device and the i th CU.

4.2.1 SDLS Analysis

In order to have a reliable link to the received device and a tolerable interference to CU, we need to set up the constraints in (4.4) and (4.5).

$$\gamma_{D_i}^{(d)} = \frac{P_D}{d_{\text{tx},D_i}^\alpha N_0} \geq \theta_d, \quad i = 1, \dots, N_d \quad (4.4)$$

and

$$I_{\text{CU}_i}^{(d)} = \frac{P_D}{d_{\text{tx},\text{CU}_i}^\alpha} \leq I_{\min}^{(\text{CU})}, \quad i = 1, \dots, N_u \quad (4.5)$$

From (4.4) and (4.5), we can obtain the radius of the reliable range and interference range by letting the equality satisfy in (4.4) and (4.5).

$$r_d \triangleq \left(\frac{P_D}{N_0 \theta_d} \right)^{\frac{1}{\alpha}} \quad (4.6)$$

$$r_u \triangleq \left(\frac{P_D}{I_{\min}^{(\text{CU})}} \right)^{\frac{1}{\alpha}} \quad (4.7)$$

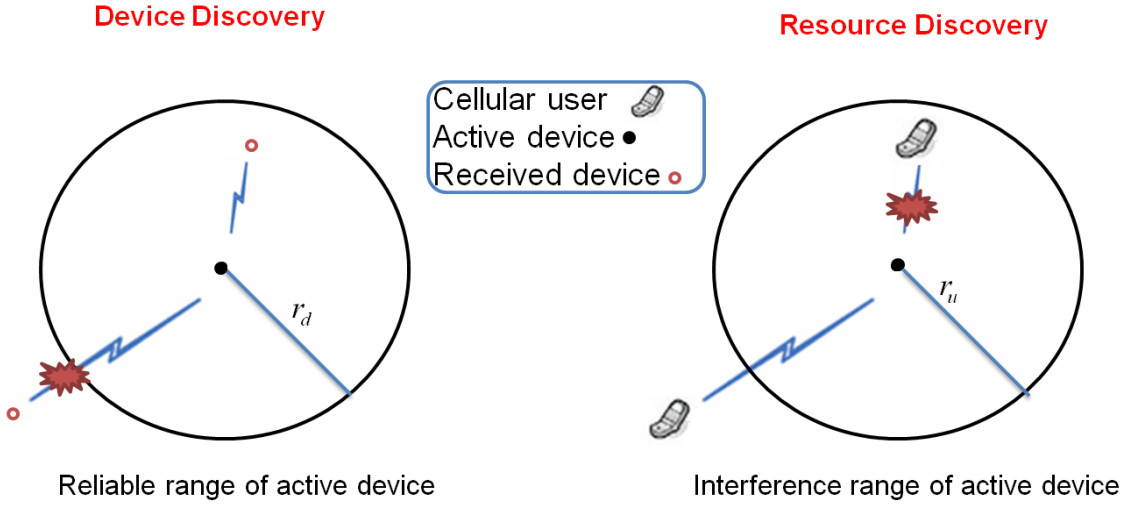


Figure 4.2: Reliable and interference ranges of the active device.

r_d is a function of P_D and θ_d . When the active device transmit power P_D is getting larger, the reliable range also becomes larger. The reliable range is relative to the SNR requirement of received device. r_u is a function of P_D and $I_{\min}^{(\text{CU})}$. When active device transmit power P_D is getting larger, the interference to CU also becomes larger. The interference range is relative to the tolerable received interference power level at the CU.

From equations (4.6), (4.7) and define the ratio between θ_d and $\frac{I_{\min}^{(\text{CU})}}{N_0}$ as ζ where $\zeta = \frac{N_0 \theta_d}{I_{\min}^{(\text{CU})}}$, the relation between r_d and r_u can be obtained.

$$r_u = r_d \zeta^{\frac{1}{\alpha}} \quad (4.8)$$

From the above assumptions, we summarize the concept of reliable and interference ranges.

1. **Reliable range:** A received device must lie within a circle of radius r_d from the active device to be able to detect the probing pilot and have a reliable communication link with the broadcaster. It can be illustrated on the left side in Fig. 4.2.
2. **Interference range:** A CU must be at a distance larger than r_u away from the

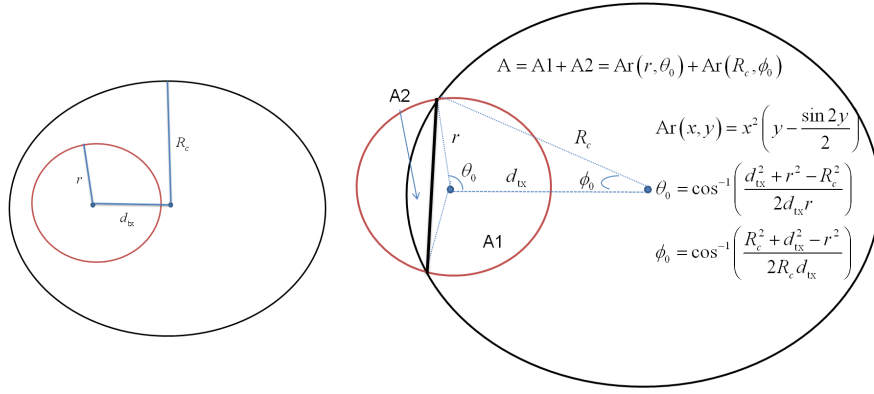


Figure 4.3: The illustration of the intersection area between two circles.

active device, so the interference to CU is tolerable. It can be illustrated on the right side in Fig. 4.2.

Lemma 1 *The intersection area between the coverage range R of the eNB and a radius- r circle centered at c with distance d_{tx} from eNB is [17]*

$$A_{intersect}(r|d_{tx}) = \begin{cases} \pi r^2, & \text{if } 0 \leq r \leq R_c - d_{tx} \\ Ar(r, \theta_0) + Ar(R_c, \phi_0), & \text{if } R_c - d_{tx} < r \leq R_c \end{cases} \quad (4.9)$$

where

$$\begin{aligned} Ar(x, y) &= x^2 \left(y - \frac{\sin 2y}{2} \right) \\ \theta_0 &= \cos^{-1} \left(\frac{d_{tx}^2 + r^2 - R_c^2}{2d_{tx}r} \right) \\ \phi_0 &= \cos^{-1} \left(\frac{d_{tx}^2 + R_c^2 - r^2}{2d_{tx}R_c} \right) \end{aligned}$$

The illustration of the intersection of two ranges can be seen in Fig. 4.3.

Device Discovery

The active device emits a probing signal with power P_D at the probing channel to check if any idle received device is within its probing range. An idle received device which is inside the reliable range of the active device will respond with a consent-to-send message along with a preferred RB number. Let $p_a(r|d_{tx})$ denote the probability that

the received device is within a radius- r circle centered at c with distance d_{tx} from eNB.

$$p_a(r|d_{tx}) = \frac{A_{\text{intersect}}(r|d_{tx})}{\pi R_c^2} \quad (4.10)$$

Therefore, the probability $\mu_d^{(k)}(r_d|d_{tx})$ is obtained.

$$\mu_d^{(k)}(r_d|d_{tx}) = \binom{N_d}{k} (p_a(r_d|d_{tx}))^k (1 - p_a(r_d|d_{tx}))^{N_d-k}, \quad k = 0, \dots, N_d \quad (4.11)$$

Next, we define the probability $\mu_d'^{(k)}(r_d|d_{tx})$ that there are k received devices inside the reliable range of the active device and exit at least one idle received device.

$$\mu_d'^{(k)}(r_d|d_{tx}) = \binom{N_d}{k} (p_a(r_d|d_{tx}))^k (1 - p_a(r_d|d_{tx}))^{N_d-k} (1 - \beta^k), \quad k = 0, \dots, N_d \quad (4.12)$$

For a given active device location, the received device discovery probability $p_{dd}^{(d)}(r_d|d_{tx})$ can be obtained in deterministic channel.

$$\begin{aligned} p_{dd}^{(d)}(r_d|d_{tx}) &= \sum_{k=1}^{N_d} \mu_d'^{(k)}(r_d|d_{tx}) = \sum_{k=1}^{N_d} \binom{N_d}{k} (p_a(r_d|d_{tx}))^k (1 - p_a(r_d|d_{tx}))^{N_d-k} (1 - \beta^k) \\ &= \sum_{k=1}^{N_d} \binom{N_d}{k} (p_a(r_d|d_{tx}))^k (1 - p_a(r_d|d_{tx}))^{N_d-k} \\ &\quad - \sum_{k=1}^{N_d} (\beta p_a(r_d|d_{tx}))^k (1 - p_a(r_d|d_{tx}))^{N_d-k} \\ &= 1 - (1 - p_a(r_d|d_{tx}))^{N_d} - (\beta p_a(r_d|d_{tx}) + 1 - p_a(r_d|d_{tx}))^{N_d} + (1 - p_a(r_d|d_{tx}))^{N_d} \\ &= 1 - (\beta p_a(r_d|d_{tx}) + 1 - p_a(r_d|d_{tx}))^{N_d} \end{aligned} \quad (4.13)$$

In (4.13), the term $\beta p_a(r_d|d_{tx})$ of $(\beta p_a(r_d|d_{tx}) + 1 - p_a(r_d|d_{tx}))$ stands for the probability that the received device is inside the reliable range, but it is busy. $(1 - p_a(r_d|d_{tx}))$ stands for the probability that the received device is outside the reliable range. Therefore, equation (4.13) means that there exists at least one idle received device inside the reliable range of the active device.

Resource Discovery

When at least one received device responded, the active device chooses one amongst all the received devices which have responded and emits a probing signal with power P_D

in the preferred RB to check if any CU is interfered. If the received SINR at CU doesn't meet his requirement, the active devices can not reuse its spectral resources. Namely, if the CU is inside the interference range of the active device, the CU will be interfered. Similar to the above results, the active device can reuse the CU's spectral resource with probability $p_{\text{rd}}^{(d)}(r_u|d_{\text{tx}})$.

$$p_{\text{rd}}^{(d)}(r_u|d_{\text{tx}}) = 1 - p_a(r_u|d_{\text{tx}}) \quad (4.14)$$

In (4.14), it stands for the probability that the active device can share the spectral resources with the CU which received interference power lower than the pre-determined threshold.

Link Setup

If the active device finishes the device and resource discovery procedures, the active device and the desired received device start a hand-shaking process to determine the modulation/coding scheme. Having reached a consensus, the communication session then commences.

