Resource Allocation Management of D2D Communications in Cellular Networks

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Abstract

Resource Allocation Management of D2D Communications in Cellular Networks

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To improve the system capacity, spectral performance, and energy efficiency, stringent requirements for increasing reliability, and decreasing delays have been intended for next-generation wireless networks. Device-to-device (D2D) communication is a promising technique in the fifth-generation (5G) wireless communications to enhance spectral efficiency, reduce latency and energy efficiency. In D2D communication, two wireless devices in close proximity can communicate with each other directly without pass through the Base Station (BS) or Core Network (CN). In this proposal, we identify compromises and challenges of integrating D2D communications into cellular networks and propose potential solutions. To maximize gains from such integration, resource management, and interference avoidance are key factors. Thus, it is important to properly allocate resources to guarantee reliability, data rate, and increase the capacity in cellular networks.

In this thesis, we address the problem of resource allocation in D2D communication underlaying cellular networks. We provide a detailed review of the resource allocation problem of D2D Communications. My Ph.D research will tackle several issues in order to alleviate the interference caused by a D2D user-equipment (DUE) and cellular user-equipment (CUE) in uplink multi-cell networks, the intra-cell and inter-cell interference are considered in this work to improve performance for D2D communication underlaying cellular networks. The thesis consists of four main results. First, the preliminary research proposes a resource allocation scheme to formulate the resource allocation problem through optimization of the utility function, which eventually reflects the system performance concerning network throughput. The formulated optimization problem of maximizing network throughput while guaranteeing predefined service levels to cellular users is non-convex and hence intractable. Thus, the original problem is broken down into two stages. The first stage is the admission control of D2D users while the second one is the power control for each admissible D2D pair and its reuse partner.

Second, we proposed a spectrum allocation framework based on Reinforcement Learning (RL) for joint mode selection, channel assignment, and power control in D2D communication. The objective is to maximize the overall throughput of the network while ensuring the quality of transmission and guaranteeing low latency requirements of D2D communications. The proposed algorithm uses reinforcement learning (RL) based on Markov Decision Process (MDP) with a proposed new reward function to learn the policy by interacting with the D2D environment. An Actor-Critic Reinforcement Learning (AC-RL) approach is then used to solve the resource management problem. The simulation results show that our learning method performs well, can greatly improve the sum rate of D2D links, and converges quickly, compared with the algorithms in the literature.

Third, a joint channel assignment, power allocation and resource allocation algorithm is proposed. The algorithm designed to allow multiple DUEs to reuse the same CUE channel for D2D communications underlaying multi-cell cellular networks with the consideration of the inter-cell and intra-cell interferences. Obviously, under satisfying the QoS requirements of both DUEs and CUEs, the more the number of the allowed accessing DUEs on a single CUE channel is, the higher the spectrum efficiency is, and the higher the network throughput can be achieved. Meanwhile, implementing resource allocation strategies at D2D communications allows to effectively mitigate the interference caused by the D2D communications at both cellular and D2D users. In this part, the formulated optimization problem of maximizing network throughput while guaranteeing predefined service levels to cellular users. Therefore, we propose an algorithm that solves this non-linear mixed-integer problem in three steps wherein the first step, subchannel assignment is carried out, the second one is the power allocation, while the third step of the proposed algorithm is the resource allocation for multiple D2D pairs based on genetic algorithm. The simulation results verify the effectiveness of our proposed algorithm.

Fourth, integrating D2D communications and Femtocells in Heterogeneous Networks (HetNets) is a promising technology for future cellular networks. Which have attracted a lot of attention since it can significantly improve the capacity, energy efficiency and spectral performance of next-generation wireless networks (5G). D2D communication and femtocell are introduced as underlays to the cellular systems by reusing the cellular channels to maximize the overall throughput in the network. In this part, the problem is formulated to maximize the network throughput under the QoS constraints for CUEs, DUEs and FUEs. This problem is a mixed-integer non-linear problem that is difficult to be solved directly. To solve this problem, we propose a joint channel selection, power control, and resource allocation scheme to maximize the sum rate of the cellular network system. The simulation results show that the proposed scheme can effectively reduce the computational complexity and improve the overall system throughput compared with existing well-known methods.

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Abbreviation

3GPP	Third Generation Partnership Project
4G	Fourth Generation of Mobile Communication
5G	Fifth Generation of Mobile Communication
AC-RL	Actor-Critic Reinforcement Learning
AWGN	Additive White Gaussian Noise
BS	Base Station
CDF	Cumulative Distribution Function
CQI	Channel Quality Information
CSI	Channel State Information
CUE	Cellular User Equipment
CN	Core Network
DUE	D2D User Equipment
D2D	Device-to-Device Communication
DL	Down-Link
eNB	evolved Node B
FDD	Frequency Division Duplexing
FUE	Femto cellular User Equipment
FMJSF	Fading Memory Joint Strategy Fictitious Play
GA	Genetic Algorithm
HetNets	Heterogeneous Networks
IoT	Internet of Things
ITU	International Telecommunication Union
IPPO	Inverse Popularity Pairing Order
LOS	Line of Sight
LTE	Long-term Evolution
LTE-A	LTE Advanced
MARL	Multi Agent Reinforcement Learning
MBS	Macro Base Station
MDP	Markov Decision Process
MINLP	Mixed-Integer Non-Linear Programming
MIMO	Multi-Input Multi-Output
ML	Machine Learning
M2M	Machine-to-Machine

mm-Wave	millimeter Wave
NP	Non-deterministic Polynomial-time hard
OFDMA	Orthogonal Frequency Division Multiple Access
PDF	Probability Distribution Function
PSO-GA	Particle Swarm Optimization-Genetic Algorithm
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource block
Rx	Receiver
RL	Reinforcement Learning
SA-PC	Spectrum Allocation and Power Control
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference plus Noise Ratio
TD	Time Difference
Tx	Transmitter
UL	Up-Link

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Chapter 1

Introduction

With the exponential development of new mobile Internet networks and the emergence of the Internet of Things (IoT) technology, the mobile wireless communication technologies in current 3GPP and 4G have become increasingly difficult to satisfy the rising demands [1]. Therefore, the new generation of mobile communication services 5G has become the focus of attention around the world. The requirement of the International Telecommunication Union (ITU) of 5G to achieve a leap-forward increase in transmission speed after 2020's, each 5G base station should provide at least 20 Gb/s downlink and 10 Gb/s uplink in transmission bandwidth [2].

The exponential growth of mobile devices number and the massive usage of mobile applications made the data traffic demand in cellular networks increase dramatically. The need to support exponential growth in data traffic as well as the availability of several mobile devices (smartphones, tablets, etc.) is leading to a sharp increase in the number and density of base station devices as well as in their complexity. The spectrum must be efficiently used for supporting ever increasing wireless traffic growth and Quality of Services (QoS) demands from users. Therefore, the future challenge of wireless networks critically depends on the network spectral efficiency and energy efficiency [3]. With the Standardization of the fifth-generation (5G), the need to support this traffic explosion is certainly the main challenge of the next-generation cellular system.

To provide full coverage and increase spectral efficiency, Device-to-Device (D2D) communication as one of the next-generation wireless communication systems (5G) [4], to provide technologies for high data rate transmission systems, is indeed being recognized as important technology components for LTE-Advanced [5, 6]. The basic idea of D2D communication is to allow mobile devices in close proximity to communicate directly [7]. D2D communication is a promising way to enhance performance providing various types of gain: reuse gain, proximity gain, and hop gain. This leads to several advantages: The traffic load on the cellular system is decreased, the coverage is increased, and performance metrics such as throughput, energy consumption, outage probability, and spectral efficiency are improved. However, the introduction of D2D requires revisiting the resource management techniques used to date for traditional cellular systems. D2D communications generate interference to the cellular network if the radio resources are not properly allocated [8]. In addition, multiple D2D pairs sharing the same channel also create mutual interference. Thus, interference management becomes one critical issue for D2D communications underlaying cellular networks [9–11].

Many scenarios of D2D communication have been previously identified [12], according to the type of D2D communication (i.e. one-to-one, one-to-many), the coverage of cellular network (i.e. in coverage, partial coverage, and out of coverage), the area of D2D communication (i.e. same cell, different cell) and the relaying functionality (i.e. capacity enhancement, coverage extending). Regardless of the application scenario, the design of multi-cell D2D-enabled systems [13–15], however, faces many technical challenges comprising mode selection, admission control, interference management, and power control. During my PhD study, we shed the light on the admission control, interference management, and power control, while we tested various spectrum sharing methods depending on which cellular resources are reused for D2D communication (which causes a different interference scenario between cellular users and D2D pairs).

Mobile users and data traffic demand in cellular networks are increasing at an exponential rate. The dense deployment of mobile users improves the spectrum efficiency, but at the same time, additional Macro Base Stations (MBS) are needed to serve those mobile users. However, it is not profitable for operators to installing new infrastructure since the capital expenditure costs are high. In order to reduce the costs, technologies based on small cell base stations are proposed, since small cells reduce the expenditure costs, improve the communication quality of mobile users close to the MBS edge. The integration of small cells in the macrocell network is referred to as a heterogeneous networks (HetNets) [16]. Small cells are deployed by low power nodes which are classified as pico, femto and relay nodes. In addition, to overcome the challenges associated with the concept of femtocell and D2D communications have emerged as promising solutions.

1.1 Motivation

According to the Third Generation Partnership Project (3GPP) considers D2D communication is one of the key roles in future mobile generations due to the fact that the number of connected users is increasing exponentially [17–19]. An increasing number of cellular users produce higher data traffic which finally dominates the current paradigm for cellular networks. In conventional cellular communication, the Cellular Users Equipment (CUEs) have to communicate with each other through the Base Station (BS) or the evolved Node B (eNB). While D2D communication allows direct communication between two devices without relaying data through the BS or eNB as illustrated in Figure (1.1).

Another promising technology that improves the quality of the communication of cellular users is D2D communication. This technology is intended to reduce signalling overhead from cellular users to the BS by allowing direct communication between cellular users. This not only improves network capacity but also increases the user's satisfaction. The expectation comes from the gains that can be achieved by adopting D2D communication in cellular networks. These gains may be listed as: the first one, providing higher data rate due to the proximity of connected devices, the second one, increasing spectral efficiency due to frequency-reuse gain, since the cellular spectrum will be reused within

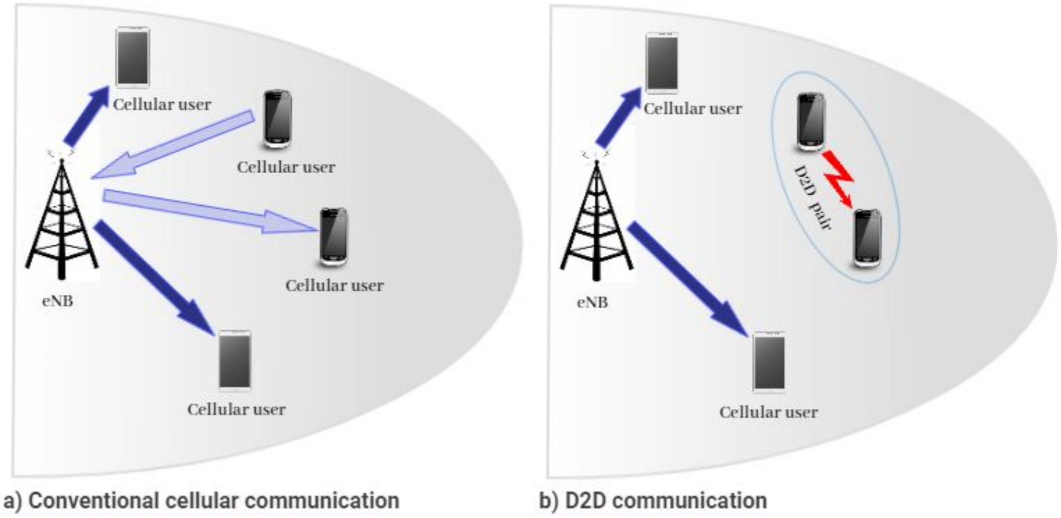


Figure 1.1: Conventional Cellular and D2D Communications

the cell instead than further cells like the case in traditional communication, while the third one, there is a potential of increasing cell coverage of the cellular network by implementing D2D communication.

D2D communication is generally non-transparent to the cellular network and it can occur on the cellular spectrum in licensed (i.e., inband) or unlicensed spectrum (i.e., outband). The inband D2D communication is further divided into underlaying and overlaying D2D communication in terms of dedication of the spectrum. In underlaying D2D, cellular and D2D communications share the same radio resources. The D2D communication underlying cellular network has recently attracted attention as it provides significant benefits to the network in terms of spectral efficiency while generating additional interference because the resources are not orthogonal. Conversely, in overlaying D2D, dedicated cellular resources are given for cellular and D2D communications. Advanced interference management techniques need to be proposed in order to efficiently allocate resources to the cellular and D2D users [20].

The motivation for D2D comes directly from the user requirements and D2D communications will provide specific future needs. These needs include new types of short-range services and data-intensive short-range applications. The emergence of context-aware and multimedia applications has constituted the motivation for using D2D communications, which will allow new types of various services such as video streaming, file-sharing, online gaming, and multimedia downloading. Compared to the conventional cellular networks, defiance such as mode selection, resource allocation, power control, and interference management are needed to be studied carefully, in order to achieve performance gain in a cellular network.

The deployment of D2D communications in a multi-cell cellular network environment encounters a wide range of technical challenges that need to be addressed [21]. Among them, the first challenge is the intra-cell interferences that exist in the presence of concurrent transmissions of DUEs and CUEs in the same cell, which can lead to mutual interference when the CUEs' allocated resources are reused by DUEs. The second challenge is the interference between different DUEs that arises due to the sharing of the same resources. The third crucial challenge that has been less explored is the inter-cell interferences wherein requirements are coordinated among multiple cells in addition to CUEs and DUEs. All of these interferences greatly impact the performance of cellular networks; therefore, they require careful consideration while formulating the problem of joint resource and power allocation [22].

To provide full coverage and increase spectral efficiency, LTE-A also allows employing femtocell and Device to Device (D2D) communications. Femtocells provide higher capacity and better indoor coverage to cellular networks. However, some issues need to be well addressed, as the use of reused or dedicated spectrum allocation. When using femtocells two-tier networks have to be taken into consideration, macrocell and femtocell. Therefore, there is a need for interference mitigation between the two tiers. Also, a dense deployment of femtocells affects interference management. On another side, D2D communications can increase spectral efficiency, reduce power consumption, and improve system performance. To accomplish this, resource allocation problems and the interference caused by D2D communication to macrocellular users should be covered [23–25].

1.2 Research Objectives

The main goal of my Ph.D research is to develop new techniques and algorithms for resource allocation in the D2D communications underlaying of the cellular network. The objective of these techniques and algorithms is to improve spectral efficiency, interference reduction, and fairness between different categories of users. Finally, the problems to be solved with this research are listed below:

Q1). How to maximize the throughput and minimize the power consumption, as well as minimize of interference level of D2D communications in a multi-cell environment?

Q2). If D2D communication is evident for meeting high throughput requirements in future networks, how can enhance spectral efficiency as well in D2D communication in HetNets?

Q3). How to deal with inter-cell interference and intra-cell interference, reduce the interference between DUEs of D2D communications, and how to limit the transmit power of each D2D pairs?

Q4). Due to combinatorial characteristics, it is challenging to obtain an optimal strategy for the joint resource allocation issue. So, How to deal with Reinforcement Learning (RL) to achieve the maximum long-term overall throughput of the network while guaranteeing the QoS requirements for both CUEs and DUEs in D2D communications underlaying cellular networks?

Q5). How to develop new techniques and algorithms for resource allocation of D2D Communication in Heterogeneous Cellular Network that comprise of integrating femtocells and D2D communications underlaying the cellular network, and how to motivate femtocell users and D2D users to cooperate in order to achieve a common benefit?

1.3 Contributions

Our research aims at minimizing the interference while satisfying the system sum-rate requirement in the process. We formulate the optimization problem as either maximizing the system sum-rate problem or minimizing the interference. Nevertheless, the resource allocation needs to satisfy the QoS constraints associated with the sufferers from the interference.

The main contributions of this research can be summarized as follows:

1.3.1 Resource Allocation for D2D Communications of Uplink Multi-Cell Networks

We propose a resource allocation scheme designed to address the intra-cell interference and inter-cell interference management issues for the uplink multi-cell network to enhance the performance of the D2D communications and the spectral efficiency in the network system. We formulate the optimization problem which aims at maximizing the overall network throughput while guaranteeing the QoS requirement for both CUEs and DUEs. Nevertheless, the optimization problem cannot be solved directly, due to the coupled relationship between resource allocation and power control scheme. Rather than using the conventional joint optimization approach with high computational complexity, we solve the overall throughput optimization problem by splitting the original problem into two sub-problems; QoS aware admission control for DUEs and optimal power allocation issue based on dual Lagrangian approach. We propose an optimal resource allocation algorithm for D2D communications underlaying cellular networks. The following paper has been published based on this work:

- A. Saied and D. Qiu, "Resource allocation for Device-to-Device (D2D) communications of uplink Multi-Cell networks," in 2020 International Symposium on Networks, Computers and Communications (ISNCC): Smart Communications Systems (ISNCC-2020 SCS), (Montreal, Canada), October 2020 [26].

1.3.2 Resource Management Based on Reinforcement Learning for D2D Communication in Cellular Network

Introduces the system model of D2D environments, therefore, how to determine the communication mode whether it is cellular, dedicated or reuse mode. We formulate a joint resource allocation (resource block (RB) assignment, mode selection, and transmits power control) issue with considering the QoS requirements, to maximize the throughput of the overall network in D2D communications. Then, the resource management problem is modelled as the Reinforcement Learning (RL) framework, thus D2D links are able to make their adaptive decisions intelligently to improve their performance based on instant observations in D2D environments. The following article has been published with respect to this work:

- A. Saied, D. Qiu, and M. Swessi, "Resource management based on reinforcement learning for D2D communication in cellular networks," in 2020 International Symposium on Networks, Computers and Communications (ISNCC): Smart Communications Systems (ISNCC-2020 SCS), (Montreal, Canada), October 2020 [27].

1.3.3 Recourse Allocation of D2D Communication in Multi-cells Networks System

Adapting the transmit power of the DUEs, to limit the interference caused to the cellular and other DUEs receivers will allow more DUEs to reuse the same resources simultaneously, which translates to higher spectrum efficiency and higher network throughput. The following article has been submitted with respect to this work:

- A. Saied and D. Qiu, "Recourse Allocation of Device-to-Device (D2D) Communication in Multi-cells Networks System," IEEE Wireless Communications Letters (WCL) (2021) (Submitted).

1.3.4 An Efficient Resource Allocation for D2D Communications Underlaying in HetNets

D2D communication and femtocell are introduced as underlays to the cellular systems by reusing the cellular channels to maximize the overall throughput in the network is a significant challenge. In this section, the problem is formulated to maximize the network throughput under the QoS constraints for CUEs, DUEs and FUEs. This problem is a mixed-integer non-linear problem that is difficult to be solved directly. To solve this problem, we propose a joint channel selection, power control, and resource allocation scheme to maximize the sum rate of the cellular network system. The following article has been submitted with respect to this work:

- A. Saied, A. Okaf, and D. Qiu, "An Efficient Resource Allocation for D2D Communications Underlaying in HetNets." 2021 International Symposium on Networks, Computers and Communications (ISNCC). IEEE, 2021. **(Status: Accepted and will be presented in June 2021)**.

