August 2019
PhD Dissertation

Performance Analysis and Enhancement of Device-to-Device Communications Underlaying LTE-A Uplink Cellular Networks Using Fractional Frequency Reuse Scheme

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Advisor: Prof. Seokjoo Shin

A dissertation submitted in partial fulfillment of the
requirements for the Degree of Doctor of Philosophy

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Graduate School of Chosun University

Department of Computer Engineering

Ningombam Devarani Devi

Ningombam Devarani Devi의

박사학위논문을 인준함

위원장	조선대학교	교 수	모상만(인)
위 원	조선대학교	교 수	강문수(인)
위 원	조선대학교	교 수	최우열(인)
위 원	대구경북과학기술원	교 수	문인규(인)
위 원	조선대학교	교 수	신석주(인)

2019 년 6 월

조선대학교 대학원

I dedicate this dissertation to my parents Ningombam Tikendrajit Singh and Rajkumari Sanatombi Devi, and to all of my siblings.

ABSTRACT

Performance Analysis and Enhancement of Device-to-Device Communications Underlaying LTE-A Uplink Cellular Networks Using Fractional Frequency Reuse Scheme

Ningombam, Devarani Devi
Advisor: Prof. Shin, Seokjoo
Department of Computer Engineering
Graduate School of Chosun University

Due to the increasing demands for various types of high data rate services, cellular networks are facing the problem of resource limitations. Future cellular networks target to deliver high data rates to fulfill the requirements for different services, with new communications standards such as device-to-device (D2D) communications. In D2D communication, two devices in close proximity can communicate directly without crossing data traffic over the evolved-NodeB (eNB). In D2D communication, two adjacent devices set up a communication by reusing the cellular resource. Hence, D2D communication is considered to be one of the promising communication standard encouraged by future cellular networks. This result in a reduced traffic load to the eNB, minimized end-to-end delay, and maximized spectral efficiency and system capacity.

Nevertheless, implementing D2D communication in an LTE-Advanced (LTE-A) cellular network generates rigorous interference to conventional cellular users and also causes mutual interference among D2D pairs. Two main types of uplink interference are: inter-cell interference caused by D2D transmitter to the cellular user and from the cellular user to the D2D receiver. Unfortunately, it has been found that the performance of system degrades with the implementation of D2D communications into the conventional cellular networks.

In this dissertation, we present a novel resource allocation method to enhance overall system performance by minimizing uplink interference. The new technique develops the resource allocation method by considering fractional frequency reuse (FFR) technique. More specifically, the work in this thesis is divided into four sections. In the first section, we study on the benefit of the non-orthogonal resource reuse scenario of cellular resources in D2D communication by allowing FFR technique. Different objectives are considered, including increasing overall system capacity and spectral efficiency. Our results demonstrate that the proposed methods can assuredly enhance system performance with reduced computational complexity. The second section of the thesis executes with the effect of distance-constrained resource allocation in D2D communications, where we evaluate outage probability of both cellular users and D2D users. Our results show that it is possible to obtain least outage probability by determining location of user from the eNB while reusing the resources. In the third section, we accomplish to take benefit of the higher frequency reuse factor by considering greedy heuristic

algorithm and binary power control algorithm in a network-assisted D2D communications. We demonstrate that the proposed scheme can indeed take benefit of the higher frequency reuse factor and accommodate optimum system performance. Finally, in the fourth section of the thesis, we study the multicast nature of D2D communications underlaying uplink cellular networks by proposing a metaheuristic-tabu search algorithm. A metaheuristic-tabu search algorithm is considered to increase the probability of finding optimal solutions by reducing uplink interference and for fairness resource distribution; Jain's fairness index is analyzed. We demonstrate that our proposed scheme is desirable to obtain optimum solution for throughout, spectral efficiency and QoS target by providing fairness in resource allocation while minimizing uplink interference.

요약

LTE-A 상향링크 셀룰러망에서의 단말간 통신 성능 분석 및 개선

닌곰밤 데브라니 데비

지도교수: 신석주

컴퓨터공학과

조선대학교 대학원

다양한 종류의 고속 데이터 서비스에 대한 요구가 증가함에 따라, 셀룰러 네트워크는 리소스 제한 문제에 직면해 있다. 더불어, 차세대 셀룰러 네트워크는 D2D (Device-to-Device) 통신과 같은 새로운 통신 패러다임을 통해 다양한 서비스에 대한 요구 사항을 충족시키기 위해 높은 데이터 전송 속도를 제공하는 것을 목표로 한다. D2D 통신에서 근접한 두 장치는 셀룰러 시스템의 기지국 (eNB)을 통하지 않고 직접 통신 할 수 있다. 이러한 D2D 통신에서 두 개의 근접한 디바이스는 기지국이 사용하는 셀룰러 스펙트럼을 재사용하여 통신을 수행할 수 있다. 따라서 D2D 통신은 미래의 셀룰러 네트워크와 함께 유망한 통신 벤치 마크 중 하나가 될 것으로 기대된다. 이로 인해 eNB 에 대한

트래픽 부하 및 종단간 지연이 감소되고 스펙트럼 효율 및 시스템 처리량이 향상된다. 그러나 LTE-Advanced (LTE-Advanced) 셀룰러 네트워크에서 D2D 통신을 허용하면 기존의 셀룰러 사용자와 D2D 송수신 단말 간의 상호 간섭이 발생한다. 예를 들어, 상향링크 간섭의 두 가지 주요 유형은 D2D 송신기로부터 셀룰러 사용자, 셀룰러 송신기에서 D2D 수신기로 발생되는 셀내 간섭이다. 불행히도, 문헌에서는 기존의 셀룰러 네트워크에 D2D 통신을 허용하면 시스템 성능이 저하되는 것으로 밝혀졌다.

본 연구에서는 D2D 통신이 공존하는 셀룰러 환경에서 상향링크 간섭을 완화하여 전반적인 시스템 성능을 향상시키는 새로운 자원 할당 기법을 제시한다. 새로운 메커니즘은 부분 주파수 재사용 (FFR) 기술을 고려하여 자원 할당 방법을 확장한 것이다. 연구의 주요 내용은 네 가지로 구분할 수 있다. 첫 번째 파트에서는 FFR 기술을 고려하여 D2D 통신에서 셀룰러 자원의 비 직교 자원 재사용 특성의 이점에 대해 논의한다. 전반적인 시스템 처리량 및 스펙트럼 효율을 최대화하는 목표 등이 고려되었다. 성능 평가 결과로부터 제안된 기법이 복잡도를 최소화하면서도 시스템 성능을 달성 할 수 있음을 보여준다. 두 번째 파트에서는 D2D 통신에서 거리가 제한된 리소스 할당 문제에 대해 연구하였다. 여기서는 셀룰러 사용자와 D2D 사용자

모두의 아웃티지 확률 (Outage Probability)을 분석하였다. 성능 평가 결과는 자원을 재사용하면서 기지국이 사용자의 위치를 분석함으로써 아웃티지 확률을 최소화 할 수 있음을 보여주었다. 세 번째 파트에서는 네트워크 지원 D2D 통신에서 greedy heuristic 알고리즘과 이진 전력 제어 알고리즘을 적용하여 높은 주파수 재사용 계수를 활용하는 연구를 수행하였다. 제안된 기법의 성능 분석 결과는 높은 주파수 재사용 계수를 활용하고 최적의 시스템 성능을 제공 할 수 있음을 보여준다. 마지막으로, 네 번째 파트에서는 metaheuristic-tabu 검색 알고리즘을 도입하여 상향링크 셀룰러 네트워크를 기반으로 하는 D2D 통신의 멀티 캐스트 특성에 대해 연구를 수행하였다. 상향링크 간섭을 최소화하여 시스템을 최적화하고 공정한 자원 분배를 위해 metaheuristic-tabu 검색 알고리즘을 적용하였으며 Jain’s index 라는 공정성 지수를 고려하였다. 성능 평가로부터 상향 링크 간섭을 완화하면서 자원 할당의 공정성을 보장함으로써 전반적인 스펙트럼 효율과 QoS 를 달성할 수 있는 최적의 솔루션을 얻을 수 있음을 보여 주었다.

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I sincerely thank them for all their love and encouragement.

Ningombam Devarani Devi

Contents

Chapter 1

Abbreviations

3GPP	Third Generation Partnership project
LTE-A	Long Term Evolution Advanced
ITU-R	International Telecommunication Union Radio Communication Sector Reports
D2D	Device-to-Device
DPs	D2D Pairs
FFR	Fractional Frequency Reuse
SINR	Signal-to-Interference-Plus-Noise Ratio
eNB	Evolved Node B
QoS	Quality of Service
SC-FDMA	Single Carrier Frequency Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
IoT	Internet of Things
RA	Resource Allocation
RB	Resource Block
PC	Power Control
CSI	Channel State Information
PDF	Probability Distribution Function
CDF	Cumulative Distribution Function
Tx	Transmitter

Rx	Receiver
M-D2D	Multicast Device-to-Device
RRA	Random Resource Allocation
RF	Reuse Factor
PL	Path Loss
LOS	Line of Sight
NLOS	Non-Line of Sight
GHRMS	Greedy Heuristic Resource Management Scheme
BPCS	Binary Power Control Scheme
mmWave	Millimeter Wave
FIFO	First-In-First-Out

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Chapter 1

Introduction

1.1. Background

The interest of the comprehensive services for high data rate transmissions has governed to the evolution of cellular networks. To fulfill the requirements of the current services for high data rate transmissions, the successor of Long Term Evolution (LTE), LTE-Advanced (LTE-A) has been investigated [1] [2]. Recent advances in communication technologies have enabled the development of devices in almost all areas of our day to day life. Third Generation Partnership Project (3GPP) LTE-A aims at providing high data rate and system capacity for variety of new techniques namely, multiple-input multiple-output, device-to-device (D2D) communication, etc. These devices can communicate with each other directly using an unlicensed spectrum or by sharing a licensed spectrum with cellular users (CUs). When the devices use dedicated licensed spectrum no additional interference occurs; but this is achieved at the cost of inefficient resource utilization. However, while sharing the licensed spectrum with CUs, it enables efficient utilization of spectrum resources. Recently, proximity based services and information have become a significant topic of interest [3]. Proximity based local area services is one of the popular communication technique that reuses the already used spectrum to enhance spectrum efficiency. However, proximity based services such as Bluetooth, ZigBee, etc. does not have control over the ad hoc network, thus the service providers cannot guarantee a stable, reliable and well maintained communication environment [4].

1.2. Overview of Device-to-Device Communication

D2D communication underlaying LTE-A cellular networks is proposed as an up-and-coming technology for next-generation cellular networks (5G). The difference between traditional cellular networks and D2D communications is, in a traditional cellular network a device can not directly communicate with each other and all communications are carried out through the eNB. as shown in Fig. 1.1(a).

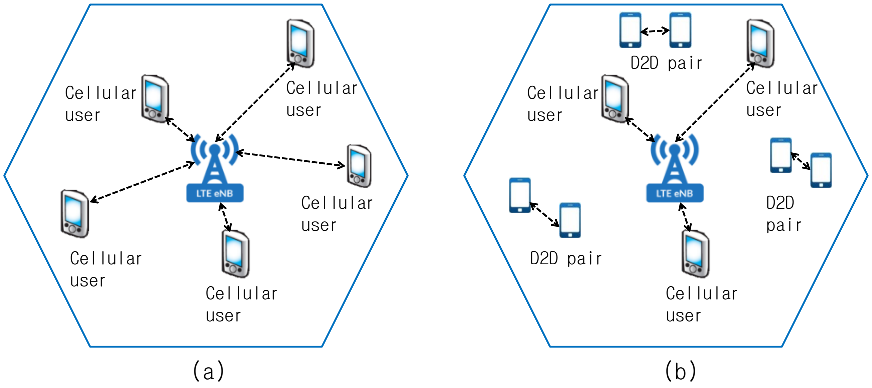


Fig. 1.1: (a) Conventional cellular communication, and (b) D2D communication.

On the other hand, D2D communication enables direct communication between two devices without passing through the eNB as shown in Fig. 1.1(b). To establish a D2D communication among the devices in close proximity to each other, there are two main mechanisms are involved. First, the peer device discovery and second, the D2D session setup. Peer device discovery can be subdivided into restricted-peer device discovery and open-peer device discovery. In restricted-peer device discovery, the device needs certain permissions to access the network, thus maintaining the user's privacy. For open-peer device discovery, the device can be identified as long as it is near another device. The device session setup initiates when the device-peer discovery is finished.

According to the link establishment, D2D communication is categorized into four primary types [5]:

I. Device relaying with operator-controlled link establishment: A device in a remote area or far away from the evolved node B (eNB) can communicate with an eNB using another device as a relay. In this communication scenario, an eNB can corroborate the relaying devices and thus preserve the privacy as well as frequency allocation of the devices.

II. Direct D2D communication with operator-controlled link establishment: A network assisted link can communicate with each other bypassing the eNB. The eNB controls the connections, frequency allocation and pecuniary communication between devices.

III. Device relaying with device-controlled link establishment: An eNB has no control over the device communication. Devices communicate with each other by using relays between them.

IV. Direct D2D communication with device-controlled link establishment: An eNB has no control over the device communication. Communication between devices is managed by the devices themselves.

Based on spectrum utilization, we can categorize D2D communication underlaying cellular networks into two primary categories as listed below [6].

a) Inband D2D communication/LTE Direct: D2D communication occurs in a cellular-licensed spectrum in a dedicated mode (overlay mode) or shared mode (underlay mode).

b) Outband D2D communication: D2D communication occurs in an unlicensed spectrum endorsed by other wireless technologies such as Wi-Fi or Bluetooth.

The main advantages of integrating D2D communication in the traditional cellular networks are listed as follows: First, D2D communication reduces mobile traffic to the eNB, which results in a higher cellular network capacity. Next, D2D communication facilitates the reutilization of the available cellular spectrum, thus enabling maximum utilization of the available spectrum. Finally, D2D communication reduces end-to-end delay as it allows direct communication between nearby devices.

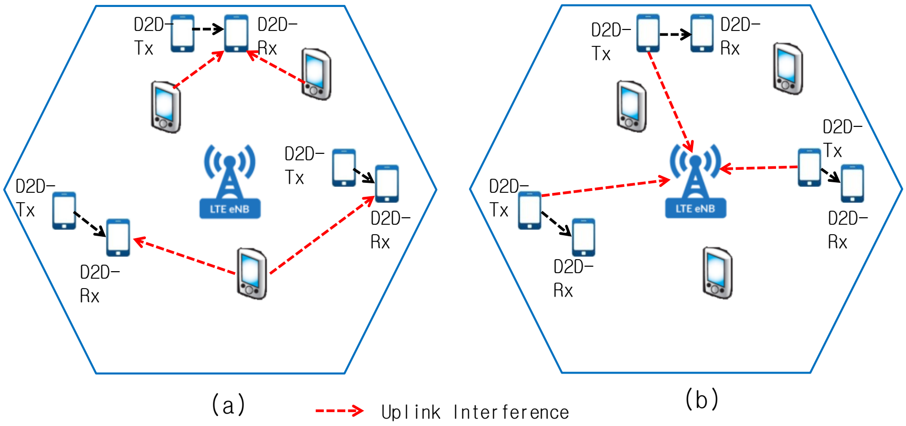


Fig.1.2: (a) Interference from CU to D2D receiver, and (b) interference from D2D transmitter to eNB.

In addition, there are various technical challenges with the introduction of the D2D communication into the traditional cellular network such as time synchronization, frequency synchronization and peer discovery between the users. Consider an uplink cellular network scenario where the DPs (DPs) are reusing the uplink cellular links: This generates two main interferences, interference to the D2D receiver caused by the signal transmitted from the eNB to the CUs, and interference to eNB caused by the signal transmitted by the D2D transmitter to D2D receiver as shown in Fig. 1.2(a) and Fig. 1.2(b). The co-channel interference caused by the D2D users to CUs and vice versa deteriorates the system quality of service (QoS) and spectral efficiency of the overall network. Therefore, co-channel interference is considered the primary challenge in the underlay inband D2D communication system. Integrating D2D communications with traditional cellular networks can resolve the problem of available spectrum discovery and avoidance of collision between DPs and CUs [7] [8]. According to a research conducted by Juniper Research in 2015, by 2020, the number of connected devices will be 38.5 billion, up from 13.4 billion in 2015 a rise of 285% [9]. Furthermore, WINNER+ project has also considered D2D communication as one of the solution to achieve the overall performance of cellular systems [10].

In order to enhance the performance for D2D communications underlaying cellular networks and satisfy QoS requirements for system, it is of great importance to design efficient resource allocation techniques. To this end, we identify resource allocation and power allocation scheme for D2D communications underlaying uplink cellular networks as an interesting research problem with significant room for improvement.

1.2.1. Radio Resource Allocation and Power Control

The idea of radio resource management is performed with the allocation of available radio resources among devices in cellular networks. In radio resource assignment technique, the main objective is to effectively utilize the whole resources while guaranteeing QoS requirements of the users. In a D2D communication underlaying a cellular network, DPs reuse the licensed cellular resource to enhance the system spectrum efficiency, which generates severe interference between CUs and DPs, and also mutual interference among the DPs. Such interference reduces the QoS determined by the users. To mitigate the interference, study on the random resource allocation (RRA) method has been proposed in the literature [11]. In the RRA method, the available DPs can reuse any available channel resources of the CUs and derived a closed-form expression for the outage probability. However, in the RRA scheme, effective utilization of the available frequency bands was not achieved. The D2D network underlaying a cellular network that reuses the traditional cellular links is presented in [12].

In addition, transmission power control is important for interference mitigation and power saving. In absence of interference, higher transmission power enables a network to communicate at higher data rate which results in higher system spectrum efficiency. However, when the co-channel interference exists, higher transmission power increases co-channel interference which results in reduced signal-to-interference-noise ratio (SINR). There have been many works in power control techniques for D2D communications in literature. The work in [13] proposed a post-resource allocation and power control scheme for CUs. Frequency reuse scenario is determined based on the interference generated by the D2D users. In [14], system capacity evaluation using a blocking queuing model has been presented. In their network, an overlay D2D communication mode is discussed and formulated a fair admission control problem. Network-assisted D2D communication and its advantages are listed in [15]. In [16], a two-step approach for D2D communication underlaying uplink cellular network has been discussed. At the first-step: a novel resource allocation based on the static transmits power was analyzed. At the second-step: interference minimization problem was formulated for dynamic reusing of cellular resources. However, in their study, QoS analysis was not considered. In [17], the authors proposed a joint resource block and power control method by using Nash Equilibrium computation technique. In order to improve spectrum efficiency, the authors in [18] proposed a context-aware cluster based D2D communications. Moreover, to mitigate these interferences generated due to D2D communications, the FFR technique is primarily used by allotting specific spectrum resources to the users.

1.2.2. Fractional Frequency Reuse (FFR)

The fractional frequency reuse (FFR) method is a well-known technique to mitigate interferences caused by the frequency reuse method. FFR is radio resource partition method in the LTE-A system [19], which partitions the cell's available band into different sections such that the users of the adjacent cell do not interfere with each other while reusing the cellular frequency by the DPs as shown in Fig. 1.3. The FFR scheme facilitates the reuse of the same frequency in cellular networks to encourage the concurrent communication demands. This can improve the system spectral efficiency and channel quality [20, 21]. The FFR scheme utilizes the entire spectrum in a cell and reduces the co-channel interference within the cell as well as among the cells.

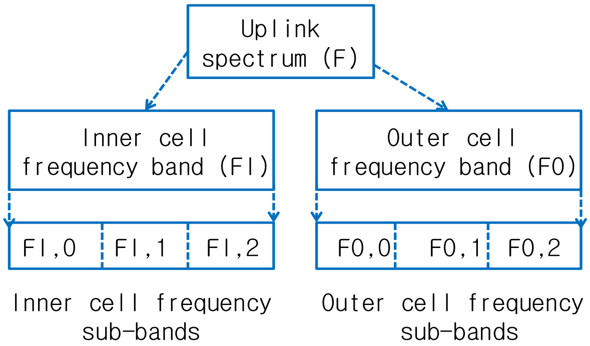


Fig. 1.3: Spectrum partition technique.

The frequency reuse factor (RF) is defined as the rate at which the available spectrum is used by the CUs and DPs at the same time in a cellular network. In literature, studies have been conducted on FFR for interference cancellation and reduction for CUs [22]. The work in [23] proposed a virtual cell sectorization method to jointly enhance resource allocation and reuse in a network-controlled D2D communication. In [24], the authors proposed a frequency-reuse method by considering different transmission powers of CUs and DPs based on the user’s accessing location.

The cellular system throughput optimization problem based on FFR is formulated in many studies in the literature. The authors in [25] proposed an optimization problem that considers QoS constraints on the CUs and DPs. In their study, the optimal conditions for power for each subchannel were analyzed. In [26], the authors proposed a resource-allocation scheme for DPs by dividing whole cell area into two non-overlapping regions, without cell sectorization (RA w/o sectorization) scheme. It has been shown that reusing more than one channel resources of CUs increases the system throughput significantly. In [27], the authors presented a D2D communication with FFR and fractional power-control schemes. The paper focused on the coverage region for both the DPs and CUs based on transmitter power. The D2D communication as the underlay to the orthogonal frequency division multiple access (OFDMA) is analyzed in [28]. In the paper, the authors presented a downlink resource-reuse method that considers only the outer cell region users to avoid interference from the eNBs. Dynamic power control for D2D communications underlaying uplink multi-cell networks has been presented in [29]. In their work, an optimization problem is formulated to minimize the uplink interference due to the integration of D2D communications to the conventional cellular communications.

1.3. Multicast D2D Communication

Recent years have witnessed rapid trending of multicast D2D (M-D2D) communications. When the same information should be transmitted from one transmitter to multiple receivers, instead of sending data through multiple unicasts, multicasting may enhance system capacity and spectral efficiency. Moreover, compared to unicast (point-to-point) communication system where a transmitter sends the signal to a single receiver, M-D2D communication reduces overhead. In M-D2D communication, nearby devices form an M-D2D communication group where D2D receivers in the group can receive the same data from the D2D transmitter over a direct link, without relying on evolved eNB as shown in Fig. 1.4.

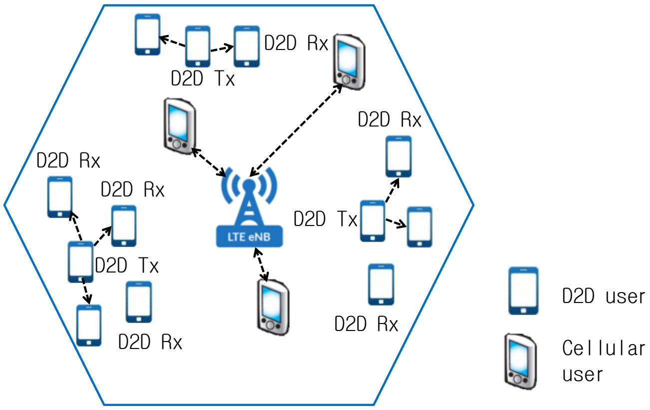


Fig. 1.4: M-D2D communication underlaying uplink cellular network.

M-D2D communications can be categorized into: single rate and multi-rate transmissions [30]. In the single-rate transmission, D2D transmitter in a multicast group transmits the same data rate to its corresponding receivers. Whereas, in the multi-rate transmission, D2D transmitter in a multicast group transmits multiple data rates according to the receiver’s demands. This concept envisaged as the promising solution for the incoming 5G system and Internet of Things (IoT) technology.

Some of the well-known applications of the M-D2D communication are media-rich applications such as local multimedia content sharing of photos, and music and also high-quality video sharing application such as video multicasting in social platforms. The resource allocation in M-D2D communications is challenging since this service is characterized by strict QoS requirements.

Considerable research has been conducted on M-D2D communications. The main issues and challenges in a multicast communications environment are summarized in [31]. The paper classifies the existing multicast protocols based on several distinct features and performance parameters. In [32], the authors discussed on modeling and analysis of M-D2D communication and an optimization problem was formulated based on the mobility and network assistance issues. The problem with this study is that the interference coordination function was not applied. In [33], the authors proposed an energy-efficient multicast scheduling scheme to achieve high energy efficiency. Also, the transmission power control method of the multi-hop D2D transmission paths was analyzed. In [34], the authors proposed an optimized opportunistic multicast scheduling over wireless cellular networks. The homogeneous network that is partitioned into rings uses different channel links. An optimization problem was formulated to achieve the optimal solution. In [35], the authors proposed an MC-CDMA transmission scheme in M-D2D communication. The results showed that their proposed scheme achieves better SINR for M-D2D communication. A dynamic power control scheme was introduced to mitigate interference from M-D2D to cellular network [36]. Comparing the result of this scheme with that of conventional multicast transmission scheme shows the improvement of system throughput.

1.4. Contributions and Overview of the Thesis

Inspired by the existing contributions in literature, in this thesis, we analyze different resource allocation techniques to leverage performance of the system with D2D communications. In Chapters 2-4, we discuss how the D2D communications can be done to improve the system performance using cell sectorization method based on different values of frequency reuse factor. In Chapter 5, we discuss resource allocation and power control for M-D2D communications. The main contributions of the thesis are listed below. In Chapter 2, we design a non-orthogonal resource sharing scheme for D2D communications using FFR scheme. We consider the RF of one, in which only one DP can reuse uplink cellular link at a time to maximize the transmission throughput of the system. A resource allocation and power control scheme is proposed to efficiently reuse cellular resources by guaranteeing QoS of both users and formulated a throughput optimization problem to find the optimal resource pairing partner. The proposed algorithm has less complexity compared to the RRA scheme.

In Chapter 3, we consider a distance-based resource allocation scheme for D2D communications with RF of 2. The system with RF of 2 enables simultaneously reusing of single cellular resource by 2 DPs. We formulate the outage probability problem of both CUs and DPs while reusing cellular resources. To maximize the overall system throughput, we analyze a throughput optimization problem. We also analyze Jain's fairness index for fairness distribution of resources.