According to the above SDLS procedure, we define the probability $p_{LS}^{(d)}$ that the active device can finish all the link setup procedures in deterministic channel. Namely it can find a close received device and reuse the same spectral resources with the CU without causing harmful interference.

$$\begin{aligned} p_{LS}^{(d)} &= p_{\text{dd}}^{(d)}(r_d|d_{\text{tx}})p_{\text{rd}}^{(d)}(r_u|d_{\text{tx}}) \\ &= \left(1 - (\beta p_a(r_d|d_{\text{tx}}) + 1 - p_a(r_d|d_{\text{tx}}))^{N_d}\right) (1 - p_a(r_u|d_{\text{tx}})) \end{aligned} \quad (4.15)$$

Therefore, (4.15) implies that there exists a CU that the active device can share its spectral resources without causing harmful interference and at least one idle device having a received SNR (with signal from the active device) greater than the pre-determined threshold.

4.3 Stochastic Channel

The difference between deterministic and stochastic channel models is the inclusion of the random channel fading effect in the latter.

With the stochastic model, the received signal power $P_{D_i}^{(s)}$ and the corresponding SNR, $\gamma_{D_i}^{(s)}$, at the i th received device are given respectively by

$$P_{D_i}^{(s)} = \frac{h_i P_D}{d_{\text{tx}, D_i}^\alpha}, \quad i = 1, \dots, N_d \quad (4.16)$$

and

$$\gamma_{D_i}^{(s)} = \frac{P_{D_i}^{(s)}}{N_0}, \quad i = 1, \dots, N_d \quad (4.17)$$

where h_i is independent and identically distributed (i.i.d.) exponential random variable with unit mean for all i in Rayleigh fading scenario.

The received interference power $I_{\text{CU}_i}^{(s)}$ at the i th CU in stochastic channel is given by

$$I_{\text{CU}_i}^{(s)} = \frac{g_i P_D}{d_{\text{tx}, \text{CU}_i}^\alpha}, \quad i = 1, \dots, N_u \quad (4.18)$$

where g_i is i.i.d. exponential random variable with unit mean for all i in Rayleigh fading scenario.

4.3.1 SDLS Analysis

As the channel fading effect is taken into account, we are unable to determine the reliability and interference range like those were done before and the cell range can not be divided into two parts anymore. In fact, these two ranges are random variables and a proper parameter would be the outage probability defined in *Definition 6*. When the distance between the active device and a received device (the CU) is r_d (r_u), the outage probability is e^{-1} .

The requirements of having a reliable link to a device with a tolerable interference to a CU are given by

$$\gamma_{D_i}^{(s)} = \frac{P_{D_i}^{(s)}}{N_0} \geq \theta_d, \quad i = 1, \dots, N_d \quad (4.19)$$

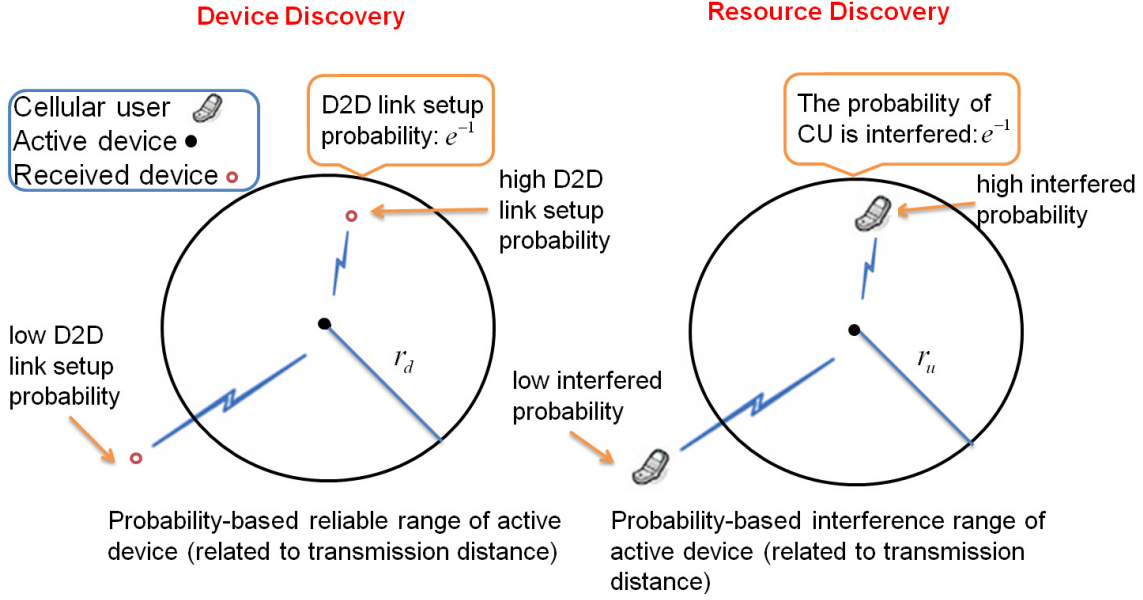


Figure 4.4: Probability-based reliable and interference ranges of an active device.

$$I_{CU_i}^{(s)} = \frac{g_i P_D}{d_{tx,CU_i}^\alpha} \leq I_{\min}^{(CU)}, \quad i = 1, \dots, N_u \quad (4.20)$$

Using the above equations, we can obtain the probability-based reliable and interference ranges by normalizing channel fading effect as shown in Fig. 4.4. Let $p_{D,\text{reliable}}^{(s)}(d_{tx,D}, r_d | d_{tx})$ be the probability that active device has a reliable link to received device with distance $d_{tx,D}$ between the active device and the received device, and $p_{CU,\text{interfered}}^{(s)}(d_{tx,CU}, r_u | d_{tx})$ be the probability that active device has an interfered link to CU with distance $d_{tx,CU}$ between the active device and the CU.

$$\begin{aligned} p_{D,\text{reliable}}^{(s)}(d_{tx,D}, r_d | d_{tx}) &= \mathbb{P}\left(\frac{h P_D}{d_{tx,D}^\alpha N_0} \geq \theta_d\right) \\ &= \mathbb{P}\left(h \geq \frac{\theta_d d_{tx,D}^\alpha N_0}{P_D}\right) \\ &= \mathbb{P}\left(h \geq \left(\frac{d_{tx,D}}{r_d}\right)^\alpha\right) \\ &= \int_{\left(\frac{d_{tx,D}}{r_d}\right)^\alpha}^{\infty} e^{-x} dx \\ &= e^{-\left(\frac{d_{tx,D}}{r_d}\right)^\alpha} \end{aligned} \quad (4.21)$$

Similarly, from (4.21), $p_{\text{CU,interfered}}^{(s)}(d_{\text{tx,CU}}, r_u | d_{\text{tx}})$ can be also derived as

$$p_{\text{CU,interfered}}^{(s)}(d_{\text{tx,CU}}, r_u | d_{\text{tx}}) = e^{-\left(\frac{d_{\text{tx,CU}}}{r_u}\right)^\alpha} \quad (4.22)$$

where the definitions of r_d and r_u are described in the previous section.

Because devices and CUs are uniformly distributed in the cell range and conditioned on fixed active device position, the term $d_{\text{tx,D}}$ in (4.21) and $d_{\text{tx,CU}}$ in (4.22) will be normalized by the below equation.

$$p(x|d_{\text{tx}}) = \begin{cases} \frac{2x}{R_c^2}, & \text{if } 0 \leq x \leq R_c - d_{\text{tx}} \\ \frac{2x \cos^{-1}\left(\frac{d_{\text{tx}}^2 + x^2 - R_c^2}{2d_{\text{tx}}x}\right)}{\pi R_c^2}, & \text{if } R_c - d_{\text{tx}} \leq x \leq R_c + d_{\text{tx}} \end{cases}$$

Based on above equation, we obtain

$$\begin{aligned} p_{\text{D,reliable}}^{(s)}(r_d | d_{\text{tx}}) &= \int_0^{R_c + d_{\text{tx}}} p_{\text{D,reliable}}^{(s)}(x, r_d | d_{\text{tx}}) p(x | d_{\text{tx}}) dx \\ &= \int_0^{R_c - d_{\text{tx}}} e^{-\left(\frac{x}{r_d}\right)^\alpha} \frac{2x}{R_c^2} dx \\ &\quad + \int_{R_c - d_{\text{tx}}}^{R_c + d_{\text{tx}}} e^{-\left(\frac{x}{r_d}\right)^\alpha} \frac{2x \cos^{-1}\left(\frac{d_{\text{tx}}^2 + x^2 - R_c^2}{2d_{\text{tx}}x}\right)}{\pi R_c^2} dx \end{aligned} \quad (4.23)$$

Similarly, $p_{\text{CU,interfered}}^{(s)}(r_u | d_{\text{tx}})$ can be calculated as

$$\begin{aligned} p_{\text{CU,interfered}}^{(s)}(r_u | d_{\text{tx}}) &= \int_0^{R_c - d_{\text{tx}}} e^{-\left(\frac{x}{r_u}\right)^\alpha} \frac{2x}{R_c^2} dx \\ &\quad + \int_{R_c - d_{\text{tx}}}^{R_c + d_{\text{tx}}} e^{-\left(\frac{x}{r_u}\right)^\alpha} \frac{2x \cos^{-1}\left(\frac{d_{\text{tx}}^2 + x^2 - R_c^2}{2d_{\text{tx}}x}\right)}{\pi R_c^2} dx \end{aligned} \quad (4.24)$$

$p_{\text{D,reliable}}^{(s)}(r_d | d_{\text{tx}})$ and $p_{\text{CU,interfered}}^{(s)}(r_u | d_{\text{tx}})$ can be computed by numerical methods.

Similarly in (4.13) and (4.14), we can obtain device discovery probability $p_{\text{dd}}^{(s)}(r_d | d_{\text{tx}})$ and resource discovery probability $p_{\text{rd}}^{(s)}(r_u | d_{\text{tx}})$ in stochastic channel.

$$p_{\text{dd}}^{(s)}(r_d | d_{\text{tx}}) = 1 - \left(\beta p_{\text{D,reliable}}^{(s)}(r_d | d_{\text{tx}}) + 1 - p_{\text{D,reliable}}^{(s)}(r_d | d_{\text{tx}}) \right)^{N_d} \quad (4.25)$$

and

$$p_{\text{rd}}^{(s)}(r_u | d_{\text{tx}}) = 1 - p_{\text{CU,interfered}}^{(s)}(r_u | d_{\text{tx}}) \quad (4.26)$$

Therefore, the probability $p_{LS}^{(s)}$ that the active device can finish all the link setup procedures in stochastic channel can be defined.

$$\begin{aligned}
 p_{LS}^{(s)} &= p_{\text{dd}}^{(s)}(r_d|d_{\text{tx}})p_{\text{rd}}^{(s)}(r_u|d_{\text{tx}}) \\
 &= \left(1 - \left(\beta p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}}) + 1 - p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}})\right)^{N_d}\right) \left(1 - p_{\text{CU, interfered}}^{(s)}(r_u|d_{\text{tx}})\right)
 \end{aligned} \tag{4.27}$$

In (4.27), the term $\beta p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}})$ of $\left(\beta p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}}) + 1 - p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}})\right)$ is the probability that although a received device may yield a SNR larger than the threshold, it is not idle. $\left(1 - p_{\text{D, reliable}}^{(s)}(r_d|d_{\text{tx}})\right)$ is the probability that the received SNR of a device is lower than the threshold. The term $\left(1 - p_{\text{CU, interfered}}^{(s)}(r_u|d_{\text{tx}})\right)$ stands for the probability that the active device can share the spectral resources with a CU which suffers from interference power less than the threshold in a stochastic channel. Therefore, (4.27) means that there exists a CU that the active device can reuse its spectral resources without causing harmful interference and at least one idle received device which received the SNR from the transmission of active device larger than the threshold in stochastic channel.