1.4 Thesis Organization

The rest of this thesis is organized as follows:

- **Chapter 2** the relevant background of D2D communications is introduced. Then, presents the literature review and state-of-art work in D2D communications.

- **Chapter 3** formulated the optimization problem of a multi-cell D2D underlay network and presents the algorithm for optima resource allocation is proposed and analyzed.

- **Chapter 4** we model the resource management problem as MDP and the AC learning methodology is embraced to solve the optimization problem of D2D communications in cellular networks.

- **Chapter 5** we proposed a resource allocation algorithm designed to allow multiple DUEs to reuse the same CUE channel for D2D communications underlaying multi-cell cellular networks with the consideration of the inter-cell and intra-cell interferences.
- **Chapter 6** D2D communication and femtocell are introduced as underlays to the cellular systems by reusing the cellular channels to maximize the overall throughput in the network is a significant challenge. The problem is formulated to maximize the network throughput under the QoS constraints for CUEs, DUEs and FUEs. We proposed a joint channel selection, power control, and resource allocation scheme to maximize the sum rate of the cellular network system.
- **Chapter 7** the conclusions of this thesis are provided and followed by the potential directions of the research in the future.

Chapter 2

Preliminaries and Background of D2D Communications

In these days, the growing popularity of mobile devices (e.g., smart devices and tablets), short-range wireless communications play important roles in fast data sharing, social discovery, proximity-based services, coverage extension, traffic offloading, and public safety [6, 10, 28]. To provide full coverage and increase spectral efficiency, Device-to-Device (D2D) communication as one of the next-generation wireless communication systems (5G), to provide technologies for high data rate transmission systems, is indeed being recognized as important technology components for LTE-Advanced [5]. The basic idea of D2D communication is to allow mobile devices in close proximity to communicate directly [9]. D2D communication is a promising way to enhance performance providing various types of gain: reuse gain, proximity gain, and hop gain. This leads to several advantages: The traffic load on the cellular system is decreased, the coverage is increased, and performance metrics such as throughput, energy consumption, outage probability, and spectral efficiency are improved.

2.1 D2D Communication Technology

The conception of device-to-device (D2D) communication recently has been introduced to allow direct link among mobile devices to transmit the data without transmitting it through the Base Station (BS) or evolved Node B (eNB). In other words, the eNB does not require to relay data between two proximate mobile users who are communicating with each other. D2D can provide system capacity benefits, and improve spectral efficiency, however, spectrum sharing leads to interference problems between D2D communication and cellular networks. Hence, a certain level of Quality-of-Service (QoS) will be guaranteed if an effective interference coordination scheme is applied. Figure (2.1) shows the evolution of a traditional cellular network path and a D2D communication path.

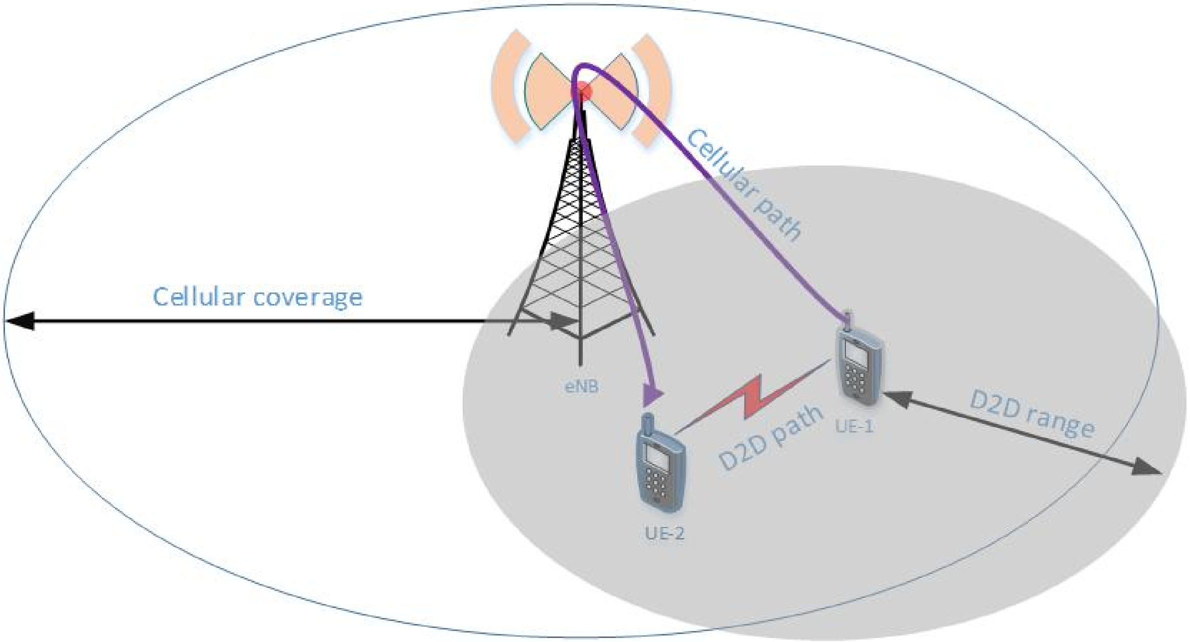


Figure 2.1: Traditional cellular network path and a D2D communication path.

Smart mobile devices have increased the possibility of deploying a D2D network that can perform direct communication between mobile users. Other benefits can be obtained when some popular data can be shared among small subgroup users in close proximity by the cellular provider which lets the D2D communication relay this information to other subscribers. The well-known traditional D2D technologies such as Wi-Fi and Bluetooth work on the unlicensed band 2.4GHz. So far, wireless operators have not standardized the D2D function as the universal cellular network standards. But this technology could be far more useful, many of the new trend services depend on the user location. Another useful approach is the machine-to-machine (M2M) system. The cellular phone of the devices' owner can be their core and make as the access to the wireless networks, e.g. washing machines, central heating and ovens. Due to these all-new applications, the wireless operator's position towards the D2D mode is changing [29].

Up to now, most research works on D2D communications have focused on resource allocation between the cellular users and D2D communication users and if it should be a centralized scheme or distributed scheme via the eNB, and how to make scheduling for it. Most of the literature assumes centralized resource allocation schemes. Concerning D2D communications, spectrum sharing is one of the main issues considered to improve spectral efficiency [30, 31]. Also, the interference mitigation is studied in [32].

2.1.1 Configuration of D2D Communication

D2D communication can be configured in three scenarios [33]:

1. **Network controlled D2D communication.** The base station fully controls D2D communication and cellular users in this scenario (e.g. resources management, the control signal, and establishing or release the connection). The centralized control results in efficient interference management and resource allocation. However, this configuration also causes high signalling overhead, specifically when the number of D2D pairs becomes large, and spectral efficiency is reduced.

2. **Autonomous D2D communication.** This scenario is similar to cognitive radio in which BS has no control over D2D users. Instead, D2D users leverage empty holes in the spectrum and sense a surrounding environment for obtaining channel state information (CSI), interference, and cellular user information. Although this method can successfully avoid signalling overhead and time delay, communication security can be a potential issue. This configuration also causes unstable communication due to a lack of control.

3. Network assisted D2D communication. In this scenario, the BS supports D2D communication by controlling the signal and discovering or establishing the connection. Then, D2D users communicate in a self-organizing way, which reduces signal overhead.

2.1.2 Classification of D2D Communication

D2D communication is classified according to the used spectrum. It can be done under a licensed spectrum, which is called inband D2D, and under an unlicensed spectrum, named outband D2D as illustrated in figure (2.2). Inband D2D is further divided into Underlay and Overlay D2D [20]. In underlay D2D, the users of the cellular and D2D communications share the same radio resources. Conversely, in overlay D2D, dedicated cellular resources are given for both cellular and D2D communications.

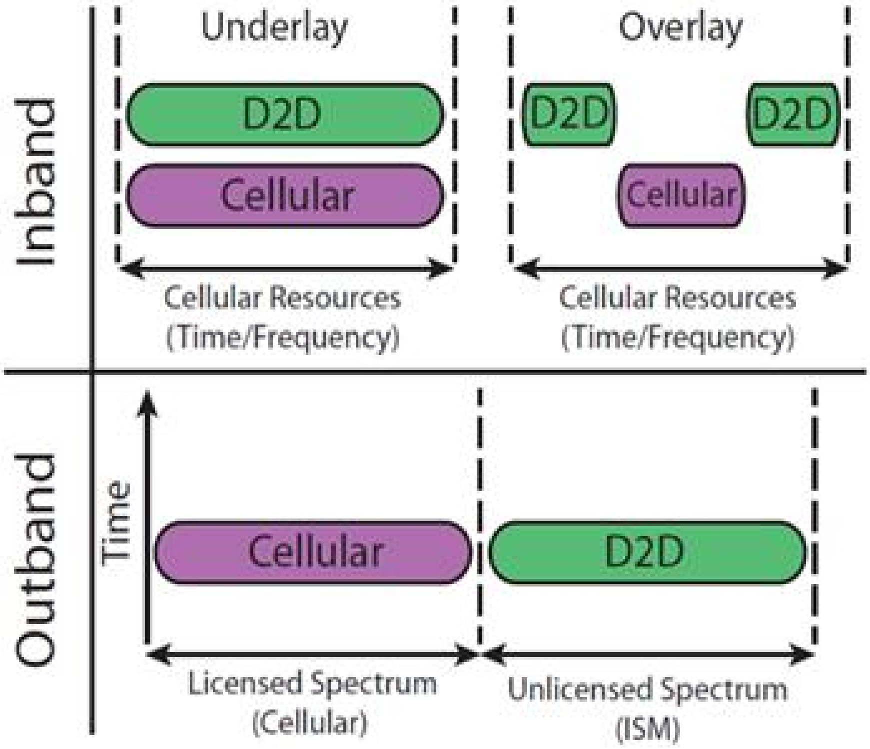


Figure 2.2: Spectrum resource for D2D communications.

In fact, the majority of the literature focuses on a cellular network with underlaying D2D communication. However, underlaying D2D communication presents further interference to cellular users which calls for harmful interference. Certainly, there is an abundance of solutions to alleviate the interference from cellular users to D2D communication by using mode selection (e.g. cellular or D2D mode), resources allocation and scheduling methods [34].

2.1.3 Advantage of D2D Communication

Integrating D2D communication into the cellular network system offers many advantages as follows [10, 12, 35]:

- Since the connected devices pair are super close to each other, high data rates will be realized.
- Low end-to-end delay (Latency) and low energy consumption.
- Multiple D2D direct link transmissions are allowed via spatial reuse of resources which leads to increased spectral efficiency of the system.
- Offloading cellular traffic, alleviating congestion, enhancing cellular network capacity and better load balancing will be provided when direct path transmission is used. In other words, one-time slot instead of two-time slots as in cellular network.
- It can extend the cell coverage area.
- Create new applications.

2.1.4 Challenges in D2D Communication

Despite these advantages, D2D communication introduces technical challenges for network design including the following:

1. Peer discovery.

Peer discovery is required before two cellular users can set up a D2D communication and start a direct link. The peer discovery phase of D2D can be categorized into centralized and distributed. In the centralized approach, a certain entity from the cellular network side detects that is possible to establish a D2D communication between two cellular users, then a D2D communication is established if it increases the cellular system throughput [9]. In the distributed approach, cellular users are periodically broadcasting their identities, and so, the remaining cellular users will be aware of its existence, and the D2D communication is realized without notifying the eNB.

2. Mode Selection for D2D Communication.

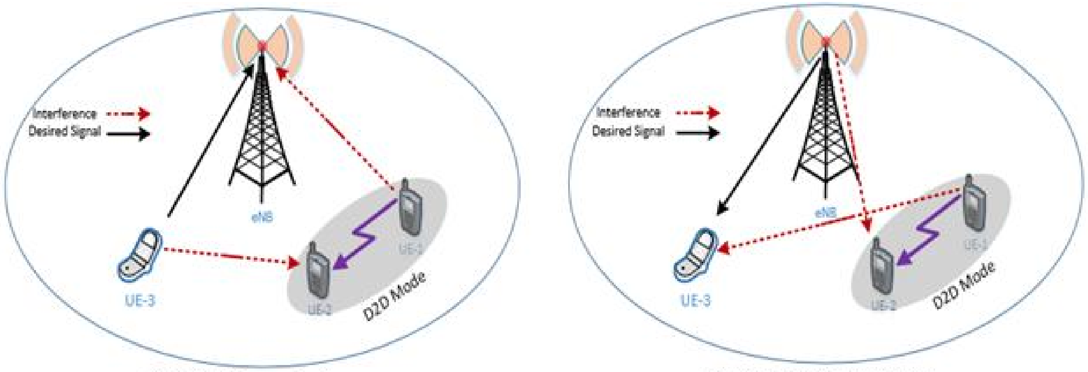
One important issue on D2D communication is the mode that devices use to communicate between them since a suitable communication mode increases the throughput. In [30] modes of D2D communications are categorized as following:

- **Reuse mode:** D2D devices reuse some resources of the cellular network, thus the transmission is direct.
- **Dedicated mode:** D2D devices directly transmit by using dedicated resources.
- **Cellular mode:** D2D traffic passes through the BS.

Accordingly, reuse mode improves the spectrum efficiency, dedicated mode and cellular mode reduce the complexity of interference management. Furthermore, D2D communications increase the overall throughput in cellular networks compared to D2D communication on cellular mode, that is the traditional communication between a cellular user and the BS.

3. Interference Management of D2D Communications.

One of the most important challenges in a wireless network system is the management and coordination of interference. The mobile users working on uplink and downlink transmissions increase the cross-tier interference and co-tier interference. Specifically, for uplink transmissions, there is interference from the cellular user to the D2D-pair receiver if it reuses the same resource and interference from the D2D-pair transmitter to eNB. For downlink transmissions, the interference signals are caused from eNB to D2D-pair receiver and interference from D2D-pair transmitter to the cellular user. Therefore, the complexity of managing the interference increases with the number of users deployed in the cellular network and reuse the same resource of the cellular user. These interference signals are shown in figure (2.3).



(a) Uplink Communication

(b) Downlink Communication

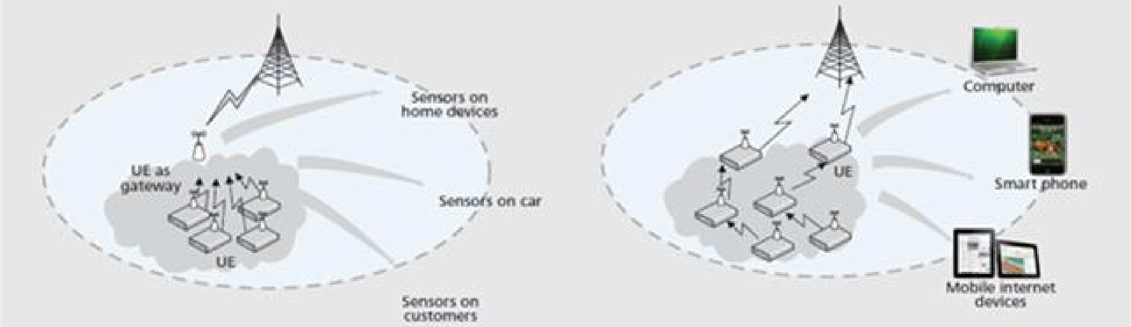
Figure 2.3: Uplink and downlink interference signals in a D2D communication and cellular scenario.

2.1.5 Usage Cases of D2D Communications

In the literature, the usage cases of D2D in LTE networks have been studied [29]. Figure (2.4) provides a summary of the information of different usage cases of D2D communication. Differentiation categories have been considered to classify all the usage cases: The first category is a peer-to-peer case, in which the source and destination of the data are D2D devices (e.g. local voice server and local data service). The second category is when the device is used as a relay to eNB, which means that the relay exchanges data with eNB and then forwards it to the final destination device (e.g. User Equipment (UE) as the gateway to the sensor networks and UE cooperative relay).

(a) Local voice service

(b) Local data service



(c) UE as a gateway to sensor networks

(d) UE cooperative relay

Figure 2.4: D2D use cases.

2.2 Elements of D2D resource management

This section discusses the different elements of D2D resource management. Resources are entities that are used to perform such functions. Figure (2.5) shows some of the main factors of resource management in D2D communication. These elements are clarified as follows:

1. Mode Selection: In D2D communication, users are allocated different modes. Mode options include cellular mode or D2D mode. In D2D communication further options may be overlay or underlay. Users are assigned optimum modes such that the overall sum rate gets maximized. If a variable representing a particular mode is selected, its binary

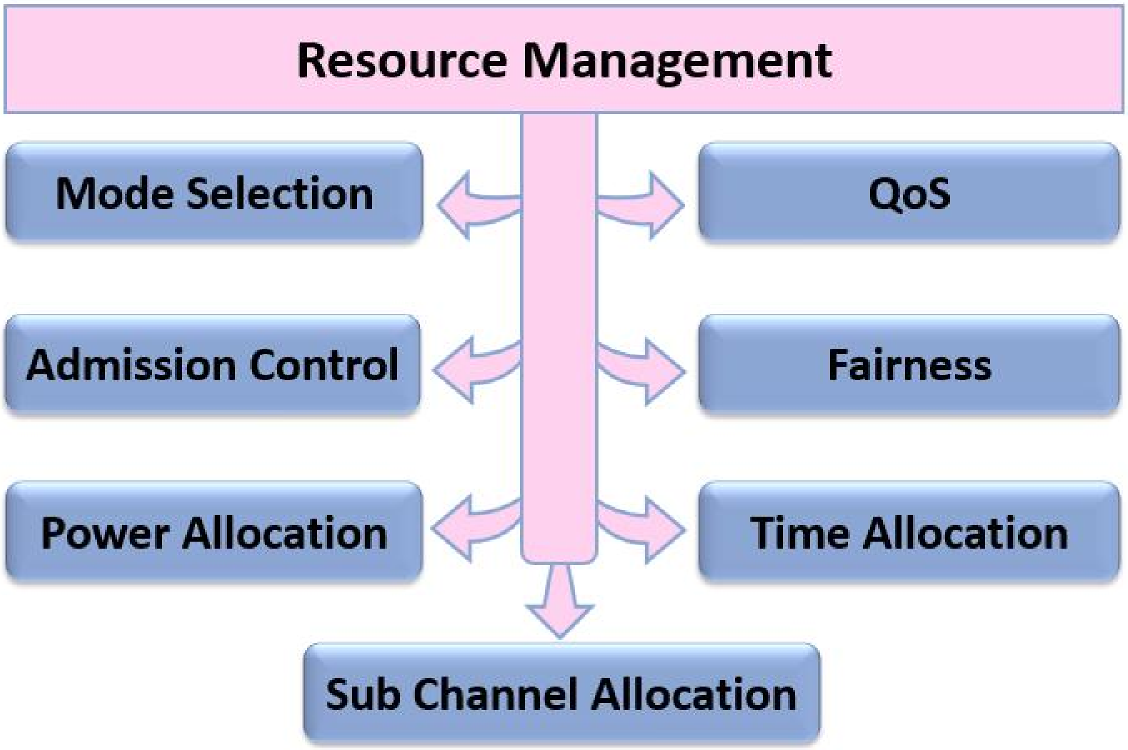


Figure 2.5: Elements of D2D resource management.

value becomes zero otherwise one. Hence, mode selection variables are integer or binary variables.