In Chapter 4, we discuss an optimal resource management scheme with higher frequency reuse factor in D2D communications. Moreover, the statistical channel information is analyzed to evaluate the SINR. Then, we formulate the throughput maximization problem by using two efficient methods: a greedy heuristic method and a binary power control method. The greedy heuristic search algorithm performs local search to find the suboptimal solution. Furthermore, in order to achieve optimal solution, we proposed a binary power control scheme. The main advantage of the binary power control scheme is that continuous channel state information (CSI) update is not required in binary power control scheme.

In Chapter 5, we study resource allocation for M-D2D communications. Due to the multicast phenomenon of data transmissions, D2D communications and existing CUs may cause severe interference between devices. We design a resource allocation scheme to maximize the overall system throughput. Moreover a metaheuristic-tabu search algorithm is analyzed, where one D2D group can simultaneously reuse the same uplink resource with the conventional CU. Tabu search is an efficient metaheuristic technique that finds an optimal and optimal solution of diverse practical applications. In metaheuristic-tabu search algorithm, a neighborhood function is defined to overcome the possibility of being trapped at a local optimum. The main benefits of proposing metaheuristic-tabu search algorithm in our work are: it requires less computation time and is efficient for large problem size network.

Chapter 2

Fractional Frequency Reuse-Based D2D Communications

Starting from this chapter, we discuss radio resource allocation and power control in D2D communications underlaying uplink cellular networks. The basic idea is to understand the advantages brought by the D2D communications using FFR scheme. The issue is first studied for a non-orthogonal reuse of uplink resources by the CUs and DPs.

2.1. Background and Related Works

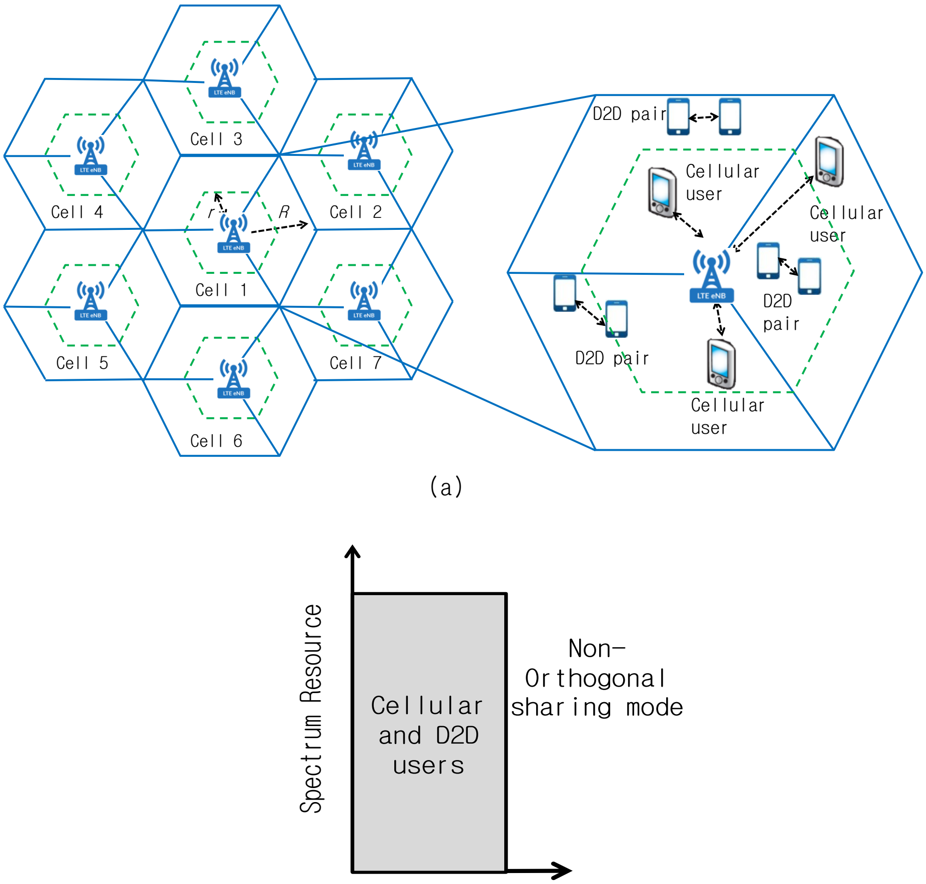
In conventional cellular communications, the CUs communicate with each other through a central node such as eNB. Underlaying D2D communication is suggested as a promising technology for the next generation cellular networks, where users in close proximity can communicate directly to one another without the base station. However, when D2D communications underlay cellular networks, the possible gain from resource sharing is highly driven by how different interference is managed. Traditional interference management methods for cellular networks will not work for a D2D underlaying a cellular network for two main reasons; firstly, D2D users are only assigned a resource that has already been assigned to a CU unlike CUs assigned a previously unassigned resource, and secondly, the D2D users have lower priority than the traditional CUs because CUs are the primary users of the cellular network and their service quality cannot be compromised because of secondary D2D users.

To analyze this problem, in literature many works have done to reduce the interference between CUs and DPs. To the extent of literature works, the authors in [37] discussed the frequency reusing technique by considering only the frequency which is not used by the conventional cellular users and select the best reuse partner to reduce the uplink interference between D2D links and CUs. Sectional frequency reuse technique is discussed in [38, 39], where different reuse factors are considered. This method can achieve higher system spectral efficiency. Finally, the authors in [40] studied a method that assigns the channel with the lowest gain to the D2D user. However, such studies have focused on the performance of the users near the eNB and have not considered users located at the edge region. Thus, do not improve the performance of the overall system. The work in [41] proposed to divide the cell region into two inner and outer regions, and then the outer region is partitioned into multiple regions. Frequency reusing structure is studied based on the interference from CUs to DPs and channel gains of DPs together. In [42], the authors proposed a frequency reuse scheme for interference mitigation and reduction in D2D communications in which the radius of inner cell region is determined based on the SINR threshold and outage probability requirement. But, using omnidirectional antenna increases the interference. In [43], different frequency bands and transmission powers of eNB and D2D transmitter have been selected based on the user’s locations in the inner and outer cell regions. However, in their scheme, whole frequency band was not considered, which degrade the performance.

2.2. Network Model

In this paper, we consider an uplink multicell cellular network as shown in Fig. 2.1. The reason for considering the hexagonal shape cell is to mitigate the propagation loss caused by the different terrains. Moreover, the hexagonal cellular geometry facilitates the analysis of cellular networks. In Fig. 2.1, the cell area is divided into two regions namely inner and outer cell regions with cell radius r and R, respectively. In each hexagonal cell, the base station is placed at the cell center. Both regions are sectored into three sub-regions using 120° directional antennas. In this network, the reuse of the channel resources occurs in two scenarios: First, the DPs in the inner cell region reuse the channel resources of the CUs in the outer cell region. Second, the DPs in the outer cell region reuse the channel resources of the CUs in the inner cell region of the corresponding sectored region. The non-orthogonal resource sharing between CUs and DPs is shown in Fig. 2.1(b). The DP located in a certain cell region can only reuse only one cellular resource of its corresponding cell region. Reusing the cellular resource by more than one DP is strictly prohibited.

Consider a cell with M CUs and N D2D users uniformly distributed in a cell. We define the sets of CUs and D2D users as $C = (1,2,\ldots,M)$ and $D = (1,2,\ldots,N)$, respectively. Similarly, the users are categorized as C_{in}, C_{out}, D_{in} and D_{out}, where C_{in} and C_{out} are the CUs belonging to inner and outer cell regions, respectively, and D_{in} and D_{out} are the D2D users belongs to cell inner and outer region respectively. In this paper, we consider the distance between the DP and the CU whose channel resource is to be reused by the DP, in which a maximum separable distance is to be maintained to avoid interference from the CU to the device receiver.



(a)

(b)

Fig. 2.1: (a) Multicell network model, and (b) non-orthogonal resource sharing.

The partitioned frequency band structure based on the power level is shown in Fig. 2.2, in which the available spectrum is partitioned into two parts, the inner cell frequency and the outer cell frequency.

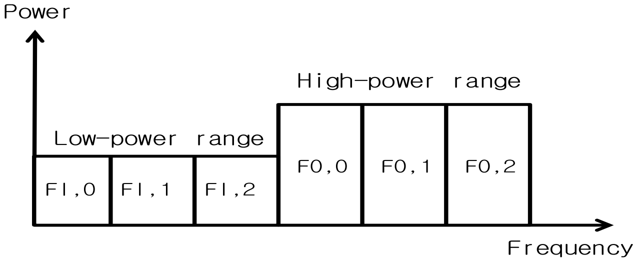


Fig. 2.2: Spectrum partition based on the power level.

Further, both frequency bands are sub-divided into three corresponding bands as, $F_{\mathrm{I},0}$, $F_{\mathrm{I},1}$, $F_{\mathrm{I},2}$, $F_{\mathrm{O},0}$, $F_{\mathrm{O},1}$ and $F_{\mathrm{O},2}$, where $F_{\mathrm{I},0}$, $F_{\mathrm{I},1}$ and $F_{\mathrm{I},2}$ are the sub-bands of the inner cell frequency F_{I} and, $F_{\mathrm{O},0}$, $F_{\mathrm{O},1}$ and $F_{\mathrm{O},2}$ are the sub parts of the outer cell frequency F_{O}. In our network model, we used the subparts of both frequencies to meet the design trade-off between spectrum utilization and interference mitigation in the cellular network.

$$F = F_I + F_O = \left(F_{I,0} + F_{I,1} + F_{I,2}\right) + \left(F_{O,0} + F_{O,1} + F_{O,2}\right), \qquad (1)$$

The location of the uniformly distributed cellular devices is expressed by considering polar coordinates (θ_C, l_c), where θ_C is an angle of θ_C and l_c is the distance from the eNB. Therefore, the probability density functions of the CU (in polar coordinates) in the inner and outer cell regions are expressed as follows [24]:

For the inner cell CUs

$$f(l_C) = \frac{2(l_C - l_S)}{(R - l_S)^2}, \forall l_s \leq l_C \leq R, \qquad (2)$$

For the outer cell CUs

$$f(l_c) = \frac{2(l_c - l_s)}{(r - l_s)^2}, \forall l_s \leq l_c \leq r, \qquad (3)$$

$$f(\theta_c) = \frac{1}{\left(\frac{2\pi}{3}\right)}, \forall 0 \leq \theta_c \leq 2\pi, \qquad (4)$$

where l_S and l_s are the shortest distance between the outer and the inner cell CUs from the eNB, respectively; R is the radius of the outer cell, and r is the radius of the inner cell. The comprehensive functional flow of the proposed scheme is presented in Algorithm 2.1.

Algorithm 2.1: Working of the Proposed Resource Allocation and Power Control Scheme

```
Step1 : Divide cell into $F_I$ and $F_O$
Step 2 : Sectorize $F_I$ into $F_{I,0}$, $F_{I,1}$ and $F_{I,2}$ , and $F_O$ into $F_{O,0}$, $F_{O,1}$ and $F_{O,2}$
Step 3 : Initialization: Set C = {1,2,3,......, N}, D = {1,2,3,....., M}
Step 4 : Check locations of cellular users
Step 5 : $P_{D_{in}}^{min} \le P_{D_{in}} \le P_{D_{in}}^{max}$, $P_{D_{out}}^{min} \le P_{D_{out}} \le P_{D_{out}}^{max}$, $P_{C_{in}}^{min} \le P_{C_{in}} \le P_{C_{in}}^{max}$,
         $P_{C_{out}}^{min} \le P_{C_{out}} \le P_{C_{out}}^{max}$
Step 6 : for d= 1 to m, D= 1 to M, c= 1 to n , C = 1 to N , do
    Step 7 : Calculate the distance between D2D pair and eNB, and D2D pair and
             cellular user
    Step 8 : Calculate $\gamma_{D_{in}}$ , $\gamma_{D_{out}}$ , $\gamma_{C_{in}}$ , $\gamma_{C_{out}}$
    Step 9 : Calculate $O_{D_{in}}$ , $O_{D_{out}}$ , $O_{C_{in}}$ and $O_{C_{out}}$
    Step 10 : if ($O_{C_{in}} \le \rho_{C_{in}}$ , $O_{D_{in}} \le \rho_{D_{in}}$)and ($O_{C_{out}} \le \rho_{C_{out}}$ , $O_{D_{out}} \le \rho_{D_{out}}$) then
        Step 11 : Compute $T_{D_{in}} = \log_2(1+\gamma_{D_{in}})$, $T_{D_{out}} = \log_2(1+\gamma_{D_{out}})$,
                  $T_{C_{in}} = \log_2(1+\gamma_{C_{in}})$, $T_{C_{out}} = \log_2(1+\gamma_{C_{out}})$, $T = T_{D_{in}} + T_{D_{out}} + T_{C_{in}} + T_{C_{out}}$
    Step 12 : else if ($O_{C_{in}} > \rho_{C_{in}}$ , $O_{D_{in}} > \rho_{D_{in}}$)and ($O_{C_{out}} > \rho_{C_{out}}$ , $O_{D_{out}} > \rho_{D_{out}}$) then
        Step 13 : Recalculate $\gamma_{D_{in}}$ , $\gamma_{D_{out}}$ , $\gamma_{C_{in}}$ , $\gamma_{C_{out}}$
    Step 14 : end if
Step 15 : end for
```

Moreover, the resource allocation scheme proposed in this paper is performed by considering different frequency sub-bands of the network. To allocate resources properly, we assumed that a DP located in $F_{I,0}$ sub-band cannot reuse the resources of same sub-band but can reuse the resources of $F_{O,0}$. In addition, the distance between the CU located in $F_{O,0}$ sub-band and DP located in $F_{I,0}$ sub-band should maintain.

This results in the least interference between the CU and DP. Since the users are assisted by directional antennas, the available resources are uniformly allocated to all the users.

2.3. Problem Formulation

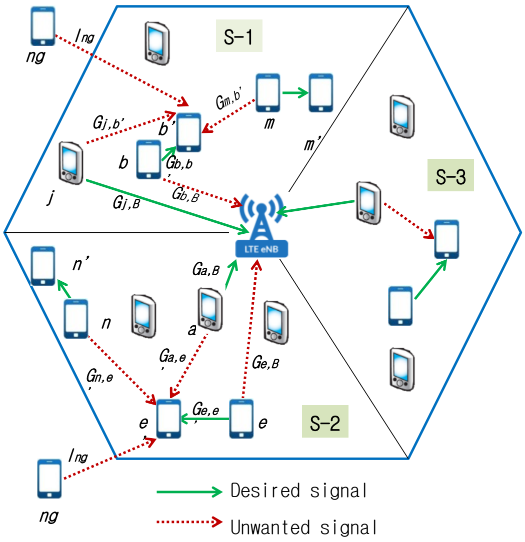
2.3.1. Interference Analysis

The received power in the communication system is defined as the product of the transmitted power and the channel coefficient i.e.,

$$P_R = P_T.\mathrm{G}, \tag{5}$$

$$\mathrm{G} = P_g.\phi^{-1}.\delta, \tag{6}$$

where P_R is the received power, P_T is the transmitted power, G is the channel coefficients, P_g is the power gain, ϕ is the path loss and δ is the shadowing coefficient.



Notations

b, *m* = inner cell D2D transmitters
b', *m'* = inner cell D2D receivers
a = inner cell cellular user
j = outer cell cellular user
e, *n* = outer cell D2D transmitters
e', *n'* = outer cell D2D receivers
ng = neighboring users

Fig. 2.3: Uplink cellular resource reuse scenario.

To maintain reliable information transmission after integrating D2D communications in the cellular networks, the

SINR requirement is set up to a minimum level for the D2D communication. We assumed that in the inner cell region, D2D transmitter b communicates with receiver $b^{'}$ by reusing resource of the CU j as shown in section S-1 of Fig.2.3. Similarly, in the outer cell region, D2D transmitter e communicates with receiver $e^{'}$ by reusing resource of the CU a, as shown in section S-2 of Fig. 2.3. The eNB is denoted as B for analysis purpose. Considering the interference scenario presented in Fig. 2.3, we can express the SINR of CUs and the D2D users of both the inner and outer cell regions as follows:

- For the inner cell user: The received SINR for the inner cell CU and the DP is given by

$$\gamma_{C_{in}} = \frac{P_a A_{a,B}^{-\alpha} |G_{a,B}|^2}{P_N + P_e A_{e,B}^{-\alpha} |G_{e,B}|^2} \geq \gamma_t, \forall a \in C_{in}, e \in D_{out}, \tag{7}$$

$$\gamma_{D_{in}} = \frac{P_b A_{b,b^{'}}^{-\alpha} |G_{b,b^{'}}|^2}{P_N + P_j A_{j,b^{'}}^{-\alpha} |G_{j,b^{'}}|^2 + I_{b^{'}} + I_{ng}} \geq \gamma_t, \forall b, b^{'} \in D_{in}, j \in C_{out}, \tag{8}$$

respectively, where $I_{b^{'}}$ is the interference to D2D receiver $b^{'}$ in the inner cell region and can be expressed as follows:

$$I_{b^{'}} = \sum_{m=1}^{2} P_m A_{m,b^{'}}^{-\alpha} |G_{m,b^{'}}|^2, \forall m, b^{'} \in D_{in,} \tag{9}$$

The interference from the neighboring cells I_{ng} can be denoted as

$$I_{ng} = \sum_{i=1}^{6} I_i, \tag{10}$$

- For the outer cell user: The received SINR for the outer cell CU and the DP is given by

$$\gamma_{C_{out}} = \frac{P_j A_{j,B}^{-\alpha} |G_{j,B}|^2}{P_N + P_b A_{b,B}^{-\alpha} |G_{b,B}|^2} \geq \gamma_t, \forall b \in D_{in}, j \in C_{out,} \tag{11}$$

$$\gamma_{D_{out}} = \frac{P_e A_{e,e^{'}}^{-\alpha} |G_{e,e^{'}}|^2}{P_N + P_a A_{a,e^{'}}^{-\alpha} |G_{a,e^{'}}|^2 + I_{e^{'}} + I_n} \geq \gamma_t, \forall e, e^{'} \in D_{out}, a \in C_{in,} \tag{12}$$

respectively, where $I_{e'}$ is the interference to user D2D receiver e' and can be listed as

$$I_{e'} = \sum_{n=1}^{2} P_n A_{n,e'}^{-\alpha} |G_{n,e'}|^2, \forall e', n \in D_{out,} \tag{13}$$

$$I_{ng} = \sum_{q=1}^{6} I_q, \tag{14}$$

Therefore, $P_a \in P_{C_{in}}$,$P_j \in P_{C_{out}}$, $(P_b, P_m) \in P_{D_{in}}$ and $(P_e, P_n) \in P_{D_{out}}$, where $P_{C_{in}}$ and $P_{C_{out}}$ are the transmit power of the CU in the inner and outer cell regions, respectively, $P_{D_{in}}$ and $P_{D_{out}}$ are the transmit power of the D2D user in the inner and outer cell regions, respectively. Similarly, $A_{a,B}$ and $A_{e,B}$ are the distance between the inner cell CU a and B, and distance between the outer cell D2D transmitter e and B. $A_{b,b'}$, $A_{j,b'}$ and $A_{m,b'}$ distance between the inner cell D2D transmitter b and receiver b', distance between the outer cell CU j and inner cell D2D receiver b', and the distance between the co-channel D2D transmitter m and receiver b'. $A_{j,B}$, $A_{b,B}$ are the distance between the outer cell CU j and B, and distance between the inner cell D2D transmitter b and B. $A_{e,e'}$, $A_{a,e'}$ and $A_{n,e'}$ are the distance between outer the cell D2D transmitter e and receiver e', distance between the co-channel D2D transmitter n and e'. Moreover, $G_{a,B}$ and $G_{e,B}$ are the channel coefficient between the inner cell CU a and B, and channel coefficient between the outer cell D2D transmitter e and B. $G_{b,b'}$, $G_{j,b'}$ and $G_{m,b'}$ are the channel coefficient between the inner cell D2D transmitter b and receiver b', channel coefficient between the outer cell CU j and inner cell D2D receiver b', and channel coefficient between the co-channel D2D transmitter m and b'. $G_{j,B}$ and $G_{b,B}$ are the channel coefficient between the outer cell CU j and B, and channel coefficient between the inner cell D2D transmitter b and B. $G_{e,e'}$, $G_{a,e'}$ and $G_{n,e'}$ are the channel coefficient between the outer cell D2D transmitter e and receiver e', channel coefficient between the inner cell CU a and outer cell D2D receiver e', and channel coefficient between the co-channel D2D transmitter n and receiver e'. P_N is the noise power, α is the path-loss exponent, and I_{ng} is the interference from the neighboring cells to the D2D receivers. In order to guarantee the QoS of the D2D users, we defined an uplink interference region of the CUs as shown in Fig. 2.4. Within this region, interference from CU to D2D receiver is very severe, hence D2D communication is not allowed in this region [25].

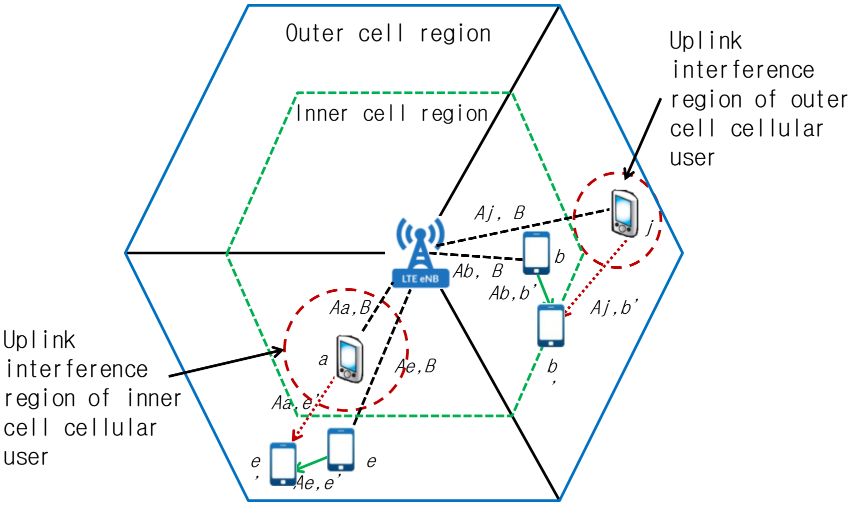


Fig.2.4: Uplink interference regions of CUs.

For interference region analysis, we consider a scenario where a communication system attains a minimum allowable SINR. From equations (7, 12), we defined the uplink interference region ($U_{C_{in}}$) as listed below.

$$\left.\begin{aligned} \frac{P_a A_{a,B}^{-\alpha} |G_{a,B}|^2}{P_e A_{e,B}^{-\alpha} |G_{e,B}|^2} = \gamma_t, \\ \frac{P_a}{P_e} = \gamma_t \frac{A_{e,B}^{-\alpha} |G_{e,B}|^2}{A_{a,B}^{-\alpha} |G_{a,B}|^2}, \end{aligned}\right\}, \tag{15}$$

$$\left.\begin{aligned} \frac{P_e A_{e,e'}^{-\alpha} |G_{e,e'}|^2}{P_a A_{a,e'}^{-\alpha} |G_{a,e'}|^2} = \gamma_t, \\ \frac{P_e}{P_a} = \gamma_t \frac{A_{a,e'}^{-\alpha} |G_{a,e'}|^2}{A_{e,e'}^{-\alpha} |G_{e,e'}|^2}, \end{aligned}\right\}, \tag{16}$$

From (15, 16), we have,

$$\left.\begin{aligned} \gamma_t \frac{A_{a,e'}^{-\alpha} |G_{a,e'}|^2}{A_{e,e'}^{-\alpha} |G_{e,e'}|^2} = \frac{A_{a,B}^{-\alpha} |G_{a,B}|^2}{\gamma_t (A_{e,B}^{-\alpha} |G_{e,B}|^2)}, \\ {\gamma_t}^2 = \frac{A_{a,B}^{-\alpha} |G_{a,B}|^2}{A_{e,B}^{-\alpha} |G_{e,B}|^2} \times \frac{A_{e,e'}^{-\alpha} |G_{e,e'}|^2}{A_{a,e'}^{-\alpha} |G_{a,e'}|^2}, \\ {\gamma_t}^2 = \left(\frac{A_{a,B}}{A_{e,B}} . \frac{A_{e,e'}}{A_{a,e'}}\right)^{-\alpha} \times \left(\frac{|G_{a,B}|}{|G_{e,B}|} . \frac{|G_{e,e'}|}{|G_{a,e'}|}\right),^2 \end{aligned}\right\}, \tag{17}$$

In (17), we assume $\left(\frac{|G_{a,B}|}{|G_{e,B}|} . \frac{|G_{e,e'}|}{|G_{a,e'}|}\right) = \gamma_t = \text{constant value}$, then

$$A_{a,e'} = U_{C_{in}} \geq \left(\frac{A_{a,B} A_{e,e'}}{A_{e,B}}\right), \tag{18}$$

We can see from (18) that to guarantee the QoS of the D2D communication in outer cell region by reusing inner cell cellular resource, the distance between inner cell CU and outer cell D2D receiver should be large.