4.4 Numerical Results

In this section we examine the analytical results of SDLS performance under the BPP assumption. The parameters of our simulation are shown in Table 4.1. We already check the analytical results which are matched to simulation results under BPP model.

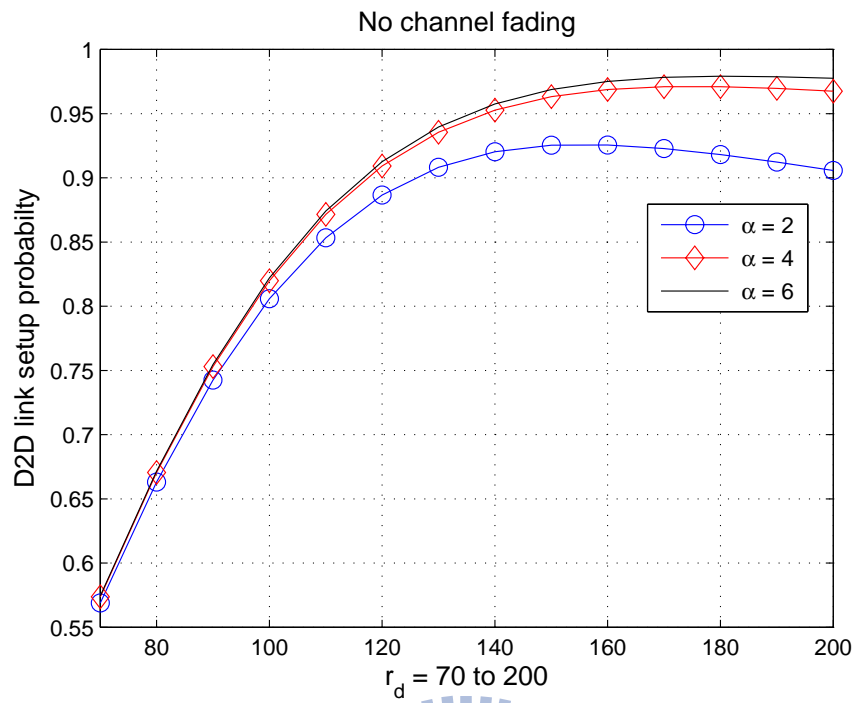
Fig. 4.5 (a) and (b) show the effect of the coverage radius r_d of the active device. If the coverage range becomes larger, the received device falls into this region with high probability. But it also increases the interference range. Therefore, when r_d is large enough, the SDLS probability decreases. The transmit power of active device needs to be limited. Fig. 4.6 (a) and (b) show the effect of received device number N_d . The D2D link is easy to set up when N_d becomes larger. It means the active device has more

Table 4.1: Simulation Parameters under BPP

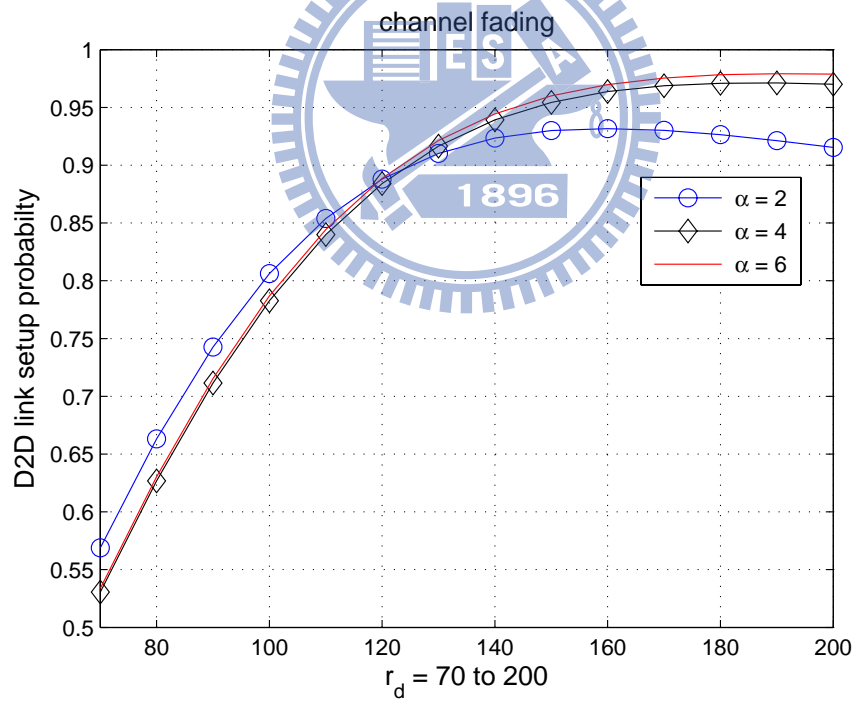
Parameter	Value
Cell radius (R_c)	2km
Path loss exponent (α)	2, 4, 6
Number of received device (N_d)	1000
Radius of reliable range (r_d)	100
Ratio between θ_d and $\frac{I_{\min}^{(CU)}}{N_0} \left(\frac{N_0 \theta_d}{I_{\min}^{(CU)}} \right)$	10
Noise power (N_0)	1
Distance between the active device and eNB (d_{tx})	1500
Busy probability of received device (β)	0.3

choices to set up a D2D link with another received device. When there is no channel fading effect, the performance increases when the path loss exponent α becomes larger for fixed r_d . The stochastic model leads us to different results. The performance with high α is not always better than the performance with low α . This phenomenon can also be seen in Fig. 4.5.

Fig. 4.7 shows the effect of the distance d_{tx} between the active device and eNB. We can see when the active device approaches the cell edge, the SDLS performance is degraded. This is due to few devices appearing in the cell edge, the active device is hard to find another device to communicate over D2D link. Fig. 4.8 shows the effect of ζ . This affects the ratio between the radius of coverage and interference ranges. If ζ becomes larger, the acceptable interference at CU is lower. The SDLS probability decreases when ζ becomes larger. The path loss exponent α also affects the ratio between the radius of coverage and interference ranges. For fixed r_d and ζ , r_u decreases as α increases. Therefore, the performance becomes better when α is high.

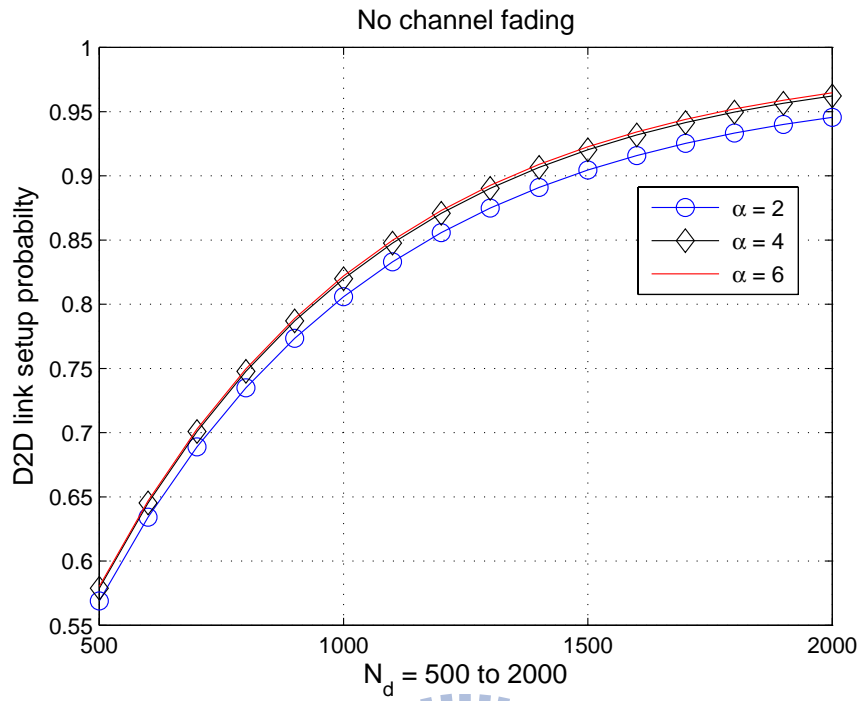


(a) Without channel fading effect.

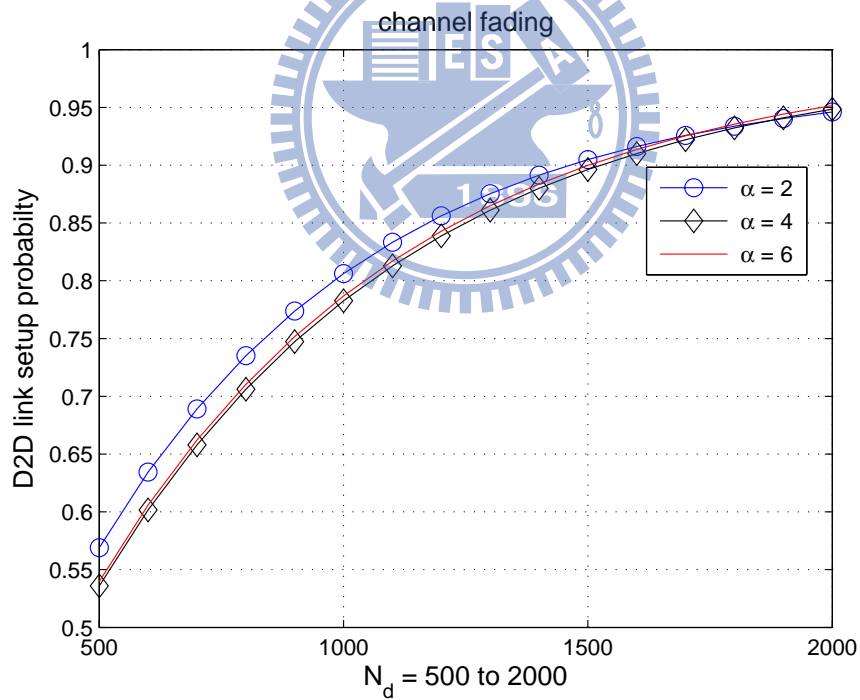


(b) With channel fading effect.