2. Admission Control: Due to limited resources and interference and other QoS constraints, optimal user admission (whether a particular user is authorized to communicate) control scheme can definitely enhance our objective i.e., enhance system sum rate.

3. Power Allocation: Users are allocated power level falling within an admissible range to have optimal performance and higher data rate at the same time. Power allocation is a continuous variable scheme.

4. QoS or rate constraints: Some times users are required to meet a certain minimum threshold of a data rate which constitutes a constraint. QoS can be generalized and be specific to user requirements for different user satisfaction parameters. It may comprise of rate needs, loss of sum rate, responsiveness, probabilities of outage and blockage. The main objectives of QoS include ensuring threshold rate, reduction in packet losses, improvement in latency and minimization of jitter.

5. Sub-Carrier Allocation: In underlay D2D communication cellular frequency subcarrier are to be allocated or shared by D2D pairs. The question of which resource is to be allocated to which D2D pair, is of paramount importance. Efficient spectrum utilization and throughput enhancement depend upon optimal sub-carrier allocation.

6. Fairness: All resources are to be shared by all users with fairness.

7. Time Allocation: All users are to be allocated appropriate time for communication commensurate with their requirements.

2.3 Related Works

In the following, we discuss some works related to the work presented here, with emphasis on those investigating spectrum efficiencies of D2D communications in cellular networks.

Recently, a lot of research works have been proposed for managing the resource allocation of D2D communications under the required quality of services (QoS) constraints. In [36], a resource allocation strategy for D2D communications was proposed to maximize the overall network uplink throughput within a single cell. A joint admission control and resource allocation scheme was proposed in [37] to aim at providing a lasting Quality of service (QoS) support to both DUEs and CUEs in the network. A resource allocation scheme for D2D communications was suggested to maximize the overall uplink network throughput in multi-cell networks is proposed in [38]. In [39], the resource allocation issue for D2D communications underlaying in multi-cell networks was investigated considering the problem of all interferences. The problem is formulated to maximize the network throughput under the QoS constraints for CUEs and DUEs.

In fact, the majority of the literature has focused on a cellular network with underlaying D2D communication. However, underlaying D2D communication presents additional interference to contemporary cellular users (CUs) in a cellular network system if not coordinated well [40]. Therefore, how to manage the interference is one of the important issues of cellular networks when the DUEs and CUEs coexist within the network. There are a set of solutions to alleviate the interference from D2D communication to cellular users by mode selection (e.g., cellular or D2D mode), resource allocation, and scheduling techniques [20, 30, 41, 42].

Allowing D2D links usage of uplink resources might also enhance resource utilization. The main drawback is that when DUEs share downlink resources, the base stations (BSs) become strong interferers to DUE receivers, and DUE transmitters could result in elevated interference to adjacent co-channel cellular CUEs, which may substantially worse the network performance. Unlike downlink resources, when DUE links use uplink resources, the interference from DUE to cellular transmissions can be better dealt with because the base stations are more robust than CUEs that suffer from DUE interference. consequently, sharing the uplink spectrum is generally favoured [17].

Resource allocation is a decisive issue in D2D communications, which is used to enhance spectrum efficiency, system capacity, and fairness among users [43–46]. Recently, a lot of research has been conducted to embrace different traditional optimization techniques to address the resource allocation issue in different application scenarios. In [36], a resource allocation strategy for D2D communications was proposed to maximize the overall network uplink throughput within a single cell. Therefore, they divided the algorithm scheme into three stages: admission control for D2D users, optimal power control; and adopting the maximum weighted matching to find the best candidates for reuse. However, it assumes a single cell and ignores the inter-cell interference and uses only one channel. Two resource allocation systems, based on PSO (Particle Swarm Optimization) and hybrid PSO-GA (Genetic Algorithm), have been proposed in [47] to optimize the system efficiency by permitting the block resource (RB) of CUE to share with at most two DUEs. In [37], a joint admission control and resource allocation scheme was proposed to aim at providing a lasting Quality of service (QoS) support to both DUEs and CUEs in the network.

2.3.1 Power Control

Controlling transmission power is yet another approach for improving spectral efficiency in cellular networks. For this solution, power control algorithms must be implemented to restrict interference among various network tiers and to reduce overall power consumption.

In [48,49] derived the optimal transmission power of D2D communication that maximizes the energy efficiency in a scenario in which D2D and cellular users share the channel. The maximization of energy efficiency was carried out by taking into account constraints related to D2D transmission rate, transmission power, and successful transmission probability of both the D2D and the cellular networks. In [50] proposed an algorithm to find the optimum D2D transmit power that maximizes the system throughput in a D2D underlay network. The authors consider power and signal-to-noise ratio (SNR) constraints of both D2D and cellular networks. In [51] obtained the optimum D2D user density and transmit power that maximizes D2D capacity under constraints related to cellular successful transmission probability. Optimal power allocation of D2D over multiple resource blocks (RBs) was presented in [52] to maximize the D2D rate and overall rate. The authors considered assigning multiple RBs from different CUEs for each D2D pair under the assumption of orthogonal RB assignments among D2D pairs. The asymptotic power solution for sum-rate maximization was obtained using convex optimization.

2.3.2 Resources Allocation

The process of determining the best way to use available resources in the completion of a given project is referred to as resource allocation. These resources are distributed in a way that helps to reduce costs while maximizing income, typically through the use of strategic planning approaches and the implementation of policies and procedures. The resource allocation technique decides the specific time and frequency resources should be allocated to each D2D user and cellular user. Efficient resource allocation of D2D communications plays a crucial role in reducing CUEs interference levels in UL reuse [53].

A resource allocation scheme was proposed in [54]. Therefore, more than one cellular user in the system. One D2D pair can reuse the resources of more than one cellular user. The proposed method can increase the data rate of D2D communication and the spectrum efficiency by giving priority to the cellular user. In [55], the greedy heuristic algorithm was proposed to utilizing channel gain information for spectrum reuse, which improved network performance in terms of cell and D2D throughput. Authors in [56, 57] applied the game theory of resource allocation for D2D communication to optimize the system sum rate of all users. In particular, a sequential, second-price auction was introduced as an allocation method in [56], and an allocation scheme based on a reverse iterative combinatorial auction was later proposed in [57]. Both solutions allowed multiple D2D to share a single cellular resource. In [58], the interference-limited area control and partial frequency reuse methods were first implemented to restrict mutual interference under a certain threshold. Then, D2D pair resources were selected to improve the overall throughput of the cellular network.

2.3.3 Joint Resources and Power Allocation

The joint resource and power allocation optimization problem have been studied with an aim to improve throughput and energy efficiency. An iterative resource and power algorithm were proposed in [59] to maximize the D2D sum rate subject to rate requirements for CUEs. In [60], the authors modelled interference relationships among various CUEs and D2D links using an interference graph with unique attributes. Based on this interference model, power and resources algorithm was presented for maximizing cellular network throughput. Joint resource and power allocation were studied in [61]. Imperfect Channel State Information (CSI) was included in both the objective function and the constraints. Researchers formulated a nominal optimization problem to improve the sum rate of the D2D system while guaranteeing QoS for CUEs.

2.3.4 Mode Selection of D2D Communication

One of the most challenging problems in the D2D underlay communication system is to decide whether communicating users should use cellular or direct communication mode by using dedicated or shared resources. Mode selection algorithms determine whether D2D users in the proximity of each other should communicate in direct mode using the D2D communication or in the cellular traditional mode. Mode selection is the problem of choosing whether two users should communicate through a direct link, using dedicated or shared resources, instead than through the base station [42, 62, 63].

The key criterion for determining the optimality of mode selection schemes is the output metric to optimize: transmit power, sum rate, energy consumption and system capacity on one side, and the state information available when making the decision such as physical distance, channel efficiency and interference level on the other side. The path loss, which is directly related to the physical distance between the nodes, is the basis for a decision in the simplest and more intuitive mode selection approaches. In [64] the mode selection method for D2D underlay communications considered and denotes path loss-based selection. Just two modes are considered in path loss-based selection: non-orthogonal resource sharing and cellular mode. Non-orthogonal resource sharing is used if the path loss between the D2D pair is less than the minimum of the path losses between the D2D users and the base station. Otherwise, a cellular mode is employed. In [65] a mode selection approach based on distance threshold criteria for all D2D users, therefore the D2D mode is selected if the path loss of the users forming the D2D pair is smaller than a given distance threshold.

2.3.5 Resource Allocation Based on Reinforcement Learning of D2D Communications

Reinforcement Learning (RL) is an advanced Machine Learning (ML) algorithm for decision-making and strategy control, which has been commonly adopted in wireless networks [66, 67]. Recently, a lot of research has been conducted to adopt RL to address resource management in D2D communication [62, 68–72]. In [68], the algorithm was proposed uses a distributed Q-learning based joint SA-PC algorithm for performing resource allocation and power control for each D2D pair. In [69], two MARL-based algorithms have been proposed for performing power control of D2D pair: centralized Q-learning algorithm and distributed Q-learning algorithm. In [70], the Q-learning based resource allocation was proposed when the CUEs and DUEs users sharing the same resources by Q-learning based policy to maximize the overall throughput of the network. A distributed Q-learning based spectrum allocation scheme has been proposed in [71], where D2D users are agents to learn the environment and select resource blocks (RBs) autonomously while mitigating the interference to the CUEs and maximizing the network throughput. In [62], a mode selection scheme that decides whether two users in proximity should communicate using D2D mode or a cellular mode has been modelling as a Markov process. It then investigated the impact of path-loss measurement errors on the maximum effective capacity of a D2D link for both overlay and underlay scenarios. Fading Memory Joint Strategy Fictitious Play (FMJSFP)-based partially distributed coupled algorithms are proposed in [72] to attain the resource allocation that maximizes the sum-rate of the D2D environment.

2.3.6 D2D Communications in HetNets

Cellular network operators face several problems, such as poor coverage that users experience when they are in indoor locations, optimal use of the resources and low data rates. These problems soon will make the cellular network unable to support mobile users' demands. Home base stations, specifically femtocells, provide a good solution for indoor coverage problems as they allow mobile users to access the cellular network through a femtocell. Furthermore, spectrum efficiency increases, since more mobile users are served through femtocells [73–77]. The backhaul connection from femtocells towards the core network benefits cell-edge mobile users. In this sense, mobile users reduce their energy consumption, increase their data rates; and even cross-tier interference is reduced [78,79].

Femtocells are home base stations that aim to improve cellular network capacity, by allowing cellular users far from the Macro Base Station (MBS) to connect to the cellular network through the nearest Femto Base Station (FBS) [16]. Accordingly, femtocell users will be able to achieve better indoor coverage and higher data rates. However, the integration of femtocells in the macrocell network will change the basic cellular network scenario, since, the resources are not only for macro users, they have to be also allocated to the new Femto users. Furthermore, the two-tier network, namely macro layer and Femto layer, creates new challenges in the Femto- macrocell scenarios, as it brings interference when several nodes use the same frequency band.

Resource allocation for D2D communications in HetNets have been studied in [80–85], In [80], a D2D feasible set was defined and derived, where a region is provided to share network resources among communication links. In [81] The Heuristic resource allocation algorithm is proposed in HetNets, which is composed of macrocells, small cells, and D2D communications to achieve the goal of maximizing system throughput. Joint mode selection and power control in D2D-enabled heterogeneous cellular networks were proposed in [82], the authors researched to identify the interference-limited area of every effective cellular user. In [83] a non-cooperative game and Stackelberg game are used to model the femtocells as selfish nodes, where the MBS protects itself by pricing subchannels. The authors aim to minimize the interference caused when femtocell users and macrocell users share the spectrum. Furthermore, in [84], a Stackelberg game is formulated to obtain the transmission strategies of the cellular and D2D users; where the cellular users act as leaders and own the channel and D2D users are the followers, which need to pay some fees for accessing the channel. In [85], non-cooperative game and auction game models are proposed to solve the resource allocation in D2D communications.

Chapter 3

Resource Allocation for Device-to-Device (D2D) Communications of Uplink Multi-Cell Networks

3.1 Introduction

Mobile users and data traffic demand in cellular networks are increasing at an exponential rate. Device-to-Device (D2D) communication as one of the next-generation wireless communication systems (5G), to provide technologies for high data rate transmission systems, is indeed being recognized as an important technology component for LTE-Advanced. D2D enables two user equipment (UEs) in the proximity of each other to communicate directly without relaying data through the base station (BS) or enhanced-Node B (eNB), and it is an underlay to the existing cellular network for improving performance including the spectral utilization, Quality-of-Service (QoS), higher data rates, energy and spectrum efficiency, network capacity and availability of service as well as a more efficient network load [9–12, 29, 33, 86, 87].

The D2D communications in a multi-cell cellular network system are faced with a wide variety of technical issues that need to be addressed [21]. Among them, the first challenge is the intra-cell interferences that between DUEs and CUEs in the same cell when the CUEs' allocated resources are reused by DUEs. The second challenge is the interference between different DUEs that arises due to the sharing of the same resources. The third crucial challenge that has been less explored is the inter-cell interferences wherein requirements are coordinated among multiple cells in addition to CUEs and DUEs. All of these interferences have a significant effect on the efficiency of cellular networks and thus require careful consideration in formulating the issue of resource allocation. In this chapter, we consider a multi-cell network with inter-cell interferences and assume D2D communications can be established between two devices located in the same cell or different cells.

The main objectives of this chapter are maximization of throughput and the minimization of power consumption, as well as minimization of interference level in multiple cells environment. The main contributions of this chapter are as follows: We propose a resource allocation scheme designed to address the intra-cell interference and inter-cell interference management issues for the uplink multi-cell network to enhance the performance of the D2D communications and the spectral efficiency in the network system. We formulate the optimization problem which aims at maximizing the overall network throughput while guaranteeing the QoS requirement for both CUEs and DUEs. Nevertheless, the optimization problem cannot be solved directly, due to the coupled relationship between resource allocation and power control scheme. Rather than using the conventional joint optimization approach with high computational complexity, we solve the overall throughput optimization problem by splitting the original problem into two subproblems; QoS aware admission control for DUEs and optimal power allocation issues based on dual Lagrangian approach. then, we propose an optimal resource allocation algorithm for D2D communications underlaying cellular networks.

3.2 System Model and Problem Formulation

3.2.1 System Model

We consider a multi-cell system in which are neighboring base stations communicate with mobile terminals over a coverage area. Figure (3.1) shows the two-cell system model used to describe multi-cell D2D communications underlying cellular networks as the basic concept. There are N subchannels in this network of OFDMA (Orthogonal Frequency Division Multiple Access), and M-DUEs coexist with N-CUEs in the serving eNB. We also assume that all eNBs in the network are identical and have the same bandwidth and that each eNB bandwidth is separated into multiple channels of equivalent bandwidth sizes. In addition, we assume that the cellular network is a fully loaded scenario in which the total quantity of channels allotted for uplink transmission is equal to the number of existed CUEs in each eNB. Besides, we assume that D2D links share uplink (UL) n-th channels $N_C = \{1, 2, ..., N\}$, occupied by cellular users. Let $BS = \{1, 2\}$, $C = \{1, 2, ..., N\}$ and $D = \{1, 2, ..., M\}$ represent the index sets of cells, CUEs/channels and DUEs, respectively. The transmitter of a D2D pair (D2D-Tx) and its receiver (D2D-Rx) are not required to be in the same cell that communicates directly under the control of the serving eNB. The network's frequency reuse is equivalent to one. Hence, the DUEs in serving eNB are victims of interference from CUEs in neighboring eNBs. Also, we assume both CUEs and D2D pairs have their minimum QoS requirements in terms of SINR on an n-th channel, the peer device discovery and the session setup are completed before the resource allocation, and the eNB has the perfect CSI information of all the links.

We further assume both the fast fading due to multi-path propagation and slow fading due to shadowing, in addition to the distance-based pathloss model used in [36]. Therefore, can be expressed the instantaneous channel gain between CUE i and the eNB as:

$$g_{i,b} = \kappa \beta_{i,b} \Gamma_{i,b} \, L_{i,b}^{-\alpha} \tag{3.1}$$

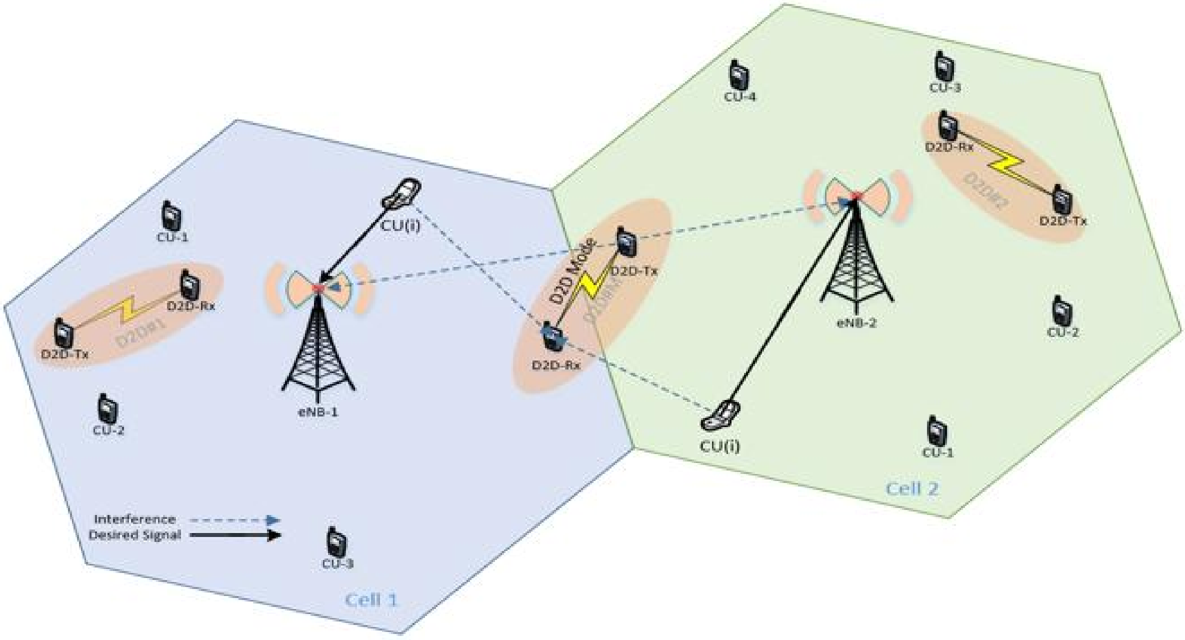


Figure 3.1: System model of D2D communications underlaying cellular networks

To achieve the desired Quality of Service (QoS) levels for CUEs and DUEs, two kinds of interference will be considered while allocating the resources for each DUE. First is the intra-cell interference between CUEs and DUEs that are using the same channels inside the same cell. The second is the inter-cell interference between CUEs and DUEs that are using the same channels but located in different cells.