Similarly, from equations (8, 11), we defined the uplink interference region ($U_{C_{out}}$) as listed below.

$$\left.\begin{aligned} \frac{P_b A_{b,b'}^{-\alpha} |G_{b,b'}|^2}{P_j A_{j,b'}^{-\alpha} |G_{j,b'}|^2} = \gamma_t, \\ \frac{P_b}{P_j} = \gamma_t \frac{A_{j,b'}^{-\alpha} |G_{j,b'}|^2}{A_{b,b'}^{-\alpha} |G_{b,b'}|^2}, \end{aligned}\right\}, \tag{19}$$

$$\left.\begin{aligned} \frac{P_j A_{j,B}^{-\alpha} |G_{j,B}|^2}{P_b A_{b,B}^{-\alpha} |G_{b,B}|^2} = \gamma_t, \\ \frac{P_j}{P_b} = \gamma_t \frac{A_{b,B}^{-\alpha} |G_{b,B}|^2}{A_{j,B}^{-\alpha} |G_{j,B}|^2}, \end{aligned}\right\}, \tag{20}$$

From (19, 20), we have,

$$\left.\begin{aligned} \gamma_t \frac{A_{b,B}^{-\alpha}|G_{b,B}|^2}{A_{j,B}^{-\alpha}|G_{j,B}|^2} &= \frac{A_{b,b'}^{-\alpha}|G_{b,b'}|^2}{\gamma_t(A_{j,b'}^{-\alpha}|G_{j,b'}|^2)}, \\ {\gamma_t}^2 &= \frac{A_{b,b'}^{-\alpha}|G_{b,b'}|^2}{A_{j,b'}^{-\alpha}|G_{j,b'}|^2} \times \frac{A_{j,B}^{-\alpha}|G_{j,B}|^2}{A_{b,B}^{-\alpha}|G_{b,B}|^2}, \\ {\gamma_t}^2 &= \left(\frac{A_{b,b'}}{A_{j,b'}}.\frac{A_{j,B}}{A_{b,B}}\right)^{-\alpha} \times \left(\frac{|G_{b,b'}|}{|G_{j,b'}|}.\frac{|G_{j,B}|}{|G_{b,B}|}\right),^2 \end{aligned}\right\}, \tag{21}$$

In (17), we assume $\left(\frac{|G_{b,b'}|}{|G_{j,b'}|}.\frac{|G_{j,B}|}{|G_{b,B}|}\right) = \gamma_t =$ constant value, then

$$A_{j,b'} = U_{C_{out}} \geq \left(\frac{A_{b,b'}A_{j,B}}{A_{b,B}}\right), \tag{22}$$

We can see from (22) that to guarantee the QoS of the D2D communication in inner cell region by reusing outer cell cellular resource, the distance between outer cell CU and inner cell D2D receiver should be large. Therefore, a larger distance between the users can mitigate uplink interference from the CU to D2D communication. In this way, we can improve D2D communication throughput and overall system throughput.

2.3.2. Outage Probability Analysis

Outage probability is important in analyzing the performance of wireless communication systems. In this paper, we analyze the outage probabilities of the D2D communications and cellular networks in a multicell system when the uplink cellular links are shared by the DPs. The outage probability is stated as the probability that the spontaneous SINR drops below a predefined threshold SINR. Therefore, the corresponding outage probability of a CU and DP in both cell regions in terms of their SINRs are illustrated as below.

1. For the inner cell user: The outage probability for the CU in the inner cell region, in terms of the received SINR is given as

$$\left.\begin{aligned} O_{C_{in}} &= 1 - \frac{1}{1+\frac{(P_{e}A_{e,B}^{-\alpha})\gamma_t}{P_a A_{a,B}^{-\alpha}}}\exp(-\frac{\gamma_t P_N}{P_a}) \leq \rho_{C_{in}}, \\ &= 1 - \frac{P_a A_{a,B}^{-\alpha}}{P_a A_{a,B}^{-\alpha} + (P_{e}A_{e,B}^{-\alpha})\gamma_t}\mathrm{e}^{\left(-\frac{P_N\gamma^{Th}}{P_a}\right)} \leq \rho_{C_{in}}, \end{aligned}\right\}, \forall a \in C_{in}, e \in D_{out}, \quad (23)$$

$$\left.\begin{aligned} O_{D_{in}} &= 1 - \frac{1}{1+\frac{\left(P_j A_{j,b'}^{-\alpha}+I_{b'}+I_n\right)\gamma_t}{P_b A_{b,b'}^{-\alpha}}}\exp\left(-\frac{\gamma_t P_N}{P_b}\right) \leq \rho_{D_{in}}, \\ &= 1 - \frac{P_b A_{b,b'}^{-\alpha}}{P_b A_{b,b'}^{-\alpha} + \left(P_j A_{j,b'}^{-\alpha}+I_{b'}+I_n\right)\gamma_t}\mathrm{e}^{\left(-\frac{P_N\gamma^{Th}}{P_b}\right)} \leq \rho_{D_{in}}, \end{aligned}\right\}, \forall b, b' \in D_{in}, j \in C_{out}, \quad (24)$$

where γ_t , $\rho_{C_{in}}$ and $\rho_{D_{in}}$ denote the threshold SINR, required outage probability of the CU and D2D user, respectively. Similarly, the outage probability for the inner cell DP in terms of received SINR is given.

2. For the outer cell user: The outage probability for the CU and the DP in the outer cell region in terms of their SINRs is expressed as

$$\left.\begin{aligned} O_{C_{out}} &= 1 - \frac{1}{1+\frac{\left(P_b A_{b,B}^{-\alpha}\right)\gamma_T}{P_j A_{j,B}^{-\alpha}}}\exp\left(-\frac{\gamma_T P_N}{P_j}\right) \leq \rho_{C_{out}}, \\ &= 1 - \frac{P_j A_{j,B}^{-\alpha}}{P_j A_{j,B}^{-\alpha} + (P_b A_{b,B}^{-\alpha})\gamma_T}\mathrm{e}^{\left(-\frac{P_N\gamma^{Th}}{P_j}\right)} \leq \rho_{C_{ou\square}}, \end{aligned}\right\}, \forall b \in D_{in}, j \in C_{out}, \quad (25)$$

$$\left.\begin{aligned} O_{D_{out}} &= 1 - \frac{1}{1+\frac{\left(P_a A_{a,e'}^{-\alpha}+I_{e'}+I_n\right)\gamma_T}{P_e A_{e,e'}^{-\alpha}}}\exp\left(-\frac{\gamma_T P_N}{P_e}\right) \leq \rho_{D_{out}}, \\ &= 1 - \frac{P_e A_{e,e'}^{-\alpha}}{P_e A_{e,e'}^{-\alpha} + \left(P_a A_{a,e'}^{-\alpha}+I_{e'}+I_n\right)\gamma_T}\mathrm{e}^{\left(-\frac{P_N\gamma^{Th}}{P_e}\right)} \leq \rho_{D_{out}}, \end{aligned}\right\}, \forall e, e' \in D_{out}, a \in C_{in}, \quad (26)$$

where γ_T, $\rho_{C_{out}}$ and $\rho_{D_{out}}$ are the threshold SINR, predefined required outage probability of the CU and D2D user, respectively.

2.4. System Throughput Optimization

The throughput is defined as

$$T = log_2(1+\gamma) \tag{27}$$

where γ denotes the user's SINR. Combining the SINR expressions (7-22) of different users in both cell regions, we can then formulate the overall system throughput optimization problem as follows:

$$\max \sum_{C=1}^{N} \sum_{D=1}^{M} [T_{C_{in}} + T_{C_{out}} + T_{D_{in}} + T_{D_{out}}] \tag{28}$$

where

$$T_{C_{in}} = log_2(1+\gamma_{C_{in}}), \quad T_{C_{out}} = log_2(1+\gamma_{C_{out}}) \tag{29}$$

$$T_{D_{in}} = log_2(1+\gamma_{D_{in}}), \quad T_{D_{out}} = log_2(1+\gamma_{D_{out}}) \tag{30}$$

subject to

$$\gamma_C \geq \gamma_C^{min}, \gamma_D \geq \gamma_D^{min} \tag{31}$$

$$P_C^{min} \leq P_C \leq P_C^{max}, P_D^{min} \leq P_D \leq P_D^{max} \tag{32}$$

where γ_C^{min} and γ_D^{min} are the minimum achievable SINRs of the CU and D2D user respectively. P_C^{min} and P_C^{max} are the lower and upper bounds power range for the CU, and P_D^{min} and P_D^{max} are the lower and upper bounds power ranges of the D2D user. The optimization problem in (28) gives the throughput maximization by considering throughput of both the CUs and DPs. Constraints in (31) stand for SINR of both the CUs and DPs should be greater than the minimum required SINR. Constraints listed in (32) represent that the power bounds should be within predefined lower and upper bounds. In a multicell D2D communication underlaying an uplink cellular network, the resource pairing criteria between CUs and DPs directly impact the transmit power of each user.

Proposition: The optimal solution of the optimization problem in (28) must be the global-optimal solution of the proposed optimization problem.

Proof: As a matter of fact, when a DP underlaying uplink cellular network reused the cellular resource, the power control mechanism is directly related with the throughput maximization problem. The upper and lower bound transmit power of both the users in cell inner and outer regions can be derived as:

$$\left.\begin{aligned} P_a &= \frac{\gamma_{C_{in}}(P_N+P_e A_{e,B}^{-\alpha}|G_{e,B}|^2)}{A_{a,B}^{-\alpha}|G_{a,B}|^2}, P_b = \frac{\gamma_{D_{in}}\left(P_N+P_j A_{j,b'}^{-\alpha}\left|G_{j,b'}\right|^2+I_{b'}+I_{ng}\right)}{A_{b,b'}^{-\alpha}|G_{b,b'}|^2}, \\ P_j &= \frac{\gamma_{C_{out}}(P_N+P_b A_{b,B}^{-\alpha}|G_{b,B}|^2)}{A_{j,B}^{-\alpha}|G_{j,B}|^2}, P_e = \frac{\gamma_{D_{out}}\left(P_N+P_a A_{a,e'}^{-\alpha}\left|G_{a,e'}\right|^2+I_{e'}+I_n\right)}{A_{e,e'}^{-\alpha}|G_{e,e'}|^2}, \end{aligned}\right\}, \quad \begin{aligned} &\forall a \in C_{in}, b \in D_{in}, \\ &j \in C_{out}, e \in D_{out} \end{aligned} \tag{33}$$

respectively, where $C_{in}, C_{out} \in C$ and $D_{in}, D_{out} \in D$. According to equation (31), if $\gamma_C^{min} > \gamma_C$ and $\gamma_D^{min} > \gamma_D$, then the desired signal cannot be detected. This directly impacts the performance of the network. Consequently, to gratify the minimum SINR, it is necessary to control transmit power of both the users. Hence, $P_C^{min} \le P_C \le P_C^{max}, P_D^{min} \le P_D \le P_D^{max}$ should be satisfied. This ensures that the transmit power of both the users does not exceed the maximum level. This completes the proof.

2.5. Channel Model

The fundamental principle for an eNB to adopt a device operating in either the cellular or D2D mode is determined by the location of the device transmitter and receiver versus the eNB. Therefore, the path loss (PL) measurement is notably considered as the benchmark for determining the device's operating mode. The path losses of different communication links in this paper are adopted using micro-urban models specified by the International Telecommunication Union Radio-

Communication Sector (ITU-R) reports. The path loss models from the base station to CUs and DPs are calculated as follows [44]:

$$\left.\begin{aligned} PL_C &= 36.7log_{10}(L) + 26log_{10}(\tfrac{F_c}{5}) + 40.9 \\ PL_D &= 40log_{10}(\tfrac{L}{1000}) + 30log_{10}(\tfrac{F_c}{1000}) + 49 \end{aligned}\right\}, \qquad (34)$$

where L is the distance from the transmitter to its corresponding receiver, and F_c is the carrier frequency.

2.6. Computational Complexity and Use Case Scenario of the Proposed Scheme

2.6.1. Computational Complexity Analysis

To improve system throughput by minimizing interference, algorithm 2.1 allows the limited communication by defining upper and lower bounds transmit power. In algorithm 2.1, all available channels for CUs and D2D users are evaluated. This results in a complexity of $O(MN)$. Furthermore, our proposed scheme assumes that each DP can only reuse single cellular resource at a time. Therefore, the complexity becomes $O(M^2N)$. The conditions $(O_{C_{in}} \le \rho_{C_{in}}, O_{D_{in}} \le \rho_{D_{in}})$ and $(O_{C_{out}} \le \rho_{C_{out}}, O_{D_{out}} \le \rho_{D_{out}})$ are the check points for the system outage level. These conditions control the number of iterations, hence reduces computational complexity of the system. Thus, our proposed resource allocation and power control scheme for D2D communications is a low complexity state-of-the-art solution, applicable for high data rate services.

2.6.2. Use Case Scenario of the Proposed Scheme

D2D communications provide various types of advantages over the conventional cellular networks. In this section, we provide some use case example scenarios of our proposed scheme. The basic concept of the proposed scheme is to allow more number of users in the network to jointly achieve higher system throughput and mitigate interference. In particular, some of the popular real-time use case scenarios are: public safety and traffic offloading. In the proposed scheme, we would like to analyze the use case scenario “traffic offloading” as an example. In this scenario, D2D users setup direct connections and triggered D2D communication by reusing available cellular resources without the control of eNB. Devices in proximity exhibit their preferences by analyzing SINR requirements. This helps to reduce the eNB from traffic burden and greatly maximizes the overall system throughput.

2.7. Performance Analysis

In this section, we analyzed both the mathematical computation and simulation using the Monte-Carlo Simulation. The proposed scheme considers full loaded cellular system that can support a high density of users. The number of CUs in all sections of the cell is uniformly distributed and at least one DP should be present in each cell section. We consider four different scenarios for sharing cellular resources with the DPs. We compare the performances of our proposed scheme with the RRA scheme [12] and RA w/o cell sectorization scheme [26]. The above mentioned references and our proposed scheme have the same characteristics of the problem statement but with different system models. The methods considered core characteristics of the uplink cellular resources like channel bandwidth, interference scenarios, noise power, user distribution model, etc. The resource-sharing scenarios with different densities of both CUs and DPs are listed below:

A. When the DPs are more than the CUs (D2D > C) as given in Table 2.1, and the D2D transmitter (Tx) and receiver (Rx) are located in different cell sections: In this scenario, all the available cellular resources can be reused by the DPs. This results in the maximum utilization of the spectrum, but the performance of the D2D communication may not be efficient, the number of available resources to be reused by the DPs is less. As the D2D Tx and Rx are located in different sections of the cell, the D2D Rx will be interfered more by the nearby CUs.
B. When the DPs are more than the CUs (D2D > C) as given in Table 2.1, and the D2D transmitter (Tx) and receiver (Rx) are located in same cell section: In this scenario, as both the D2D Tx and Rx are located in the same cell section, the D2D communication have less interfering devices to the D2D Rx. This scenario is more efficient than scenario
C. When the number of CUs are more than the number of DPs (C > D2D) as given in Table 2.2, and the D2D transmitter (Tx) and receiver (Rx) are located in different cell sections: Here, more cellular links will not be utilized by the DPs as the number of sources is high but the consumers are few. However, when some of the available cellular links are disconnected or are in sleep mode, the DP can have other options to choose the remaining active cellular links.

Table 2.1: Scenario 1 and 2: D2D > C.

Cell region	Number of devices
Cell inner region	D2D=15, C=40
Cell outer region	D2D=50, C=10

Table 2.2: Scenario 3 and 4: C > D2D.

Cell region	Number of devices
Cell inner region	D2D=15, C=50
Cell outer region	D2D=30, C=30

D. When the number of CUs is more than the number of DPs (C > D2D) as given in Table 2.2, and the D2D transmitter (Tx) and receiver (Rx) are located in the same cell section: As the D2D Tx and Rx exist in the same cell section, the communication will have less interference.

2.7.1. Simulation Parameters and Values

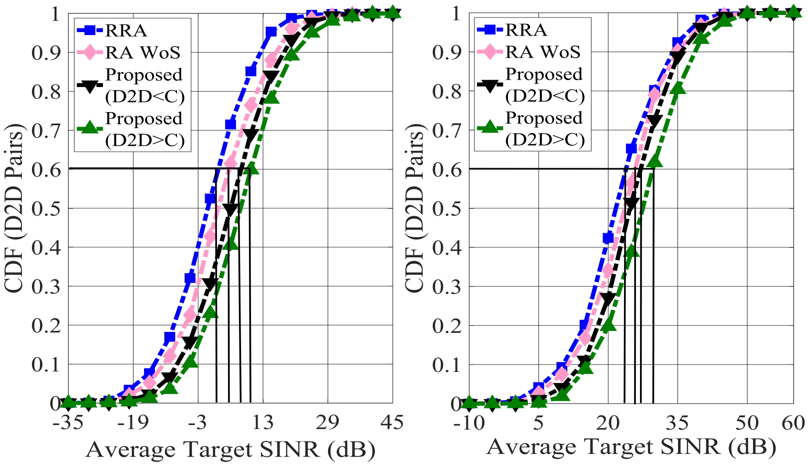
This section provides the detailed simulation parameters and its values as given in Table 3. Without loss of generality, we assumed that the transmitter and receiver of a DP are placed in the same section of the cell and distance between them is short, i.e. 1-50 m.

Table 2.3: Main simulation parameters.

Parameter	Value
eNB transmission power	40-46 dBm(inner cell)
eNB transmission power	43-49 dBm(outer cell)
D2D transmission power	8-15 dBm
Noise power	-174 dBm/Hz
Carrier frequency	2 GHz
Uplink bandwidth	5 MHz
Path loss exponent	4

2.7.2. Simulation Results and Discussions

This section demonstrates the simulation results and shows the performance comparison. Fig. 2.5(a and b) shows the average target SINR vs. cumulative distribution function (CDF) plot for both the DPs. This Fig. shows that the performance of the system with more DPs than CUs achieved closer to the average target SINR compared to the communication scenario with less DPs. Our proposed scheme also benefit SINR of around (≈ 3.5dB) at the outer cell D2D users compared to the existing schemes. This is because of the effective distribution of the SINR based on the distance between the DPs and CUs.



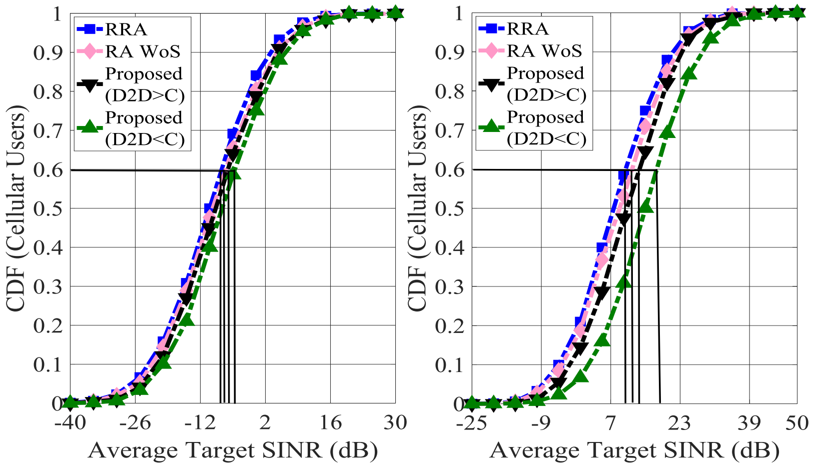
(a) for outer cell region

(b) for inner cell region

Fig. 2.5: Average target SINR vs CDF for DPs.

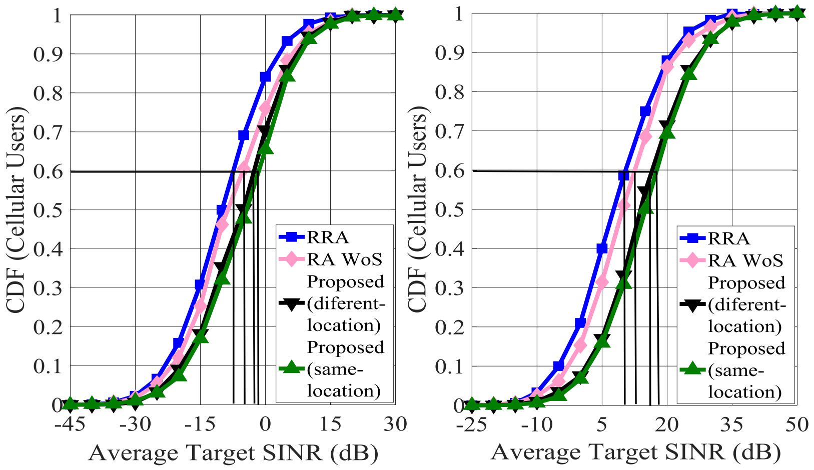
Fig. 2.6(a and b) shows the average target SINR vs. cumulative distribution function (CDF) plot for both the CUs. The performance of the CUs is affected little by the varying number of DPs in both cell regions. Also, CUs in inner cell region attain a gain of somewhat (≈ 4dB) from the existing schemes. From Fig. 2.6(a), it is seen that in all the communication scenarios, 60% of CUs can establish communication with SINR from -7dB to 5.5dB. Moreover, from Fig. 2.6(b), it is seen that in all the communication scenarios, 60% of CUs can establish communication with SINR from

10.5dB to 18dB. From Figs. 2.5 and 2.6, our proposed scheme outperforms the RRA and RA w/o sectorization schemes by maintaining a specific distance between the D2D Rx and CUs, as well as between the D2D Tx and Rx.



(a) for outer cell region (b) for inner cell region

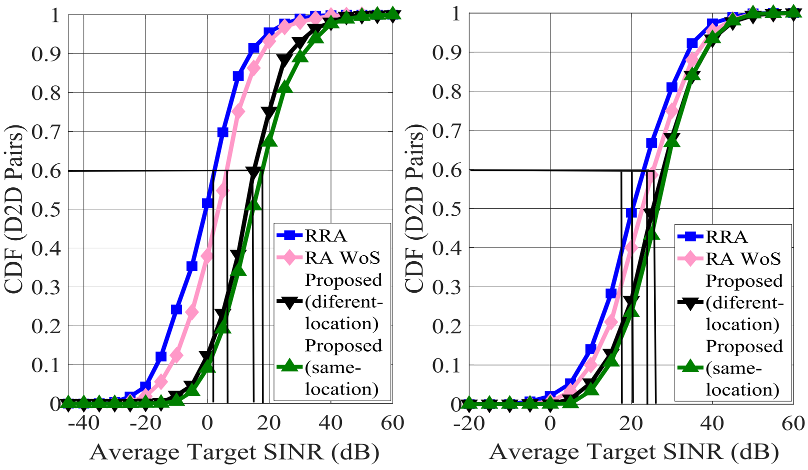
Fig. 2.6: Average target SINR vs CDF for CUs.



(a) for outer cell region (b) for inner cell region

Fig. 2.7: Average target SINR vs CDF for CUs with the same and different locations of D2D Tx and Rx.

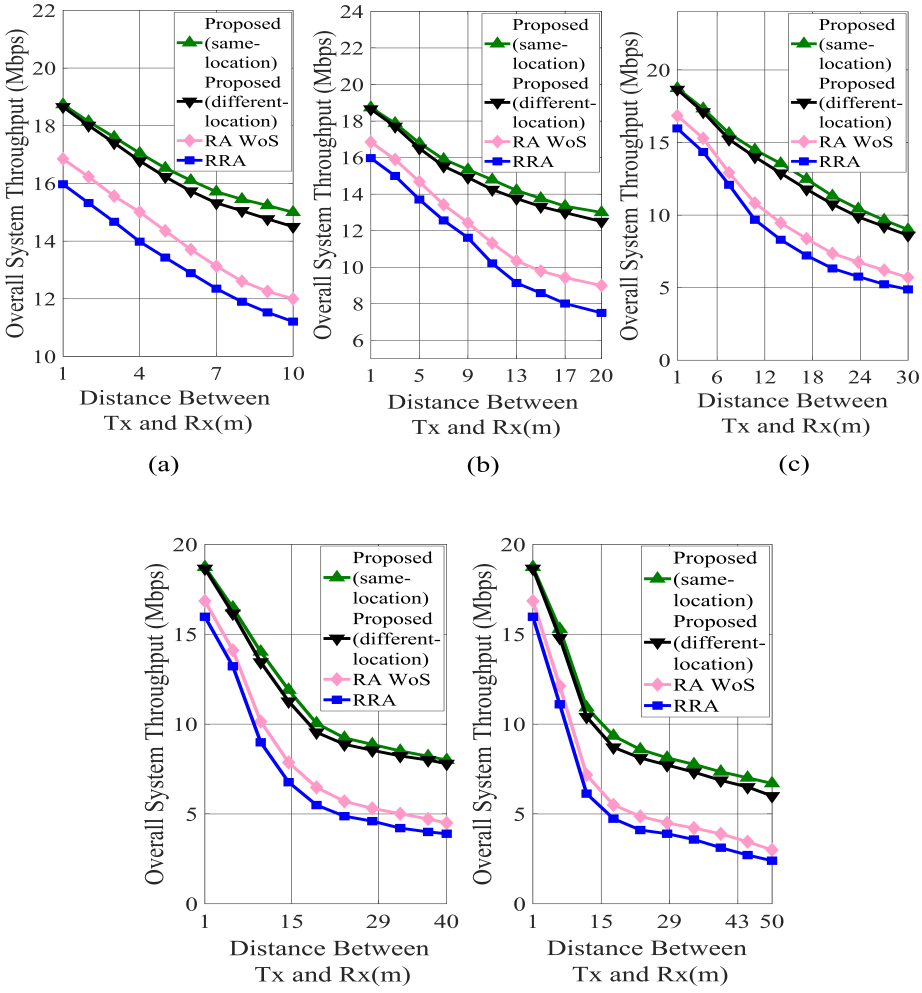
Fig. 2.7(a and b) and 8(a and b) show the SINR distributions of CUs and DPs by keeping D2D Tx and Rx in same and different locations in a cell, respectively. Figs. 2.7(a) and 2.7(b) show that for all the communication scenarios, 60% of CUs can establish communication with SINR from -7.5dB to -2dB and 9dB to 17dB, respectively.



(a) for outer cell region (b) for inner cell region

Fig. 2.8: Average target SINR vs CDF for DPs with the same and different locations of D2D Tx and Rx.