Figure 4.5: SDLS probability as a function of radius of coverage range r_d .



(a) Without channel fading effect.



(b) With channel fading effect.

Figure 4.6: SDLS probability as a function of received device number N_d .

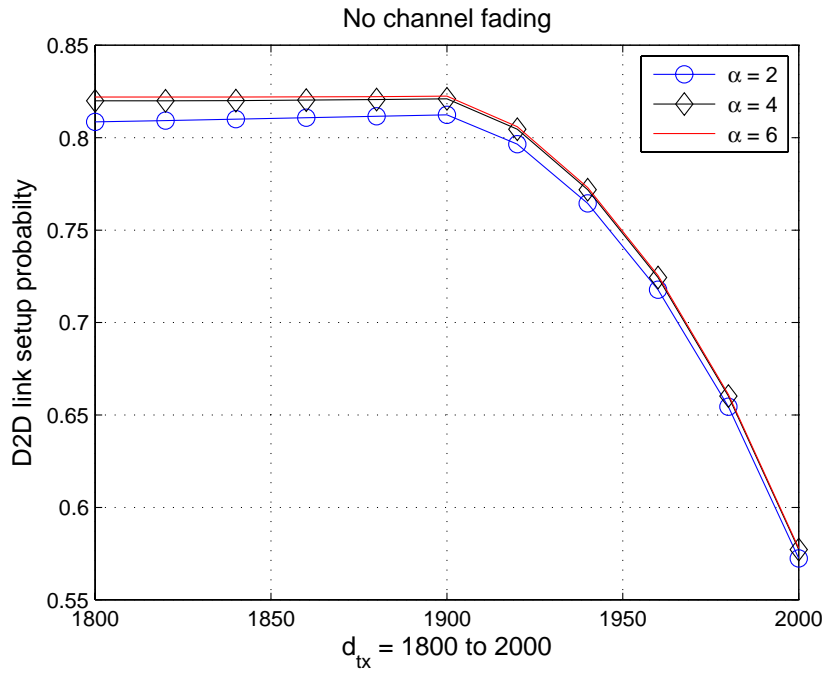


Figure 4.7: SDLS probability as a function of distance d_{tx} (between the active device and eNB).

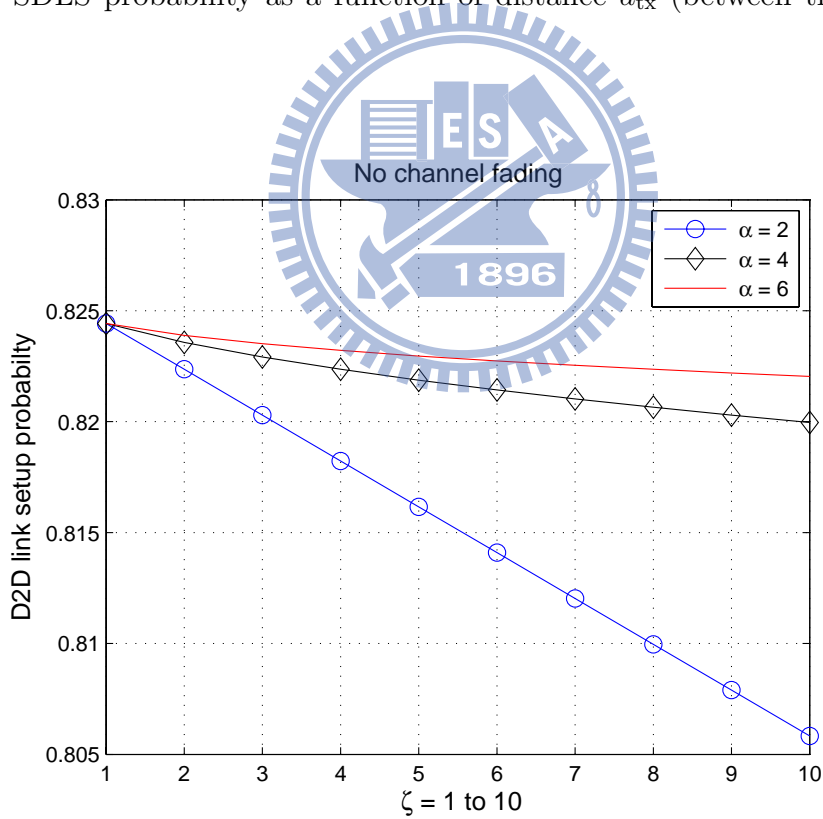


Figure 4.8: SDLS probability as a function of ζ (ratio between θ_d and $\frac{I_{\min}^{(CU)}}{N_0}$).

Chapter 5

Performance Analysis in PPP Environments

We have analyzed the SDLS probability using the BPP model in the previous chapter. In this chapter, we consider another point process model, namely the PPP model. We consider there are multiple active devices that want to establish D2D links using the same CU band simultaneously. To maintain the existing CU links' qualities, the transmit device has to be constrained. We shall analyze the corresponding SDLS performance according to *Definition 7*. We use an approximate scenario and a upper bound scenario to model the interference sources which are generated by PPP model. For the latter scenario, we convert the problem of computing the SDLS probability into an optimization problem. We then propose a solution and obtain some analytical results for the SDLS performance.

5.1 System Model

The PPP model is a more realistic scenario where both the numbers and locations of devices are random variables. The difference between BPP and PPP models is that the active and received devices are modeled by two independent homogeneous PPPs Φ_a and Φ_d with intensity λ_a and λ_d respectively (over an area much larger than the coverage range R of the eNB). The common transmit power of all active devices is P_D . The

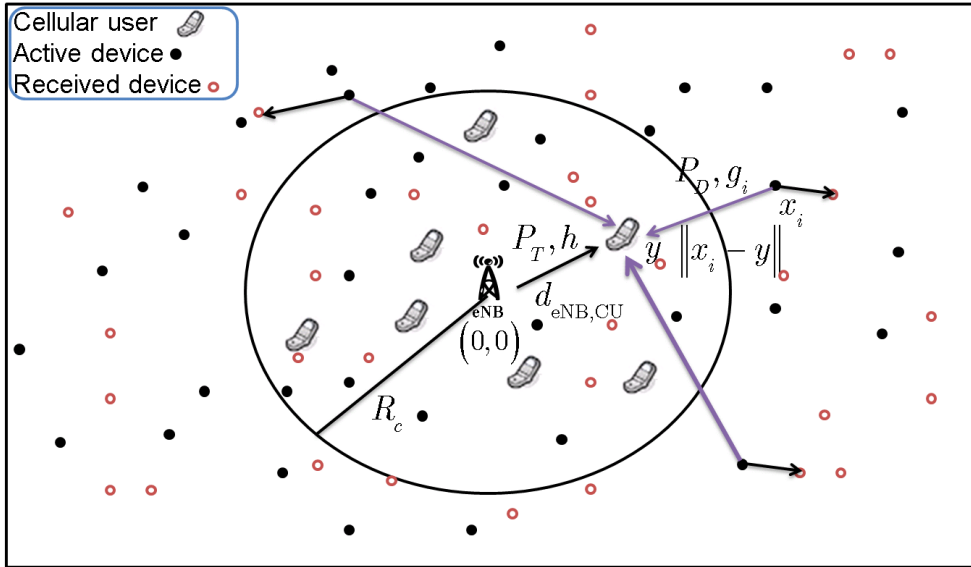


Figure 5.1: A two-dimensional network in which multiple active devices share the spectrum with CUs when they result in aggregated interference to the latter.

system architecture under PPP model is shown in Fig. 5.1. Denote the given position of CU by y , the eNB transmit power by P_T , and the distance between eNB and CU by $d_{\text{eNB,CU}}$. We further define a parameter which is the ratio between the number of dimensions of the network and path loss exponent.

$$\delta \triangleq \frac{d}{\alpha} \quad (5.1)$$

Because we consider a two-dimensional system, δ is equal to $\frac{2}{\alpha}$ in our scenario.

5.2 SDLS Analysis

According to chapter 3, SDLS procedure includes four steps:

1. Access the probing channel for active devices.
2. Idle device discovery.
3. Resource discovery: find proper resources to share with CUs without causing harmful interference.

4. D2D link setup.

5.2.1 Access Probing Channel

The active devices use CSMA-type MAC scheme to sense the probing channel. The received interference power I_r at the active device A from the transmission of another active device terminal in deterministic channel is given by

$$I_r = \frac{P_D}{d_{\text{tx},D_a}^\alpha} \quad (5.2)$$

where d_{tx,D_a} is the distance between the active device A and another active device.

If the two active devices can use the probing channel simultaneously, the distance between these two active devices needs to satisfy the constraint in (5.3).

$$I_r = \frac{P_D}{d_{\text{tx},D_a}^\alpha} \leq \theta_a \quad (5.3)$$

where θ_a is the tolerable interference for accessing.

From (5.3), we can obtain the minimum acceptable distance r_a that the two active devices can communicate through the probing channel simultaneously by letting the equality satisfy in (5.3).

$$r_a \triangleq \left(\frac{P_D}{\theta_a} \right)^{\frac{1}{\alpha}} \quad (5.4)$$

Let p_a be the probability for accessing the probing channel successfully. According to equation (2.16), the p_a is obtained.

$$p_a = \exp(-\lambda_a \pi r_a^2) = \exp\left(-\lambda_a \pi \left(\frac{P_D}{\theta_a}\right)^\delta\right) \quad (5.5)$$

In (5.5), it means that there are no other active devices within a radius- r_a circle centered at the active device A , so the active device A can access the probing channel successfully.

5.2.2 Device Discovery

If the active device A senses that there are no other active devices using the probing channel around it, it emits a probing signal with power P_D at the probing channel to

check if any idle received device is within its probing range. An idle received device which received the SNR larger than the pre-determined threshold θ_d will respond with a consent-to-send message along with a preferred RB number.

The average received signal power P_r at the received device terminal from the transmission of active device A and the corresponding SNR γ_r in deterministic channel are given respectively by

$$P_r = \frac{P_D}{d_{\text{tx},D_r}^\alpha} \quad (5.6)$$

and

$$\gamma_r = \frac{P_r}{N_0} \quad (5.7)$$

where d_{tx,D_r} is the distance between the active device A and the received device.

In order to have a reliable link to the received device, we need to set up the constraint in (5.8).

$$\gamma_r = \frac{P_r}{N_0} \geq \theta_d \quad (5.8)$$

where θ_d is the SNR requirement of the received device.