3.2.2 Problem Formulation

D2D communications may be used to enhance the overall performance of multi-cell cellular networks if it designed properly. A D2D pair is set up only when the minimum SINR requirement can be guaranteed and incurred interference to the CUEs is below a threshold. In this case, we call it an admissible pair and the CUE to be a shared channel as a reuse partner. Our goal is to maximize the total transmission rate of the CUEs and the D2D pairs while satisfying the rate requirements of all CUEs. Mathematically, the overall optimization problem of the network throughput can be formulated as follows:

$$\left.\begin{array}{lr}
\max\limits_{\omega_{i,j},P_j^d} R_{overall} = \sum\limits_{b\in B_S}\sum\limits_{i\in C}\left[\log_2(1+\xi_i^{c,b}) + \sum\limits_{j\in D}\omega_{i,j}\log_2(1+\xi_j^d)\right] & \\
\qquad\qquad Subject\ to: & \\
\xi_i^{c,b} = \dfrac{P_i^{c,b}g_{i,b}}{\sum_{j\in D}\omega_{i,j}P_j^d h_{j,b}+\sigma_N^2} \geq \xi_{i,min}^{c,b}, \qquad \forall i\in C, \forall b\in B_S & (3.2.a) \\
\xi_j^d = \dfrac{P_j^d g_{j,j}}{\sum_{B\in B_S}\sum_{i\in C}\omega_{i,j}P_i^{c,B}h_{i,j}^B+\sigma_N^2} \geq \xi_{j,min}^d, \qquad \forall j\in D & (3.2.b) \\
\qquad \omega_{i,j}\in\{0,1\}, \qquad \forall i\in C, \forall j\in D & (3.2.c) \\
\qquad \sum\limits_j \omega_{i,j}\leq 1,\ \omega_{i,j}\in\{0,1\}, \forall i\in C & (3.2.d) \\
\qquad \sum\limits_i \omega_{i,j}\leq 1,\ \omega_{i,j}\in\{0,1\}, \forall j\in D & (3.2.e) \\
\qquad 0\leq P_i^{c,b}\leq P_{max}^{c,b} \quad \forall i\in C & (3.2.f) \\
\qquad 0\leq P_j^d\leq P_{max}^d \quad \forall j\in D & (3.2.g)
\end{array}\right\} \quad (3.2)$$

Where $\omega_{i,j}$ is the channel reuse indicator for CUE i and D2D pair j, $\omega_{i,j}$=1 when D2D pair j reuses the channel of CUE i; otherwise, $\omega_{i,j}$=0. Constraints $(3.2.a)$ and $(3.2.b)$ represent the QoS requirements of CUEs and DUEs, respectively. The constraint $(3.2.c)$ represents the channel reuse relationship between CUEs and DUEs combined with resource partition model. Constraint $(3.2.d)$ guarantees that CUE′ RB can be shared at most by one DUE. While constraint $(3.2.e)$ indicates that a DUE share at most one existing CUE′ RB. All constraints are used to reduce the complex interference environment caused by D2D communications. Constraints $(3.2.f)$ and $(3.2.g)$ ensure that the power budget of DUE and CUE users are limited to the maximum. All the notations used are given in Table (3.1).

Specifically, a resource allocation optimization problem in (3.2) is formulated as a Mixed-Integer Nonlinear Programming (MINLP) problem under power, spectrum resource reusing and QoS constraints. The formulation derived utilizes a continuous variable to represent power control strategy (how much transmission power should be assigned to D2D transmitter for the potential D2D), and a binary variable to represent the resource allocation decision (which D2D pair can share the same spectrum resource with CUE). To solve the original optimization problem by splitting it into two steps.

Table 3.1: Notations and their Definitions

Notation	***Definitions***
κ	*Constant determined by system parameters.*
$\beta_{i,b}$	*Fast fading gain with exponential distribution.*
$\Gamma_{i,b}$	*Slow fading gain with log-normal distribution.*
$L_{i,b}$	*Distance between CUE i and the eNB b.*
$L_{i,j}$	*Distance between CUE i and the receiver of DUE j.*
α	*Pathless exponent.*
$g_{j,j}$	*Channel gain of D2D pair j.*
$g_{i,b}$	*Channel gain of the Links, from CUE i to the eNB b.*
$h_{j,b}$	*Interference gains of the links, from the transmitter of DUE j to eNB b.*
$h_{i,j}^{B}$	*Interference gains of the links, from CUE i in eNB B to the receiver of D2D pair j.*
σ_N^2	*The energy of the additive white Gaussian noise (AWGN) on each channel.*
$\xi_{i,min}^{c,b}$	*The minimum SINR requirements of CUE i in eNB b.*
$\xi_{j,min}^{d}$	*The minimum SINR requirements of DUE j.*
$\xi_i^{c,b}$	*The SINR of CUE i in eNB b.*
ξ_j^{d}	*The SINR of DUE j.*
$P_{max}^{c,b}$	*The maximum transit power of CUE in eNB b.*
P_{max}^{d}	*The maximum transit power of DUE.*
$P_i^{c,b}$	*Transmit power of CUE i in eNB b.*
P_j^{d}	*Transmit power of DUE j.*

3.3 Optimal Resource Allocation

In this section, we will focus on how to allocate resource reuse among cellular users and D2D users in order to enhance the overall throughput when the introduction of D2D communication. We will solve the overall throughput optimization issue by switch the original one into two subproblems. The first one, how we can find the optima reuse candidate for each DUE with minimum-SINR. Next, the power control for a DUE and its reuse partner, where we allocate transmit power to increase the overall throughput of each user (e.g. CUEs and DUEs), where we find the optimal resource pairing relationship between CUEs and DUEs.

3.3.1 Admission control for D2D pairs

By limiting in the original problem (3.2), a two-cell cellular network is considered. We first need to know whether a DUE pair can be admitted or not. Furthermore, the purpose of this step is to select the initial set of candidate CUEs' channel that can be reused by each DUE. Since the key objective of this chapter is to maximize the overall uplink network throughput taking all the interferences into consideration. If DUE j can reuse the channel of CUE i, those following constraints must be simultaneously satisfied, that are,

$$\left.\begin{array}{ll} \xi_i^{c,b} = \dfrac{P_i^{c,b} g_{i,b}}{P_j^d h_{j,b} + \sigma_N^2} \geq \xi_{i,min}^{c,b}, & \forall i \in C, \forall b \in B_S \\ \xi_j^d = \dfrac{P_j^d g_{j,j}}{\sum_{B \in B_S} \sum_{i \in C} P_i^{c,B} h_{i,j}^B + \sigma_N^2} \geq \xi_{j,min}^d, & \forall j \in D \\ 0 \leq P_i^{c,b} \leq P_{max}^{c,b} \quad \forall i \in C & \\ 0 \leq P_j^d \leq P_{max}^d \quad \forall j \in D & \end{array}\right\} \tag{3.3}$$

The admission constraints in (3.3) can be shown as in Figure (3.2), where lines l_c and l_d represent constraints ($\xi_i^{c,b} \geq \xi_{i,min}^{c,b}$) and ($\xi_j^d \geq \xi_{j,min}^d$) with equality, respectively. The square area as shown in Figure (3.2) indicated the limited power constraints of CUE i and DUE j. Therefore, the area inside the square on the right of line l_d is where the minimum-SINR for DUE j is satisfied, as well as the area above line l_c is where the minimum-SINR of CUE i is satisfied.

To ensure l_c and l_d to have an intersection point, let denoted point A, it should be existing in the first quarter so that all constraints in (3.3) are simultaneously satisfied, to do so, the slope of l_d must be larger than that of l_c.

$$\left.\begin{array}{lll} l_c: & P_i^{c,b} & = \dfrac{h_{j,b} * \xi_{i,min}^{c,b}}{g_{i,b}} P_j^d + \dfrac{\xi_{i,min}^{c,b} * \sigma_N^2}{g_{i,b}} \\ l_d: & P_i^{c,b} & = \dfrac{g_{j,j}}{h_{i,j}^b * \xi_{j,min}^d} P_j^d - \dfrac{\sum_{B \in B_S, B \neq b} \sum_{i \in C} P_i^{c,B} h_{i,j}^B + \sigma_N^2}{h_{i,j}^b} \end{array}\right\} \tag{3.4}$$

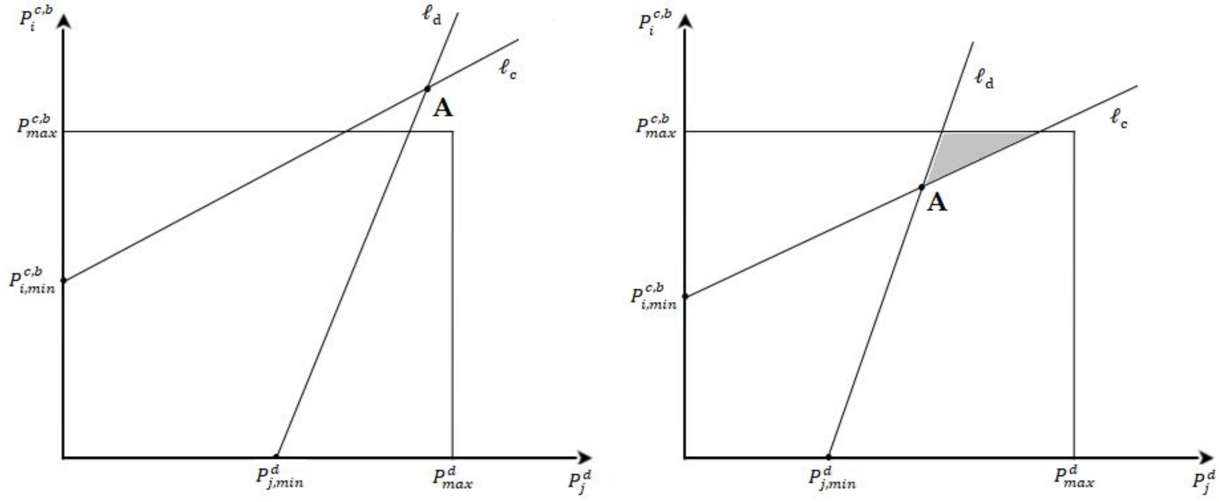


Figure 3.2: Admissible area of D2D communication

If the intersection of l_c and l_d (e.g. point A in Figure (3.2)) is within the square area (e.g. feasible solution range of power allocation), then it is possible to determine the transmit power pair in the admissible region (e.g. CUEs and DUEs), to satisfy all constraints in (3.3). If point A is outside the square area, DUE j is not admissible to reuse the resource of CUE i due to the constraint of maximum power limit.

$$\frac{g_{j,j}}{h_{i,j}^b * \xi_{j,min}^d} > \frac{h_{j,b} * \xi_{i,min}^{c,b}}{g_{i,b}} \tag{3.5}$$

In summary, the admissible conditions to allow CUE i is a reuse candidate of DUE j will be as following:

$$\begin{cases} \xi_i^{c,b} \geq \xi_{i,min}^{c,b} \\ \xi_j^d \geq \xi_{j,min}^d \\ g_{j,j} g_{i,b} - \xi_{i,min}^{c,b} \xi_{j,min}^d h_{i,j}^b h_{j,b} > 0 \end{cases} \tag{3.6}$$

Moreover, when (3.6) holds, the intersection of the two lines, by mapping this intersection into the power domain, a two-cell mobile network is considered, those constraints in (3.3) must be satisfied, that are,

$$\left.\begin{array}{lll} \dfrac{P_i^{c,1} g_{i,1}}{P_j^d h_{j,1} + \sigma_N^2} \geq \xi_{i,min}^{c,1} & & (3.7.a) \\ \dfrac{P_i^{c,2} g_{i,2}}{P_j^d h_{j,2} + \sigma_N^2} \geq \xi_{i,min}^{c,2} & & (3.7.b) \\ \dfrac{P_j^d g_{j,j}}{P_i^{c,1} h_{i,j}^1 + P_i^{c,2} h_{i,j}^2 + \sigma_N^2} \geq \xi_{j,min}^d & & (3.7.c) \\ 0 \leq P_i^{c,1} \leq P_{max}^{c,1} & \forall i \in C & (3.7.d) \\ 0 \leq P_i^{c,2} \leq P_{max}^{c,2} & \forall i \in C & (3.7.e) \\ 0 \leq P_j^d \leq P_{max}^d & \forall j \in D & (3.7.f) \end{array}\right\} \tag{3.7}$$

It means a DUE j will share the resource with a CUE i only if both of the minimum-SINR requirements and power budgets are satisfied. Let D_r denote the set of reuse candidates for DUE j. DUE j is admittable $(j \in D)$ if and only if $D_r \neq \emptyset$. When there is no candidate reuse partner for the DUE j, we have $D_r = \emptyset$, $\omega_{i,j} = 0, \forall i \in C$, and P_j^d is set to zero.

To allow DUE j to share a resource, the DUE's and CUE's powers should be controlled to achieve the constraints (3.7.d)–(3.7.f). Therefore, the minimum permissible power for DUE j, CUE i in the first cell, and CUE i in the second cell to attain the required minimum SINR can be represented as a certain point A with coordinates $(P_{iA}^{c,1}, P_{iA}^{c,2}, P_{jA}^d)$ which can be found through the following set of equations

$$\left.\begin{array}{ll} \dfrac{P_i^{c,1} g_{i,1}}{P_j^d h_{j,1} + \sigma_N^2} \geq \xi_{i,min}^{c,1} & (3.8.a) \\ \dfrac{P_i^{c,2} g_{i,2}}{P_j^d h_{j,2} + \sigma_N^2} \geq \xi_{i,min}^{c,2} & (3.8.b) \\ \dfrac{P_j^d g_{j,j}}{P_i^{c,1} h_{i,j}^1 + P_i^{c,2} h_{i,j}^2 + \sigma_N^2} \geq \xi_{j,min}^d & (3.8.c) \end{array}\right\} \tag{3.8}$$

Therefore, the power of DUE j (P_j^d), the power of CUE i in the first cell $(P_i^{c,1})$, and the power of CUE i in the second cell $(P_i^{c,2})$ at the point A can be calculated as follows:

$$\left.\begin{aligned}
P_{j,A}^{d} &= \frac{\sigma_N^2 * (g_{i,2} h_{i,j}^{1} \xi_{i,min}^{c,1} \xi_{j,min}^{d} + g_{i,1} h_{i,j}^{2} \xi_{i,min}^{c,2} \xi_{j,min}^{d} + g_{i,1} g_{i,2} \xi_{j,min}^{d})}{g_{i,1} g_{i,2} g_{j,j} - g_{i,2} h_{j,1} h_{i,j}^{1} \xi_{i,min}^{c,1} \xi_{j,min}^{d} - g_{i,1} h_{j,2} h_{i,j}^{2} \xi_{i,min}^{c,2} \xi_{j,min}^{d}} && (3.9.a)\\
P_{i,A}^{c,1} &= \left(\frac{\sigma_N^2 * h_{j,1} \xi_{i,min}^{c,1} \xi_{j,min}^{d}}{g_{i,1}} \right.\\
&\qquad \left. * \frac{g_{i,2} h_{i,j}^{1} \xi_{i,min}^{c,1} + g_{i,1} h_{i,j}^{2} \xi_{i,min}^{c,2} + g_{i,1} g_{i,2}}{g_{i,1} g_{i,2} g_{j,j} - g_{i,2} h_{j,1} h_{i,j}^{1} \xi_{i,min}^{c,1} \xi_{j,min}^{d} - g_{i,1} h_{j,2} h_{i,j}^{2} \xi_{i,min}^{c,2} \xi_{j,min}^{d}} \right)\\
&\qquad + \frac{\sigma_N^2 * \xi_{i,min}^{c,1}}{g_{i,1}} && (3.9.b)\\
P_{i,A}^{c,2} &= \left(\frac{\sigma_N^2 * h_{j,2} \xi_{i,min}^{c,2} \xi_{j,min}^{d}}{g_{i,2}} \right.\\
&\qquad \left. * \frac{g_{i,2} h_{i,j}^{1} \xi_{i,min}^{c,1} + g_{i,1} h_{i,j}^{2} \xi_{i,min}^{c,2} + g_{i,1} g_{i,2}}{g_{i,1} g_{i,2} g_{j,j} - g_{i,2} h_{j,1} h_{i,j}^{1} \xi_{i,min}^{c,1} \xi_{j,min}^{d} - g_{i,1} h_{j,2} h_{i,j}^{2} \xi_{i,min}^{c,2} \xi_{j,min}^{d}} \right)\\
&\qquad + \frac{\sigma_N^2 * \xi_{i,min}^{c,2}}{g_{i,2}} && (3.9.c)
\end{aligned}\right\} \quad (3.9)$$

This represents the minimum transmission powers for DUE j and CUE i in the first and second cells that satisfy the minimum SINR-requirements for both CUEs and DUEs. In summary, the admissible conditions will be:

$$
\left.
\begin{aligned}
&0 \le \frac{\sigma_N^2 * (g_{i,2}h_{i,j}^1\xi_{i,min}^{c,1}\xi_{j,min}^d + g_{i,1}h_{i,j}^2\xi_{i,min}^{c,2}\xi_{j,min}^d + g_{i,1}g_{i,2}\xi_{j,min}^d)}{g_{i,1}g_{i,2}g_{j,j} - g_{i,2}h_{j,1}h_{i,j}^1\xi_{i,min}^{c,1}\xi_{j,min}^d - g_{i,1}h_{j,2}h_{i,j}^2\xi_{i,min}^{c,2}\xi_{j,min}^d} \le P_{max}^d \quad (3.10.a)\\
&0 \le \Bigg(\frac{\sigma_N^2 * h_{j,1}\xi_{i,min}^{c,1}\xi_{j,min}^d}{g_{i,1}} \\
&\qquad * \frac{g_{i,2}h_{i,j}^1\xi_{i,min}^{c,1} + g_{i,1}h_{i,j}^2\xi_{i,min}^{c,2} + g_{i,1}g_{i,2}}{g_{i,1}g_{i,2}g_{j,j} - g_{i,2}h_{j,1}h_{i,j}^1\xi_{i,min}^{c,1}\xi_{j,min}^d - g_{i,1}h_{j,2}h_{i,j}^2\xi_{i,min}^{c,2}\xi_{j,min}^d} \Bigg) \\
&\qquad\qquad + \frac{\sigma_N^2 * \xi_{i,min}^{c,1}}{g_{i,1}} \le P_{max}^{c,1} \quad (3.10.b)\\
&0 \le \Bigg(\frac{\sigma_N^2 * h_{j,2}\xi_{i,min}^{c,2}\xi_{j,min}^d}{g_{i,2}} \\
&\qquad * \frac{g_{i,2}h_{i,j}^1\xi_{i,min}^{c,1} + g_{i,1}h_{i,j}^2\xi_{i,min}^{c,2} + g_{i,1}g_{i,2}}{g_{i,1}g_{i,2}g_{j,j} - g_{i,2}h_{j,1}h_{i,j}^1\xi_{i,min}^{c,1}\xi_{j,min}^d - g_{i,1}h_{j,2}h_{i,j}^2\xi_{i,min}^{c,2}\xi_{j,min}^d} \Bigg) \\
&\qquad\qquad + \frac{\sigma_N^2 * \xi_{i,min}^{c,2}}{g_{i,2}} \le P_{max}^{c,2} \quad (3.10.c)
\end{aligned}
\right\} \quad (3.10)
$$

Therefore, the eNB can easily find suitable CUE candidates for a DUE based on the admissible conditions in (3.10). It may be also seen that a DUE with a smaller SINR requirement, $\xi_{j,min}^d$, and bigger D2D channel gain, $g_{j,j}$, will be easier to find a reuse candidate. Similarly, a CUE with a better channel gain, $g_{i,b}$, and a lower SINR requirement, $\xi_{i,min}^{c,b}$, is more likely to be a reuse candidate.