Moreover, Figs. 2.8(a) and 2.8(b) show that for all the communication scenarios, 60% of D2D users can establish communication with SINR from 2dB to 18dB and 23dB to 28.5dB, respectively. Compared to the RRA scheme and RA w/o cell sectorization scheme, the proposed optmization method based on the location-based resource sharing scheme outperforms in terms if the SINR gain. These results validate the communication performance scenarios as explained above.



(a) (b) (c)

(d) (e)

Fig. 2.9: Throughput with varying distance between D2D Tx and Rx. (a) 1-10 m, (b) 1-20 m, (c) 1-30 m, (d) 1-40 m, and (e) 1-50 m.

Fig. 2.9(a-e) shows the overall system throughput at the various distance between the D2D Tx and Rx. As shown in the Fig., as the targeted D2D Rx is located far away from the Tx, the strength of the desired signal becomes weaker. Thus, the received power in the D2D Rx and average target SINR of the system reduces. It can be seen that when the D2D Tx and Rx are located in the same section, the co-channel interference is alleviated, thus a higher spectrum efficiency is gained. Therefore, our proposed scheme achieves better spectral efficiency than the traditional schemes proposed in the literature for different distances.

2.8. Conclusion

DPs reusing the uplink cellular resources in LTE-A multicell cellular networks using the FFR scheme are presented in this paper. The proposed scheme integrates the power control mechanism for both the DPs and CUs, which guarantees the effective calculation of the system outage probability in terms of their SINR. Based on our mathematical analysis, we guaranteed that the distance-based resource allocation and power-control scheme could support the QoS requirements of both the cellular and DPs. This paper provides the network operators with less computation complexity, to reduce the interference between the DPs, and between CUs and DPs. The simulation results show that the proposed scheme alleviates the overall system throughput and achieves higher spectral efficiency as compared to the existing schemes.

Chapter 3

Distance-Constrained Outage Probability Analysis for D2D Communications

Motivated by the literature works on D2D communications using FFR scheme for sharing resources, in this chapter we propose a distance-based resource allocation method for D2D communications with FRF of 2.

3.1. Background and Related Works

The challenges of D2D communication underlaying uplink cellular network have been the major concern of many researchers. The authors in [45] discussed a solution to mitigate uplink interference caused by the D2D communications into the conventional cellular networks. Also, the throughput maximization problem is evaluated as: initially the available spectrum is assigned with a constant power, and then interference reduction phenomenon is considered by dividing multiple sub problems per available resources. However, the proposed resource allocation scheme was analyzed without directional antennas. Therefore, this method is not spectrally efficient. D2D communication that reuses uplink cellular resources was discussed in [46] and a novel method for evaluating an optimal solution was presented. The disadvantage of this method is: proposed orthogonal resource sharing technique was considered for DPs and CUs. Therefore, the proposed scheme could not mitigate intra-cell interference. The work in [47] proposed to partition the available spectrum into different sections to minimize the interference caused by the D2D communications. In their work, resource allocation (RA) method is discussed by considering the value of FRF as 1 and a throughput optimization problem is formulated to maximize the overall system capacity by minimizing system outage probability. In [48], the authors formulated an optimization problem to enhance the overall system capacity. The disadvantage of the proposed method is that the performance analysis of D2D users is not considered distinctly. In [49], an exhaustive study on different fairness models used for wireless networks is presented. Different fairness models are studied to analyze the fairness distribution of resources among the users. The work in [42] proposed a resource allocation scheme by accommodating system efficiency and Jain's fairness index for multiple D2D users. In [50], the authors introduced a fairness scheduling algorithm for D2D communication that shares resources with the conventional cellular communication. At first, power control method is analyzed and discussed a Hungarian algorithm. The authors proposed a Hungarian algorithm to increase the overall system spectral efficiency by fulfilling the SINR requirement. The work in [51] study on outage probability analysis method based on the rate of uplink interference, SINR, and Rayleigh multipath fading phenomenon, where the additive white Gaussian noise is assumed. At first, based on the stochastic geometry the network model is analyzed and using Laplace transforms, and probability density function the throughput optimization problem is formulated. In [52], the authors studied outage probability analysis. The limitation of this scheme is that the network model does not accommodate large capacity of users. Hence, we can achieve a higher system capacity by increasing the FRF.

3.2. Network Model

In the proposed method, we suppose that there are totally M D2D users forming a set $D=\{1,2,\ldots\ldots,M\}$, the total number of cellular users (CUs) forming a set $C=\{1,2,\ldots\ldots, N\}$. All the D2D users and CUs follow uniform distribution inside the cell as shown in Fig. 3.1. A D2D transmitter and its corresponding receiver form a DP. For analysis, we considered a single hexagonal cell environment with the eNB located at center of the cell. The probability density function (PDF) of a DP is defined as:

$$f_i(l) = \frac{2l}{(R_i)^2},\ 0< l \leq R_i, \qquad (35)$$

The cumulative distribution function (CDF) is expressed by:

$$F_i(l) = \int_l^{R_i} f_i(l)\, dl = 1 - \left(\frac{l}{R_i}\right)^2, \qquad (36)$$

where R_i is the D2D communication range.

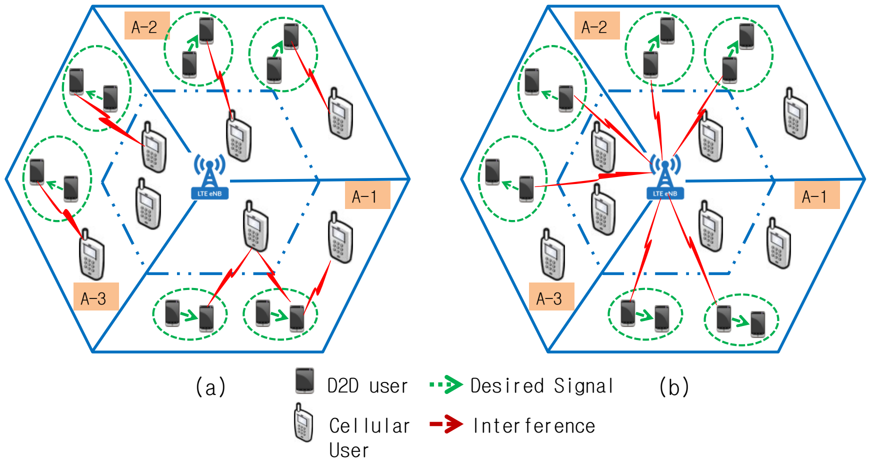


Fig. 3.1: Uplink interference scenarios: (a) interference from CU to D2D-Rx and (b) interference from D2D-Tx to eNB.

It is seen from Fig. 3.1 that there exist two main types of uplink interference due to the integration of D2D communications in conventional cellular networks. In Fig. 3.1(a), signal transmitted from CU causes interference to D2D-Rx, and Fig. 3.1(b) shows the uplink interference produced by D2D-Tx to eNB. Therefore, according to Fig. 3.1(b), the available spectrum is partitioned into different bands. The band N_{in} is used to serve inner region cellular users, M_{in} is used to serve inner region DPs. Similarly, the band N_{edge} is used to serve outer region cellular users, M_{edge} is used to serve outer region DPs. In the network model, it is assumed that the locations of DPs and CUs are modeled in terms of distance of the users from the eNB. Then, each region is subdivided into three equivalent sub-sections. In our analysis the available resources are orthogonally assigned by eNB to available CUs, hence there is no interference between CUs.

Hence, the signal power received by the user from eNB is expressed as:

$$P_{rec} = P_T d^{-\alpha} |h|^2, \tag{37}$$

where P_T is the transmission power, d is the distance from the transmitter to its corresponding receiver, and h is the channel coefficient. Hence, the signal received by a user is given by:

$$r(t) = r_{A1}(t) + \sum_{ne \neq A1} r_{ne}(t) + x(t), \tag{38}$$

where $r_{A1}(t)$ is the signal received from the specified user in a section of the cell, $r_{ne}(t)$ is the signal from the neighborhood, and *x(t)* is the noise.

3.3. Proposed Scheme

Here, in each cell DPs in inner cell region reuse the resources of CUs in the edge cell region and vice versa. The pseudo code of the proposed scheme is presented in Algorithm 3.1.

Algorithm 3.1: Pseudo Code for Resource Allocation Method

```
1.  Get all active cellular users and D2D pairs
2.  Set $P_C = P_C^{max}$ and $P_D = P_D^{max}$
3.  for t=1 to RB do
4.          Calculate $\gamma_j$, $\gamma_{j'}$, and $\gamma_k$
5.          Calculate $P_j^{out}$, $P_{j'}^{out}$, and $P_k^{out}$
6.          Calculate $T_C = W log_2(1+\gamma_j)$ and $T_D = W[log_2(1+\gamma_j) + log_2(1+\gamma_{j'})]$
7.              if ($T_C \geq T_C^{min}$, $T_D \geq T_D^{min}$) then
8.                  Calculate $T_{overall} = \sum_{c=1}^{N} T_c + \sum_{D=1}^{M} T_D$
9.              else if ($T_C < T_C^{min}$, $T_D < T_D^{min}$) then
10.                 recalculate $\gamma_j$, $\gamma_{j'}$, and $\gamma_k$ and repeat the step 6
11.             end if
12. end for
```

3.3.1. Analysis of Signal-to-Interference-Plus-Noise Ratio (SINR)

The SINR received by a device can be calculated as follows,

$$\gamma \geq \gamma^{Th}, \tag{39}$$

where γ^{Th} is the predefined SINR threshold. To analyze the received SINR, we consider a CU k that exists in inner cell region of A-1 (shown in Fig. 3.1) and two-pairs of D2D exist in edge cell region of A-1. We denote P_i as the transmission power of D2D-Tx i, $P_{i'}$ as the transmit power of D2D-Tx i', P_k as the transmit power of CU k, $l_{i,B}$ is the distance from D2D-Tx i to eNB, $l_{i',B}$ is the distance from D2D-Tx i' to eNB, $l_{k,j}$ is the distance from CU k to D2D-Tx j, $l_{k,j'}$ is the distance from CU k to D2D-Tx j', and $l_{k,B}$ is the distance from CU k to eNB, $h_{i,B}$ and $h_{i',B}$ are the channel coefficients between eNB and D2D-Tx i, and D2D-Tx i', respectively, $h_{k,j}$ and $h_{k,j'}$ represent the channel coefficients from CU k to D2D-Tx i and D2D-Tx i', respectively, and $h_{k,B}$ represent the channel coefficients from eNB to CU k, $I_{i'}$ is the interference from D2D-Tx i to D2D-Rx j' and I_i is the interference from D2D-Tx i' to D2D-Rx j, $I_{j,ne}$ is the interference from neighboring D2D-Tx to D2D-Rx *j* and $I_{j',ne}$ is the interference from D2D-Tx to D2D-Rx *j'*. Hence, the received SINRs can be calculated as:

$$\gamma_j = \frac{P_i . l_{i,B}^{-\alpha} . |h_{i,B}|^2}{P_k . l_{k,j}^{-\alpha} . |h_{k,j}|^2 + I_{i'} + \sum_{ne \neq A1} I_{j,ne} + P_N}, \tag{40}$$

$$\gamma_{j'} = \frac{P_{i'} . l_{i',B}^{-\alpha} . |h_{i',B}|^2}{P_k . l_{k,j'}^{-\alpha} . |h_{k,j'}|^2 + I_i + \sum_{ne \neq A1} I_{j',ne} + P_N}, \tag{41}$$

respectively, where α is the path loss coefficient and P_N is the noise power.

Similarly, the received SINR of CU k is given by:

$$\gamma_k = \frac{P_k . l_{k,B}^{-\alpha} . |h_{k,B}|^2}{P_i . l_{i,B}^{-\alpha} . |h_{i,B}|^2 + P_{i'} . l_{i',B}^{-\alpha} . |h_{i',B}|^2 + \sum_{ne \neq A1} I_{B,ne} + P_N}, \tag{42}$$

where

$$I_{i'} = P_{i'} . l_{i',j}^{-\alpha} . |h_{i',j}|^2, \tag{43}$$

$$I_i = P_i . l_{i,j'}^{-\alpha} . |h_{i,j'}|^2, \tag{44}$$

$$I_{j,ne} = P_{ne} . l_{ne,j}^{-\alpha} . |h_{ne,j}|^2, \tag{45}$$

$$I_{j',ne} = P_{ne} . l_{ne,j'}^{-\alpha} . |h_{ne,j'}|^2, \tag{46}$$

$$I_{B,ne} = P_{ne} . l_{ne,B}^{-\alpha} . |h_{ne,B}|^2, \tag{47}$$

Therefore, the channel coefficient relationship should satisfy following conditions to mitigate interference between users [53].

$$\left.\begin{aligned} \delta_i &= \frac{|h_{k,B}|^2}{|h_{k,j}|^2} . \frac{|h_{i,j}|^2}{|h_{i,B}|^2} \\ \delta_{i'} &= \frac{|h_{k,B}|^2}{|h_{k,j'}|^2} . \frac{|h_{i',j'}|^2}{|h_{i',B}|^2} \end{aligned}\right\}, \tag{48}$$

where δ_i and $\delta_{i'}$ are channel gains. High values of δ_i and $\delta_{i'}$ achieve better system performance.

3.3.2. Analysis of Outage Probability (P^{out})

The outage probability is expressed as [54]:

$$P^{out} = P_r[\gamma \leq \gamma^{Th}], \tag{49}$$

where γ^{Th} is the predefined threshold SINR value. The average SINR is calculated as,

$$\tilde{\gamma} = \frac{Transmit\ power\ of\ a\ user}{Noise\ power} = \frac{P}{P_N}, \tag{50}$$

Considering Equations (39-49) and substituting $\gamma = \gamma^{Th}$, the outage probability for both DPs and CU can be obtained as:

$$\left.\begin{aligned} P_j^{out} &= 1 - \frac{1}{1+\frac{\left(P_k.l_{k,j}^{-\alpha}+P_{i\prime}.l_{i\prime,j}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,j}^{-\alpha}\right)\gamma^{Th}}{P_i.l_{i,B}^{-\alpha}}} \mathrm{e}^{\left(-\frac{\gamma^{Th}}{\tilde{\gamma}}\right)} \\ &= 1 - \frac{P_i.l_{i,B}^{-\alpha}}{P_i.l_{i,B}^{-\alpha} + \left(P_k.l_{k,j}^{-\alpha}+P_{i\prime}.l_{i\prime,j}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,j}^{-\alpha}\right)\gamma^{Th}} \mathrm{e}^{\left(-\frac{P_N \gamma^{Th}}{P_i}\right)} \end{aligned}\right\}, \tag{51}$$

$$\left.\begin{aligned} P_{j\prime}^{out} &= 1 - \frac{1}{1+\frac{\left(P_k.l_{k,j\prime}^{-\alpha}+P_i.l_{i,j\prime}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,j\prime}^{-\alpha}\right)\gamma^{Th}}{P_{i\prime}.l_{i',B}^{-\alpha}}} \mathrm{e}^{\left(-\frac{\gamma^{Th}}{\tilde{\gamma}}\right)} \\ &= 1 - \frac{P_{i\prime}.l_{i',B}^{-\alpha}}{P_{i\prime}.l_{i',B}^{-\alpha} + \left(P_k.l_{k,j\prime}^{-\alpha}+P_i.l_{i,j\prime}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,j\prime}^{-\alpha}\right)\gamma^{Th}} \mathrm{e}^{\left(-\frac{P_N \gamma^{Th}}{P_{i\prime}}\right)} \end{aligned}\right\}, \tag{52}$$

and

$$\left.\begin{aligned} P_k^{out} &= 1 - \frac{1}{1+\frac{\left(P_i.l_{i,B}^{-\alpha}+P_{i\prime}.l_{i',B}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,B}^{-\alpha}\right)\gamma^{Th}}{P_k.l_{k,B}^{-\alpha}}} \mathrm{e}^{\left(-\frac{\gamma^{Th}}{\tilde{\gamma}}\right)} \\ &= 1 - \frac{P_k.l_{k,B}^{-\alpha}}{P_k.l_{k,B}^{-\alpha} + \left(P_i.l_{i,B}^{-\alpha}+P_{i\prime}.l_{i',B}^{-\alpha}+\sum_{ne\neq A1} P_{ne}.l_{ne,B}^{-\alpha}\right)\gamma^{Th}} e^{\left(-\frac{P_N \gamma^{Th}}{P_k}\right)} \end{aligned}\right\}, \tag{53}$$

3.3.3. Channel Model

We consider log-normal fading path loss models for both CU and DPs as [55]:

$$\left.\begin{aligned} PL_i = &\ 49 + 40\ log_{10}\left(\frac{l_{i,j}}{1000}\right) + 30log_{10}\left(\frac{f_c}{1000}\right) \\ PL_{i'} = &\ 49 + 40\ log_{10}\left(\frac{l_{i',j'}}{1000}\right) + 30log_{10}\left(\frac{f_c}{1000}\right) \end{aligned}\right\}, \tag{54}$$

$$PL_k = 40.9 + 36.7\ log_{10}(l_k) + 26\ log_{10}\left(\frac{f_c}{5}\right), \tag{55}$$

where $l_{i,j}$, $l_{i',j'}$, and l_k are the distance between D2D-Tx i and D2D-Rx j, between D2D-Tx i' and D2D-Rx j', and between cellular transmitter and receiver, respectively, and f_c is the carrier frequency in GHz.

3.3.4. Optimization

Throughput of the overall system is defines as:

$$T_{overall} = \sum_{c=1}^{N} T_c + \sum_{D=1}^{M} T_D, \tag{56}$$

where T_c and T_D are the throughput of CU and DPs, respectively, which is defined by:

$$T_c = log_2(1 + \gamma_k), \tag{57}$$

$$T_D = \left[log_2\left(1 + \gamma_j\right) + log_2(1 + \gamma_{j'})\right], \tag{58}$$

Therefore, the throughput maximization problem can be formulated by:

$$\max_{c \in N, D \in M}(\sum_{c=1}^{N} T_c + \sum_{D=1}^{M} T_D)\}, \tag{59}$$

subject to

$$\left.\begin{aligned} P_C^{min} \le P_C \le\ P_C^{max}; P_D^{min} \le P_D \le\ P_D^{max}, \forall\ C\ \epsilon\ N, D\ \epsilon\ M \\ \gamma_C^{min}\ \le \gamma_C;\ \gamma_C^{min}\ \le \gamma_C, \forall\ C\ \epsilon\ N, D\ \epsilon\ M \end{aligned}\right\}, \tag{60}$$

where γ_C^{min} and γ_D^{min} are the minimum allowable SINRs of the CU and DP respectively. P_C^{min} and P_C^{max} are the minimum and maximum power range for the CU, and P_D^{min} and P_D^{max} are the minimum and maximum power ranges of the DP. Equation (60) ensures that the transmit power of both CUs and DPs should be within the minimum and maximum transmit power range. Simillarly, Equation (60) ensures that the SINR of both CUs and DPs should be greater than or equal to minimum SINR threshold. Hence, the upper and lower bounds transmit power of CU should satisy the following criteria.

$$P_C^{min} \leq \frac{\gamma_k (P_i . l_{i,B}^{-\alpha} . \left|h_{i,B}\right|^2 + P_{i'} . l_{i',B}^{-\alpha} . \left|h_{i',B}\right|^2 + \sum_{ne \neq A1} I_{B,ne} + P_N)}{l_{k,B}^{-\alpha} . \left|h_{k,B}\right|^2} \leq P_C^{max}, \tag{61}$$

Simillarly, the upper bound and lower bounds transmit power of both D2D-Rxs are derived as:

$$P_D^{min} \leq P_i, P_{i'} \leq P_D^{max}, \tag{62}$$

$$P_D^{min} \leq \frac{\gamma_j (P_k . l_{k,j}^{-\alpha} . \left|h_{k,j}\right|^2 + I_{i'} + \sum_{ne \neq A1} I_{j,ne} + P_N)}{P_i . l_{i,B}^{-\alpha} . \left|h_{i,B}\right|^2}, \frac{\gamma_{j'} (P_k . l_{k,j'}^{-\alpha} . \left|h_{k,j'}\right|^2 + I_i + \sum_{ne \neq A1} I_{j',ne} + P_N)}{P_{i'} . l_{i',B}^{-\alpha} . \left|h_{i',B}\right|^2} \leq P_D^{max}, \tag{63}$$

3.3.5. Jain's fairness Index (JFI)

JFI can be calculated as [56].

$$JFI(T_D) = \frac{\left(\sum_{D=1}^{M} T_D\right)^2}{(M).\ \sum_{D=1}^{M} {T_D}^2}, \forall\ D \in M \tag{64}$$

From Equation (58), we have,

$$\left. \begin{aligned} JFI(T_D) &= \frac{\left(\sum_{D=1}^{M} W[log_2(1+\gamma_j) + log_2(1+\gamma_{j'})]\right)^2}{(M).\ \sum_{D=1}^{M} \left(W[log_2(1+\gamma_j) + log_2(1+\gamma_{j'})]\right)^2} \\ &= \frac{\left(\sum_{D=1}^{M} [log_2(1+\gamma_j) + log_2(1+\gamma_{j'})]\right)^2}{(M).\ \sum_{D=1}^{M} [log_2(1+\gamma_j) + log_2(1+\gamma_{j'})]^2} \end{aligned} \right\}, \forall\ D \in M \tag{65}$$

From Equation (65), it is clearly seen that *JFI* (T_D) value is having an interval $\left[{}^{1}\!/_{M}, 1\right]$, i.e.

$$JFI = \begin{cases} 1, & Proposed\ scheme\ attains\ optimal\ fair\ allocation\ of\ resources \\ {}^{1}\!/_{M}, & Proposed\ scheme\ attains\ least\ fair\ allocation\ of\ resources \end{cases}, \tag{66}$$

3.3.6. Complexity Analysis

The complexity of the resource allocation algorithm for two DPs sharing same cellular resource is $O(M^2).O(N)$.

3.4. Performance Analysis

3.4.1. Simulation Parameters and Values

In this subsection, we will provide the main simulation parameters and values used for the proposed resource allocation scheme. The main simulation parameters are listed in Table 3.1.

Table 3.1: Simulation parameters and values.

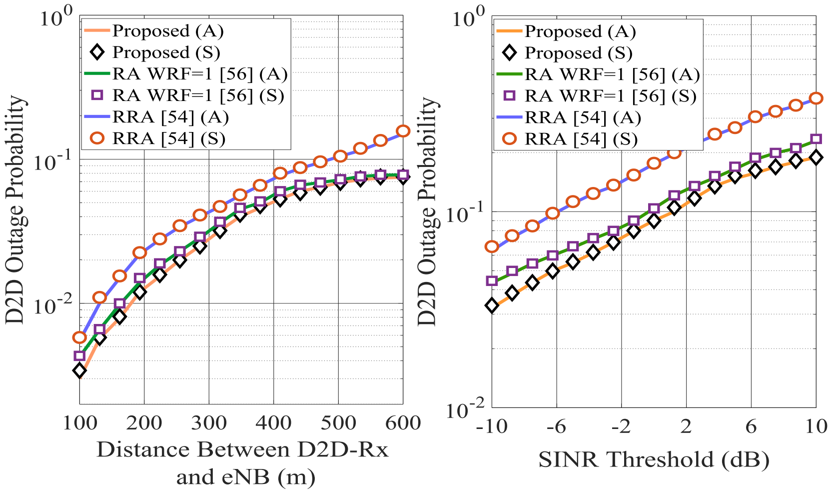
Simulation Parameters	**Values**
Cell outline	hexagonal shaped
Total number of resource blocks	50 [39]
CU transmission power	20 dBm
D2D transmission power	15 dBm
Noise Power	-174 dBm/Hz
DP distance	1-50 m
Carrier frequency	2 GHz
Uplink bandwidth	10 MHz [39]
Path loss exponent	4

3.4.2. Simulation Results and Discussion

We compare our proposed scheme with the random resource allocation scheme (labeled as RRA) presented in [54] and resource allocation scheme with RF of 1 (labeled as RA w/ RF=1) presented in [56]. In RRA scheme, multiple DPs residing in a cell can reuse the uplink cellular resources at the same time. However, due to coexistence of both CUs and DPs in same region of a cell imposed the aggregate interference. Whereas in the case of the RA w/ RF=1 scheme, allowing only one DP to access a cellular resource at a time cannot accommodate high capacity of a system.

- **Performance of D2D communications**

Fig. 3.2(a) shows the outage probability distribution of D2D communications at varying distance from the eNB to D2D-Rx. We can see from the Fig. 3.2(a) that the D2D outage probability of the proposed scheme is much lower as compared to the RRA scheme because a definite interference level is maintained.



(a) (b)

Fig. 3.2: (a) D2D outage probability with varying distance from eNB to D2D-Rx, (b) D2D outage probability with varying SINR threshold.

In the RA w/ RF=1 scheme, increasing the distance between D2D_Rx and eNB increases the outage probability significantly. It is observed that the analytical calculation of outage probability results of D2D is very close from Monte-Carlo simulation. Fig. 3.2(b) presents the outage probability distribution at varying SINR threshold value. From Fig. 3.2(b), we can see that the D2D outage probability increases with the increase of threshold value of SINR. Also, we can see that the proposed scheme achieves much lower outage probability (-10 dB) than existing schemes. Moreover, our proposed resource allocation scheme with FRF of 2 yields a 20% reduction in outage probability, thus achieved higher throughput by maintaining an upper bound and lower bound transmit power. We observe that the analytical calculation result is very close to that from simulation result.