From (5.8), we can derive the radius of the reliable range of the active device A by letting (5.8) to an equality.

$$r_d \triangleq \left(\frac{P_D}{N_0 \theta_d} \right)^{\frac{1}{\alpha}} \quad (5.9)$$

Due to the received busy probability β , even if the received SNR satisfies the requirement, it won't respond a message. Therefore, based on the thinning property of PPP, the equivalent intensity λ'_d of Φ'_d for the received devices which are idle will be defined in the following.

$$\lambda'_d = (1 - \beta)\lambda_d \quad (5.10)$$

Let p_d be the probability for discovering the received device successfully. Therefore, based on equation (2.16), the p_d is obtained.

$$p_d = 1 - \exp(-\lambda'_d \pi r_d^2) = 1 - \exp\left(- (1 - \beta)\lambda_d \pi \left(\frac{P_D}{N_0 \theta_d}\right)^\delta\right) \quad (5.11)$$

In (5.11), it means that there exists at least one idle received device which satisfies the SNR requirement.

5.2.3 Resource Discovery

If at least one received device responds, the active device A will choose one amongst all the received devices which have responded and emit a probing signal with power P_D in the preferred RB to check if any CU is interfered. If CU's SINR doesn't meet the requirement, the active devices can not reuse the CU's spectral resources. Therefore, we will analyze the interference from active devices to CU first [24].

Not every active device has a chance to probe to check whether there exist usable RBs or not. The realistic interference to CU is very complicated. We use another method to make the analysis tractable. In order to model the interference sources as PPP model (the interference analysis is tractable), we introduce two scenarios.

One is an approximate scenario, we will limit the intensity λ_a of active devices. Following by the access the probing channel step, there are no active devices that the distance between one active device and another one smaller than r_a . Based on equation (2.16), we let probability that the distance between two active devices smaller than r_a bound by ε . Somehow we can use an approximate scenario to model the interference sources which are generated by PPP model.

$$F_D(r_a) = 1 - \exp(-\lambda_a \pi r_a^2) \leq \varepsilon \quad (5.12)$$

Therefore, the intensity λ_a of active devices needs to satisfy

$$\lambda_a \leq -\frac{\ln(1 - \varepsilon)}{\pi r_a^2} \quad (5.13)$$

In addition to the limit of intensity of active device, another idea is that the interference is upper bounded by letting the interference sources at the same RB as a homogeneous PPP with intensity $\lambda'_a = \frac{p_d}{M} \lambda_a$ (ignore the effect of step-1).

Interference Analysis under PPP

We will see the total interference $I(y)$ at the location y from the other interferers positioned at the points by using the point process Φ . We define Φ as a d -dimensional homogeneous PPP with intensity λ . If we condition the y at the origin, that will yield the Palm distribution for other devices. The conditional distribution keeps the same as the original one by Slivnyak's theorem [21]. By mapping the d -dimensional homogeneous PPP onto \mathbb{R}^+ , it will become an inhomogeneous PPP $\Phi \triangleq \{r_i = \|x_i\|\}$ which is the distance between the device and the origin. Because Φ is a stationary PP, the intensity measure function becomes $\Lambda(r) = \lambda c_d dr^{d-1}$.

The Poisson shot noise process [24] at location y as $I(y)$ in Fig. 5.1 is defined as

$$I(y) = \sum_{x \in \Phi} P_D g_x \|x - y\|^{-\alpha} \quad (5.14)$$

where g_x is the channel fading effect of the active device at location x .

By Slivnyak's theorem [21], $I(y)$ can also be defined as I .

$$I = \sum_{x \in \Phi} P_D g_x \|x\|^{-\alpha} \quad (5.15)$$

By mapping the d -dimensional homogeneous PPP onto \mathbb{R}^+ , it will become an inhomogeneous PPP $\Phi_r \triangleq \{r_i = \|x_i\|\}$. Therefore, the interference I can be defined in the following.

$$I = \sum_{r \in \Phi_r} P_D g_r r^{-\alpha} \quad (5.16)$$

where g_r is the channel fading effect of the active device at distance r . g_r and g_x have the same distribution.

The received signal power P_c from the transmission of eNB at the CU and the corresponding SINR γ_c in stochastic channel are given respectively by

$$P_c = \frac{h P_T}{d_{\text{eNB,CU}}^\alpha} \quad (5.17)$$

and

$$\gamma_c = \frac{P_c}{I + N_0} \quad (5.18)$$

where $d_{\text{eNB,CU}}$ is the distance between eNB and CU, h is the channel fading effect which follows a unit mean exponential distribution and I (random variable) is the interference from the active devices which reuse the same CU's spectral resources.

The success probability $p_s(\theta_u)$ of CU which received the SINR larger than the pre-determined threshold θ_u .

$$p_s(\theta_u) = \mathbb{P}\left(\frac{P_c}{I + N_0} > \theta_u\right) = \mathbb{E}_I [e^{-s(I+N_0)}] = \mathcal{L}_I(s) \exp(-sN_0) \quad (5.19)$$

where $s = \frac{\theta_u}{P_T d_{\text{eNB,CU}}^{-\alpha}}$ and $\mathcal{L}_I(s)$ is the Laplace transform of random variable I .

The Laplace transform of random interference I can be defined as below.

$$\begin{aligned} \mathcal{L}_I(s) &\triangleq \mathbb{E}_{\Phi_r, g_r} [e^{-sI}] = \mathbb{E}_{\Phi_r, g_r} \left[\exp \left(-s \sum_{r \in \Phi_r} P_D g_r r^{-\alpha} \right) \right] \\ &\stackrel{(a)}{=} \mathbb{E}_{\Phi_r} \left[\prod_{r \in \Phi_r} \mathbb{E}_{g_r} [\exp(-s P_D g_r r^{-\alpha})] \right] \\ &\stackrel{(b)}{=} \exp \left\{ -\mathbb{E}_g \left[\int_0^\infty (1 - \exp(-s P_D g r^{-\alpha})) \Lambda(r) dr \right] \right\} \end{aligned} \quad (5.20)$$

where (a) follows the independence between PPP and channel fading effect, and (b) is based on the intensity measure and PGFL of PPP.

We define the integral equation F as below.

$$\begin{aligned} F &= \int_0^\infty (1 - \exp(-s P_D g r^{-\alpha})) \Lambda(r) dr \\ &\stackrel{(a)}{=} \lambda c_d \int_0^\infty (1 - \exp(-s P_D g r^{-\alpha})) dr^{d-1} dr \\ &\stackrel{(b)}{=} \lambda c_d \int_0^\infty (1 - \exp(-s P_D g r^{-1/\delta})) dr \\ &\stackrel{(c)}{=} \lambda c_d \int_0^\infty (1 - \exp(-s P_D g/x)) \delta x^{\delta-1} dx \\ &= \lambda c_d \int_0^\infty \int_0^{s P_D g/x} e^{-y} \delta x^{\delta-1} dy dx \\ &= \lambda c_d \int_0^\infty \int_0^{s P_D g/y} e^{-y} \delta x^{\delta-1} dx dy \\ &= \lambda c_d \int_0^\infty \left(\frac{s P_D g}{x} \right)^\delta e^{-x} dx \\ &\stackrel{(d)}{=} \lambda c_d (s P_D g)^\delta \mathbb{E} [X^{-\delta}] \stackrel{(e)}{=} \lambda c_d (s P_D g)^\delta \Gamma(1 - \delta) \end{aligned} \quad (5.21)$$

where (a) is derived from the definition of intensity measure $\Lambda(r)$, (b)-(c) uses the change of variable, (d) is that we see X as an exponential random variable with unit mean, and (e) is based on Corollary 1. According to the (5.21), the equation (5.20) can be obtain by

$$\mathcal{L}_I(s) = \exp(-\lambda c_d \mathbb{E}[g^\delta] \Gamma(1 - \delta) s^\delta P_D^\delta) \quad (5.22)$$

If the channel fading gain g is followed by exponential distribution with unit mean, $\mathbb{E}[g^\delta]$ will equal to $\Gamma(1 + \delta)$ which is from the Corollary 1. By using the Euler's reflection formula, we can obtain the closed-form of equation (5.20). This equation also can be seen in [24].

$$\mathcal{L}_I(s) = \exp\left(-\lambda c_d \frac{\pi \delta}{\sin(\pi \delta)} s^\delta P_D^\delta\right) \quad (5.23)$$

Assume the responded received device randomly chooses one preferred RB from M RBs. Therefore, based on the thinning property of PPP, the equivalent intensity λ'_a of Φ'_a for the active devices which have the responded received device with probability p_d and commonly transmit on the same RB with probability $\frac{1}{M}$ will be defined in the following. Namely, Φ'_a is the PPP which the active device will transmit signal to another received device by reusing the same CU's spectral resources.

$$\lambda'_a = \frac{p_d}{M} \lambda_a \quad (5.24)$$

The scenario that we consider is a two-dimensional environment. Therefore, the Laplace transform of I can be shown.

$$\mathcal{L}_I(s) = \exp\left(-\lambda'_a \frac{\pi^2 \delta}{\sin(\pi \delta)} s^\delta P_D^\delta\right) \quad (5.25)$$

For example: by letting $\alpha = 4$ ($\delta = \frac{1}{2}$), then

$$\mathcal{L}_I(s) = \exp\left(-\lambda'_a \frac{\pi^2}{2} \sqrt{s P_D}\right)$$

Resource Sharing

If the CU's transmission is not outage (successful transmission), the active devices can reuse its spectral resources.

The success probability of CU:

$$\begin{aligned}
p_s(\theta_u) &= \mathcal{L}_I \left(\frac{\theta_u}{P_T d_{\text{eNB,CU}}^{-\alpha}} \right) \exp \left(-\frac{\theta_u N_0}{P_T d_{\text{eNB,CU}}^{-\alpha}} \right) \\
&= \exp \left(-\frac{p_d}{M} \lambda_a \frac{\pi^2 \delta}{\sin(\pi \delta)} \left(\frac{P_D \theta_u}{P_T} \right)^\delta d_{\text{eNB,CU}}^2 \right) \times \exp \left(-\frac{\theta_u N_0}{P_T d_{\text{eNB,CU}}^{-\alpha}} \right) \quad (5.26)
\end{aligned}$$

For example: with $\alpha = 4$ ($\delta = \frac{1}{2}$), then

$$p_s(\theta_u) = \exp \left(-\frac{p_d}{M} \lambda_a \frac{\pi^2}{2} \sqrt{\frac{P_D \theta_u}{P_T}} d_{\text{eNB,CU}}^2 \right) \times \exp \left(-\frac{\theta_u N_0}{P_T d_{\text{eNB,CU}}^{-4}} \right)$$

From the equation (5.26), the success probability of CU is an inverse proportion to the active device intensity λ_a , active device transmit power P_D , SINR requirement θ_u of CU, noise power N_0 , device discovery probability p_d , and the distance $d_{\text{eNB,CU}}$ between eNB and CU. It is proportional to the eNB transmit power P_T and the number of RBs M . It is very intuitive for our thought. The larger the values of λ_a and P_D are, the stronger the interference to CU will be. P_T and $d_{\text{eNB,CU}}$ will affect the CU's received power. θ_u is the SINR requirement of CU, so the larger of this value is, the lower the success probability of CU will be.