3.3.2 Optimal Power Allocation

In the previous section, we have discussed how to find the optimal reuse candidates for a D2D pair. Thus, from there, we will address the problem of how to assign power for each DUEs and its corresponding CUEs reuse partners so that the sum throughput is maximized while all constraints are satisfied. Therefore, the optimization problem is to find the optimal power in the admissible area for a single D2D pair, which can be expressed as:

$$\left.\begin{array}{c} U\left(P_j^{d*}\right) = \arg \max\limits_{P_j^d \in \Re} \quad \sum\limits_{b\in B_S} \sum\limits_{i\in C} \left[\log_2(1+\xi_i^{c,b}) + \sum\limits_{j\in D} \log_2(1+\xi_j^d) \right] \\ Subject\ to: \\ \xi_i^{c,b} = \dfrac{P_i^{c,b} g_{i,b}}{P_j^d h_{j,b} + \sigma_N^2} \geq \xi_{i,min}^{c,b}, \qquad \forall i \in C, \forall b \in B_S \\ \xi_j^d = \dfrac{P_j^d g_{j,j}}{\sum_{B\in B_S} \sum_{i\in C} P_i^{c,B} h_{i,j}^B + \sigma_N^2} \geq \xi_{j,min}^d, \quad \forall j \in D \\ 0 \leq P_i^{c,b} \leq P_{max}^{c,b} \quad \forall i \in C \\ 0 \leq P_j^d \leq P_{max}^d \quad \forall j \in D \end{array}\right\} \tag{3.11}$$

In this section, we will focus on the D2D power allocation optimization.

1. D2D-Rate Maximization

The total transmit power at the D2D j transmitter is constrained by the maximum transmit power limitation as follows:

$$P_j^d \leq P_{max}^d \qquad \forall j \in D \tag{3.12}$$

This problem is formulated as a constrained optimization problem that maximizing DUE sum-rate as follows:

$$\left.\begin{array}{c} U\left(P_j^{d*}\right) = \arg \max\limits_{P_j^d \in \Re} \quad \sum\limits_{b\in B_S} \sum\limits_{i\in D_r} \sum\limits_{j\in D} \log_2 \left(1 + \dfrac{P_j^d g_{j,j}}{\sum_{B\in B_S} \sum_{i\in C} P_i^{c,B} h_{i,j}^B + \sigma_N^2} \right) \\ Subject\ to: \\ \xi_j^d = \dfrac{P_j^d g_{j,j}}{\tilde{I}_j^d} \geq \xi_{j,min}^d, \ \forall j \in D \qquad (3.13.a) \\ 0 \leq P_j^d \leq P_{max}^d, \qquad \forall j \in D \qquad (3.13.b) \end{array}\right\} \tag{3.13}$$

Where $\tilde{I}_j^d = \sum_{B\in B_S} \sum_{i\in C} P_i^{c,B} h_{i,j}^B + \sigma_N^2$ is the total interference at the receiver of DUE j. We can solve the problem by Lagrangian dual optimization. The Lagrangian function of the above problem is defined as follows:

$$L\left(P_j^d, \vec{\lambda}, \vec{\mu}\right) = \sum_{b \in B_S} \sum_{i \in D_r} \sum_{j \in D} \log_2\left(1 + \frac{P_j^d g_{j,j}}{\tilde{I}_j^d}\right) - \sum_{j \in D} \lambda_j \left(P_j^d g_{j,j} - \tilde{I}_j^d \xi_{j,min}^d\right)$$
$$- \sum_{j \in D} \mu_j \left(P_j^d - P_{max}^d\right) \tag{3.14}$$

Where $\vec{\lambda} = [\lambda_1, \dots \dots \dots, \lambda_k]^T \succeq 0$, and $\vec{\mu} = [\mu_1, \dots \dots \dots, \mu_k]^T \succeq 0$ denote the Lagrange multiplier vectors. By using Karush-Kuhn-Tucker (KKT) conditions [88], the optimal solution of (3.14) can be found to obtain the optimal power allocation. So, for each DUE j, the optimal power can be derived as:

$$P_j^{d*} = \left[\frac{1}{(\lambda_k\, g_{j,j} + \mu_k)\ln 2} - \frac{\tilde{I}_j^d}{g_{j,j}}\right] \tag{3.15}$$

Using the sub-gradient method, the Lagrange multipliers are iteratively updated until convergence as follows:

$$\left.\begin{aligned} \lambda_k^{t+1} &= \lambda_k^t - \alpha\left(\tilde{I}_j^d\, \xi_{j,min}^d - P_j^d\, g_{j,j}\right) \\ \mu_k^{t+1} &= \mu_k^t - \beta\left(P_{max}^d - P_j^d\right) \end{aligned}\right\} \tag{3.16}$$

Let t denotes the update time, α and β are the step sizes for Lagrangian factors update.

2. Sum-Rate Maximization

Note that the sum-rate of cellular users over RBs in cellular mode, prior to the D2D pair entering the system, is given by:

$$R = \sum_{i \in C} \log_2\left(1 + \frac{P_i^{c,b}\, g_{i,b}}{\sigma_N^2}\right) \tag{3.17}$$

We estimate the expected D2D throughput gain, defined as the difference between the maximum expected sum-rate of the system and the maximum sum-rate of the partner

CUE without D2D, given by:

$$U\left(P_j^{d*}\right) = \arg\max_{P_j^d \in \Re} \sum_{b\in B_S}\sum_{i\in C}\sum_{j\in D}\left[\log_2(1+\xi_i^{c,b}) + \log_2(1+\xi_j^d) - \log_2(1+\frac{P_i^{c,b}\, g_{i,b}}{\sigma_N^2})\right] \tag{3.18}$$

Given these SINR threshold constraints, we can approximate the capacity in higher SINR cases by removing the term "1" from the logarithm functions for all term.

$$\begin{aligned} U\left(P_j^{d*}\right) &= \arg\max_{P_j^d \in \Re} \sum_{b\in B_S}\sum_{i\in C}\sum_{j\in D}\left[\log_2(\xi_i^{c,b}) + \log_2(\xi_j^d) - \log_2(\frac{P_i^{c,b}\, g_{i,b}}{\sigma_N^2})\right] \\ &= \arg\max_{P_j^d \in \Re} \sum_{b\in B_S}\sum_{i\in C}\sum_{j\in D}\log_2\left(\frac{P_j^d\, g_{j,j} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d}\right) \end{aligned} \tag{3.19}$$

Where $\tilde{I}_i^c = \sum_{j\in D} P_j^d\, h_{j,b} + \sigma_N^2$ and $\tilde{I}_j^d = \sum_{B\in B_S}\sum_{i\in C} P_i^{c,B}\, h_{i,j}^B + \sigma_N^2$ are the total interference at CUE i and DUE j, respectively. Since the transmit power for all CUEs are assumed to be fixed, so the overall uplink network throughput can be maximized by determining the optimal power allocation for each DUE-TX on each channel that maximizes the DUEs sum-rate while maintaining the required QoS for both CUEs and DUEs. This problem is formulated as a constrained optimization problem that Sum-Rate Maximization, which is equivalent to:

$$\left.\begin{aligned} &U\left(P_j^{d*}\right) = \arg\max_{P_j^d \in \Re} \sum_{b\in B_S}\sum_{i\in C}\sum_{j\in D}\log_2\left(\frac{P_j^d\, g_{j,j} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d}\right) \\ &\qquad Subject\ to: \\ &\xi_i^{c,b} = \frac{P_i^{c,b}\, g_{i,b}}{\tilde{I}_j^c} \geq \xi_{i,min}^{c,b}, \qquad \forall i \in C, \forall b \in B_S \\ &\xi_j^d = \frac{P_j^d\, g_{j,j}}{\tilde{I}_j^d} \geq \xi_{j,min}^d, \qquad \forall j \in D \\ &0 \leq P_i^{c,b} \leq P_{max}^{c,b}, \qquad \forall i \in C \\ &0 \leq P_j^d \leq P_{max}^d, \qquad \forall j \in D \end{aligned}\right\} \tag{3.20}$$

We can solve the problem by Lagrangian dual optimization. The Lagrangian of the above problem is defined as:

$$
\begin{aligned}
L\left(P_j^d, \vec{\lambda}, \vec{\beta}, \vec{\nu}, \vec{\mu}\right) = & \sum_{b \in B_S} \sum_{i \in C} \sum_{j \in D} \log_2 \left(\frac{P_j^d \; g_{j,j} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d} \right) \\
& - \sum_{i \in C} \lambda_i \left(P_i^{c,b} \; g_{i,b} - \tilde{I}_i^c \; \xi_{i,min}^{c,b} \right) \\
& - \sum_{j \in D} \beta_j \left(P_j^d \; g_{j,j} - \tilde{I}_j^d \; \xi_{j,min}^d \right) \\
& - \sum_{i \in C} \nu_i \left(P_i^{c,b} - P_{max}^{c,b} \right) \\
& - \sum_{j \in D} \mu_j \left(P_j^d - P_{max}^d \right)
\end{aligned}
\tag{3.21}
$$

Where $\vec{\lambda} = [\lambda_1, \dots\dots\dots, \lambda_k]^T \succeq 0$, $\vec{\beta} = [\beta_1, \dots\dots\dots, \beta_k]^T \succeq 0$, $\vec{\nu} = [\nu_1, \dots\dots\dots, \nu_k]^T \succeq 0$, and $\vec{\mu} = [\mu_1, \dots\dots\dots, \mu_k]^T \succeq 0$ are vectors of dual variables. By using Karush-Kuhn-Tucker (KKT) conditions [88], the optimal solution of (3.21) can be found to obtain the optimal power allocation. So, for each DUE j, the optimal power can be derived as:

$$
P_j^{d*} = \left[\frac{1}{\sum_{b \in B_S} \sum_{i \in C} \sum_{j \in D} \left(\frac{h_{j,b}}{\tilde{I}_i^c} \right) + (\beta_k \; g_{j,j} + \mu_k) \ln 2} \right]
\tag{3.22}
$$

Using the sub-gradient method, the Lagrange multipliers are iteratively updated until convergence as in the previous section.

3.3.3 Optimal Resource Allocation Algorithm

By solving (3.10), (3.15) and (3.22), each admissible D2D pair is assigned one channel and allocated the power for each DUEs. Algorithm (3.1) solves the resource allocation problem in (3.2).

Algorithm 3.1 Optimal Resource Allocation Algorithm

```
C: The set of active CUEs
D: The set of D2D pairs
$D_r$: The set of reuse candidates for DUE $j$.
$N_c$: The set of uplink channels
Initialization { $D_r = \emptyset$, $\omega_{i,j} = 0 \ \forall i \in C \ \& \ \forall j \in D$, $P_j^d = 0 \ \forall j \in D$, $\lambda, \beta, \nu, \mu$ and set $t = 0$ .
while $N_c \neq \emptyset$ & $D \neq \emptyset$ do
    Step 1 Admission Control
    for $\forall$ CUE $i \in C$ & $\forall$ DUE $j \in D$ do
        Using equations (3.10.$a$) - (3.10.$c$) to find the power for DUE and their reuse partners which satisfy minimum SINR.
        if their powers achieve equations (3.8.$a$) - (3.8.$c$) then
            Set $D_r = D_r \cup i$.
        end if
        if $D_r = \emptyset$ then
            $D = D \backslash j$        // DUE $j$ is not admissible.
        end if
    end for
    Step 2 Power Control
    Repeat
    for $\forall$ DUE $j \in D$ & $\forall$ CUE $i \in D_r$ do
        Calculate ($P_j^{d*}$ ) from (3.15) or (3.22).
    end for
    Update $\lambda, \beta, \nu, \mu$ and $t = t + 1$
    Until convergence or $t_{max}$.
    if $|D| = 1$ then
        $\omega_{i,j} = 1$
    end if
    If there is the same channel candidate for multiple DUEs, it will be reused for DUE which achieves higher throughput.
end while
```

3.4 Performance Evaluation and Discussion

In our simulation, we consider two cells each with the width of 2R, which are neighbours for each other, where DUEs share uplink resources with CUEs. Where the CUEs are uniformly distributed in all cells. We adopt the clustered distribution model for D2D pairs, in which the transmitter (DUE-Tx) and the receiver (DUE-Rx) of each D2D pair are uniformly distributed in a cluster with radius r; and clusters are uniformly distributed in all cells so that the transmitter and the receiver of each pair may be situated in the same cell or different cells. Our simulation parameters are shown in Table (3.2).

To evaluate the performance of the proposed resource allocation and power control system, we consider two metrics that are used to evaluate the efficiency: D2D throughput gain defined as increased throughput of the network brought by D2D pairs which accessed, and system throughput gain defined as the overall network throughput due to resources sharing by DUEs. Moreover, we compare our scheme with two proposed power allocation algorithms based on sum-rate maximization and D2D-rate maximization.

Table 3.2: Simulation Parameters

Parameter	***Value***
System bandwidth	5 MHz
Channel bandwidth	180 kHz
Number of cells	2 cells
Cell radius	500 m
Maximum distance between DUE-TX and DUE-RX	10, 20, 30, ... , 100 m
Noise power (σ_N^2)	-114 dBm
Pathloss exponent (α)	4
Pathloss constant (κ)	10^{-2}
Maximum transmit power for CUE (P_{max}^c)	24 dBm
Maximum transmit power for DUE-TX (P_{max}^d)	24 dBm
Simulation type	MATLAB

Figure (3.3) depicts the system throughput curve of D2D users. D2D throughput gain versus maximum distance between a D2D pair, where M=10 is the number of D2D pairs and N=20 is the number of CUEs. So, from the figure, it is observed that D2D throughput gain decrease with the increase of the radius of the D2D cluster. Meanwhile, when r

increases, the channel gain between the D2D pair is decreased, requiring a higher transmit power to guarantee D2D's required SINR and satisfy its QoS requirement. This increases the interference caused by the D2D pair on the reuse partner, which in turn forces CUEs to increase their transmit power levels to maintain their required SINRs.

Figure (3.4) depicts the system throughput gain versus maximum distance between a D2D pair, where M=10, N=20. The figure shows the increase in the total system uplink throughput when D2D links are allowed as compared to the case in which D2D links are not permitted.

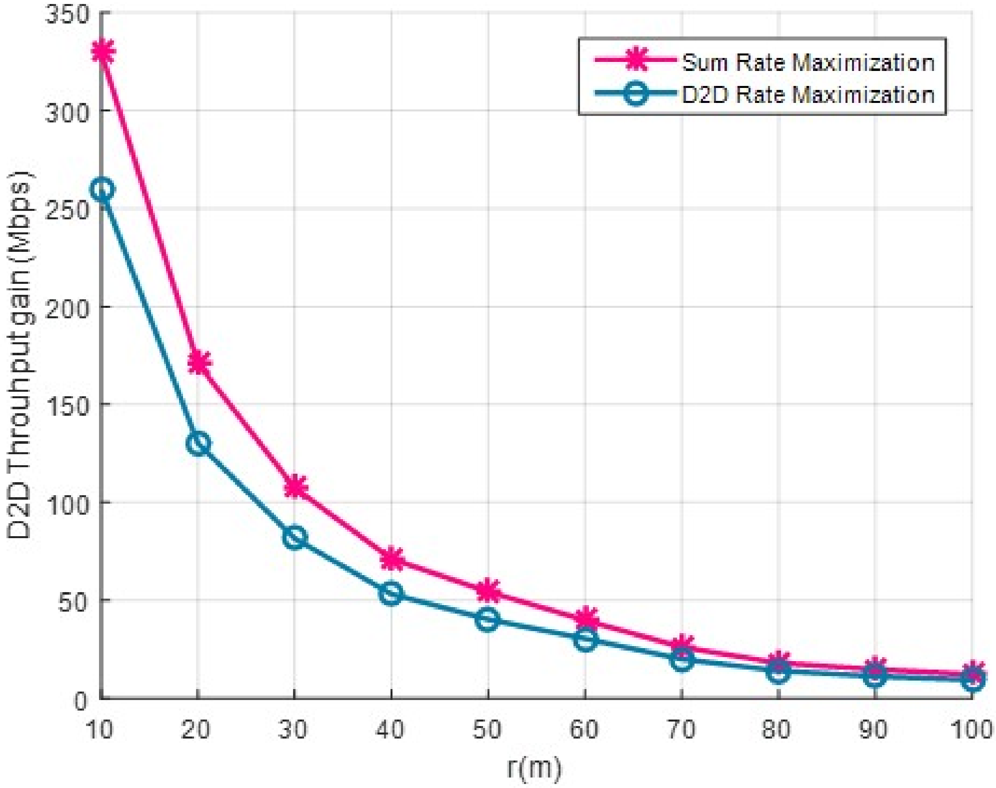


Figure 3.3: D2D throughput gain versus maximum distance between a D2D pair, where M=10, N=20.

Figure (3.5) illustrates compare the performance of our proposed scheme of the effect for different values of the number of D2D pairs and the number of CUEs as ratio each together, when the distance between the D2D pair fixed at 20 m and 60 m. From figure

(3.5), when M is increased, more D2D pairs may reuse uplink channels, which means that the D2D throughput gain can increase. On the other hand, for a given M/N, when N is increased, each D2D pair has more options for choosing its reuse partner, resulting in an average throughput gain of D2D communications increases linearly with the ratio of DUEs.

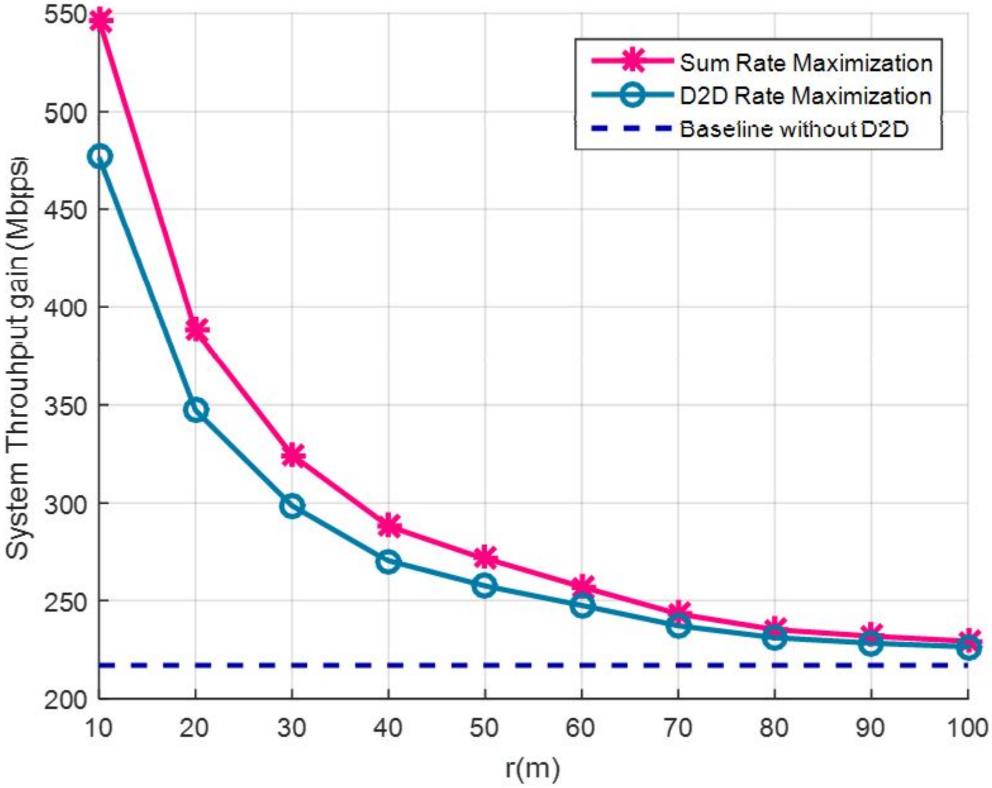


Figure 3.4: System throughput gain versus maximum distance between a D2D pair, where M=10, N=20.