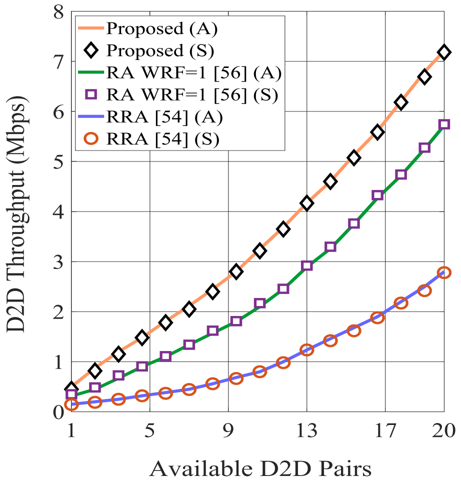
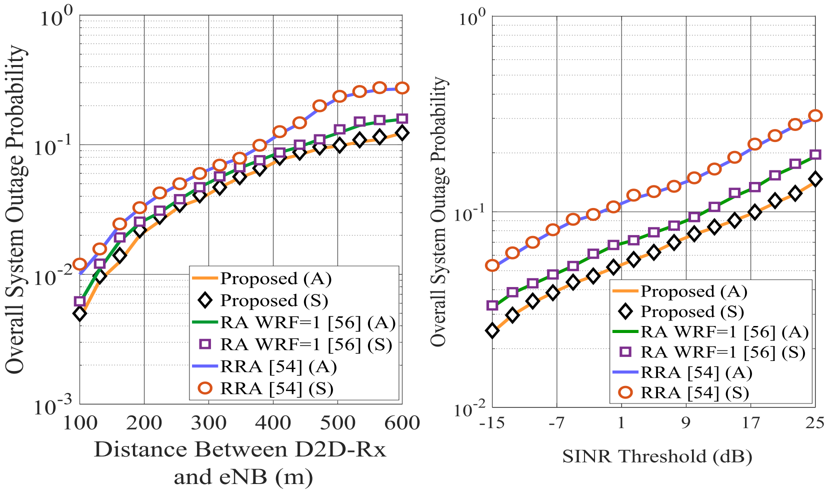


Fig. 3.3: D2D throughput with varying number of available DPs.

Fig. 3.3 presents the D2D throughput at varying number of available DPs in a cell. We can see from the Fig. that the throughput increases with the increase of DPs. Our proposed scheme yields highest throughput as compared with other existing schemes. By using our proposed scheme, data traffic through the CUs is control; hence it maximizes the success rate of transmission. Using D2D communications with cellular resource RF of 2 achieves a 4.43 gain in the D2D throughput as compared with RRA scheme. Hence, our proposed scheme yields a 1.5 gain in the D2D throughput as compared with RA w/ FRF of 1.

- **Performance of overall system**

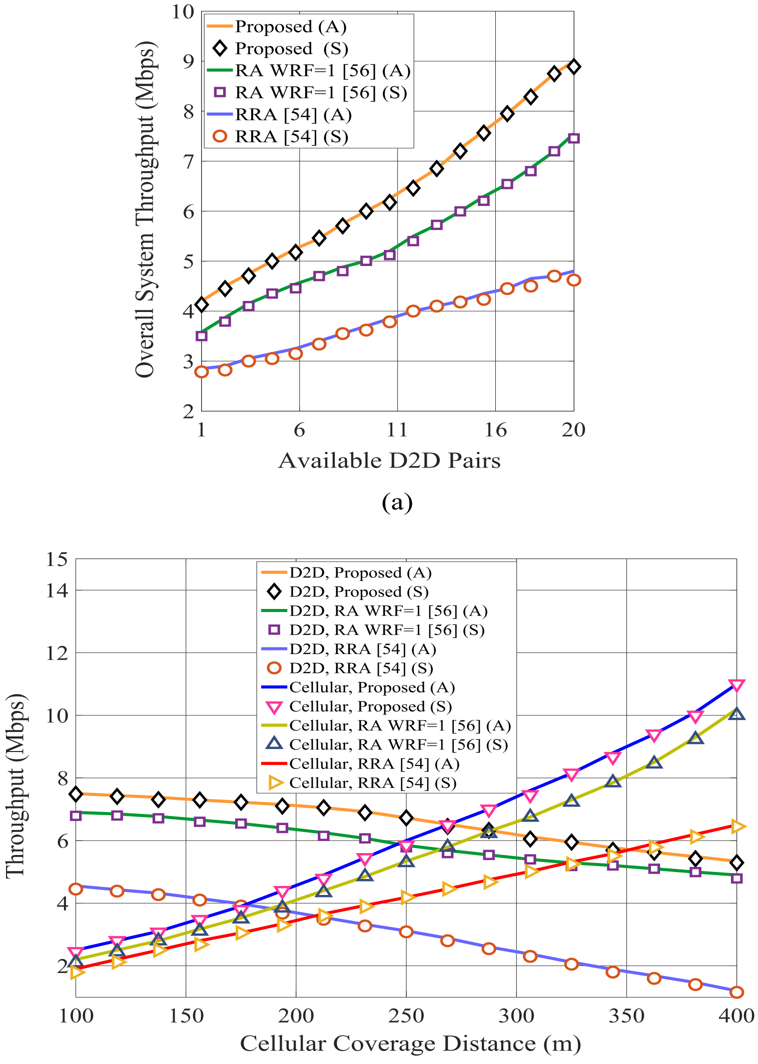
Fig. 3.4(a) depicts the outage probability of the overall system for different values of distance from the eNB to D2D-Rx.



(a) (b)

Fig. 3.4: (a) Overall system outage probability with varying distance from eNB to D2D-Rx, (b) system outage probability with varying SINR threshold.

When the distance increases, the channel gain decreases, thus increases outage probability. The significance of the proposed scheme is that, because of the FFR scheme with FRF of 2, the proposed scheme provides high utilization of resources within the distance of 100 m. In Fig. 3.4(b), the outage probability of the system under varying threshold SINR is shown. The value of definite value of SINR threshold is varied from -15 dB to 25 dB. The proposed scheme has very low outage probability as compared to other existing schemes. It can be seen that, with the SINR threshold of 17 dB, the system outage value for the proposed scheme, FRF of 1 scheme, and RRA scheme are 0.0989, 0.125, and 0.20, respectively. This implies that the proposed scheme minimizes outage probability by means of joint resource allocation and power control method.



(a)

(b)

Fig. 3.5: (a) System outage probability with varying number of available DPs, (b) throughput of D2D user and CU at varying CU coverage distance.

Performance result for the system throughput at varying number of available DPs is depicted in Fig. 3.5(a). We observed that with the increase of DPs, RA scheme achieved very less throughput because there is high rate of interference, in contrast proposed scheme yields highest throughput by maximizing the system capacity. Comparing to RA scheme, our proposed scheme provides a 4.38 throughput gain as compared with RRA scheme and a 1.45 throughput gain as compared with RA w/ FRF of 1. The throughput gain of D2D communications at maximum number of available DPs is higher than that of the overall system throughput; this is because as the DPs increases CU throughput decreases.

In Fig. 3.5(b), the throughput of the D2D users and CUs over varying CU coverage distance. As expected, throughput of the D2D users is decreases with the increase of cellular coverage distance. It is observed that CU in the proposed scheme can afford more capacity as compared with other existing schemes.

3.5. Conclusion

To deal with the ever increasing traffic through the CUs, D2D communications has been considered as one of the promising technique. We studied the problem of non-orthogonal resource sharing between CUs and DPs in an uplink network to enable traffic offloading from eNB. In the paper, two-pairs of D2D users simultaneously shared the same uplink cellular resource. This introduced severe interference between the CUs and D2D users. In order to minimize the resource reuse interference, a resource allocation and power control scheme using FFR method with FRF of 2 was proposed. Outage probability has become an imperative topic in cellular networks as it determines the capacity of the network. Based on the distances, the outage probability was calculated by ensuring SINR requirements of CUs and DPs. Moreover, the proposed scheme analyzed channel coefficient relationship based on the distances. We evaluated D2D throughput and overall system throughput mathematically and simulated using Monte-Carlo simulation. Moreover, we analyzed the fair allocation of cellular resource among two DPs by using Jain's fairness index. Precisely it is showed that the proposed scheme leverages higher system throughput by minimizing system outage value. Our analytical and simulation results showed a promising solution for accommodating demands for high data rate services. In the future research, we will extend our work into the D2D communication scenario with large reuse factor.

Chapter 4

Resource Management in Network-Assisted D2D Communications for Higher Frequency Reuse Factor

In the D2D approach, communications can be generated in two ways: network-assisted communications and non-network-assisted communications [58]. Network-assisted D2D communications can be established with the aid of a radio access network. In LTE-A, the eNB provides information regarding the DPs (DPs). In the non-network-assisted D2D approach, communications can be independently established without a radio access network. To attain a massive number of connected devices with minimal interference in D2D communications, in this chapter we propose a greedy heuristic search algorithm and binary power control scheme for an underlaying D2D communications using FFR scheme.

4.1. Background and Related Works

In [59, 60], the authors proposed a novel dynamic power control scheme based on the FFR technique to maximize the overall system throughput. A Heuristic search algorithm is discussed for finding local optimal value. In [61], a resource management method was discussed for interference cancellation and maximization of system capacity. In [62], the authors proposed a resource allocation scheme to mitigate interference mitigation for D2D communication. Also, the effects of orthogonal frequency assignment technique to the system performance were analyzed. A distance dependent resource assignment scheme for D2D communications was proposed in [63]. In this paper, the authors analyzed outage probability. In [64], the authors proposed a resource allocation scheme by considering scalable resource reuse method for D2D communication. A resource reuse scheme for D2D communication underlaying cellular network was discussed in [65]. In this study, the Stackelberg game approach was analyzed for multi-sharing D2D communications to maximize the independent set of users that simultaneously reused the same subchannels. Therefore, the performance of the proposed scheme increases. In [66], the authors proposed a fast spectrum reuse and power control scheme for D2D communications. In their study, the analysis was performed in two steps: First, resource assignment was performed based on the maximum independent set to reduce the number of iterations, and second, resource assignment was performed using the Stackelberg power algorithm to reduce the computational complexity of the proposed method. A dynamic FFR scheme to mitigate intercell interference was presented in [67]. In this study, the authors proposed a non-orthogonal multiple access multicellular communication system to simultaneously share subchannels, which results in improved spectral efficiency.

4.2. Network Model and Problem Formulation

4.2.1 Network Model

In this paper, we focus on an uplink cellular network in which uplink resources are assigned to CUs by the eNB in an orthogonal manner, which avoids mutual interference among CUs. The main benefit of the uplink resource reuse phenomenon is that the eNB can exclusively coordinate the interference in a fully loaded cellular network [68]. We consider a regular multicell cellular network, where eNBs are placed at the center of the cells. It is also assumed that all cells are non-overlapping. For analysis, in our network architecture, we estimate that each cell has *M* DPs forming a set *D*, *D={1, 2, 3, …, M}*, coexisting with *N* CUs forming a set *C*, *C={1, 2, 3, …, N}*. Thus, there are *K* subcarriers forming a set *X*, *X= {1, 2, 3, …, K}.* With an objective of improving system spectrum utilization rate, it is assumed that DPs and CUs simultaneously share the same subchannels, and multiple DPs are allowed to reuse the same subchannel at a time. In order to mitigate uplink interference, we assume that DPs in the center cell region can reuse the resources of CUs located in the edge zone and vice versa. However, DPs in the center cell region cannot reuse the resources of CUs located in the center zone, and DPs located in the edge zone cannot reuse the resources of CUs located in the center zone. In order to indicate the resource reuse factor, we define a binary variable $\delta_{m,n}^{k}$, where $m\epsilon D, n\epsilon N$ and $k\epsilon X$. When $\delta_{m,n}^{k} = 1$, DP m can simultaneously reuse subcarrier k with CU n, otherwise $\delta_{m,n}^{k} = 0$. In our proposed scheme, we have formulated the resource reuse factor (F) as follows:

$$F = \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{m,n}^{k} + 1. \tag{67}$$

Hence, the objective function is proportionate to maximizing $\sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{m,n}^{k}$. This facilitates maximum resource reuse factor. To simplify the analysis, we have made the following assumption. We consider that the cell structure is analogous to circle. Therefore, to analyze the resource reuse scenario, the probability density function (PDF) of users in center zone in terms of polar coordinates (ρ_{in}, φ) is [69]

$$f(\rho_{in}) = \frac{2(\rho_{in} - \rho_{in}^{min})}{(r - \rho_{in}^{min})^2} \tag{68}$$

and
$$f(\varphi) = \frac{3}{2\pi}, \forall\, 0 \le \varphi \le \frac{2\pi}{3}. \tag{69}$$

Therefore, the corresponding cumulative distribution function (CDF) is

$$\left.\begin{aligned} P(\rho_{in}) &= \int_{\rho_{in}^{min}}^{r} f(\rho_{in}) d\rho_{in} \\ &= \int_{d_{mi\rho_{in}^{min}n}}^{r} \frac{2(\rho_{in} - \rho_{in}^{min})}{(r - \rho_{in}^{min})^2} d\rho_{in} \\ &= \frac{1}{(r - \rho_{in}^{min})^2} [2(\rho_{in})^2 - 2\rho_{in}.\rho_{in}^{min}]_{\rho_{in}^{min}}^{r} \\ &= \frac{2r}{(r - \rho_{in}^{min})} \end{aligned}\right\}, \rho_{in}^{min} \le \rho_{in} < r \tag{70}$$

Similarly, the PDF of users in edge zone in terms of polar coordinates (ρ_{out}, φ) is

$$f(\rho_{out}) = \frac{2(\rho_{out} - \rho_{out}^{min})}{(R - \rho_{out}^{min})^2} \tag{71}$$

and
$$f(\varphi) = \frac{3}{2\pi}, \forall\, 0 \le \varphi \le \frac{2\pi}{3}. \tag{72}$$

Therefore, the corresponding cumulative distribution function (CDF) is

$$\left.\begin{aligned} P(\rho_{out}) &= \int_{\rho_{out}^{min}}^{R} f(\rho_{out}) d\rho_{out} \\ &= \int_{\rho_{out}^{min}}^{R} \frac{2(\rho_{out} - \rho_{out}^{min})}{(R - \rho_{out}^{min})^2} d\rho_{out} \\ &= \frac{1}{(R - \rho_{out}^{min})^2} [2(\rho_{out})^2 - 2\rho_{out}.\rho_{out}^{min}]_{\rho_{out}^{min}}^{R} \\ &= \frac{2R}{(R - \rho_{out}^{min})} \end{aligned}\right\}, \rho_{out}^{min} \le \rho_{out} < R, \tag{73}$$

4.2.2. Problem Formulation

The transmission powers of CU n and DP m is formulated as [70]:

$$P_n = P_n^{max}.\frac{P_N}{l_{n,B}^{-\alpha}} \tag{74}$$

and
$$P_{m_t} = P_{m_t}^{max}.\frac{P_N}{l_{m_t,m_r}^{-\alpha}}, \tag{75}$$

respectively, where P_n and P_{m_t} represent the transmit power for CU n and D2D transmitter m_t, respectively, and P_n^{max} and $P_{m_t}^{max}$ represent the maximal transmit powers of CU n and D2D transmitter m_t, respectively. P_N represents the normalized power density, α denotes the path loss exponent, $l_{n,B}$ denotes the distances from the eNB to CU n, and l_{m_t,m_r} denotes the distance between D2D transmitter m_t and receiver m_r.

Hence, the received powers for CU n and DP m are as follows [44]:

$$\left.\begin{aligned} P_{R_n} &= P_n.l_{n,B}^{-\alpha}.\left|h_{n,B}\right|^2 \\ &= P_n^{max}.\frac{P_N}{l_{n,B}^{-\alpha}}.l_{n,B}^{-\alpha}.\left|h_{n,B}\right|^2 \\ &= P_n^{max}.P_N.\left|h_{n,B}\right|^2 \end{aligned}\right\} \tag{76}$$

and
$$\left.\begin{aligned} P_{R_m} &= P_{m_t}.l_{m_t,m_r}^{-\alpha}.\left|h_{m_t,m_r}\right|^2 \\ &= P_{m_t}^{max}.\frac{P_N}{l_{m_t,m_r}^{-\alpha}}.l_{m_t,m_r}^{-\alpha}.\left|h_{m_t,m_r}\right|^2 \\ &= P_{m_t}^{max}.P_N.\left|h_{m_t,m_r}\right|^2 \end{aligned}\right\}, \tag{77}$$

respectively, where $h_{n,B}$ represents the channel coefficient between the eNB and the CU n and h_{m_t,m_r} represents the channel coefficient between the D2D transmitter m_t and receiver m_r.

4.2.3. Channel Model

In this study, we assume the Winner II B5f PL model for urban areas. Therefore, the PL model is expressed as [71]

$$PL_{DP} = 57 + 23.5log_{10}(l) + 23log_{10}\left(\frac{f}{5}\right), \tag{78}$$

where l denotes the distance from a transmitter to its corresponding receiver in meters (30 m< l < 1.5 km) and f is the carrier frequency in GHz (2 GHz < f < 6 GHz).

4.2.4. Interference Management

In the network-assisted D2D communications, first the eNB collects CSI and required SINR information of all the users. Then, eNB calculates the transmit powers of CUS and DPs. In this subsection, we formulate the SINR problem which aims at minimizing the sum interference [72]. The uplink interference scenarios for a multicell cellular network are shown in Fig. 4.1. Taking the cell 1 as target cell, in which the D2D transmitter m_t communicates with D2D receiver m_r located in edge zone by reusing subcarrier resource k of the CU n located in center zone. During data transmission between the D2D transmitter m_t and receiver m_r, the possible uplink interference introduced in the network are, namely co-channel interference from D2D transmitter m_t to eNB($I_B^{m_t}$), co-channel interference from CU n to D2D receiver $m_r(I_{m_r}^{n})$, interference from the D2D transmitter m_t' of neighboring cell 2 to eNB of cell 1($I_B^{{m_t}'}$), interference from the CU n' of neighboring cell 2 to D2D receiver m_r of cell 1($I_{m_r}^{n'}$), and mutual interference between D2D receiver m_r and neighboring cell D2D transmitter m_t' ($I_{m_r}^{m'}$).

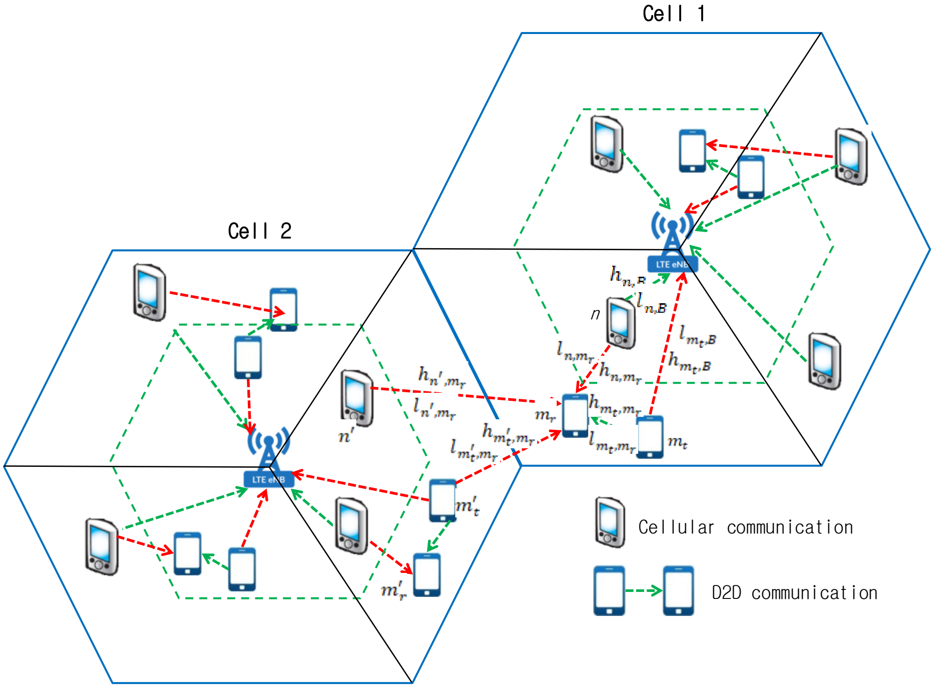


Fig. 4.1: Demonstration of the interference between two neighboring cells, when a D2D communications is overlapped on a cellular resource.

Therefore, the SINRs of CU n and DP m on subcarrier k are

$$\gamma_n^k = \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{I_B^{m_t} + I_B^{m'_t} + \sigma_n{}^2}, \forall n \in C, m \in D, k \in X \qquad (79)$$

and $$\gamma_m^k = \frac{\delta_{m,n}^k . P_{m_t}^k . l_{m_t,m_r}^{-\alpha} |h_{m_t,m_r}|^2}{I_{m_r}^n + I_{m_r}^{n'} + I_{m_r}^{m'_t} + \sigma_n{}^2}, \forall n' \in C, m_t, m_r, m'_t \in D, k \in X, \qquad (80)$$

respectively, where P_n^k and $P_{m_t}^k$ represent the transmit power of CU n and D2D transmitter m_t for channel k, respectively, and σ_n is the noise power.

Thus, we define the interference terms as follows:

$$I_B^{m_t} = \sum_{m=1}^{M} \sum_{n=1}^{N} \delta_{m,n}^k . P_{m_t}^k . l_{m_t,B}^{-\alpha} |h_{m_t,B}|^2, \qquad (81)$$

$$I_B^{m_t'} = \sum_{\substack{m=1 \\ m_t' \neq m_t}}^{M} P_{m_t'}^{k} . l_{m_t',B}^{-\alpha} |h_{m_t',B}|^2, \tag{82}$$

$$I_{m_r}^{n} = \sum_{m=1}^{M} \sum_{n=1}^{N} P_n^k . l_{n,m_r}^{-\alpha} |h_{n,m_r}|^2, \tag{83}$$

$$I_{m_r}^{n'} = \sum_{m=1}^{M} \sum_{\substack{n=1 \\ n \neq n'}}^{N} P_{n'}^{k} . l_{n',m_r}^{-\alpha} |h_{n',m_r}|^2, \tag{84}$$

$$I_{m_r}^{m_t'} = \sum_{\substack{m=1 \\ m_t' \neq m_t}}^{M} \sum_{n=1}^{N} \delta_{m,n}^{k} . P_{m_t'}^{k} . l_{m_t',m_r}^{-\alpha} |h_{m_t',m_r}|^2 , \tag{85}$$

where $l_{m_t,B}$ and $l_{m_t',B}$ denote the distance from the eNB to D2D transmitter m_t and D2D transmitter m_t', respectively, l_{n,m_r}, l_{n',m_r}, and l_{m_t',m_r} denote the distance from D2D receiver m_r to CU n, CU n', and D2D transmitter m_t', respectively. $h_{m_t,B}$ and $h_{m_t',B}$ denote the channel coefficient between the eNB and D2D transmitterm_t, and between the eNB and D2D transmitter m_t', respectively, h_{n,m_r}, h_{n',m_r}, and h_{m_t',m_r} denote the channel coefficient between D2D receiver m_r and CU n, between D2D receiver m_r and CU n', and between D2D receiver m_r and D2D transmitter m_t', respectively. From Equations (79)–(85), the throughput of the system can be calculated using Shannon's equation as follows:

$$T = log_2(1 + SINR). \tag{86}$$

Therefore, the sum throughput of the system can be expressed as

$$T = T_n + T_m. \tag{87}$$

From (86), we can derive the overall system throughput as follows:

$$T = \sum_{m=1}^{M} \sum_{n=1}^{N} \left[log_2\left(1 + \gamma_n^k\right) + log_2\left(1 + \gamma_m^k\right) \right]. \tag{88}$$

From Equations (79) and (80), Equation (88) becomes

$$T = \left\{ \sum_{n=1}^{N} \sum_{m=1}^{M} \left[\begin{array}{c} log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{I_B^{m_t} + I_B^{m_t'} + {\sigma_n}^2} \right) + \\ log_2 \left(1 + \frac{\delta_{m,n}^k . P_{m_t}^k . l_{m_t,m_r}^{-\alpha} |h_{m_t,m_r}|^2}{I_{m_r}^{n} + I_{m_r}^{n'} + I_{m_r}^{m_t'} + {\sigma_n}^2} \right) \end{array} \right] \right\}. \tag{89}$$

Therefore, we can calculate the spectral efficiency of CUs as follows [73]:

$$E_n = log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{{\sigma_n}^2} \right) - log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{I_B^{m_t} + I_B^{m_t'} + {\sigma_n}^2} \right). \tag{90}$$

Thus, the throughput gain of CUs is expressed as follows:

$$G_n = log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{I_B^{m_t} + I_B^{m_t'} + {\sigma_n}^2} \right) + log_2 \left(1 + \frac{\delta_{m,n}^k . P_{m_t}^k . l_{m_t,m_r}^{-\alpha} |h_{m_t,m_r}|^2}{I_{m_r}^{n} + I_{m_r}^{n'} + I_{m_r}^{m_t'} + {\sigma_n}^2} \right) - log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{{\sigma_n}^2} \right). \tag{91}$$

4.3. Throughput Optimization

Here, the sum throughput optimization problem of the network can be formulated as follows:

$$\textbf{A1}. \quad \arg \max_{m \,\epsilon D, k \epsilon K} \sum_{n=1}^{N} F \left(log_2 \left(1 + \frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{{\sigma_n}^2} \right) + \sum_{n=1}^{C} G_n \right) \tag{92}$$

subject to

$$\frac{P_n^k . l_{n,B}^{-\alpha} |h_{n,B}|^2}{I_B^{m_t} + I_B^{m_t'} + {\sigma_n}^2} \geq \gamma_{n_{min}}^k, \forall n \in C, m_t, m_t' \in D, k \in X, \tag{93.a}$$

$$\frac{\delta_{m,n}^k . P_{m_t}^k . l_{m_t,m_r}^{-\alpha} |h_{m_t,m_r}|^2}{I_{m_r}^{n} + I_{m_r}^{n'} + I_{m_r}^{m_t'} + {\sigma_n}^2} \geq \gamma_{m_{min}}^k, \forall n \in C, \; m_t, m_t' \in D, k \in X, \tag{93.b}$$

$$P_n^{min} \leq P_n^k \leq P_n^{max}, \forall n \in C, k \in X, \tag{93.c}$$

$$P_{m_t}^{min} \leq P_{m_t}^k \leq P_{m_t}^{max}, \forall \, m_t \,\epsilon\, D, k \in X, \tag{93.d}$$

$$\delta_{m,n}^k \,\epsilon\, \{0,1\}, \; \forall \, m \,\epsilon\, D, n \,\epsilon\, C, k \in X, \tag{93.e}$$

where $\gamma_{n_{Th}}^{k}$ and $\gamma_{m_{Th}}^{k}$ denote the minimum SINR requirements of CU n and DP m using channel k, respectively. P_{n}^{min} and $P_{m_t}^{min}$ are the minimal transmit power of CU n and D2D transmitter m_t, respectively. P_{n}^{max} and $P_{m_t}^{max}$ represent the maximal transmit power of CU n and $P_{m_t}^{max}$, respectively. The constraints in Equations (93.a) and (93.b) imply that the SINRs of both CUs and DPs should be equal to or more than the minimum required SINR to achieve the QoS requirements. The constraints in Equations (93.c) and (93.d) guarantee that the transmit power of CUs and DPs should be within the upper and lower bound power levels. The constraint in Equation (93.e) guaranteed the versatility of resource reuse factor within the upper and lower bounds power level. From the optimization problem formulated in Equation (92), it is observe that the problem statement aimed to find the optimal solution with an exhaustive search.