5.2.4 Link Setup

If the active device A finishes the first three steps, the active device and the desired received device start a hand-shaking process to determine the modulation/coding scheme. Having reached a consensus, the communication session then commences.

5.3 Link Setup Performance

According to the SDLS procedure, an active device may find a close received device and some usable resources to use. Therefore, we define the probability p_{LS} that an active device can finish all the SDLS procedures. In other words, it finds a close idle received device which received the SNR larger than the pre-determined threshold and shares the

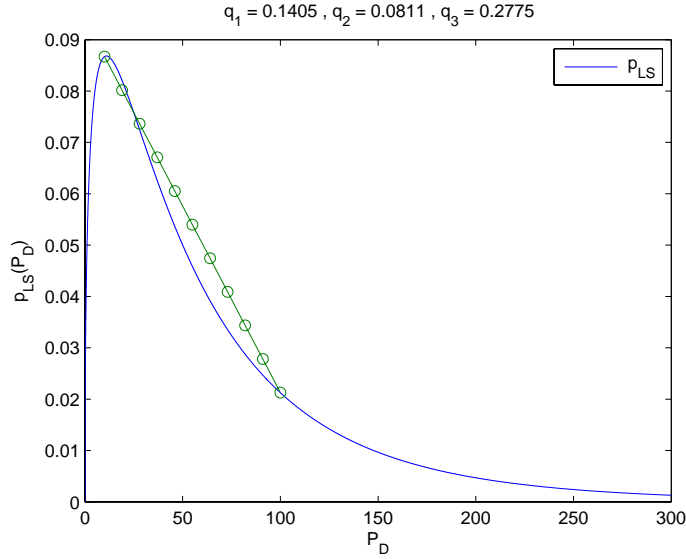


Figure 5.2: p_{LS} is not a concave function.

same spectral resources with the CU without causing harmful interference.

$$p_{LS} \triangleq p_a p_d p_s(\theta_u) = e^{-q_1 P_D^\delta} \left(1 - e^{-q_2 P_D^\delta}\right) e^{-\frac{\theta_u N_0}{P_T d_{eNB,CU}^\alpha}} e^{-q_3 \left(1 - e^{-q_2 P_D^\delta}\right) P_D^\delta} \quad (5.27)$$

where $q_1 = \lambda_a \pi \theta_a^{-\delta}$, $q_2 = (1 - \beta) \lambda_d \pi (\theta_d N_0)^{-\delta}$, $q_3 = \lambda_a \frac{1}{M} \frac{\pi^2 \delta}{\sin(\pi \delta)} \theta_u^\delta \left(\frac{P_T}{d_{eNB,CU}^\alpha}\right)^{-\delta}$, and q_1 , q_2 , and q_3 are positive numbers.

Therefore, we can model this problem as an optimization problem in upper bound scenario without limiting the transmit power P_D of active devices.

$$\max_{P_D \geq 0} p_{LS} = e^{-q_1 P_D^\delta} \left(1 - e^{-q_2 P_D^\delta}\right) e^{-\frac{\theta_u N_0}{P_T d_{eNB,CU}^\alpha}} e^{-q_3 \left(1 - e^{-q_2 P_D^\delta}\right) P_D^\delta} \quad (5.28)$$

According to *Definition 4*, the objective function p_{LS} is not a concave function by providing an example a counterexample which is shown in Fig. 5.2. We can not use optimization tool [25] to solve this problem. We try another method to find the optimal solution.

The partial differential of p_{LS} on P_D is given by

$$\begin{aligned} \frac{\partial p_{LS}(P_D)}{\partial P_D} &= e^{-\frac{\theta_u N_0}{P_T d_{eNB,CU}^\alpha}} \delta P_D^{\delta-1} e^{-(q_1+2q_2+q_3)P_D^\delta} e^{q_3 e^{-q_2 P_D^\delta} P_D^\delta} \\ &\quad \times \left[(q_1 + q_2 + q_3) e^{q_2 P_D^\delta} - (q_1 + q_3) e^{2q_2 P_D^\delta} + \left(e^{q_2 P_D^\delta} - 1 \right) (q_3 - q_2 q_3 P_D^\delta) \right] \end{aligned}$$

The partial differential of p_{LS} is the slope of p_{LS} . The term that we care is its sign, not the real value. The term $e^{-\frac{\theta_u N_0}{P_T d_{eNB, CU}} \delta P_D^{\delta-1} e^{-(q_1+2q_2+q_3)P_D^\delta} e^{q_3 e^{-q_2 P_D^\delta} P_D^\delta}$ is always positive ($\because P_D > 0$), so we can ignore this term. By letting $z = e^{q_2 P_D^\delta}$ ($z \geq 1, \because P_D \geq 0$), we define function $f(z)$ to determine the sign of $\frac{\partial p_{LS}(P_D)}{\partial P_D}$.

$$f(z) = -(q_1 + q_3) \left(z^2 - \frac{q_1 + q_2 + 2q_3}{q_1 + q_3} z + \frac{q_3}{q_1 + q_3} \right) - q_3(z - 1)\ln z \quad (5.29)$$

Theorem 1 *There exists only one solution to make $f(z) = 0$ for $z \geq 1$. If the solution of $f(z) = 0$ is z' , then*

$$\begin{cases} f(z) > 0, & \text{if } z' \geq z \geq 1 \\ f(z) < 0, & \text{if } z \geq z' \end{cases} \quad (5.30)$$

$P_D^* = \left(\frac{\ln z'}{q_2} \right)^{\frac{1}{\delta}}$ is the optimal solution of the optimization problem (5.28).

Proof: The 1st derivative and 2nd derivatives of $f(z)$ are given respectively by

$$\frac{\partial f(z)}{\partial z} = -2(q_1 + q_3)z - q_3 \ln z + (q_1 + q_2 + q_3) + \frac{q_3}{z} \quad (5.31)$$

and

$$\frac{\partial^2 f(z)}{\partial z^2} = -2(q_1 + q_3) - \frac{q_3}{z} - \frac{q_3}{z^2} \quad (5.32)$$

Due to $z \geq 1$, the term $\frac{\partial^2 f(z)}{\partial z^2}$ is negative. Therefore, $\frac{\partial f(z)}{\partial z}$ is a strictly decreasing function of z . Because $f(1) = q_2 > 0$, $\frac{\partial f(z)}{\partial z}$ is a strictly decreasing function for $z \geq 1$, if we assume $f(z') = 0$, we can know there is no other solutions to make $f(z) = 0$ for $z > z'$. Therefore, there exists only one solution to make $f(z) = 0$ for $z \geq 1$. We can also know $f(z) > 0$ for $z' \geq z \geq 1$ and $f(z) < 0$ for $z \geq z'$. This phenomenon can be illustrated in Fig. 5.3. Due to z is a strictly increasing function of P_D , $p_{LS}(P_D)$ is an increasing function for $0 \leq P_D \leq \left(\frac{\ln z'}{q_2} \right)^{\frac{1}{\delta}}$ and a decreasing function for $P_D \geq \left(\frac{\ln z'}{q_2} \right)^{\frac{1}{\delta}}$. Because we want to find the maximum value of p_{LS} , $P_D^* = \left(\frac{\ln z'}{q_2} \right)^{\frac{1}{\delta}}$ is the optimal solution of p_{LS} . ■

Corollary 2 *The function $-p_{LS}(P_D)$ is a quasiconvex function.*

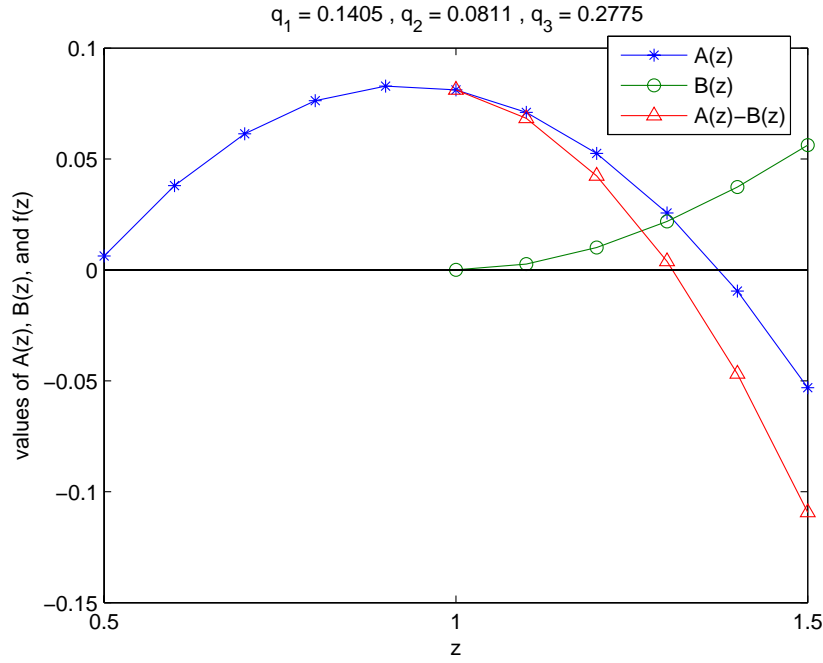


Figure 5.3: The intersection between z axis and $f(z)$ (one solution).

Proof: The domain of $-p_{LS}(P_D)$ is convex set ($\because P_D \geq 0$). According to *Theorem 1*:

$$\begin{cases} -\frac{\partial p_{LS}(P_D)}{\partial P_D} < 0, & \text{if } P_D^* \geq P_D \geq 0 \\ -\frac{\partial p_{LS}(P_D)}{\partial P_D} > 0, & \text{if } P_D \geq P_D^* \end{cases} \quad (5.33)$$

We assume $x > y$. We can divide into three cases for setting x and y .