Figure (3.6) depicts the compare our scheme of two proposed power allocation algorithms based on sum-rate maximization and D2D rate maximization with the fixed margin approach in [89] and heuristic method in [55]. For the fixed margin approach in [89], which assumes a margin k in each CUE's required SINR to take into account the interference caused by D2D transmitters. However, maintaining a margin k in each CUE's SINR can modify its transmit power to guaranteeing the QoS requirements. In such a way, all the D2D reuse candidates can be found and adapt powers for D2D pairs and the reuse partner CUEs may be allocated. For the heuristic method in [55], the base station has priority to selects the CUE with the highest channel power gain to share the resource with the D2D pair with the lowest interference channel power gain between the CUE and (DUE-Rx) of D2D pair. The uplink resource allocation scheme in [55] has executed with the maximum power constraints for both DUEs and the partner CUEs.

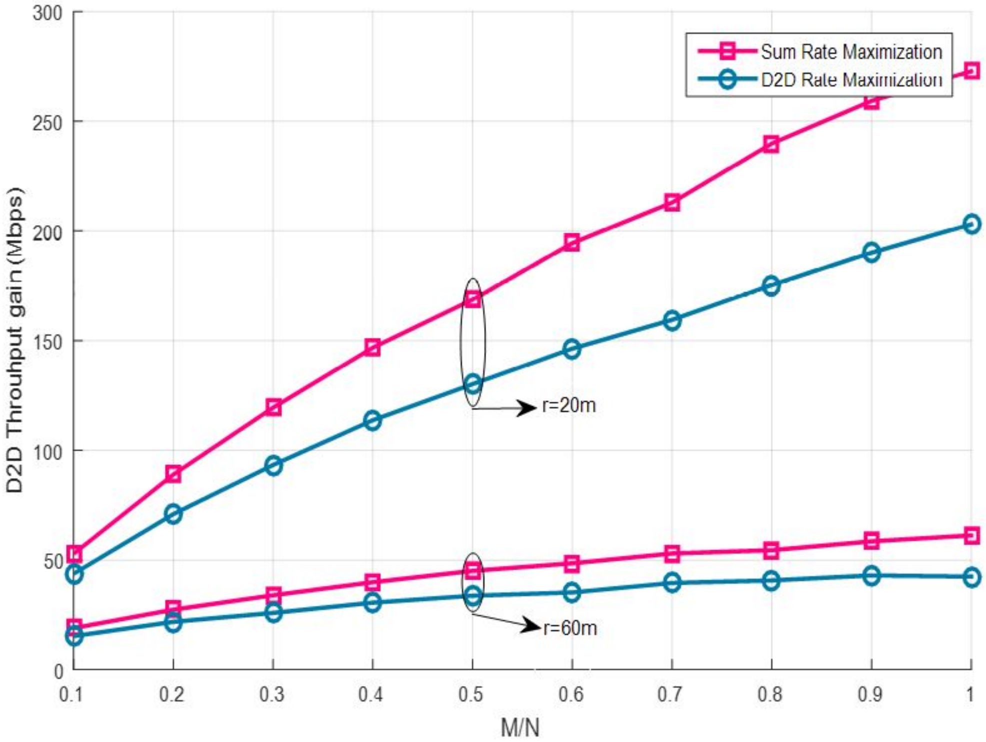


Figure 3.5: D2D throughput gain with vary the ratio of the number of D2D pairs (M) to the number of CUEs (N).

Thus, in general, it is clear in figure (3.6) show that our proposed algorithm constantly gives the best performance between the three approaches for three reasons: In the first one, our proposed algorithm always assigns the optimal powers for each DUE and its reuse partner to mitigate the interference as well as to reduces energy consumption. In the second one, our proposed algorithm checks all the reuse candidates for every DUE while some feasible reuse candidates are missing in the other two approaches. In the third one, we consider both intra-cell interference and inter-cell interference issues for power allocation and optimal channel selection while the other compared approaches consider

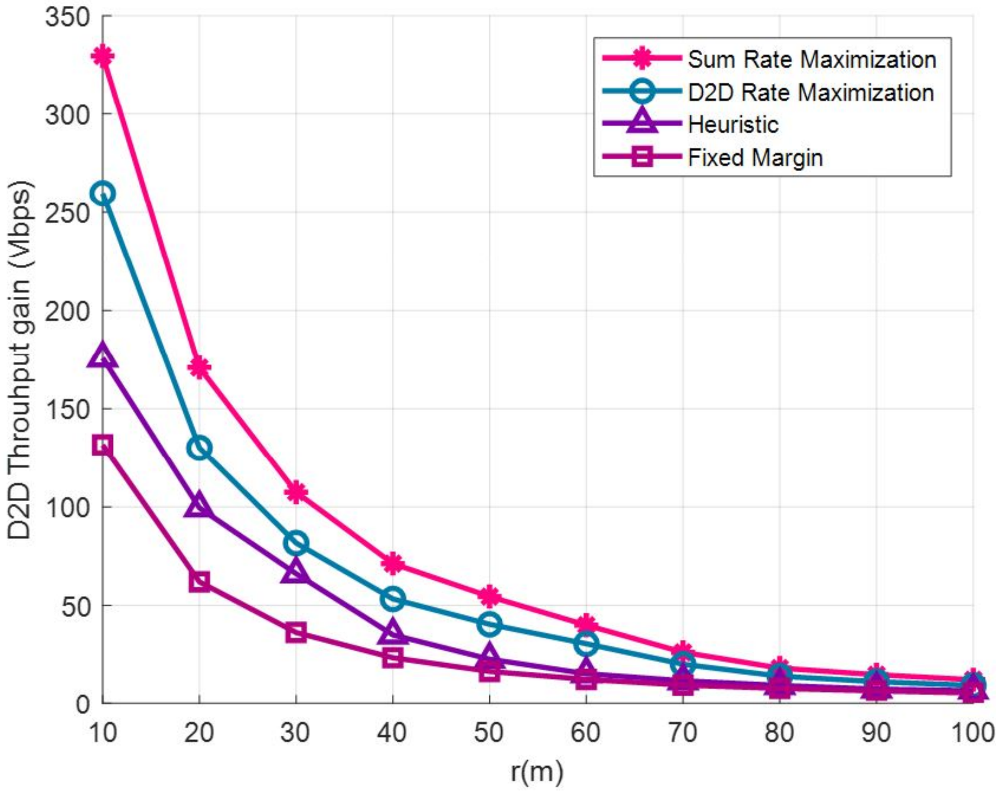


Figure 3.6: D2D throughput gain versus maximum distance between a D2D pair, compare with other approaches.

only intra-cell interference. Furthermore, the DUE transmits power usage under the sum-rate maximization approach is slightly lower than that under the D2D rate maximization approach. A lower DUE transmit power usage in the neighboring cells causes lower interference to the CUEs. This results in an increased total D2D rate of the sum-rate maximization approach.

3.5 Conclusion

D2D communications offer an affirmation of a significant role in upcoming communication systems. This chapter presented investigated resource allocation for D2D communications sharing uplink resources in a fully loaded cellular network. In order to maximize the overall throughput while ensuring the QoS requirements of both CUEs and

DUEs, we formulated the optimization problem and then found the solution through two stages: The first stage is admission control of D2D users while the second one is the power control for each admissible DUE and its reuse partner. However, the resource allocation algorithm-based scheme is developed to select a suitable reuse partner for each D2D pair, and the algorithm is designed to consider both intra-cell interference and inter-cell interference issues for optimal channel selection as well as power allocation. The simulation results have indicated that the proposed scheme can offer near-optimal performance and outperforms the algorithms in the literature, in achievable throughput. Overall, we have proven that the performance of D2D communications underlaying cellular uplink multi-cell networks fundamentally depends on different system parameters such as D2D user locations, the number of neighboring cells, the distance between the transmitter and the receiver of the D2D pair, and the numbers of active CUEs and DUEs.

Chapter 4

Resource Management Based on Reinforcement Learning for D2D Communication in Cellular Network

4.1 Introduction

In this chapter, we consider joint mode selection, resource block (RB) assignment, and power control. Meanwhile, Q-learning has a low convergence speed and may not always suitable to deal with continuous-valued state and action spaces [90]. The Actor-Critic- Reinforcement Learning (AC-RL) approach is adopted to solve the resource management problem of D2D communication networks [91], to maximize the overall network throughput while guaranteeing low latency communications requirements of D2D communications. The AC-RL approach can efficiently deal with the continuous-valued state and action spaces (e.g., RB occupy status, channel status information (CSI), etc.), where the actor is used to exploit the stochastic actions and the critic is applied to estimate the state-action value function. The main contributions of this chapter can be summarized as follows:

- This chapter firstly introduces the system model of D2D environments, therefore, how to determine the communication mode whether it is cellular, dedicated or reuse mode.

- We formulate a joint resource allocation (resource block (RB) assignment, mode selection, and transmits power control) issue with considering the QoS requirements, to maximize the throughput of the overall network in D2D communications.

- Then, the resource management problem is modelled as the RL framework, thus D2D links are able to make their adaptive decisions intelligently to improve their performance based on instant observations in D2D environments.

4.2 System Model and Problem Formulation

4.2.1 System Model

As illustrated in figure (4.1), we consider a single-cell cellular system consisting of one eNB, with a two-tier cellular network: a set of ***K*** cellular user equipments (CUEs) is denoted by $\mathbf{C} = \{C_1, C_2, \ldots, C_K\}$ are located in the coverage area of an eNB, sharing the orthogonal ***N*** resource blocks (RBs), and the set of ***M*** D2D users equipments (DUEs) is denoted by $\mathbf{D} = \{D_1, D_2, \ldots, D_M\}$. Without loss of generality, each CUE occupies one RB which can be shared by multiple DUE pairs, and one DUE pair can only occupy one RB. We assume the peer device discovery and the session setup are completed before the resource allocation.

In this system model, we assume that the potential D2D users share the uplink resources of cellular users. The key parameters analyzed are the signal-to-interference-plus-noise ratio (SINR), the effect of variation in D2D transmitter power, sum rate, outage probability, mode selection of D2D communication, and low latency requirements of D2D links.

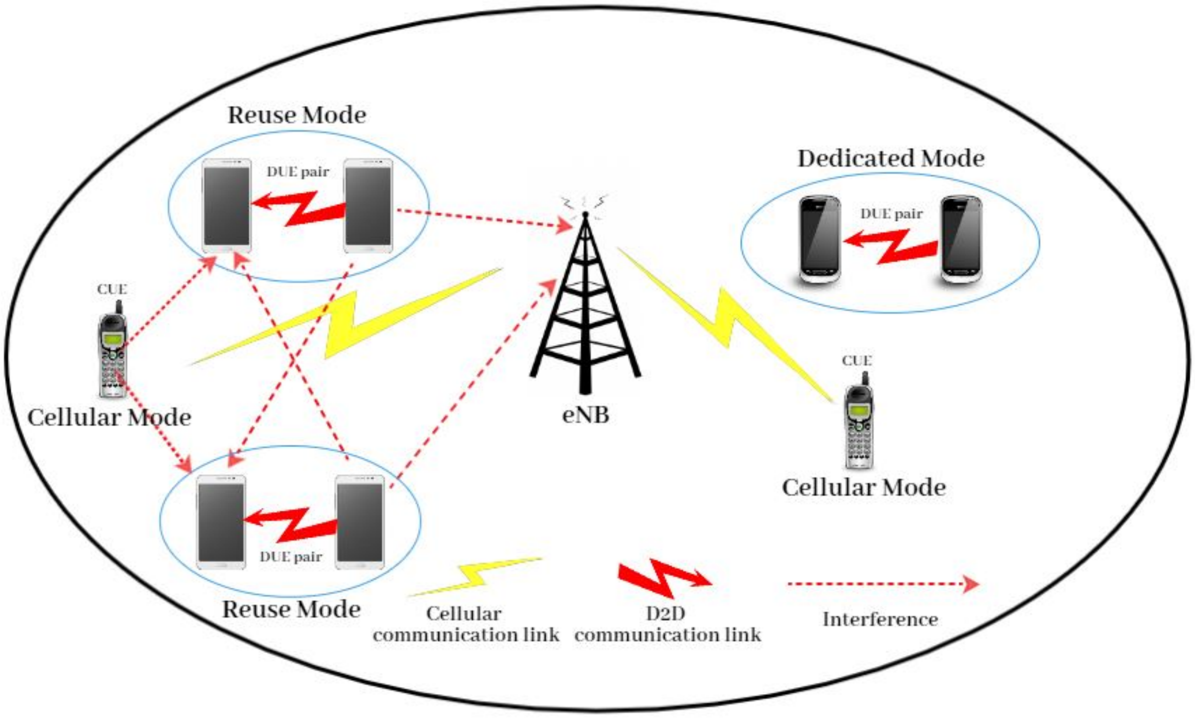


Figure 4.1: System model for D2D communications network

4.2.2 D2D Communication Modes

One important issue on D2D communication is the mode that devices use to communicate between them since a suitable communication mode increases the network throughput. In [30,92] modes of D2D pairs, which can choose one of three communication modes from among the following:

1) **Reuse Mode:** In this mode, when the two DUEs are close together, two DUEs communicate directly by sharing CUEs' uplink RBs resource. In this case, even the efficiency of the spectrum can be improved, interference is experienced between the DUEs and cellular users. In reuse mode, if CUE it shares its RB resource with the D2D pair, the CUE will suffer interference from the D2D pair. Then, the SINR received at the eNB can be expressed as:

$$\xi_i^{c,R} = \frac{P_i^{c,R} g_{i,b}}{\sum_{j \in D} P_j^{d,R} h_{j,b} + \sigma_N^2} \tag{4.1}$$

Similarly, for a DUE pair j that shares the RB k, where the interference is caused on the reused RB from the co-channel CUE i. Instead, when reusing the RB of CUE i, the SINR at the receiver of the DUE pair j is given by:

$$\xi_j^{d,R} = \frac{P_j^{d,R} g_{j,j}}{\sum_{k \in D,\, k \neq j} P_k^{d,R} h_{k,j} + P_i^{c,R} h_{i,j} + \sigma_N^2} \tag{4.2}$$

2) **Dedicated Mode:** Two DUEs communicate directly using a RBs resource that is not currently use. DUEs in this mode consume fewer channel resource compared to those in the cellular mode and can increase the spectrum efficiency due to proximity gain. Then, the SINR can be expressed as:

$$\xi_j^{d,D} = \frac{P_j^{d,D} g_{j,j}}{\sigma_N^2} \tag{4.3}$$

3) **Cellular Mode:** When two DUEs are distant from each other or the channel gain among them is poor, in this mode, there cannot directly communicate with each other. Thus, in this case, they can communicate through the Base Station BS (as a relay) as traditional cellular users. So, the SINR can be expressed as:

$$\xi_j^{d,C} = \frac{P_j^{d,C} g_{j,b}}{\sigma_N^2} \tag{4.4}$$

In addition, the CUE′ RB will not suffer interference from DUEs, when is not currently reused by any DUEs. Then, the SINR may be expressed as:

$$\xi_i^{C} = \frac{P_i^{C} g_{i,b}}{\sigma_N^2} \tag{4.5}$$

The minimum data rate requirement constraints of CUE i and DUE pair j may be expressed as:

$$R_i^c \geq R_i^{c,req},\ \forall i \in C,\ and\ R_j^d \geq R_j^{d,req},\ \forall j \in D \tag{4.6}$$

Due to the latency requirement, let T_{max} denote the maximum tolerable latency threshold. The latency constraint for DUE j pair is assured by controlling the probability of exceeding the threshold value, where the transmission delay T_{tx} is beyond the threshold T_{max}. Then the probability must be a smaller than the tolerable threshold p_{max}^{delay}, which may be expressed as:

$$p_j^{delay} = P_r \left\{ T_{tx} \geq T_{max} \right\} \leq p_{max}^{delay} \tag{4.7}$$

The outage probability is used to characterize the reliability requirement of DUE pair j, and it can be defined as the probability that the transmission data rate R_j^d is less than the requirement threshold $R_j^{d,req}$. Therefore, the outage probability must be below the tolerable outage probability p_{max}^{outage}, which may be expressed as:

$$p_j^{outage} = P_r \left\{ R_j^d \leq R_j^{d,req} \right\} \leq p_{max}^{outage} \tag{4.8}$$

4.2.3 Problem Formulations

Our goal in this chapter is to optimize the overall network throughput while guaranteeing the above-mentioned DUEs' QoS criteria and satisfying the network's resource constraints. Therefore, the joint mode selection, channel assignment, and power control of resource management issue can be formulated mathematically as:

$$\begin{aligned} U\left(P^{*}, \delta^{*}\right) = \arg\max_{P,\delta} \Bigg\{ & \sum_{j \in D} \delta_j^C \log_2(1 + \frac{P_j^{d,C} g_{j,b}}{\sigma_N^2}) + \sum_{j \in D} \delta_j^D \log_2(1 + \frac{P_j^{d,D} g_{j,j}}{\sigma_N^2}) \\ & + \sum_{i \in C} \sum_{j \in D} \delta_{i,j}^R \log_2(1 + \frac{P_j^{d,R} g_{j,j}}{\sum_{k \in D,\, k \neq j} P_k^{d,R} h_{k,j} + P_i^{c,R} h_{i,j} + \sigma_N^2}) \\ & + \sum_{i \in C} \sum_{j \in D} \delta_{i,j}^R \log_2(1 + \frac{P_i^{c,R} g_{i,b}}{\sum_{j \in D} P_j^{d,R} h_{j,b} + \sigma_N^2}) \\ & + \sum_{i \in C} (1 - \sum_{j \in D} \delta_{i,j}^R) \log_2(1 + \frac{P_i^c g_{i,b}}{\sigma_N^2}) \Bigg\} \end{aligned} \tag{4.9}$$

$$Subject\ to:$$

$$(4.6), (4.7), (4.8);$$

$$\delta_j^C, \delta_j^D, \delta_{i,j}^R \in \{0,1\}, \qquad \forall j \in D \qquad (4.9.a)$$

$$\sum_{j\in D} \delta_{i,j}^R \leq 1, \qquad \forall i \in C \qquad (4.9.b)$$

$$\sum_{i\in C} \delta_{i,j}^R + \delta_j^C + \delta_j^D \leq 1, \quad \forall i \in C \qquad (4.9.c)$$

$$\sum_{j\in D} \delta_j^C + \sum_{j\in D} \delta_j^D \leq N, \qquad (4.9.d)$$

$$\sum_{i\in C} (\delta_{i,j}^R\, P_j^{d,R}) + \delta_j^D\, P_j^{d,D} + \delta_j^C\, P_j^{d,C} \leq P_{max}^d \quad \forall j \in D \qquad (4.9.e)$$

$$\delta_{i,j}^R\, P_i^{c,R} + (1 - \sum_{j\in D} \delta_{i,j}^R)\, P_i^c \leq P_{max}^c, \quad \forall i \in C \qquad (4.9.f)$$

Where δ_j^C, δ_j^D, and $\delta_{i,j}^R$ are the mode selection indicators, representing the cellular mode, the dedicated mode, and the reuse mode, respectively. The constraint $(4.9.a)$ represents the channel reuse relationship between CUEs and DUEs combined with the resource partition model. Constraint $(4.9.b)$ make sure that the resource of an existing CUE may be shared at most by one D2D pair. However, constraint $(4.9.c)$ is a guarantee that any DUE will select one of the three modes at most. Constraints $(4.9.d)$ indicates that the RBs used by DUE in the cellular mode and the dedicated mode should not exceed the total number of RBs. Constraints $(4.9.e)$ and $(4.9.f)$ guarantee that the transmit powers of CUEs and DUEs are within the maximum limit. All the notations used are given in Table (4.1).