The throughput optimization problem has complexity of $O(N \times K)$. Finally, we allocate the subcarrier resources to DPs, such that the resource reuse factor is greater than one. Hence, the complexity of the final step is $O(M \times K \times F)$. Therefore, the overall computational complexity of the network is $O(N \times K) + O(M \times K \times F)$.

4.4. Proposed Scheme

4.4.1. Greedy Heuristic Resource Management Scheme (GHRMS)

In this section, we discuss a greedy heuristic resource management scheme (GHRMS). The GHRMS is a well-known method for solving optimization problems [74]. Therefore, the interference induced by CU n to D2D receiver m_r, interference induced by D2D transmitter m_t to eNB, and mutual interference between DPs should be less than a certain threshold level. That is,

$$G_{n,m_r} \leq G_{n,m_r}^{Th}, \forall n \in C, m_r \epsilon D, \tag{94}$$

$$G_{m_t,B} \leq G_{m_t,B}^{Th}, \forall m_t \epsilon D, \tag{95}$$

and
$$G_{m_t',m_r} \leq G_{m_t',m_r}^{Th}, \forall m_t', m_r \epsilon D, \tag{96}$$

where $G_{n,m_r} = l_{n,m_r}^{-\alpha}|h_{n,m_r}|^2$ and $G_{m_t,B} = l_{m_t,B}^{-\alpha}|h_{m_t,B}|^2$ and $G_{m_t',m_r} = l_{m_t',m_r}^{-\alpha}|h_{m_t',m_r}|^2$. G_{n,m_r}^{Th} , $G_{m_t,B}^{Th}$ and G_{m_t',m_r} are the predefined threshold channel gains. The pseudo code for the GHRMS is shown in Algorithm 4.1. In this algorithm, in Step 5, we first define $U_k = (U_n, U_m)$ as the function of CUs U_n and DPs U_m that introduces the least interference among them.

At the initiation of resource management process, the eNB gathers the channel information for all CUs and DPs in a cell (Step 6). From Step 7 to Step 9, starting from n=1, the algorithm iterates through all CUs. For all n and m, the GHRMS searches the DPs that can reuse cellular resources. In Step 10, if DPs can reuse CUs resources, then Step 11 presents the benchmarks for selecting the users that can reduce the uplink interference induced due to the integration of D2D communications into the traditional cellular networks. In Step 12, based on the channel conditions, we calculate the SINRs for CUS and DPs. Step 13 declines the remaining matching subcarrier resource assignment and computes the QoS requirements with the current SINRs. In Step 14, we solved the throughput maximization problem with higher resource reuse factor. Else the state of the resource reuse condition is rechecked in Step 16.

Algorithm 4.1: Greedy Heuristic Resource Management Scheme

```
Initialization
Step 1: $C$= Set of CUs
Step 2: $D$= Set of DPs
Step 3: $X$= Set of uplink subcarriers
Step 4: $F$= Resource reuse factor
Step 5: $U_k = (U_n, U_m)$
Resource management
Step 6: Obtain all channel information for CUs and DPs
Step 7: $n=1$
Step 8: for each $n \epsilon U_n$ do
Step 9:         for each $m \epsilon U_m$ do
Step 10:            if $\delta_{m,n}^k = 1$ then
Step 11:                if $G_{n,m_r} \leq G_{n,m_r}^{Th}, G_{m_t,B} \leq G_{m_t,B}^{Th}$ and $G_{m_t^{'},m_r} \leq G_{m_t^{'},m_r}^{Th}$ then
Steo 12:                    Calculate $\gamma_n^k$ and $\gamma_m^k$
Step 13:                    Decline all matching subcarrier assignments and
                            compute the QoS requirements with the current SINR value
Step 14:                    Solve A1
Step 15:                else
Step 16:                    Check $\delta_{m,n}^k$
Step 17:                    Solve the subcarrier assignments problem to obtain the
                            minimum interference solution
Step 18:                end
Step 19:            end
Step 20:        end
Step 21: end
```

Finally, in Step 17, we continue the matching for subcarrier resource assignment until the benchmark is achieved. In the GHRMS, the set of DPs included in the previous search for an optimal solution is removed from the remaining search procedures. This step reduces interference and overcomes the complexity of the search procedure.

4.4.2. Binary Power Control Scheme (BPCS)

The use of the binary power control scheme (*BPCS*) for network-assisted multicell cellular networks is well known [75,76]. To solve the optimization problem formulated in Equation (92), we can reformulate the throughput problem for CU n and DP m as follows:

$$T_n^* = \frac{1}{C}\sum_{n=1}^{C} log_2\left(1+\gamma_n^k\right) \tag{97}$$

and

$$T_m^* = \frac{1}{F}\sum_{m=1}^{D} log_2\left(1+\gamma_m^k\right), \tag{98}$$

respectively, where T_n^* and T_m^* represent the optimal throughput for CUs and DPs, respectively.

Therefore, the transmit powers of CUs $(P_1^1, \dots, P_N^K)$ and DPs $(P_1^1, \dots, P_M^K)$ should satisfy the following conditions:

$$\textbf{A2}.\ (P_1^1, \dots, P_N^K) = \arg\ \max_{n\,\epsilon C, k \in X} \sum_{n=1}^{C}[T_n^*] \tag{99}$$

$$\textbf{A3}.\ (P_1^1, \dots, P_M^K) = \arg\ \max_{m\,\epsilon\,D, k\,\epsilon\,X} \sum_{m=1}^{D}[T_m^*] \tag{100}$$

subject to

$$G_{n,B} \leq G_{n,B}^{Th}, \forall n \in C, \tag{101.a}$$

$$G_{m,B} \leq G_{m,B}^{Th}, \forall m\,\epsilon\,D, \tag{101.b}$$

$$P_n^{min} \leq\ P_n^k \leq\ P_n^{max}, \forall n \in C, k \in X, \tag{101.c}$$

$$P_{m_t}^{min} \leq\ P_{m_t}^k \leq\ P_{m_t}^{max}, \forall\ m_t\ \epsilon\ D, k \in X, \tag{101.d}$$

$$\delta_{m,n}^k\ \epsilon\ \{0,1\},\ \forall\ m\ \epsilon\ D, n\ \epsilon\ C, k \in X. \tag{101.e}$$

The pseudo code for the *BPCS* is shown in Algorithm 4.2. In *BPCS*, the transmission is initiated only if the channel quality is sufficient, i.e., $G_{n,B} \leq G_{n,B}^{Th}$ and $G_{m,B} \leq G_{m,B}^{Th}$. This constraint implies that the smaller values of $G_{n,B}$ and $G_{m,B}$ minimize interference between CUs and DPs, resulting in higher throughput and spectral efficiency. Therefore, Algorithm 4.2 is applied to control the transmit power of CUs and DPs that have a higher channel gain for the eNB and low interference.

Algorithm 4.2: Binary Power Control Scheme

```
Initialization
Step 1: $N$= Set of CUs
Step 2: $M$= Set of DPs
Step 3: $K$= Set of uplink subcarriers
Step 4: $\delta_m^k$= Resource reuse factor
Step 5: $U_k = (U_n, U_m)$
Step 6: $G_{n,B} \leq G_{n,B}^{Th}$
Step 7: $G_{m,B} \leq G_{m,B}^{Th}$
Step 8: $\delta_{m,n}^k \in \{0,1\}$
Step 9: $P_n^k = P_n^{max}$ , $P_{m_t}^k = P_{m_t}^{max}$
Power Control Algorithm
Step 10: $n=1$
Step 11: for each $n \in U_n$ do
Step 12:     for each $m \in U_m$ do
Step 13:         if $T_n \leq T_n^*$ and $T_m \leq T_m^*$ then
Step 14:             $P_n^k \leftarrow P_n^{max}$ and $P_{m_t}^k \leftarrow P_{m_t}^{max}$
Step 15:         else $P_n^k \leftarrow P_n^{max}$ and $P_{m_t}^k \leftarrow P_{m_t}^{min}$
Step 16:     end
Step17:         end
Step 18: end
```

4.4.3. Complexity Analysis

The proposed scheme has computational complexity of $O[K\{N + (M \times F)\}]$ for estimating resource reuse partner for all CUs and DPs.

4.5. Simulation Results and Discussion

In this section, we first present the simulation environment used for our analysis and then evaluate the simulation results.

4.5.1. Simulation Environment

Here, we provide the simulation environment to evaluate the performance of the proposed scheme. The network assumes log-normal shadowing effect with standard deviation of 8dB and also assumes a path-loss exponent of 4. The main simulation parameters are listed in Table 1, and other simulation parameters were selected based on the 3GPP LTE regulation [77]. We evaluate the performance using Monte Carlo simulation with a total of 10,000 iterations. We compare the performance of the proposed method in terms of the system capacity, spectrum efficiency, and transmit power.

Table 4.1: Simulation parameters and values.

Parameter	**Value**
Number of cells	7
Noise power density	-174 dBm/Hz
Distance between D2D transmitter and receiver	1~70 m
Carrier frequency	2 GHz [31]
Uplink bandwidth	5 MHz [31]
Path-loss exponent	4
Antenna type	120° directional antenna
Number of CUs per cell	65
Number of DPs per cell	80

4.5.2. Simulation Results and Discussion

This subsection presents a comparative performance analysis of the resource management method without FFR scheme (RRM), resource management with greedy heuristic scheme (RM-WGHRMS) and resource management with binary power control scheme (RM-WBPCS). Fig. 4.2 shows the CDF of the SINR for DPs, CUs, and the overall system. We can see from Fig. 4.2(a) that the GHRMS and BPCS allocate uplink resources to DPs that fulfill the SINR requirements. Thus, the SINR of DPs in our proposed method is higher than those in both resource management method without FFR scheme and resource management method with GHRMS.

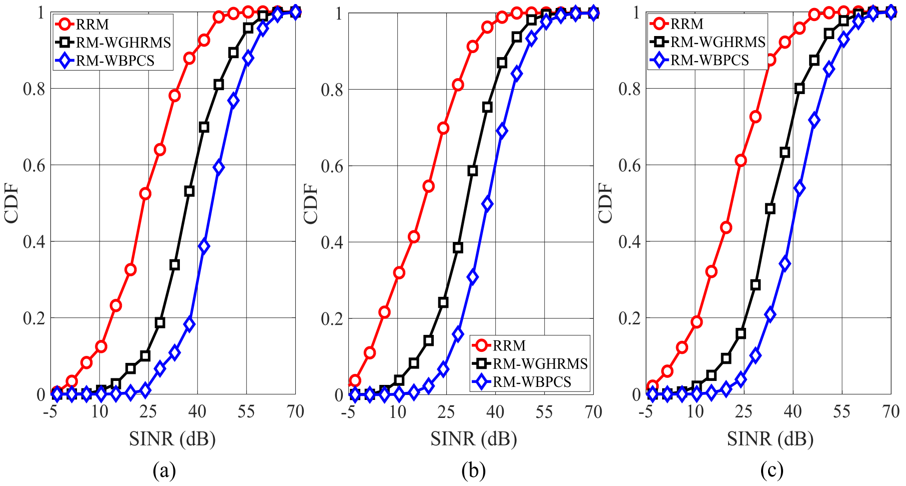


Fig. 4.2: CDF of the SINR for (a) DPs, (b) CUs, and (c) the overall system.

However, Fig. 4.2(b) shows that the SINR of CUs in our proposed method is less than the SINR of DPs. This is because of the matter that CUs experiences interference from DPs. Finally, Fig. 4.2(c) shows that the overall system SINR distribution of our proposed scheme achieves the highest value. We observed that the proposed scheme outperforms the other schemes in terms of SINR.

Fig. 4.3 presents the achievable capacity distribution for DPs, CUs, and the overall system. From Fig. 4.3(a), we can denote that the capacity distribution of DPs for our proposed scheme has the best performance. In contrast, from Fig. 4.3(b), we can observe that the capacity distribution of CUs is less than that of DPs. This result arises from the fact that the CUs experienced interference from co-channel DPs.

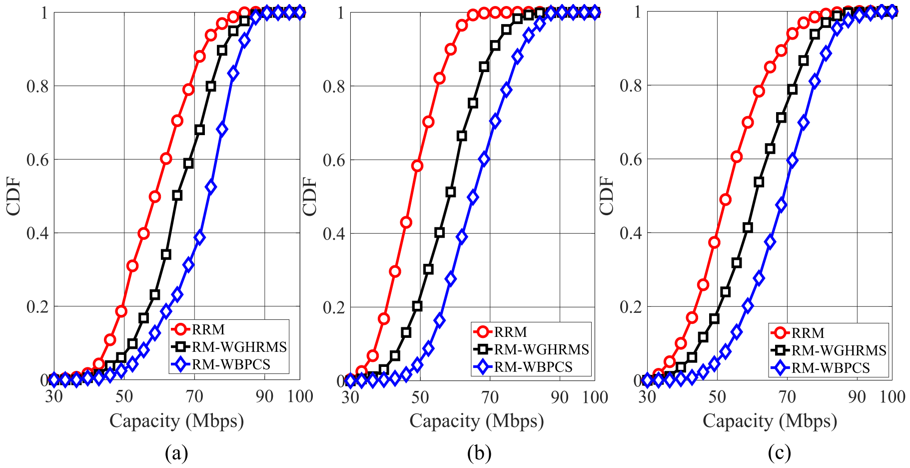


Fig. 4.3: Total achievable capacity for (a) DPs, (b) CUs, and (c) the overall system.

In addition, we can observe from Fig. 4.3(c) that the proposed scheme has the best capacity among existing schemes, since a larger frequency reuse factor increases the capacity of the system. Moreover, the results depicted in Fig. 5 show that the FFR scheme assures the QoS requirements for DPs and CUs and achieves the optimal resource reuse partner between CUs and DPs.

The CDFs of the spectral efficiency for DPs, CUs, and the overall system are shown in Figs. 4.4(a), 4.4(b), and 4.4(c), respectively. Fig. 4.4(a) shows that our proposed scheme has the best spectral efficiency for DPs among the existing schemes. Moreover, Fig. 4.4(b) demonstrates that the proposed scheme yields a higher spectral efficiency for CUs compared to the other schemes. In addition, we can see from Fig. 4.4(c) that our proposed scheme attains the highest overall system spectral efficiency; since the proposed resource management with GHRMS combined with the BPCS increases the spectrum utilization of the cell.

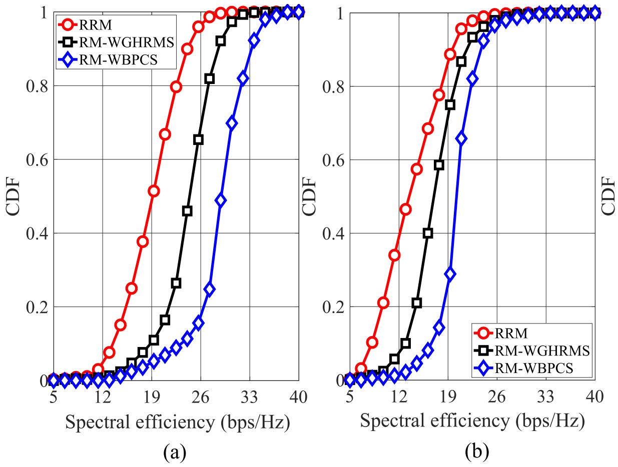


Fig. 4.4: CDF of the spectral efficiency for (a) DPs, (b) CUs, and (c) the overall system.

In Fig. 4.5, the average throughput of our proposed scheme is compared with existing schemes. Fig. 4.5(a) demonstrates that the throughput of DPs increases significantly with varying number of DPs. In contrast; Fig. 4.5(b) shows that the throughput of CUs decreases dramatically with increasing DP number, which occurs because an increased DP number generates high uplink interference for traditional CUs. But, we can see from Fig. 4.5(c) that the overall system throughput increases with varying number of DPs and that our proposed scheme outperforms the other schemes. The throughput increases with the increase of number of active DPs in a cell at first, then after reaching a peak number of affordable active DPs, the throughput saturates. We can see from Fig. 4.5(c) that, after the number of active DPs exceeds 65, the throughput saturates.

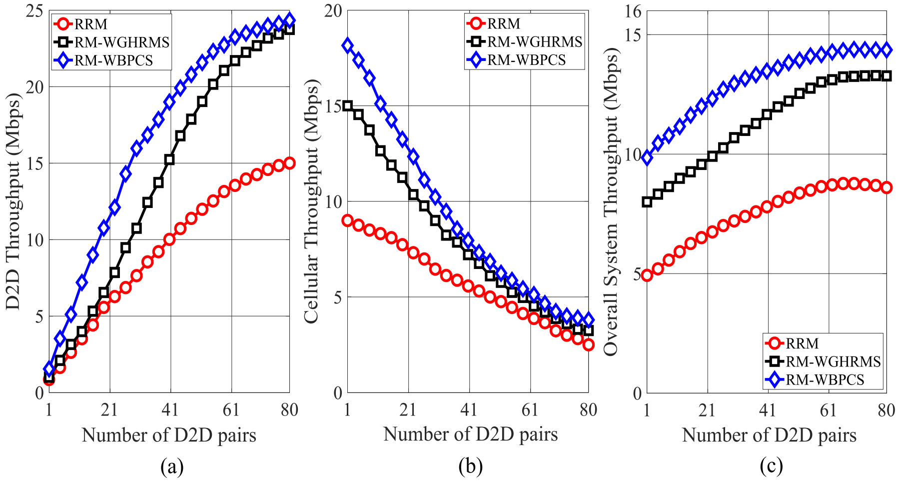
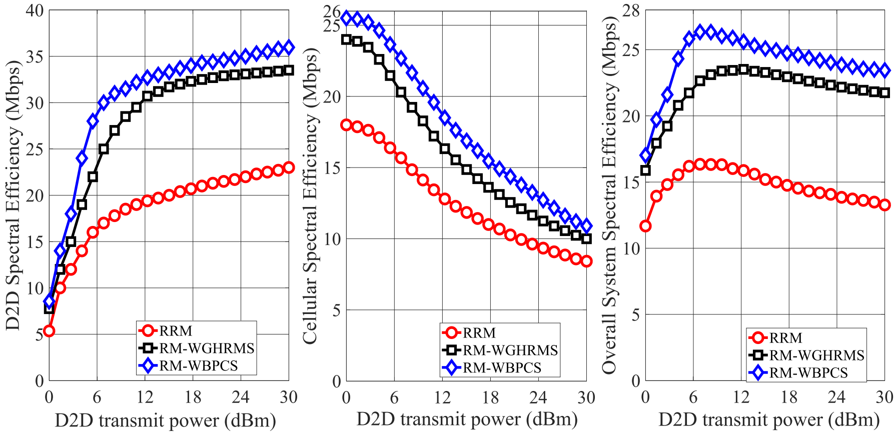


Fig. 4.5: Average throughput analysis with varying numbers of available DPs for (a) DPs, (b) CUs, and (c) the overall system.

Fig. 4.6 shows the spectral efficiency for varying D2D transmit power. We can observe from Fig. 4.6(a) that the spectral efficiency DPs increases with increasing D2D transmit power. In contrast, we can see from Fig. 4.6(b) that the spectral efficiency of the CUs decreases with increasing D2D user transmit power, which occurs because a higher D2D transmit power increases the uplink interference for CUs. Moreover, Fig. 4.6(c) shows that our proposed scheme yields the highest spectral efficiency among the studied schemes. We can see from Fig. 4.6(c) that the spectral efficiency increases promptly as the D2D transmit power increases. However, after the D2D transmit power exceeds 11 dBm, the spectral efficiency decreases.



(a) (b) (c)

Fig. 4.6: Spectral efficiency analysis with varying transmits power consumption of D2D for (a) DPs, (b) CUs, and (c) overall system.

4.5. Conclusion

We have performed a brief analysis on the interference scenarios and techniques to mitigate the interference for underlay D2D communications in cellular networks. To mitigate the uplink interference and improve the overall system throughput, we have proposed an optimal resource management and power control scheme with cell sectorization method. We also considered the FFR technique, which allows fractional reuse of resources between the traditional CUs and DPs in a non-orthogonal fashion. Then, we formulated an optimization problem for multiple DPs simultaneously sharing the same cellular resources to fulfill the required QoS of both CUs and DPs. We analyzed the proposed scheme in two steps. We first solved a greedy heuristic algorithm with a local search scenario to overcome the complexity of the resource reuse pairing phenomenon. Then, we proposed a binary power control scheme to maximize the system capacity for large scale networks. From the simulation results, we can see that the proposed scheme attains high system throughput and spectral efficiency, and also minimizes uplink interference generated by the M-D2D communication.

Chapter 5

Multicast D2D (M-D2D) Communications Underlaying LTE-A Uplink Cellular Networks

In this chapter, we discuss the problem of throughput optimization for M-D2D communications underlaying uplink cellular networks, to achieve high throughput and spectrum efficiency.

5.1. Background and Related Works

Due to the increasing demands for various types of high data rate services, cellular networks are facing the problem of resource limitations. For solving these problems, M-D2D communications underlaying LTE-Advanced (LTE-A) cellular networks have become enormously favorable [78]. In M-D2D communication, nearby devices form an M-D2D group where D2D receivers in the group can receive the same data from the D2D transmitter over a direct link, without relaying on eNB [79]. M-D2D communications can be categorized into: single rate and multi-rate transmissions [80]. In the single-rate transmission, D2D transmitter in a multicast group transmits the same data rate to its corresponding receivers. Whereas, in the multi-rate transmission, D2D transmitter in a multicast group transmits multiple data rates according to the receiver’s demands. Compared to unicast (point-to-point) communication system where a transmitter sends the signal to a single receiver, M-D2D communication reduces overhead and increases spectral efficiency. This concept envisaged as the promising solution for the incoming 5G system and Internet of Things (IoT) technology. However, the system faces challenges in coordinating conventional cellular communication and D2D communication over single resource simultaneously. The interference from CU to D2D receivers in a multicast group and interference from M-D2D transmitter to eNB are incorporated as the main challenge. In [81, 82], the authors proposed an MC-CDMA transmission scheme in M-D2D communication. The results showed that their proposed scheme achieves better SINR compared with conventional scheme. Interference coordination mechanisms for M-D2D communication underlying uplink cellular networks are discussed in [55]. A dynamic power control scheme was introduced to mitigate interference from M-D2D to cellular network. Comparing the result of this scheme with that of conventional multicast transmission scheme shows the improvement of system throughput.

With the introduction of M-D2D communications into the conventional cellular networks motivate to open the door to various use cases. Some of the well-known applications of the M-D2D communication are media-rich applications such as local multimedia content sharing of photos, and music and also high-quality video sharing application such as video multicasting in social platforms. The main issues and challenges in a multicast communications environment are summarized in [36]. The paper classifies the existing multicast protocols based on several distinct features and performance parameters. In [31], the authors discussed on modeling and analysis of M-D2D communication and an optimization problem was formulated based on the mobility and network assistance issues. Comparing the result of this scheme with that of the static network demonstrates the enhancement in mean number of covered receivers. The problem with this study is that the interference coordination function was not applied. A millimeter wave (mmWave) small cell is becoming popular as a promising solution for D2D communications due to availability of abundant spectrum. In [32], the authors proposed an energy-efficient multicast scheduling scheme to achieve high energy efficiency. Also, the transmission power control method of the multi-hop D2D transmission paths was analyzed. The disadvantage of their scheme is that the mmWave communications have high path loss problems. In [83], the authors proposed an optimized opportunistic multicast scheduling over wireless cellular networks. The homogeneous network that is partitioned into rings uses different channel links. An optimization problem was formulated to achieve the optimal solution and results showed that their proposed scheme achieves significant performance gain.

5.2. Proposed Scheme

This section presents the proposed network model. A detail of users' distribution has been given. Problem formulation is discussed later in this section. To make this paper easy to follow, we present some frequently used notations in the proposed scheme in Table 5.1.

Table 5.1: Notations used in problem formulation.