1. If $\{P_D^* \geq x, y \geq 0\}$, $-p_{LS}(\theta x + (1-\theta)y) \leq -p_{LS}(y) \leq \max\{-p_{LS}(x), -p_{LS}(y)\}$.
2. If $\{x, y \geq P_D^*\}$, $-p_{LS}(\theta x + (1-\theta)y) \leq -p_{LS}(x) \leq \max\{-p_{LS}(x), -p_{LS}(y)\}$.
3. If $\{P_D^* \geq x \geq 0\}$ and $\{y \geq P_D^*\}$, we can find the θ' to let $\theta'x + (1-\theta')y = P_D^*$.

Therefore, for any $x, y \in \mathbf{dom} -p_{LS}(P_D)$, $-p_{LS}(\theta x + (1-\theta)y) \leq \max\{-p_{LS}(x), -p_{LS}(y)\}$ for $0 \leq \theta \leq 1$.

According to *Definition 5*, $-p_{LS}(P_D)$ is a quasiconvex function. Similarly, $p_{LS}(P_D)$ is a quasiconcave function. ■

Because the solution of $f(z) = 0$ is hard to find by solving it directly, we will show how another method to find the optimal solution P_D^* to make $\frac{\partial p_{LS}(P_D)}{\partial P_D} = 0$. Divide (5.29)

into two equations as following ($f(z) = A(z) - B(z)$):

$$A(z) = -(q_1 + q_3) \left(z^2 - \frac{q_1 + q_2 + 2q_3}{q_1 + q_3} z + \frac{q_3}{q_1 + q_3} \right)$$

$$B(z) = q_3(z - 1) \ln z$$

As the discriminant of equation $A(z)$ is always positive, there exist two real-number solutions.

$$z_A^+ = \frac{\frac{q_1 + q_2 + 2q_3}{q_1 + q_3} + \sqrt{\left(\frac{q_1 + q_2 + 2q_3}{q_1 + q_3}\right)^2 - 4\frac{q_3}{q_1 + q_3}}}{2} = \frac{q_1 + q_2 + 2q_3 + \sqrt{(q_1 + q_2)^2 + 4q_2q_3}}{2(q_1 + q_3)}$$

$$z_A^- = \frac{\frac{q_1 + q_2 + 2q_3}{q_1 + q_3} - \sqrt{\left(\frac{q_1 + q_2 + 2q_3}{q_1 + q_3}\right)^2 - 4\frac{q_3}{q_1 + q_3}}}{2} = \frac{q_1 + q_2 + 2q_3 - \sqrt{(q_1 + q_2)^2 + 4q_2q_3}}{2(q_1 + q_3)}$$

where $z_A^- < 1$ and $z_A^+ > 1$. Therefore, only z_A^+ is the feasible solution. Because $f(z_A^+) < 0$ and $f(1) > 0$, we will use bisection method to find the solution that $f(z') = 0$ is satisfied.

Due to $z = e^{q_2 P_D^\delta}$, let the upper limit of bisection method as P_D^{upper} by translating z_A^+ into the form of P_D .

$$P_D^{\text{upper}} = \left(\frac{\ln(z_A^+)}{q_2} \right)^{\frac{1}{\delta}} = \left(\frac{\ln\left(\frac{q_1 + q_2 + 2q_3 + \sqrt{(q_1 + q_2)^2 + 4q_2q_3}}{2(q_1 + q_3)}\right)}{q_2} \right)^{\frac{1}{\delta}} \quad (5.34)$$

The bisection method is executed between 0 and P_D^{upper} . By letting $P_D(k)$ is the midpoint of the interval in the k th step, the difference between $P_D(k)$ and an optimal solution P_D^* is bounded by

$$|P_D(k) - P_D^*| \leq \frac{P_D^{\text{upper}}}{2^k} \quad (5.35)$$

The active device will execute this algorithm. The eNB will broadcast the network conditions to devices. According to these information, active devices find the common optimal transmit power P_D respectively.

Difference at Interference Sources

In the upper bound scenario, the transmit power P_D of active devices is unbounded. But in approximate scenario, the intensity of active device is relative to P_D . Therefore, we will fix P_D in approximate scenario.

Table 5.1: Simulation Parameters under PPP

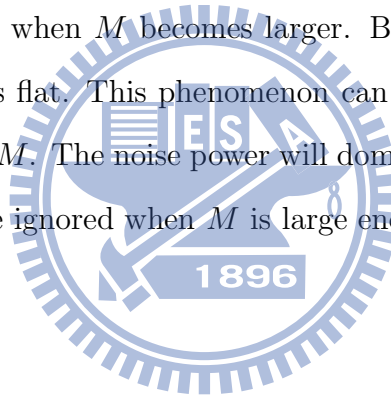
Parameter	Value
Path loss exponent (α)	4
Received power at CU ($P_r = \frac{P_T}{d_{\text{eNB,CU}}^\alpha}$)	5, 10, 15, 20dB
Noise power (N_0)	1
Tolerable interference for accessing (θ_a)	5dB
SINR requirement of CU (θ_u)	10dB
SNR requirement of received device (θ_d)	15dB
Radius of sensing range (r_a)	20
Approximate threshold (ϵ)	0.1
Received device intensity (λ_d)	0.005
Number of RBs (M)	10
Busy probability of received device (β)	0.3

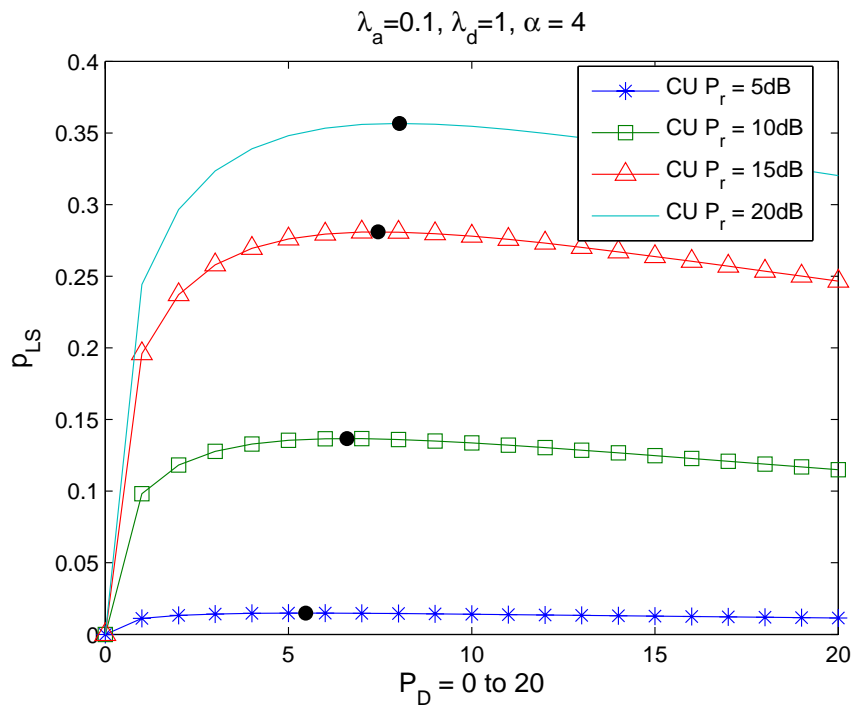
5.4 Analytical Results

In this section we examine the analytical results of SDLS performance under PPP model. The parameters of our simulation are shown in Table 5.1. The radius refers to the transmit power of active devices ($P_D = r_a^\alpha \theta_a$, the corresponding λ_a to approximate the interference sources as PPP is 0.0001). Fig. 5.4 which is based on upper bound scenario shows the solution which is from the bisection method is also the optimal solution. Because the SINR requirement of CU, the received power at CU will affect the SDLS probability. When the CUs have very reliable links (more tolerable interference), the SDLS probability also increased. The gap is very evident. Compare Fig. 5.4 (a) with (b), when path loss exponent α is larger, the path loss will more severe. The interference and coverage range of active device also decreased. The total effect of α leads to the better performance under large α . When the received power at CU is 5dB (the channel gain between the CU and eNB needs to be very large to meet the SINR requirement), the SDLS probability is below 0.02.

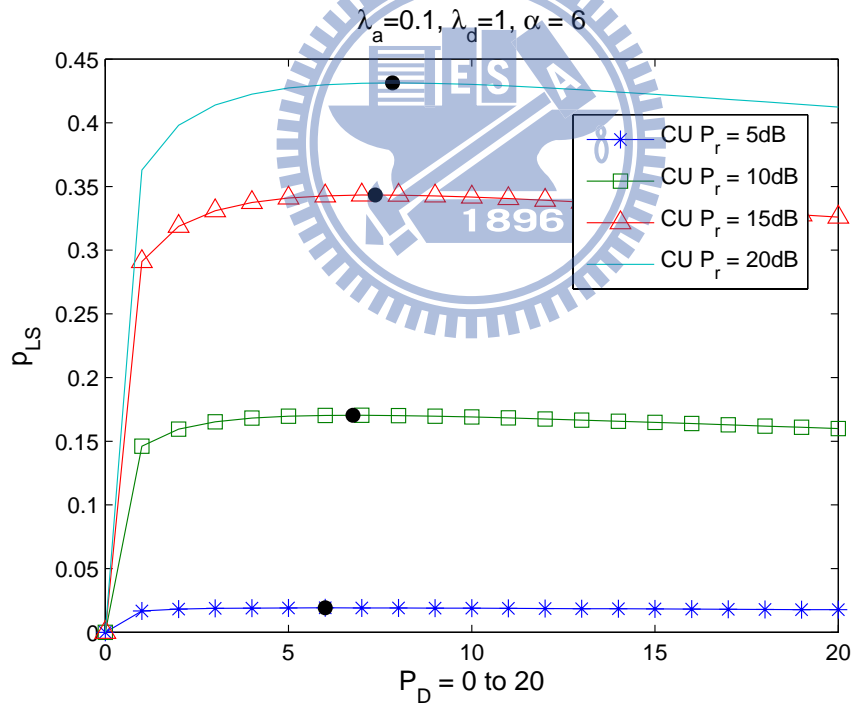
The following Figures are obtained using the approximate scenario. Fig. 5.5 shows

the effect of busy probability β of received device. The parameter β means the busy state of the network. In the intuitive sense, the D2D link probability is a monotonic decreasing function of β . We verify this idea in the Fig. 5.5. Even the received signal power at CU is large, the link setup probability is below 0.15 under high β . Fig. 5.6 show the effect of the intensity of received device. The parameter λ_d means the number of received device stochastically. When λ_d becomes larger, the D2D link is easy to set up. It means the active device has more choices to set up a D2D link with another received device. Fig. 5.7 shows that the value of noise power affects the D2D link and CU's SINR. Even when the received power at CU is 20dB, the SDLS probability is very low under high noise power level. At low received power at CU, the link setup probability approaches to zero. Fig. 5.8 shows the effect of the number of RBs. M affects the probability that the active device chooses the same RB. Therefore, the interference at the common RB will decrease when M becomes larger. But when M is large enough, the SDLS probability becomes flat. This phenomenon can be explained by the success probability of CU under large M . The noise power will dominate the success probability of CU. The effect of M can be ignored when M is large enough.