4.3 Reinforcement Learning (RL) for Resource Management

We use Markov decision processes (MDP) to model the optimization problem in (4.9), which is hard to solve as it is a non-convex combination and NP-hard problem. Then, the solution to the formulated MDP problem can be attained by making use of Actor-Critic RL (AC-RL) algorithm [93]. On the other hand, the main parts of the reinforcement

Table 4.1: Notations and their Definitions

Notation	***Definitions***
R_i^c	*The data rate of CUE i.*
$R_i^{c,req}$	*The minimum data rate requirements of CUE i.*
R_j^d	*The data rate of DUE j.*
$R_j^{d,req}$	*The minimum data rate requirements of DUE j.*
$g_{j,j}$	*Channel gain of D2D pair j.*
$g_{i,b}$	*Channel gain of the Links, from CUE i to the eNB b.*
$h_{j,b}$	*Interference gains of the links, from the transmitter of DUE j to eNB b.*
$h_{i,j}$	*Interference gains of the links, from CUE i to the receiver of DUE j.*
σ_N^2	*The energy of the additive white Gaussian noise (AWGN) on each channel.*
P_{max}^c	*The maximum transit power of CUE.*
P_{max}^d	*The maximum transit power of DUE.*
P_i^c	*Transmit power of CUE i.*
$P_i^{c,R}$	*Transmit power of CUE i in the Reuse mode.*
$P_j^{d,R}$	*Transmit power of DUE j in the Reuse mode.*
$P_j^{d,D}$	*Transmit power of DUE j in the Dedicated mode.*
$P_j^{d,C}$	*Transmit power of DUE j in the Cellular mode..*

learning (RL) based on MDP are indicated with a new proposed reward function, and an AC-RL framework is used to solve the resource management problem.

4.3.1 Markov Decision Process (MDP) for Resource Management

Markov Decision Processes (MDP) are widely used as optimization tools for determining optimal strategies in communication systems. We apply MDP to model the strategy searching process in the RL formwork. At each time step, the process is in some state, and the decision-maker (agent) may decide any action that is available in the current state. Then selecting an action, the agent receives some reward associated with the played action in that state, and the process randomly moves to a new state according to some transition matrix. Our MDP is a 5-tuple (S, A, P, R, γ), in which the state S, the action A, the transition probability P, the reward R, and $\gamma \in (0, 1)$ is the discount factor.

In D2D environments, the probabilities of state transition and expected rewards are generally unknown for all states. Thus, we formulate that the problem of resource allocation in a D2D communication is a model-free reinforcement framework in which the MDP has a continuous action and state space. The goal of applying MDP is to find the optimal strategy and then to address the problem of decision making to optimize the reward [93]. In a reinforcement learning framework, As shown in the figure (4.2), there are agent, environment, action, state, reward and other basic elements. The agent corresponding to a D2D pair, interacts with the environment and generates trajectory, which changes the state $s \rightarrow s'$ by executing action. And agent will receive a reward from environment. By continuing these interactions, agents accumulate more and more experiences, and then update the policy.

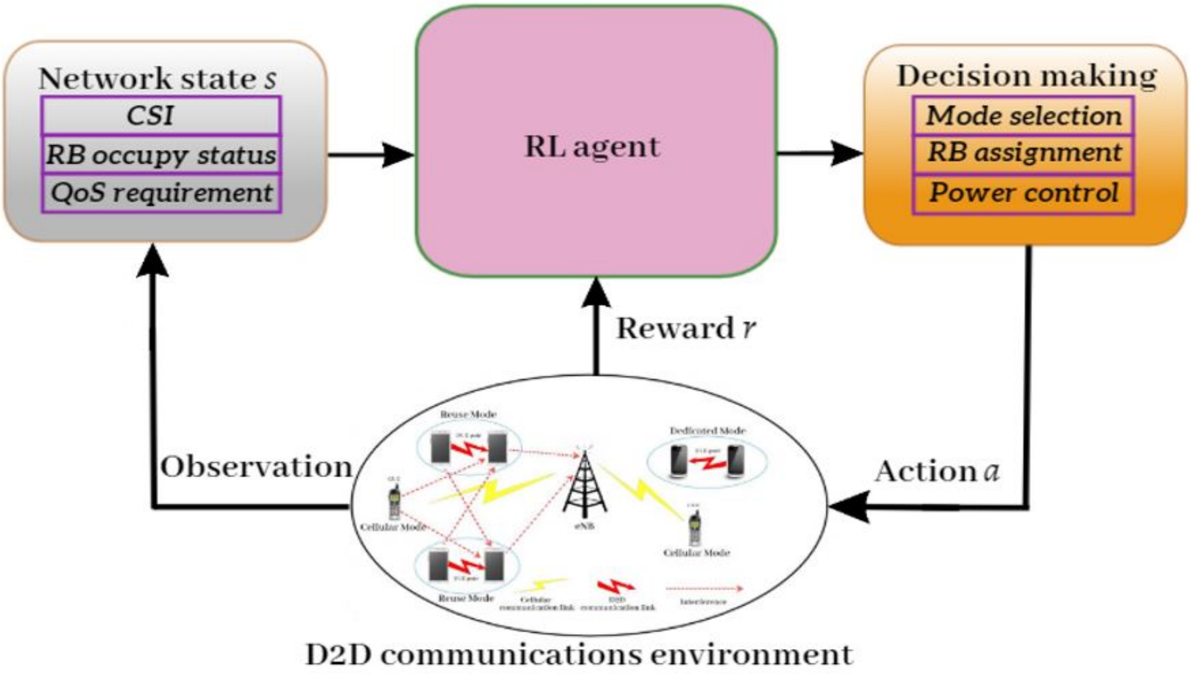


Figure 4.2: Framework of RL for the spectrum allocation in D2D communications.

To be more precise, when an agent executes an action $a \in A$ and receives a reward $r \in R$, the environment transitions from state $s \in S$ to $s' \in S$. R is the reward obtained after action a is executed.

Agent: For each communication link (agent). The agent learns and makes decisions by interacting with the environment.

State: The system state can be described as $S = \{\mathfrak{S}_{CSI}, \mathfrak{S}_{RB}, \mathfrak{S}_{QoS}\}$, where $\mathfrak{S}_{CSI}$ shows the observed channel information, $\mathfrak{S}_{RB}$ denotes all RBs occupy status between users, and $\mathfrak{S}_{QoS}$ indicates the requirements of QoS (e.g., the latency, the minimum data rate, and the reliability requirements).

Action: There are three actions considered in each for the learning process, are defined as $a = \{\mathcal{A}_{MS}, \mathcal{A}_{PC}, \mathcal{A}_{RB}\} \in A$. The agent will take the action $a \in A$ according to the current state $s \in S$, after making a decision in terms of the communication mode selection $\mathcal{A}_{MS}$, transmit power control $\mathcal{A}_{PC}$, and the RB assignment $\mathcal{A}_{RB}$.

Transition probability: The transition probability $P(s'|s,a)$ describes the probability when the agent takes the action $a \in A$ from the state $s \in S$ to a new state $s' \in S$.

$$P(s'|s,a) = \begin{cases} 1, & s' = state(a) \\ 0, & otherwise. \end{cases} \tag{4.10}$$

Reward: The main target of using RL is to learn the optimal strategy by increasing the reward. Thus, it is very important how to design an efficient reward function, which directly decides the optimal strategy that the agent finds, and which actions it will take. furthermore, we have built a new reward function for the resource management issue, which may be given by:

$$\begin{aligned} r = U\left(P^{*}, \delta^{*}\right) - \alpha_1 \left(\sum_{j \in D} (p_j^{delay} + p_j^{outage}) \right) \\ - \alpha_2 \left(\sum_{i \in C} (R_i^{c,req} - R_i^{c}) \right) - \alpha_3 \left(\sum_{j \in D} (R_j^{d,req} - R_j^{d}) \right) \end{aligned} \tag{4.11}$$

Where part 1 is the immediate utility (the throughput of the overall network), part 2 indicates the cost functions in terms of the unsatisfied latency and unsatisfied reliability of D2D link, part 3 and part 4 are the cost functions in terms of the unsatisfied minimum sum data rate requirements of cellular link and D2D link, respectively. The coefficient

$\alpha_k, k \in \{1, 2, 3\}$ are the weights of the last three parts, which are also used to balance the utility and the cost.

Policy: The policy is a function which decides the action selection with the given state. Let $\pi(s)$ denotes a policy: $\pi(s) : S \to A$, which is a mapping from the state S to the action A. In the network, the objective of the agent aims to choose a policy $\pi(s)$ to maximize its expected reward. Let $V^{\pi}(s)$ denotes the state-value function, which called as a cumulative discounted reward, which is expressed as:

$$\begin{aligned} V^{\pi}(s) &= E_{\pi}\left[\sum_{t=0}^{\infty} \gamma^t r_t(s_t, a_t) | s_0 = s, \pi\right] \\ &= E_{\pi}\left[r(s, a_t) + \gamma \sum_{s' \in S} P(s'|s, a_t) V^{\pi}(s')\right] \end{aligned} \tag{4.12}$$

The optimal policy $\pi^*(s)$ satisfies the Bellman equation [93], is achieved to maximizing the cumulative discounted reward starting from the state s.

$$V^*(s) = V^{\pi^*}(s) = \max_{a \in A}\left\{E_{\pi^*}\left[r(s, a) + \gamma \sum_{s' \in S} P(s'|s, a) V^{\pi^*}(s')\right]\right\} \tag{4.13}$$

Since the optimal policy maximizes the cumulative discounted reward from the beginning, it contributes to design the resource management scheme in D2D communication cellular networks.

4.3.2 Actor-Critic (AC) Learning for Resource Management

In this subsection, a model-free RL is utilized to address the resource management and to learn the optimal strategy for the resource management of D2D communication with continuous action. The actor-critic reinforcement learning method is one of the RL tools, which is a combination of the value-based reinforcement learning method and the strategy-based reinforcement learning method. Moreover, according to whether the environmental elements (i.e. reward function and state transition probability) are known.

The actor-critic is an architecture reinforcement learning algorithm based on the policy gradient, where the actor is represented through adopting a control policy with action selections based on the observed network state, then the critic evaluates the input policy by a reward function from the environment feedback [93].

We adopted the Actor-Critic Reinforcement Learning (AC-RL) to optimize the policy numerically to solve intelligent resource management in D2D communications. In networks, D2D links may be regarded as agents and the network represents the environment. Each agent observes the current network state and then decides which action may be decided based on its learned policy strategy by itself. Then, the D2D environment provides a new network state and the immediate reward r in (4.11) to the agents. According to the feedback, all agents learn a new policy in the next step and so on.

We design an Actor-Critic Reinforcement Learning (AC-RL) framework for intelligent resource management in D2D communications as illustrated in figure (4.2).

1) ***Action selection:*** In the D2D environment, the D2D transmitter is set as an agent. The agent interacts with the environment and then takes the action. During the learning process, the agent continuously updates the policy until the optimal strategy is learned. Subsequently, the agent needs to select an action according to a stochastic strategy, the purpose of which is to enhance performance while explicitly balancing two competing objectives: (a) chooses the communication mode and (b) then combines the channel assignment and power level where the agent has two various actions to achieve a goal.

We adopt *softmax* policy for long-term optimization. $\pi(s,a)$, which determines the probability of taking action a, can be determined by utilizing Boltzmann distribution as [93]

$$\pi(s,a) = \frac{exp\left(\frac{P(s,a)}{\tau}\right)}{\sum_{a' \in A} exp\left(\frac{P(s,a')}{\tau}\right)} \tag{4.14}$$

where τ is a positive parameter called temperature. In addition, $P(s,a)$ defines the affinity to select action a at state s; it is updated after every iteration. The Boltzmann distribution is chosen to avoid jumping into exploitation phase before testing each action in every state [93].

2) ***State-Value Function Update:*** Once the agent chooses an action, the system changes the state $s \in S$ to a new state $s' \in S$ with a transition probability in (4.10). Meanwhile, the total reward for the taken action a would be $r(s, a)$. Consequently, the Time Difference (TD) error $\delta(s, a)$ would be computed by the difference between the state-value function $V^{\pi}(s')$ estimated at the preceding state which in (4.12), and $r(s, a)+V^{\pi}(s')$ at the critic [94],

$$\begin{aligned} \delta(s, a) &= r(s, a) + \gamma \sum_{s' \in S} P(s'|s, a)V(s') - V(s) \\ &= r(s, a) + \gamma . V(s') - V(s) \end{aligned} \tag{4.15}$$

After that, the TD error would feed back to the actor. By the way, the state-value function would be updated as

$$V(s') = V(s) + \alpha \left[v_1(s, t)\right] \delta(s, a) \tag{4.16}$$

Here, $v_1(s, t)$ indicates the occurrence time of state s in these t stages. $\alpha(.)$ is a positive step-size parameter that affects the convergence rate. On the other hand, $V(s')$ remains as $V(s)$ in case of $s \neq s'$.

3) ***Policy Update:*** The critic would utilize the TD error to evaluate the selected action by the actor, and the policy can be updated as [94],

$$p(s, a) = p(s, a) - \beta \left[v_2(s, a, t)\right] \delta(s, a) \tag{4.17}$$

Where $v_2(s, a, t)$ denotes the executed times of action a at state s in these t stages. $\beta(.)$ is a positive step-size parameter. Equations (4.14) and (4.17) ensure one action under a specific state can be selected with higher probability, if we reach the highest minimum reward, i.e., $\delta(s, a) < 0$.

If every action is executed for infinite times in each state and the learning strategy is greedy with infinite exploration, the value function $V(s)$ and the policy function $\pi(s,a)$ will eventually converge to $V^*(s)$ and π^*, respectively, with a probability of 1. The complete proposed AC-RL approach is shown in Algorithm (4.1).

Algorithm 4.1 AC-RL Algorithm

```
{$Initialization$}
for each $s \in S$ , each $a \in A$ do
    Initialize state-value function $V(s)$, policy function $p(s,a)$, and strategy function $\pi(s,a)$.
end for
Repeat until convergent
Choose an action $a$ in state $s$ according to $\pi(s,a)$ in (4.14);
Observe the rewards and receive the current reward using (4.11);
Identify the network state and accordingly update state $s \rightarrow s'$ and compute the TD error by (4.15);
Update the state-value function (4.16) for $s = s'$;
Update the policy function by (4.17) for $s = s'$ and $a = a'$, respectively;
Update the strategy function $\pi'(s,a)$ using (4.14).
```

4.4 Performance Evaluation

In this part, simulation results are being performed in MATLAB 2018a to evaluate the overall performance of our proposed resource management based on the AC-RL approach in the D2D environment. Then, we evaluate it with the following tactics: Q-learning approach (referred to as Q-learning) that is utilized in [68]; and random search approach (referred to as random search).

In our simulation, we consider a single cell scenario with the radius of 500 m. Where the CUEs are uniformly distributed in the cell. we adopt the clustered distribution model for D2D pairs, in which the transmitter (DUE-Tx) and the receiver (DUE-Rx) of each D2D pair are uniformly distributed in a cluster with radius r; and clusters are uniformly distributed in the cell. Our simulation parameters are shown in the Table (4.2).

Table 4.2: Simulation Parameters

Parameter	***Value***
System bandwidth	5 MHz
Channel bandwidth	180 kHz
Number of cells	1 cell
Cell radius	500 m
Maximum distance between DUE-TX and DUE-RX	70 m
Noise power (σ_N^2)	-114 dBm
Pathloss exponent (α)	4
Pathloss constant (κ)	10^{-2}
Maximum transmit power for CUE (P_{max}^{c})	24 dBm
Maximum transmit power for DUE-TX (P_{max}^{d})	24 dBm
Simulation type	MATLAB

Snapshot for the distribution of CUEs and DUEs in a cell network as illustrated in figure (4.3). The eNB is located at the origin of the cell while the locations of CUEs and DUEs are randomly distributed within the serving cell coverage area.

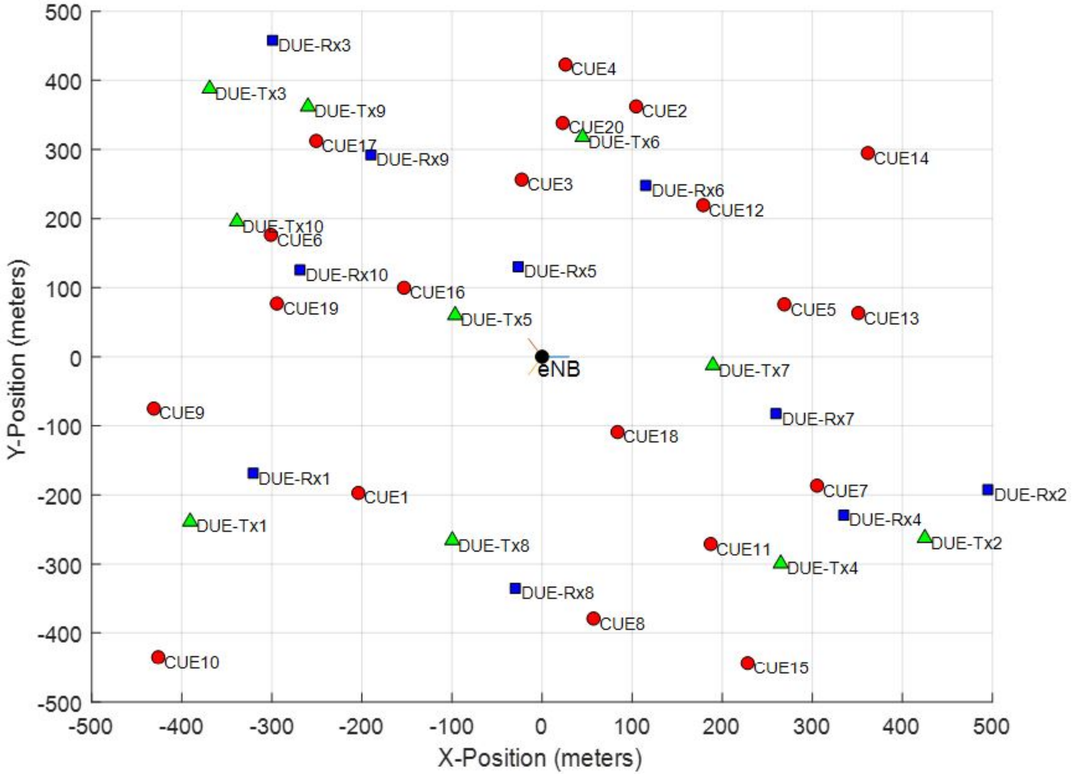


Figure 4.3: Snapshot for CUEs and DUEs distribution in the cell with radius 500m where K = 20 and M = 10.