Notation	**Definition**
R	Radius of outer region of cell
r	Radius of inner region of cell
P_B	Transmission power of eNB
$P_{g^{edge}}$	Transmission power of M-D2D group g^{edge}
$l_{c^{in},B}$	Distance between CU c^{in} and eNB
$l_{g_t^{edge},B}$	Distance between M-D2D transmitter g_t^{edge} and eNB
$l_{g_t^{edge},g_r^{edge}}$	Distance between M-D2D transmitter g_t^{edge} and receiver g_r^{edge}
$l_{c^{in},g_r^{edge}}$	Distance between CU c^{in} and M-D2D receiver g_r^{edge}
$l_{c^{in},B}^{min}$	Minimum possible distance of CU from the eNB
$H_{c^{in},B}$	Channel coefficient between CU c^{in} and eNB
$H_{g_t^{edge},B}$	Channel coefficient between M-D2D transmitter g_t^{edge} and eNB
$H_{g_t^{edge},g_r^{edge}}$	Channel coefficient between M-D2D transmitter g_t^{edge} and receiver g_r^{edge}
$H_{c^{in},g_r^{edge}}$	Channel coefficient between CU c^{in} and M-D2D receiver g_r^{edge}
α	Path loss coefficient
σ_n^2	Noise power
γ_{Th}	Minimum SINR requirement of a user defined by the system

5.2.1. Network Model

For easy analysis, we assume CUs as primary users that can access the available resources assigned by the eNB and D2D users as the secondary users that can reuse the cellular resources to generate a transmission. Suppose in each cell there are totally N_C CUs constituting a set C, where $C = \{1, 2, \ldots, N_C\}$, the total number of D2D users constituting a set D, where $D = \{1, 2, \ldots, N_D\}$, and the total number of M-D2D groups constituting a set G, where $G = \{1, 2, \ldots, N_G\}$. We assumed that all CUs and D2D users are uniformly distributed in each cell. In each M-D2D group, we select a D2D user as multicast transmitter, which transmits the same signal to multiple receivers in the group. Thus, the total sum throughput increases with the number of successful communications of the group. We assumed that one M-D2D group can reuse only one cellular link at a time.

In the network model, we assume that the available resources are allotted to CUs by the eNB in an orthogonal manner. Therefore, there is no intra-cell interference between the CUs. For resource reuse method, we assume that the outer region M-D2D communication is allowed to reuse only the inner region cellular resource of each cell. In order to calculate the number of resource blocks assigned to different sub-bands, it is necessary to analyze the density of CUs in the inner region of each cell. Hence, the probability density function (PDF) of the CU c^{in} in polar coordinates $(l_{c^{in},B}, \theta)$ is expressed as [84]

$$f\left(l_{c^{in},B}\right) = \frac{2\left(l_{c^{in},B} - l^{min}_{c^{in},B}\right)}{\left(r - l^{min}_{c^{in},B}\right)^2}, \forall\, l^{min}_{c^{in},B} \leq l_{c^{in},B} \leq r \qquad (102)$$

and
$$f(\theta) = \frac{1}{\left(\frac{2\pi}{3}\right)}, \forall 0 \leq \theta \leq \frac{2\pi}{3}, \qquad (103)$$

where θ is the angle of CU location and $l_{c^{in},B}$ is the distance between CU c^{in} in the inner region of a cell and eNB. In the proposed scheme, we considered that the uplink interference of a cellular network is known and is defined by the matrix **I** as

$$\mathbf{I} = \begin{bmatrix} I_{1,1}, & I_{1,2}, \cdots\cdots, & I_{N_G,1} \\ I_{1,2}, & I_{1,2}, \cdots\cdots, & I_{N_G,2} \\ \vdots & \vdots & \vdots \\ I_{1,N_C}, & I_{1,N_C}, \cdots\cdots, & I_{N_G,N_C} \end{bmatrix}. \qquad (104)$$

The main goal of this paper is to minimize the interference into the least value so as to improve the system performance. Considering the interference matrix, we assumed a communication scenario where an M-D2D group is reusing the resource of a CU. Then, the resource assignment matrix **Z** is defined as

$$\mathbf{Z} = \begin{bmatrix} Z_{1,1}, & Z_{1,2}, \ldots\ldots, & Z_{N_G,1} \\ Z_{1,2}, & Z_{1,2}, \ldots\ldots, & Z_{N_G,2} \\ \vdots & \vdots & \vdots \\ Z_{1,N_C}, & Z_{1,N_C}, \ldots\ldots, & Z_{N_G,N_C} \end{bmatrix}. \tag{105}$$

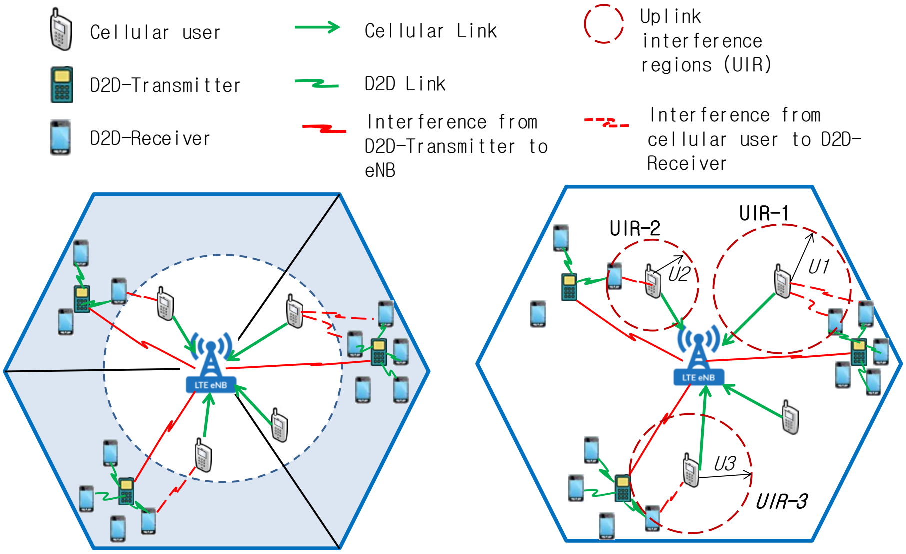
To formulate the problem of an optimal resource allocation scheme, we assume one M-D2D group reuses at most one cellular resource, and each resource can be reused by at most one M-D2D group. That is

$$\left.\begin{array}{l} \sum_{c=1}^{N_C} Z_{c,g} \le 1, \forall\ g \in G \\ \sum_{g=1}^{N_G} Z_{c,g} \le 1, \forall\ c \in C \end{array}\right\}. \tag{106}$$

Note that the number of receivers in a group should be more than one; if the number of receiver in a group is equal to one then the system is in unicast communication scenario. In the network model, each cellular communication has a serving eNB and we considered that the D2D transmitters are reusing cellular links. Each D2D transmitter has the same signal for all the determined D2D receivers and the serving eNB has the knowledge of the multicast message of each D2D transmitter. In the proposed method, to guarantee the QoS requirements of the CUs and D2D users, D2D users are allowed to reuse the resources only when the distance between CUs and D2D users is far enough. If CUs and D2D users are close to each other, considerable interference will generate.

5.2.2. Problem Formulation

In order to enhance the system performance, we should minimize both co-channel interference and inter-cell interference. Then, we can find the optimal resource sharing pair between CUs and M-D2D groups. In the general case, to find the resource sharing partner for the M-D2D communications, we suppose in each cell there are totally R_T uplink interference regions as shown in Fig. 5.1, constituting a set R_U, where $R_U = \{1,2,\dots,R_T\}$. Within these regions, the D2D receivers are interfered by CUs, thus D2D communications cannot guarantee the system QoS [44].



(a) (b)

Fig. 5.1: (a) M-D2D transmission by reusing uplink cellular resource, (b) Uplink interference scenarios.

Without loss of generality, in the proposed method, we assume one of the uplink interference regions, say uplink interference region-1 having the radius U_1. In order to avoid high interference from CUs to D2D receivers, we should maintain an enough distance between CUs and M-D2D groups. Therefore, we assumed that the M-D2D groups in cell outer-region can only reuse the resources of CUs exist in the cell inner-region. Reusing of cellular resource by the M-D2D groups in the same section of cell is not allowed.

Proposition 1. The radius U_1 of uplink interference region-1 can be expressed as

$$U_1 = \frac{\gamma_{Th}^{\frac{2}{\alpha}} . l_{c^{in},B} \cdot l_{g_t^{edge},g_r^{edge}}}{l_{g_t^{edge},B}}, \tag{107}$$

where γ_{Th} is the threshold SINR.

Proof. The proof is presented in Appendix A.

In cellular communication, the received power P_R is the multiplication of transmitted power P_T and channel gain L as

$$P_R = P_T \times L, \tag{108}$$

where $L = l^{-\alpha} \times |H|^2$. The term l is the channel distance and H is the channel coefficient. Therefore, we can express the SINR as

$$\gamma = \frac{P_R}{I + \sigma_n^2}, \tag{109}$$

where I is the interference in the network. To maintain reliable transmission, in the proposed method we assume that M-D2D groups are located in cell outer region and CUs are located in cell inner region. According to Fig. 5.1, we can express the SINR of CU c^{in} and M-D2D group g^{edge} as

$$\gamma_{c^{in}} = \frac{P_B . \, l_{c^{in},B}^{-\alpha} \cdot \left|H_{c^{in},B}\right|^2}{P_{g^{edge}} . \, l_{g_t^{edge},B}^{-\alpha} \cdot \left|H_{g_t^{edge},B}\right|^2 + I_{c,B} + \sigma_n^2} \tag{110}$$

and

$$\gamma_{g^{edge}} = \frac{P_{g^{edge}} . \, l_{g_t^{edge},g_r^{edge}}^{-\alpha} \cdot \left|H_{g_t^{edge},g_r^{edge}}\right|^2}{P_B . \, l_{c^{in},g_r^{edge}}^{-\alpha} \cdot \left|H_{c^{in},g_r^{edge}}\right|^2 + I_{g,m} + \sigma_n^2}. \tag{111}$$

where $I_{c,B}$ denotes co-channel interference from eNBs to CU and $I_{g,m}$ denotes co-channel interference from D2D transmitters in upper layers of network to M-D2D receivers. We can express $I_{c,B}$ and $I_{g,m}$ as

$$I_{c,B} = \sum_{n \neq c, n=1}^{6} P_B . l_{n,B}^{-\alpha} . \left|H_{n,B}\right|^2 \tag{112}$$

and

$$I_{g,m} = \sum_{m=1}^{6} P_m . l_{g,m}^{-\alpha} . \left|H_{g,m}\right|^2 . \tag{113}$$

5.2.3. Coverage Probability

Coverage probability is defined as the probability that a user can successfully transmit the signal from a transmitter to its corresponding receiver, with the SINR equal to or higher than the threshold SINR. In other words, the coverage probability of a system is complementary of the outage probability. Therefore, the coverage probability P^{Cov} can be expressed as

$$P^{Cov} = 1 - P^{Out}, \tag{114}$$

where

$$P^{Out} = \sum_{c^{in}=1}^{N_C} P_{c^{in}}^{Out} + \sum_{g^{edge}=1}^{N_G} P_{g^{edge}}^{Out} . \tag{115}$$

where P^{Out} is the outage probability of the system.

Substituting $\bar{\gamma} = \frac{P_B . l_{c^{in},B}^{-\alpha}}{\sigma_n^2}$ into Equation (110), we have

$$\gamma_{c^{in}} = \frac{\left|H_{c^{in},B}\right|^2}{\frac{P_{g^{edge}} . l_{g_t^{edge},B}^{-\alpha}}{P_B . l_{c^{in},B}^{-\alpha}} . \left|H_{g_t^{edge},B}\right|^2 + \frac{I_{c,B}}{P_B . l_{c^{in},B}^{-\alpha}} + \frac{1}{\bar{\gamma}}} \tag{116}$$

Let $Y = \frac{\left(P_{g^{edge}} . l_{g_t^{edge},B}^{-\alpha} + I_{c,B}\right)}{P_B . l_{c^{in},B}^{-\alpha}}$, then according to [45], the outage probabilities for CU c^{in} ($P_{c^{in}}^{Out}$) can be expressed as

$$P_{c^{in}}^{Out} = 1 - \frac{1}{1 + Y . \gamma_{Th}} e^{\left(-\frac{\gamma_{Th}}{\bar{\gamma}}\right)} . \tag{117}$$

Substituting all the values of Y and $\bar{\gamma}$ in Equation (117), we have

$$P^{Out}_{c^{in}} = 1 - \frac{1}{1+\frac{\left(P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},B} + I_{c,B}\right)\gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}\right)}. \tag{118}$$

Similarly, the outage probability of M-D2D group g^{edge} ($P^{Out}_{g^{edge}}$) in terms of their respective SINR can be expressed as

$$P^{Out}_{g^{edge}} = 1 - \frac{1}{1+\frac{\left(P_B \cdot l^{-\alpha}_{c^{in},g_r^{edge}} + I_{g,m}\right)\gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}\right)}. \tag{119}$$

Substituting Equations (118) and (119) into Equation (115), we have

$$P^{Out} = \sum\nolimits_{c^{in}=1}^{N_C} 1 - \frac{1}{1+\frac{\left(P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},B} + I_{c,B}\right)\gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}\right)} +$$

$$\sum\nolimits_{g^{edge}=1}^{N_G} 1 - \frac{1}{1+\frac{\left(P_B \cdot l^{-\alpha}_{c^{in},g_r^{edge}} + I_{g,m}\right)\gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}\right)}. \tag{120}$$

Therefore, Equation (114) can be listed as

$$P^{Cov} = 1 - \left[\begin{array}{l} \sum_{c^{in}=1}^{N_C} 1 - \frac{1}{1+\frac{\left(P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},B} + I_{c,B}\right)\gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l^{-\alpha}_{c^{in},B}}\right)} + \\ \sum_{g^{edge}=1}^{N_G} 1 - \frac{1}{1+\frac{\left(P_B \cdot l^{-\alpha}_{c^{in},g_r^{edge}} + I_{g,m}\right)\gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}}}\right)} \end{array}\right]. \tag{121}$$

The throughputs of the CU c^{in} ($T_{c^{in}}$) and D2D group g^{edge} ($T_{g^{edge}}$) can be respectively listed as

$$T_{c^{in}} = log_2\left(1 + \frac{P_B .\ l_{c^{in},B}^{-\alpha} . \left|H_{c^{in},B}\right|^2}{P_{g^{edge}} .\ l_{g_t^{edge},B}^{-\alpha} . \left|H_{g_t^{edge},B}\right|^2 + I_{c,B} + \sigma_n^2}\right) \tag{122}$$

and $$T_{g^{edge}} = log_2\left(1 + \frac{P_{g^{edge}} .\ l_{g_t^{edge},g_r^{edge}}^{-\alpha} . \left|H_{g_t^{edge},g_r^{edge}}\right|^2}{P_B .\ l_{c^{in},g_r^{edge}}^{-\alpha} . \left|H_{c^{in},g_r^{edge}}\right|^2 + I_{g,m} + \sigma_n^2}\right). \tag{123}$$

5.3. Throughput Optimization

Combined with the SINR expressions of both CUs and M-D2D groups, we formulate the overall throughput optimization problem as follows:

$$T = \arg_{c^{in} \epsilon C, g^{edge} \epsilon G} \max \left(\sum_{c^{in}=1}^{N_C} T_{c^{in}} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}}\right) \tag{124}$$

subject to

$$\left.\begin{array}{c} P_B^{min} \leq P_B \leq P_B^{max},\ P_{g^{edge}}^{min} \leq P_{g^{edge}} \leq P_{g^{edge}}^{max}, \forall\ g^{edge}\ \epsilon\ G, \\ \gamma_{Th}\ \leq\ \gamma_{c^{in}}, \forall\ c^{in}\ \epsilon\ C, \\ \gamma_{Th}\ \leq\ \gamma_{g^{edge}}, \forall g^{edge}\ \epsilon\ G, \end{array}\right\}. \tag{125}$$

where P_B^{min} and $P_{g^{edge}}^{min}$ denote the minimum transmit power of eNB and M-D2D group g^{edge}, respectively. P_B^{max} and $P_{g^{edge}}^{max}$ denote the maximum transmit power of eNB and M-D2D group g^{edge}, respectively. In the power control mechanism, the M-D2D transmitter in a group selects its transmission power such that the signal power at the destined receivers will be under predefined range. From the optimization problem formulated in (124), we observed that the resource allocation and power control approach are closely related with each other. During resource pairing between CUs and D2D users, the variation of interference scenario can impact on the transmit power.

Proposition 2. The transmit power of eNB and M-D2D group g^{edge} in Equation (125) can be recalculated as follows:

$$\left.\begin{aligned} P_B^{min} \le \frac{\sigma_n^2 \cdot \gamma_{c_{in}}^{Th} \cdot \ \beta_{g_t^{edge},B}\left(\beta_{g_t^{edge},g_r^{edge}} \cdot \gamma_{c_{in}}^{Th} + \gamma_{g^{edge}}\right) + \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}}\left(I_{B,c} \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},g_r^{edge}} + I_{g,m}\right)}{\left(\beta_{c^{in},B} \cdot \beta_{g_t^{edge},g_r^{edge}} - \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \ \beta_{c^{in},g_r^{edge}}\right)} \le P_B^{max} \\ P_{g^{edge}}^{min} \le \frac{\sigma_n^2 \cdot \gamma_{g^{edge}}\left(\beta_{c^{in},B} \cdot \gamma_{g^{edge}} + \gamma_{c_{in}}^{Th} \cdot \beta_{c^{in},g_r^{edge}}\right) + I_{c,B} \cdot \gamma_{c_{in}}^{Th} \cdot \gamma_{g^{edge}} \cdot \ \beta_{c^{in},g_r^{edge}}}{\left(\beta_{g_t^{edge},g_r^{edge}} \cdot \beta_{c^{in},B} - \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \ \beta_{c^{in},g_r^{edge}}\right)} \le P_{g^{edge}}^{max} \end{aligned}\right\}. \tag{126}$$

Proof. The proof is presented in Appendix B.

The pseudo code of the proposed resource allocation is shown in Algorithm 5.1.

Algorithm 5.1: Pseudo Code of the Resource Allocation Algorithm

```
Initialization
    $C$: The set of cellular users
    $D$: The set of D2D users
    $G$: The set of D2D groups
Resource allocation
    for $c^{in} \in C$, $g^{edge} \in G$ do
        Calculate $\gamma_{c^{in}}, \gamma_{g^{edge}}$
        Calculate $P_{c^{in}}^{Out}, P_{g^{edge}}^{Out}$, $P^{Out} = \sum_{c^{in}=1}^{N_C} P_{c^{in}}^{Out} + \sum_{g^{edge}=1}^{N_G} P_{g^{edge}}^{Out}$
        if ($P^{Out*} \le \arg_{c^{in} \in C, g^{edge} \in G} \min P^{Out}$) then
            Calculate $T_{c^{in}}, T_{g^{edge}}$, $T = \arg_{c^{in} \in C, g^{edge} \in G} \max\left(\sum_{c^{in}=1}^{N_C} T_{c^{in}} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}}\right)$
        else if ($P^{Out*} > \arg_{c^{in} \in C, g^{edge} \in G} \min P^{Out}$) then
            Recalculate $\gamma_{c^{in}}, \gamma_{g^{edge}}$
            Recalculate $P_{c^{in}}^{Out}, P_{g^{edge}}^{Out}$, $P^{Out} = P_{c^{in}}^{Out} + P_{g^{edge}}^{Out}$
            Recalculate $T_{c^{in}}$, $T_{g^{edge}}$
            $T = \arg_{c^{in} \in C, g^{edge} \in N_G} \max\left(\sum_{c^{in}=1}^{N_C} T_{c^{in}} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}}\right)$
        end if
end for
```

The overall resource allocation mechanism includes optimal matching of sub-channel resources between CUs and D2D groups and SINR assignment. At the beginning of the sub-channel resource allocation, the eNB collects the information of all M-D2D groups and match one sub-channel resource of the CU to M-D2D group. This phenomenon repeats for all available M-D2D groups. The main objective of the optimal resource allocation is to improve aggregate D2D throughput and achieve higher values of SINR. After the sub-channel resource allocation is completed, optimal SINR is determined. Then, we calculate the outage probability in terms of the SINR for each M-D2D group and CU. Finally, we formulated the aggregate throughput optimization problem.

5.3.1. Computational Complexity

Therefore, the overall complexity of the proposed scheme is $[O(N_C \times N_G) + N_D \times O(N_G)]$.

5.4. Metaheuristic-Tabu Search Algorithm

Metaheuristic-tabu search algorithm is an optimization algorithm which maintains a short term memory of the definite changes of existent search procedure within a specific region. Thus, it prevents nullification of the definite changes in next search steps and controls the embedded heuristic technique. In addition, this algorithm can reduce interference from CUs to D2D users while reusing uplink cellular resources. The metaheuristic-tabu search starts with an initial viable solution and solves the optimization problem by managing neighborhood exploration heuristic. Then, a tabu list is initialized with this initial solution. Tabu list is dynamic in nature and used to browse the solution space efficiently, thus prevents cycling of search steps. If the tabu list is very long, then all moves will become forbidden.

Algorithm 5.2: Metaheuristic-tabu search algorithm.

```
Initialization
    $E$: The number of iterations
    $A$: The initial solution
    % generate initial solution and stored in a temporary location
    $\mathrm{COST}_{best} \leftarrow \mathrm{COST}(A)$
    $B \leftarrow A$ % consider the initial solution as the best solution
    $L_T \leftarrow \emptyset$ % initialization of TABULIST
Search for an optimal solution from the valid move
    while TABUSEARCH()
    do $V_{move} \leftarrow \{i \in E\}, V_{move} \notin L_T$
    % find a valid move with an iteration
    if $V_{move} \neq \emptyset$
        then $C \leftarrow V_{move}$
        % obtained a solution from the valid move
        $L_T \leftrightarrow C \mid L_T \leftarrow C$
        % exchanging or replacing new solution for all
        elements of TABULIST CHECK $\{\mathrm{COST}(C') \leq \mathrm{COST}(C'')\}$
        % select best solution among $C'$ and $C''$
        UPDATE TABULIST($A'$)
            if $\mathrm{COST}(A, A') < \mathrm{COST}_{best}$
                then $B \leftarrow A'$
              $\mathrm{COST}_{best} \leftarrow \mathrm{COST}(A')$
                $A \leftarrow A'$
            return $B$
           end
        end
     end
```

On the other hand, if the tabu list is very short, then the search mechanism ends up examining a local optimum. The main factor that affects the tabu list is the size of neighborhood of the current solution. Therefore, adjusting length of the tabu list is considered as a critical approach in finding an optimal solution. Once the tabu list is full, previous elements of the list are removed and generate a neighborhood solution, which has the highest matching with optimal solution for the newly added solution. If the neighborhood solution does not matched with the current solution, then another solution that has the highest matching value becomes the best solution. In the literature, a tabu-search-based metaheuristic algorithm is presented to find the optimal solution for scalable video coding multicast system [82]. The paper proposed a multicast transmission scheme by converting a simplified problem into a well-defined orienteering problem over relay-based wireless networks. The pseudo code of the proposed metaheuristic-tabu search algorithm is presented in Algorithm 5.2. The tabu list structure considered in the proposed scheme followed first-in-first-out (FIFO) mechanism.

5.5. Jain's Fairness Index

Fairness distribution of resources is an important basis in designing cellular networks, where two or more devices have to share the same sub-channel resource. In this section, we introduce Jain's fairness index to analyze the fair distribution of resources among M-D2D groups [83]. In the proposed scheme, while allocating sub-channel resource to M-D2D group, such that the receivers in the group should attain an aggregate throughput $T_{g^{edge}}$. Therefore, in order to analyze the fair distribution of sub-channel resources, we introduce Jain's fairness index (*JFI*) for the system as follows:

$$JFI = \frac{\left|\sum_{g^{edge}=1}^{N_G} T_{g^{edge}}\right|^2}{N_G \cdot \sum_{g^{edge}=1}^{N_G} T_{g^{edge}}{}^2}, \forall\, g^{edge} \in G. \tag{127}$$

Substituting Equation (123) in Equation (127), we have,

$$JFI = \frac{\left|\sum_{g^{edge}=1}^{N_G} log_2\left(1+\frac{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}} \cdot \left|H_{g_t^{edge},g_r^{edge}}\right|^2}{P_B \cdot l^{-\alpha}_{c^{in},g_r^{edge}} \cdot \left|H_{c^{in},g_r^{edge}}\right|^2 + I_{g,m} + \sigma_n^2}\right)\right|^2}{N_G \sum_{g^{edge}=1}^{N_G}\left(log_2\left(1+\frac{P_{g^{edge}} \cdot l^{-\alpha}_{g_t^{edge},g_r^{edge}} \cdot \left|H_{g_t^{edge},g_r^{edge}}\right|^2}{P_B \cdot l^{-\alpha}_{c^{in},g_r^{edge}} \cdot \left|H_{c^{in},g_r^{edge}}\right|^2 + I_{g,m} + \sigma_n^2}\right)\right)^2}, \forall\, g^{edge} \in G. \tag{128}$$

The value of *JFI* is confined between 0 and 1. If all M-D2D groups receive the same amount of resources, then *JFI* is 1, this means the overall resource allocation is 100% fair.

5.6. Performance Discussion

In this section, we present simulation parameters and several simulation results to verify the performance of the proposed resource sharing scheme.

5.6.1. Simulation Environment

We consider a multi-cell cellular network in which the available resources are allocated to the CUs and there is no interference between the CUs. The main simulation parameters are listed in Table 5.2. The path loss model for CUs and D2D users are considered to be in LOS model. In the proposed scheme, all the users are uniformly placed in a cell and each simulation result is analyzed by averaging over a large number of iterations. The proposed algorithm for M-D2D communications has been implemented in Matlab using Monte-Carlo simulation. Other simulation parameters are selected based on 3GPP E-UTRA regulation [50].

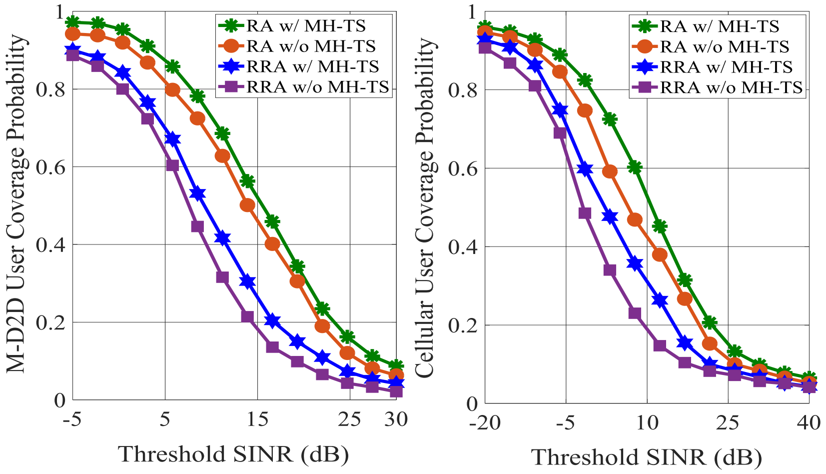
Table 5.2: Simulation parameters and values.