(a) $\alpha=4$. The black solid circle represents the solution by bisection method.



(b) $\alpha=6$. The black solid circle represents the solution by bisection method.

Figure 5.4: SDLS probability (p_{LS}) performance as a function of the active device transmit power P_D in the upper bound scenario.

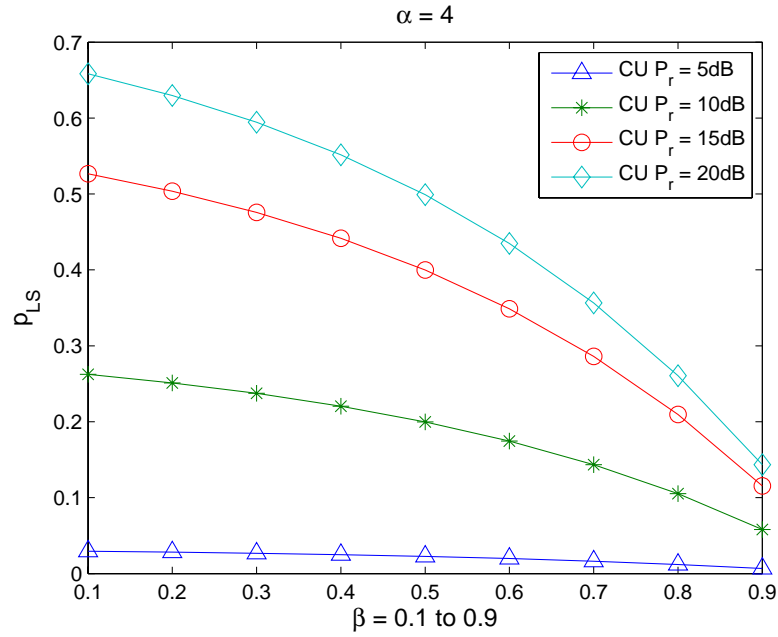


Figure 5.5: SDLS probability (p_{LS}) performance as a function of busy probability β of received device in approximate scenario.

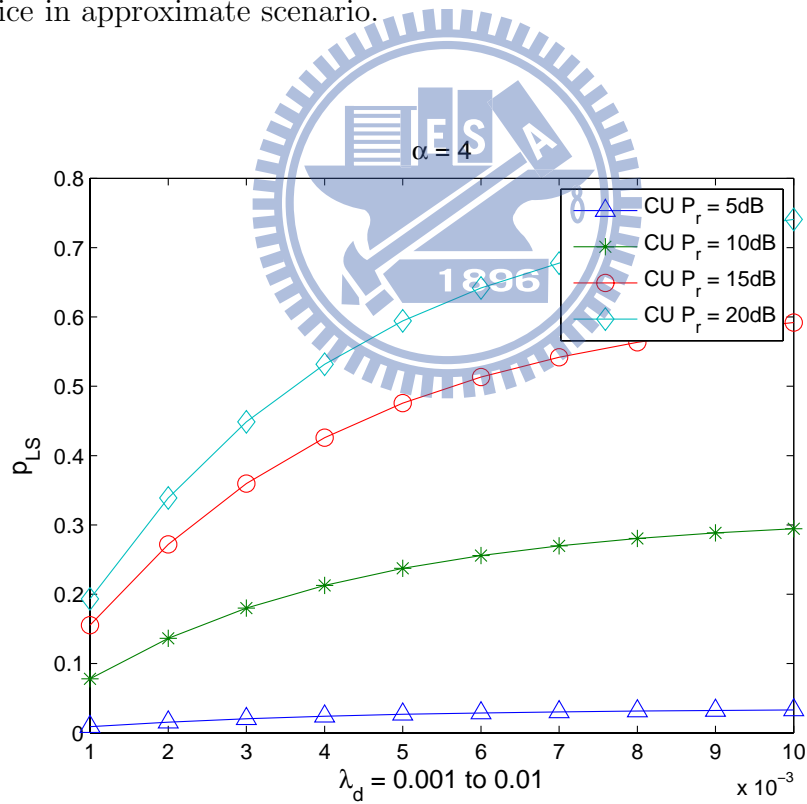


Figure 5.6: SDLS probability (p_{LS}) performance as a function of received device intensity λ_d in approximate scenario.

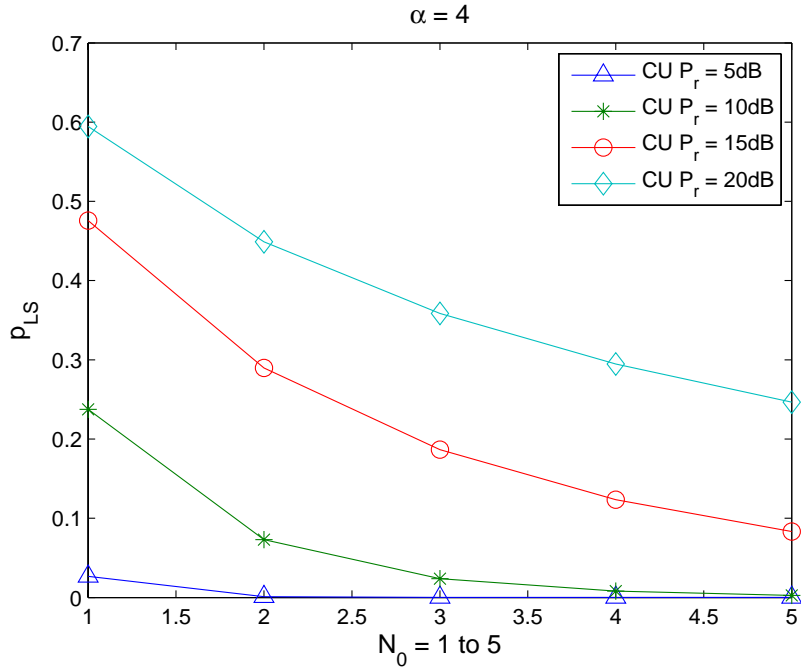


Figure 5.7: SDLS probability (p_{LS}) performance as a function of noise power N_0 in approximate scenario.

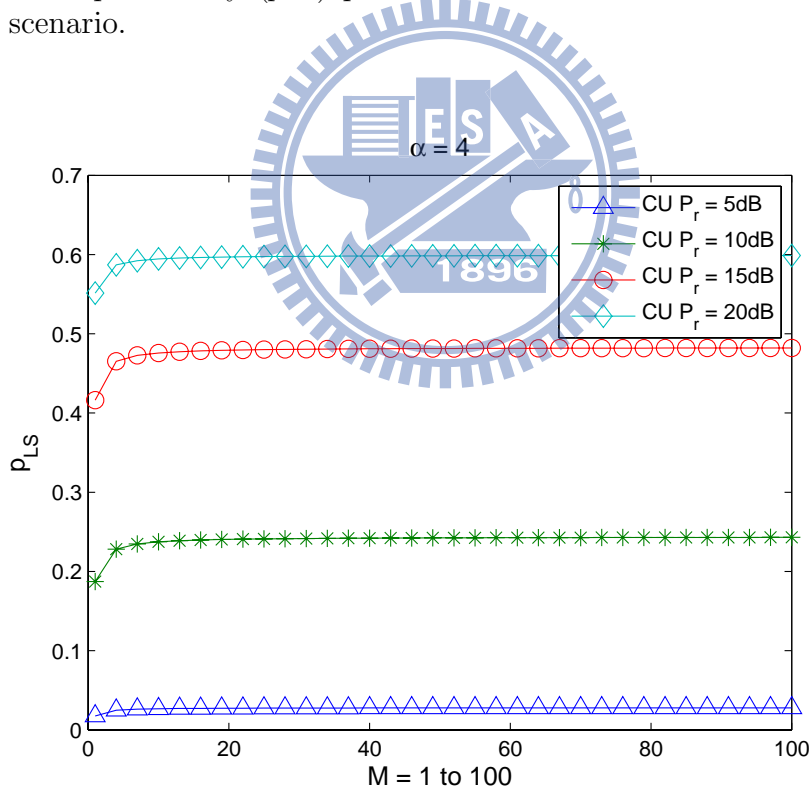


Figure 5.8: SDLS probability (p_{LS}) performance as a function of the number of RB M in approximate scenario.

Chapter 6

Conclusions and Future Works

In this thesis, we review the concept of D2D communications and some stochastic geometric related point processes. We study the SDLS probability under two device/mobile terminal location distributions characterized by Binomial point process (BPP) and Poisson point process (PPP), respectively. We propose a D2D link setup protocol and analyze the corresponding link setup performance.

For the BPP model, we consider both deterministic path loss and stochastic channel fading in our analysis. For the deterministic case, we obtain closed-form expression of the SDLS probability. But for the latter scenario, we evaluate the SDLS probability performance through numerical computing. When the coverage radius of an active device increases, so is the interference to CUs. Our analysis indicates that a judicious choice of the device transmit power is needed to maximize the SDLS probability. The optimal transmit power depends on the network condition, i.e., the parameters of the associated BPPs.

By constraining the peak transmit device power and the minimum distance between two active devices which use the shared macrocell spectrum in their D2D links, we obtain a proper PPP parameter to characterize the location distribution of active devices who have successfully establish D2D links and evaluate the associated average sum interference power. An upper bound for the latter power is obtained by removing the minimum distance constraint. We refer to these two scenarios as the constrained device

separation and the worst case scenarios.

The SDLS probabilities for both scenarios are functions of the active device' average transmit power P_D . We prove that the corresponding functions are quasiconcave and apply the bisection search to find the optimal solution. We present a scheme to set an upper limit of this approach. The optimal transmit power P_D^* is a function of the parameters of the communication environment (e.g., the intensity of the associated PPP and the devices' busy probability) and proper power control is needed to maximize the SDLS probability. We examine how system parameters like device intensity, average transmit power, noise power, allocated resource blocks, affect the SDLS probability through either analysis or computer evaluations.

Our analysis is based on a simplified wireless environment. There is no consideration of the shadowing effect and only single cell system is considered. Furthermore inhomogeneous PPPs may be more appropriate in characterizing the device/terminal locations. A protocol which allows multiple devices to multiple devices communications that minimizes the collision probability and solve the device identification problem is called for. Finally, our investigation can be regarded as a first step in an autonomous piconet setup protocol which partitions devices into groups (local networks) so that intra-net D2D communication becomes much easier. In forming such groups, a device discovery process is definitely needed.

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