Parameters	**Values**
Noise power	-174 dBm/Hz
D2D grouping radius	1~50 m
Total number resource blocks	50 [50]
Link bandwidth	180 kHz
The maximum transmission power of D2D user	15 dBm
The maximum transmission power of CU	25 dBm
Number of D2D groups	20
Number of D2D receivers in a group	2~5
User distribution	Uniform
Channel bandwidth	10 MHz [50]
Path loss exponent	4

5.6.2. Simulation Results

In this Subsection, we compare our proposed spectrum reuse-based throughput optimization for M-D2D communications against random resource allocation scheme discussed in [20]. The study analyzed a cluster formation based resource allocation method, which allocates the resources randomly. For performance comparison, we level our proposed scheme as RA w/ MH-TS. Specifically, we denote our proposed resource allocation scheme before introducing the metaheuristic-tabu search algorithm as RA w/o M-TS. We denote the reference scheme [20] as RRA w/ MH-TS and RRA w/o MH-TS.

The variation of coverage probability of M-D2D users with respect to threshold SINR is shown in Fig. 5.2(a). From Fig. 5.2(a), we can see that our proposed scheme attains highest coverage probability as compared with other schemes. Moreover, we observe that as the threshold SINR increases the coverage probability decreases. Specifically, for all the methods, M-D2D users achieved 63.54% to 87.76% of coverage probability at threshold SINR of 5dB.

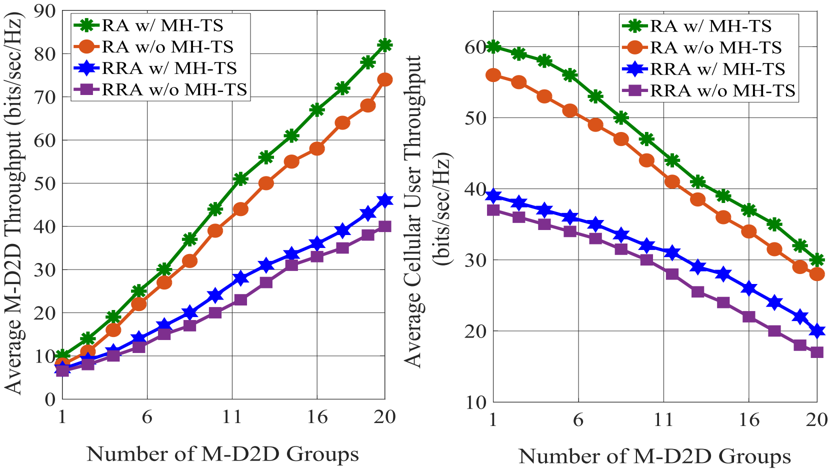


(a) (b)

Fig. 5.2: (a) Coverage probability of M-D2D user with varying threshold SINR, (b) coverage probability of CU with varying threshold SINR.

Fig. 5.2(b) depicts the variation of coverage probability of CUs with respect to threshold SINR. It can be seen from Fig. 5.2(b) that for all the methods, the CU with metaheuristic-tabu search algorithm attained 65% to 86.84% of coverage probability at threshold SINR of -5dB. As shown in Figs. 5.2(a) and 5.2(b), coverage probability becomes worse for both M-D2D and CUs with the increase in the threshold SINR of the network. Finally, we observe that for given threshold SINR, the coverage probabilities of M-D2D communications are greater than those for cellular communications. This is due to the fact that the communication distances in M-D2D communications are less.

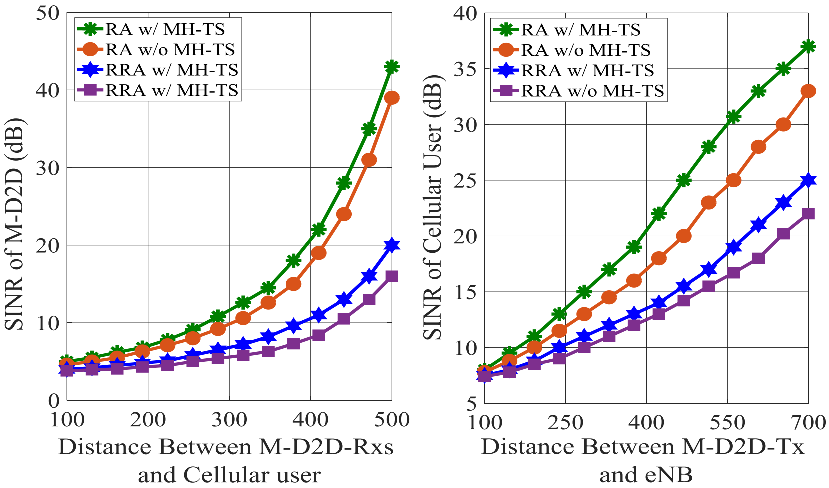
The variation of average throughput of M-D2D user as a function of number of M-D2D groups in a cell is shown in Fig. 5.3(a). We observe that the throughput increases as the number of number of M-D2D groups in a cell increases. Moreover, it is seen that the throughput of our proposed resource allocation scheme shows a trend of continuous increase. Therefore, we can conclude from our observation that FFR technique significantly employed for designing a high throughput cellular network.



(a) (b)

Fig. 5.3: (a) Average throughput of M-D2D user as a function of number of M-D2D groups in a cell, (b) average throughput of CU as a function of number of M-D2D groups in a cell.

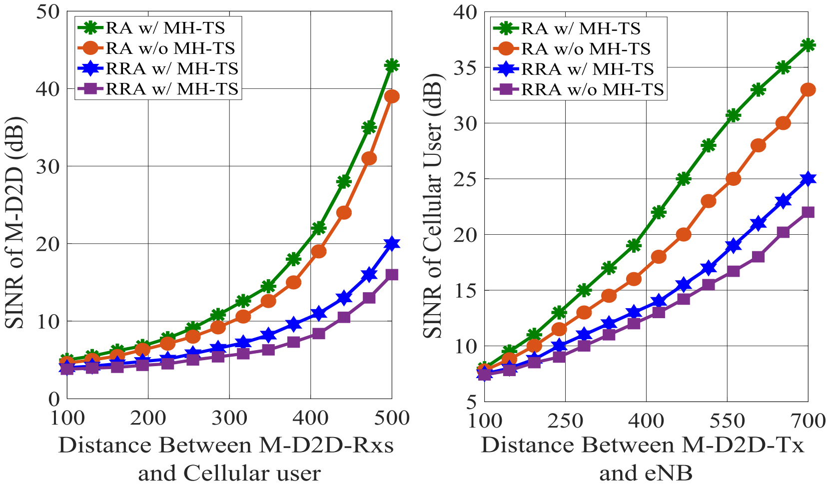
In Fig. 5.3(b), we plot the average throughput achieved by the CU as a function of number of M-D2D groups in a cell. With the increase in the number of M-D2D groups in a cell, CU throughput decreases. This is due to the fact that the M-D2D transmitter generates uplink interference to the eNB, which directly impacts on the performance of CUs.



(a) (b)

Fig. 5.4: (a) Received SINR of M-D2D as a function of distance between M-D2D receivers and CU, (b) received SINR of CU as a function of distance between M-D2D transmitter and eNB.

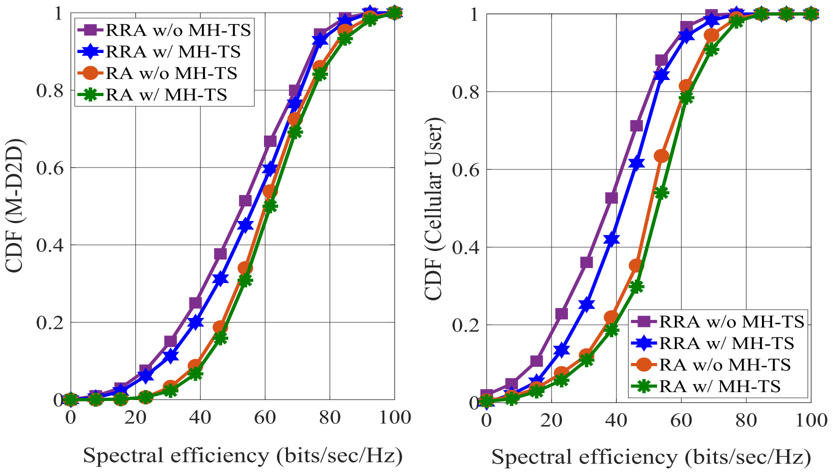
Fig. 5.4(a) shows the received SINR of M-D2D user with respect to the variable distance between M-D2D receivers and CU. As shown in Fig. 5.4(a), the received SINR of M-D2D increases with the increase of distance between M-D2D receivers and CUs. This is due to the fact that the larger the distance, the lower the aggregate uplink interference from CUs to M-D2D receivers. Observed from Fig. 5.4(a), our proposed resource allocation and metaheuristic-tabu search scheme has the best performance compared with other schemes. The variation of received SINR of CU with respect to distance between M-D2D transmitter and eNB is plotted in Fig. 5.4(b). As can be seen, received SINR increases as distance increases and compared with RRA scheme, our proposed scheme can accommodate high SINR.



(a) (b)

Fig. 5.5: (a) Power consumption of overall system as a function of distance between D2D transmitter and D2D receiver, (b) fairness as a function of distance between D2D transmitter and receiver.

The total power consumption as a function of distance between D2D transmitter and its corresponding receivers in an M-D2D group is shown in Fig. 5.5(a). It is seen from Fig. 5.5(a) that as the distance increases the link quality decreases, therefore M-D2D transmitter has to transmit data to its corresponding receivers with a higher transmission power. However, the overall power consumption of our proposed scheme is much lesser than RRA scheme with and without metaheuristic-tabu search algorithm. This is due to the fact that metaheuristic-tabu search algorithm ignores certain repetitions while finding best resource reuse partners. Fig. 5.5(b) shows the fairness of resource distribution against the distance between D2D transmitter and receiver. For simple analysis, we assumed the optimal fairness index as 1. It can be seen from Fig. 5.5(b) that as the distance between D2D transmitter and receiver of a multicast group increases, the fairness index decreases drastically. We observe that our proposed scheme obtains nearly optimal fairness index as compared with the existing scheme.



(a) (b)

Fig. 5.6: (a) Cumulative distribution of spectral efficiency of M-D2D user, (b) cumulative distribution of spectral efficiency of CU.

Fig. 5.6(a) plots the spectral efficiency distribution of M-D2D users. Observed from Fig. 5.6(a), our proposed joint resource allocation and metaheuristic-tabu search algorithm has the best performance compared with other schemes. This is because our proposed metaheuristic-tabu search algorithm finds the most promising resource sharing partner between CUs and M-D2D users which can reduce the total uplink interference. On the other hand, RRA scheme without metaheuristic-tabu search algorithm experiences lower spectral efficiency; this is due to the interference from CUs to nearby M-D2D receivers. Finally, we notice that 70% of M-D2D users in our proposed scheme achieved a spectral efficiency of

71.08bits/sec/Hz. Spectral efficiency distribution of CUs is shown in Fig. 5.6(b). We can observe that our proposed scheme has the best throughput performance compared with existing schemes. This is because our proposed scheme aims at maximizing the user's throughput based on the resource partition technique. Also, from Fig. 5.6(b), it is seen that in the proposed communication scenario, 60% of users achieved a spectral efficiency of 72.51bps/Hz. Finally, we notice that the spectral efficiencies of M-D2D users are greater than those for CUs, due to generally smaller communication distances in M-D2D communications.

5.7. Conclusion

In this paper, we have considered joint resource allocation and metaheuristic-tabu search algorithm for M-D2D communications reusing uplink cellular resources. The main drawback of M-D2D communications underlaying cellular network is the interference caused by D2D users to conventional cellular networks. To mitigate the interference, we proposed a spectrum reuse method based on the FFR technique. Then, to achieve higher system performance, we formulated a sum throughput optimization problem. However, the computational complexity of the optimization problem was high due to large number of iterations. To achieve low computational complexity, we introduced a metaheuristic-tabu search algorithm. Moreover, fairness of the resource allocation was analyzed by using efficient Jain's fairness index, which maintains a level of required SINR. For analysis, we assumed the optimal value of the fairness index as 1. We performed extensive simulations in terms of target SINR, distance between D2D transmitter and receiver, threshold SINR, and number of successful D2D receivers in an M-D2D group. We compared our proposed scheme with the RRA scheme with and without metaheuristic-tabu search algorithm. The results demonstrated that our proposed scheme provides a good tradeoff between the interference mitigation and required throughput, thus effectively increases overall system throughput and spectral efficiency. As a future work, this approach can be extended by assuming resource reuse factor more than 1 for the M-D2D communications.

Appendix A

For uplink interference region analysis, the general expressions of the received SINRs of CU c^{in} and D2D group g are calculated as follows:

$$\frac{P_B.\, l^{-\alpha}_{c^{in},B}}{P_{g^{edge}}.\, l^{-\alpha}_{g_t^{edge},B}+\sigma_n^2} \geq \gamma_{Th} \text{ and } \frac{P_{g^{edge}}.\, l^{-\alpha}_{g_t^{edge},g_r^{edge}}}{P_B.\, l^{-\alpha}_{c^{in},g_r^{edge}}+\sigma_n^2} \geq \gamma_{Th}. \tag{A.1}$$

Neglecting noise power from above Equation (A.1), we have

$$\frac{P_B.\, l^{-\alpha}_{c^{in},B}}{P_{g^{edge}}.\, l^{-\alpha}_{g_t^{edge},B}} \geq \gamma_{Th} \text{ and } \frac{P_{g^{edge}}.\, l^{-\alpha}_{g_t^{edge},g_r^{edge}}}{P_B.\, l^{-\alpha}_{c^{in},g_r^{edge}}} \geq \gamma_{Th}. \tag{A.2}$$

Solving Equation A.2, $l^{\alpha}_{c^{in},g_r^{edge}}$ can be expressed as

$$\left.\begin{aligned} \frac{\gamma_{Th}\, l^{-\alpha}_{g_t^{edge},B}}{l^{-\alpha}_{c^{in},B}} &= \frac{l^{-\alpha}_{g_t^{edge},g_r^{edge}}}{\gamma_{Th} l^{-\alpha}_{c^{in},g_r^{edge}}} \\ l^{-\alpha}_{c^{in},g_r^{edge}} &= \frac{l^{-\alpha}_{g_t^{edge},g_r^{edge}}.l^{-\alpha}_{c^{in},B}}{l^{-\alpha}_{g_t^{edge},B}.\gamma_{Th}^2} \\ l^{\alpha}_{c^{in},g_r^{edge}} &= \frac{\gamma_{Th}^2.l^{-\alpha}_{g_t^{edge},B}}{l^{-\alpha}_{g_t^{edge},g_r^{edge}}.l^{-\alpha}_{c^{in},B}} \end{aligned}\right\}. \tag{A.3}$$

Since the uplink interference region is defined by the distance between CU and M-D2D receiver, we have

$$U_1 = \frac{\gamma_{Th}^{\frac{2}{\alpha}}.l_{c^{in},B} \cdot l_{g_t^{edge},g_r^{edge}}}{l_{g_t^{edge},B}}. \tag{A.4}$$

This completes the proof.

Appendix B

Substituting $\gamma_{c^{in}} = \gamma^{Th}_{c_{in}}$ and $P_B = P_B^{Th}$ in Equation (113), we have

$$\gamma^{Th}_{c_{in}} = \frac{P_B^{Th}.\, l^{-\alpha}_{c^{in},B}.\left|H_{c^{in},B}\right|^2}{P_{g^{edge}}.\, l^{-\alpha}_{g_t^{edge},B}.\left|H_{g_t^{edge},B}\right|^2 + I_{B,c} + \sigma_n^2}. \tag{B.1}$$

Let $\beta_{c^{in},B} = l_{c^{in},B}^{-\alpha}.\left|H_{c^{in},B}\right|^{2}$ and $\beta_{g_t^{edge},B} = l_{g_t^{edge},B}^{-\alpha}.\left|H_{g_t^{edge},B}\right|^{2}$, then Equation (B.1) becomes

$$\gamma_{c^{in}}^{Th} = \frac{P_B^{Th}.\ \beta_{c^{in},B}}{P_{g^{edge}}.\beta_{g_t^{edge},B} + I_{B,c} + \sigma_n^2}, \tag{B.2}$$

$$P_{g^{edge}} = \frac{P_B^{Th}.\ \beta_{c^{in},B}}{\gamma_{c^{in}}^{Th}.\beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}}. \tag{B.3}$$

From Equation (114), we have

$$\gamma_{g^{edge}} = \frac{P_{g^{edge}}.\ \beta_{g_t^{edge},g_r^{edge}}}{P_B.\ \beta_{c^{in},g_r^{edge}} + I_{g,m} + \sigma_n^2}, \tag{B.4}$$

$$P_B^{Th} = \frac{P_{g^{edge}}.\ \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}}.\ \beta_{c^{in},g_r^{edge}}} - \frac{I_{g,m}}{\beta_{c^{in},g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{c^{in},g_r^{edge}}}, \tag{B.5}$$

Substituting Equation (B.3) in (B.5), we have

$$P_{g^{edge}} = \frac{\left(\frac{P_{g^{edge}}.\ \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}}.\ \beta_{c^{in},g_r^{edge}}} - \frac{I_{g,m}}{\beta_{c^{in},g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{c^{in},g_r^{edge}}}\right).\ \beta_{c^{in},B}}{\gamma_{c^{in}}^{Th}.\beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}}, \tag{B.6}$$

$$P_{g^{edge}}\left(\beta_{g_t^{edge},g_r^{edge}}.\beta_{c^{in},B} - \gamma_{c^{in}}^{Th}.\beta_{g_t^{edge},B}.\gamma_{g^{edge}}.\ \beta_{c^{in},g_r^{edge}}\right) = \sigma_n^2.\gamma_{g^{edge}}\left(\beta_{c^{in},B}.\gamma_{g^{edge}} + \gamma_{c^{in}}^{Th}.\beta_{c^{in},g_r^{edge}}\right) + I_{B,c}.\gamma_{c^{in}}^{Th}.\gamma_{g^{edge}}.\beta_{c^{in},g_r^{edge}}, \tag{B.7}$$

$$P_{g^{edge}} = \frac{\sigma_n^2.\gamma_{g^{edge}}\left(\beta_{c^{in},B}.\gamma_{g^{edge}} + \gamma_{c^{in}}^{Th}.\beta_{c^{in},g_r^{edge}}\right) + I_{B,c}.\gamma_{c^{in}}^{Th}.\gamma_{g^{edge}}.\ \beta_{c^{in},g_r^{edge}}}{\left(\beta_{g_t^{edge},g_r^{edge}}.\beta_{c^{in},B} - \gamma_{c^{in}}^{Th}.\beta_{g_t^{edge},B}.\gamma_{g^{edge}}.\ \beta_{c^{in},g_r^{edge}}\right)}. \tag{B.8}$$

Similarly, from Equation (B.5), we have

$$P_B^{Th} = \frac{\left(\frac{P_B \cdot \beta_{c_{in},B}}{\gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}}\right) \cdot \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}} \cdot \beta_{c_{in},g_r^{edge}}} - \frac{I_{g,m}}{\beta_{c_{in},g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{c_{in},g_r^{edge}}}, \tag{B.9}$$

$$\begin{aligned} P_B^{Th}\left(\beta_{c_{in},B} \cdot \beta_{g_t^{edge},g_r^{edge}} - \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \beta_{c_{in},g_r^{edge}}\right) = \\ \sigma_n^2 \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B}\left(\beta_{g_t^{edge},g_r^{edge}} \cdot \gamma_{c_{in}}^{Th} + \gamma_{g^{edge}}\right) + \\ \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}}\left(I_{B,c} \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},g_r^{edge}} + I_{g,m}\right), \end{aligned} \tag{B.10}$$

$$P_B^{Th} = \frac{\sigma_n^2 \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B}\left(\beta_{g_t^{edge},g_r^{edge}} \cdot \gamma_{c_{in}}^{Th} + \gamma_{g^{edge}}\right) + \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}}\left(I_{B,c} \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},g_r^{edge}} + I_{g,m}\right)}{\left(\beta_{c_{in},B} \cdot \beta_{g_t^{edge},g_r^{edge}} - \gamma_{c_{in}}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \beta_{c_{in},g_r^{edge}}\right)}. \tag{B.11}$$

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Appendix C: Representative Publications

1. Following are the representative journal publications based on the contributions of this dissertations:
    - i. **D.D. Ningombam,** and S. Shin, "Optimal Resource Management and Binary Power Control in Network-Assisted D2D Communications for Higher Frequency Reuse Factor," *Sensors*, vol. 19, no.2, p. 251, 2019.
    - ii. **D.D. Ningombam,** and S. Shin, "Throughput Optimization Using Metaheuristic-Tabu Search in the Multicast D2D Communications Underlaying LTE-A Uplink Cellular," *Electronics*, vol. 7, no. 12, p. 440, 2018.
    - iii. **D.D. Ningombam,** and S. Shin, "Non-Orthogonal Resource Sharing Optimization for D2D Communication in LTE-A Cellular Networks: A Fractional Frequency Reuse-Based Approach," *Electronics*, vol. 7, no. 10, p. 238, 2018.
    - iv. **D.D. Ningombam,** and S. Shin, "Distance-Constrained Outage Probability Analysis for Device-to-Device Communications Underlaying Cellular Networks with Frequency Reuse Factor," *Computers*, vol. 7, no. 4, p. 5, 2018.
2. Following are the representative conference publications based on the contributions of this dissertations:
    - i. **D.D. Ningombam**, S.-S. Hwang, and S. Shin. "Decentralized Resource Allocation for Multicast D2D Communications Using Stochastic Geometry," *In 11th*

International Conference on Ubiquitous and Future Networks (ICUFN), 2019 (Accepted).

ii. **D.D. Ningombam**, and S. Shin, "Combinatorial Auction Approach to Optimal Resource Sharing in Device-to-Device Communication Underlaying Uplink Cellular Networks," *In Proceeding to the 5th International Conference on Next Generation Computing*, 2019.

iii. **D.D. Ningombam,** S.-S. Hwang, and S. Shin, "Resource-Sharing Optimization for Multicast D2D Communications Underlaying LTE-A Uplink Cellular Networks," *In 34th ACM/SIGAPP Symposium on Applied Computing*, pp. 2001-2007, 2019.

iv. **D.D. Ningombam**, S.-S. Hwang, and S. Shin, "Energy Efficient Device Sensing for Device-to-device Communication in LTE-Enabled Wearable sensor Networks," *In KICS Winter Conference*, pp. 1-3, 2019 **(Best paper award).**

v. **D.D. Ningombam**, S.-S. Hwang, and S. Shin, "Interference Mitigation in Multicast D2D Communications Underlay Cellular Network," *1st International Conference on Artificial Intelligence in Information and Communication*, pp. 459-462, 2019.

vi. **D.D. Ningombam**, S.-S. Hwang, and S. Shin, "A Novel Resource Sharing Mechanism for Device-to-Device Communications Underlaying LTE-A Uplink Cellular Networks," *In Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 829-833, 2018.

vii. **D.D. Ningombam,** and S. Shin, "Outage probability Analysis of Device-to-Device Communications with Frequency Reuse-2 in Fractional Frequency Reuse Method," *In International Conference on Information Networking (ICOIN),* pp. 341-345, 2018.

viii. **D.D. Ningombam**, and S. Shin, "Channel Allocation Scheme in Multicast Device-to-Device Communications Underlaying Cellular Networks," *In Symposium of the Korean Institute of Communications and Information sciences,* pp. 352-353, 2018.

ix. **D.D. Ningombam**, and S. Shin, "Device-to-Device Communication in Fractional Frequency Reuse Aided Cellular Network," *In Proc. of the 28th Joint Conference on Communications and Information (JCCI)*, 2018.

x. **D.D. Ningombam**, J.-Y. Pyun, S.-S. Hwang, and S. Shin, "Fractional Frequency Reuse Scheme for Interference Mitigation in Device-to-Device Communication Underlying LTE-A Network," *In 51st Asilomar Conference on Signals, Systems, and Computers*, pp. 1402-1406, 2017.

xi. **D.D. Ningombam**, and S. Shin, "Radio Resource Allocation and Power Control Scheme for Device-to-Device Communication in LTE-A Cellular Networks," *In 8th International Conference on ICT Convergence (ICTC),* pp. 962-964, 2017 (Invited).

xii. **D.D. Ningombam**, S.-S. Hwang, and S. Shin, "Radio Resource Allocation and Power Control Scheme for Device-to-Device Communication in LTE-A Cellular Networks," *In annual Conference of the Korean Institute* *of Communication Sciences,* pp. 473-474, 2017 **(Best paper award).**

xiii. **D.D. Ningombam**, G.-T. Ha, and S. Shin, "Consumer Load Scheduling Based on Real-Time Pricing of Electricity for Smart Grid," *In Proceeding to the 2nd International Conference on Next Generation Computing,* 2017**(Best paper award)**.

xiv. A. Pudasaini, **D.D. Ningombam**, S.-S. Hwang, and S. Shin, "*Directional Random Routing for Enhancing Source-Location Privacy in Wireless Sensor Networks," In Ninth International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 344-348, 2017.

xv. M. Razzaq, **D.D. Ningombam**, and S. Shin, "Energy Efficient K-Means Clustering-Based Routing Protocol for WSN Using Optimal Packet Size," *In International Conference on Information Networking (ICOIN),* pp. 632-635, 2018.