In figure (4.4), the system throughput analysis under different numbers of D2D users is performed. The result indicates an enhanced performance while using the proposed algorithm over the existing algorithms. On the other hand, the total system throughput as a function of the D2D number. AC-RL approach with two different approaches is compared, it can be observed obviously that the total system throughput grows as D2D number increases, and the AC-RL approach is of higher performance than Q-learning approaches as well as the random search approach.

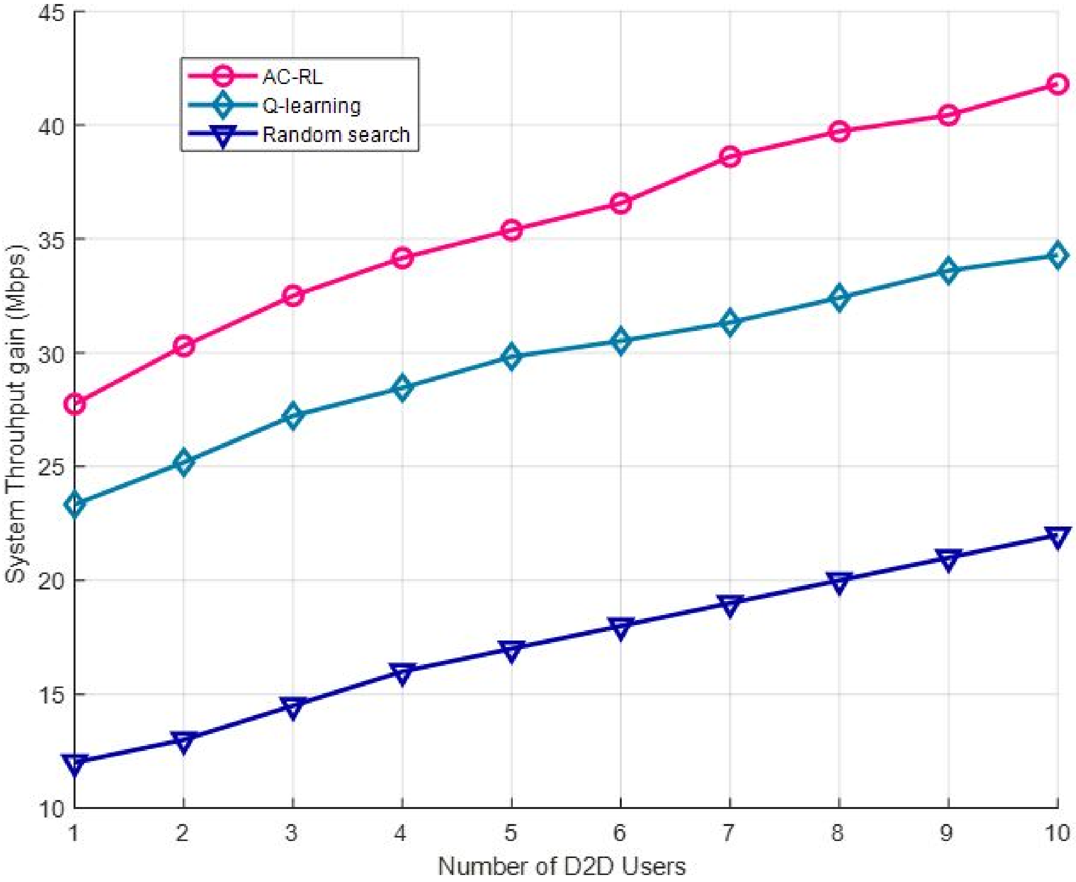


Figure 4.4: System throughput gain for different D2D numbers.

As shown in figure (4.5), the learning process of the three approaches in terms of the reward performance when the number of DUEs is 10. We can see that the AC-RL approaches greatly outperform the Q-learning approach and the random search approach, especially, the proposed algorithm accomplishes the best performance in reward with the highest convergence rate.

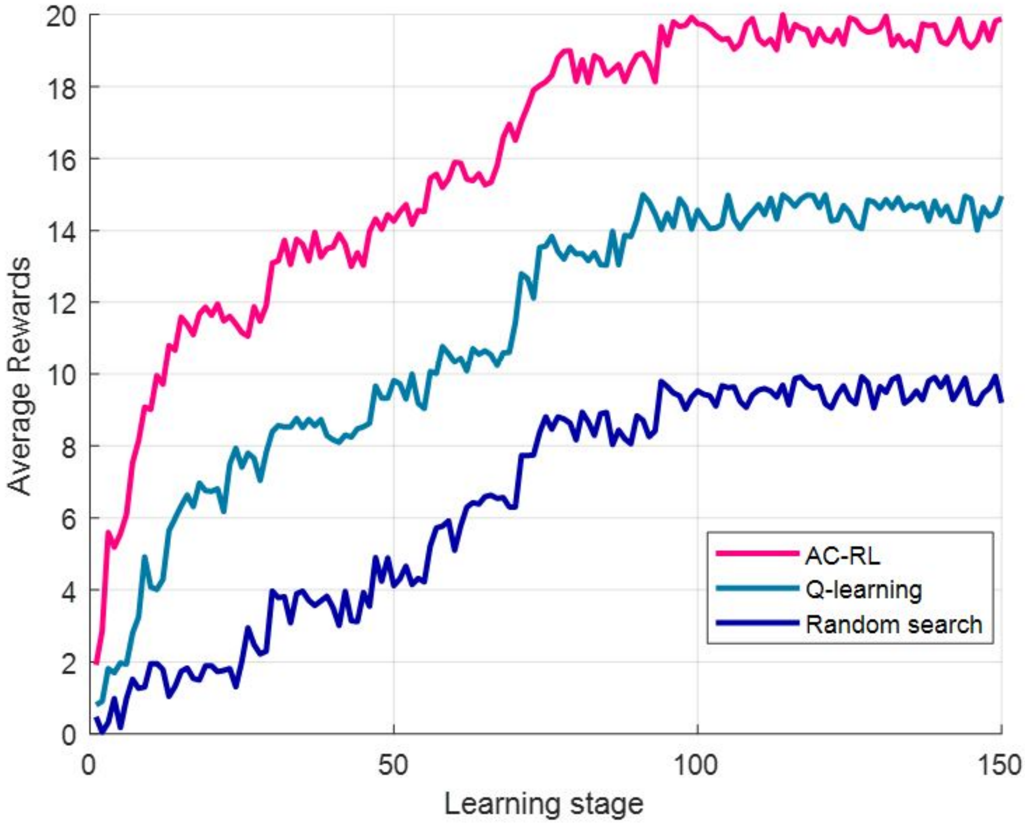


Figure 4.5: Learning process comparisons of AC-RL algorithms.

Thus, in general, D2D communications will typically coexist and share RBs with cellular users for their data transmission. The proposed joint resource management can maximize the throughput whilst avoiding interference caused due share the RBs of cellular networks. The agent continually upgrades the policy throughout the learning process to discover how to select power levels and allocate resources. based on the simulation outcomes, every agent discovers a way to meet the cellular communication constraints whilst avoiding interference with D2D communications and increasing the throughput of the overall network.

4.5 Conclusion

The integration of Device-to-Device (D2D) communication to cellular networks became a vitality task with the growth of mobile devices, as well as requirements of enhanced network performance in terms of spectral efficiency, energy efficiency, and latency. In this chapter, we formulated joint resource management (mode selection, resource block assignment and transmits power control) problem with the constraints of QoS requirements of D2D links, to maximize the throughput of the overall network in D2D communications. The resource management problem is solved with an RL framework based on MDP. With the RL algorithm, D2D links are able to intelligently making their adaptive selections to enhance their overall performance based on the immediate observations in D2D environments. The results show that the proposed solution can efficaciously guarantee the transmission quality and enhance the sum rate of the cellular and D2D users, and outperform other existing algorithms by having better convergence and overall throughput of the network.

Chapter 5

Resource Allocation for Multiple D2D Communications in Uplink Multi-Cell Networks

5.1 Introduction

In this chapter, we consider a multi-cell network with inter-cell interferences and assume D2D communications can be established between two devices located in the same cell or different cells. The main objectives of this chapter are maximization of throughput and the minimization of power consumption, as well as minimization of interference level in multiple cells environment. We propose a resource allocation scheme designed to address all the interferences issues for the uplink multi-cell network to enhance the performance and the spectral efficiency in the network system. We formulate the optimization problem which aims at maximizing the overall network throughput while guaranteeing the QoS requirement for both CUEs and DUEs. Rather than using the conventional joint optimization approach with high computational complexity, we solve the overall throughput optimization problem by splitting the original problem into three subproblems; candidate channel selection for DUEs, optimal power allocation issues based on the dual Lagrangian approach and the resource allocation for multiple D2D pairs based on a genetic algorithm. Then, we propose an optimal resource allocation algorithm for D2D communications underlaying cellular networks.

5.2 System Model and Problem Formulation

5.2.1 System Model

We consider a multi-cell system in which are neighboring base stations communicate with mobile terminals over a coverage area. Figure (5.1) shows the two-cell system model used to describe multi-cell D2D communications underlying cellular networks as the basic concept. There are N subchannels in this network of OFDMA (Orthogonal Frequency Division Multiple Access), and M-DUEs coexist with N-CUEs in the serving eNB. We also assume that all eNBs in the network are identical and have the same bandwidth and that each eNB bandwidth is separated into multiple channels of equivalent bandwidth sizes. In addition, we assume that the cellular network is a fully loaded scenario in which the total quantity of channels allotted for uplink transmission is equal to the number of existed CUEs in each eNB. Besides, we assume that D2D links share uplink (UL) i-th channels occupied by cellular users. Let $B_S = \{1, 2, ..., B\}$, $C = \{1, 2, ..., N\}$ and $D = \{1, 2, ..., M\}$ represent the index sets of cells, CUEs/channels and DUEs, respectively. The transmitter of a D2D pair (D2D-Tx) and its receiver (D2D-Rx) are not required to be in the same cell that communicates directly under the control of the serving eNB. The network's frequency reuse is equivalent to one. Hence, the DUEs in serving eNB are victims of interference from CUEs in neighboring eNBs. Also, we assume both CUEs and D2D pairs have their minimum QoS requirements in terms of SINR on an i-th channel, the peer device discovery and the session setup are completed before the resource allocation, and the eNB has the perfect CSI information of all the links.

Let consider both the fast fading due to multipath propagation and slow fading due to shadowing [36]. Thus, the channel gain between CUE i and the eNB can be expressed as:

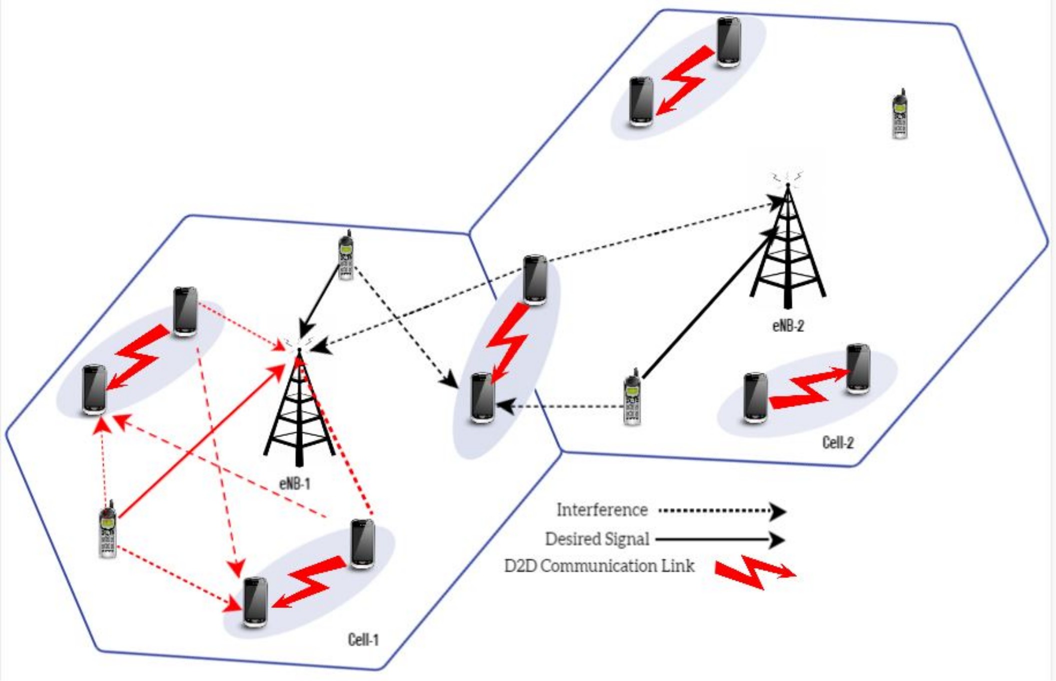


Figure 5.1: System model for D2D communications in uplink multi-cell network.

$$g_{i,b}^{(i)} = \kappa \beta_{i,b} \Gamma_{i,b} \, L_{i,b}^{-\alpha} \tag{5.1}$$

D2D communication realizing to maximize the utilization of cellular network spectrum and enhance system throughput, based on the designed resource allocation algorithm for DUEs should be characterized by the following three features: a) Multiple DUEs are allowed to reuse the same CUE channel, b) Adaptive power control for both CUEs and DUEs and c) Reasonable complexity.

To achieve the desired Quality-of-service (QoS) levels for CUEs and DUEs, three kinds of interference will be considered while allocating the resources for each DUE. First is the intra-cell interference between CUEs and DUEs that are using the same channels inside the same cell. The second is the inter-cell interference between CUEs and DUEs that are using the same channels but located in different cells, and the third one is the interference between different D2D pairs when reuses the same channel.

5.2.2 Problem Formulation

A D2D pair is set up only when the minimum SINR requirement can be guaranteed and incurred interference to the CUEs is below a threshold. In this case, we call it an admissible pair and the CUE to be shared resources as a reuse partner. So, in this chapter, we focus on the problem of how to exploit D2D communications to improve the overall throughput.

All D2D pairs (DUEs) and CUE's have a minimum rate constraint in order to satisfy their QoS requirements. These minimum rate requirements can be translated into minimum SINR constraints. Our objective is to maximize the total transmission rate of the CUEs and the DUEs and maximize the number of served D2D pairs to reuse the CUE's channel while satisfying the rate requirements of all CUEs. This is subject to minimum SINR constraints for the cellular and D2D pairs to enhance the overall throughput of the network. Since all the related channel gains, $g_{i,b}^{(i)}$, $h_{j,b}^{(i)}$ are known, rate constraint can be translated into an SINR constraint. The SINR constraint for the CUE i can be expressed as:

$$\xi_i^{c,b} = \frac{P_i^{c,b} g_{i,b}^{(i)}}{\sum_{j \in D} \rho_{i,j} P_j^d h_{j,b}^{(i)} + \sigma_N^2} \geq \xi_{i,min}^{c,b}, \qquad \forall i \in C, \forall b \in B_S \tag{5.2}$$

Due to fixed SINR constraint, with the known channel $g_{i,b}^{(i)}$, and for given transmit powers P_j^d, the maximum interference limit for a CUE i at B_S can be expressed as:

$$I_{max,B}^{(i)} = \frac{P_i^{c,b} g_{i,b}^{(i)}}{\xi_{i,min}^{c,b}} - \sigma_N^2, \qquad \forall i \in C, \forall b \in B_S \tag{5.3}$$

Where $I_{max,B}^{(i)}$ denotes the maximum interference limit to satisfy required SINR in CUE i's channel. Similarly, the minimum SINR requirements of DUE j, given that it is reuse channel i may be expressed as:

$$\xi_j^d = \frac{\rho_{i,j} P_j^d g_{j,j}^{(i)}}{\tilde{I}_j^d} \geq \xi_{j,min}^d, \qquad \forall j \in D \tag{5.4}$$

Where $\tilde{I}_j^d = \sum_{B\in B_S}\sum_{i\in C} P_i^{c,B} h_{i,j}^{(i),B} + \sum_{k\in D,\, k\neq j} \rho_{i,k} P_k^d h_{k,j}^{(i)} + \sigma_N^2$ is the total interference at the receiver of DUE j. Our goal is to maximize the total sum-rate of the CUEs and the D2D pairs while satisfying the rate requirements of all CUEs and DUEs. Whereas combined with the SINR expressions of different users, we can formulate the overall throughput optimization problem. Mathematically, the overall optimization problem of the network throughput can be formulated as follows:

$$\max_{\rho_{i,j}, P_j^d} R_{overall} = \sum_{b\in B_S}\sum_{i\in C}\left[\log_2(1+\xi_i^{c,b}) + \sum_{j\in D}\rho_{i,j}\log_2(1+\xi_j^d)\right] \tag{5.5}$$

$$, \qquad Subject\ to:$$

$$\xi_i^{c,b} \geq \xi_{i,min}^{c,b}, \qquad \forall i\in C, \forall b\in B_S \tag{5.6}$$

$$\xi_j^d \geq \xi_{j,min}^d, \qquad \forall j\in D \tag{5.7}$$

$$\rho_{i,j} \in \{0,1\}, \qquad \forall i\in C, \forall j\in D \tag{5.8}$$

$$\sum_i \rho_{i,j} \leq 1,\ \rho_{i,j}\in\{0,1\},\ \forall j\in D \tag{5.9}$$

$$0 \leq P_i^{c,b} \leq P_{max}^{c,b} \quad \forall i\in C \tag{5.10}$$

$$0 \leq P_j^d \leq P_{max}^d \quad \forall j\in D \tag{5.11}$$

Where $\rho_{i,j}$ is the channel reuse indicator for CUE i and D2D pair j, $\rho_{i,j}=1$ when D2D pair j reuses the channel of CUE i; otherwise, $\rho_{i,j}=0$. Constraints (5.6) and (5.7) represent the QoS requirements of CUEs and DUEs, respectively. The constraint (5.8) represents the channel reuse relationship between CUEs and DUEs combined with resource partition model. Constraint (5.9) ensures that a DUE share at most one existing CUE's resource. Constraints (5.10) and (5.11) guarantee that the transmit powers of cellular users and D2D pairs are within the maximum limit. All the notations used are given in Table 5.1.

Specifically, a resource allocation optimization problem in (5.5) is not concave and the problem is NP-hard as a mixed-integer nonlinear programming (MINLP) problem under power, spectrum resource reusing and QoS constraints. The formulation derived

Table 5.1: Notations and their Definitions

Notation	*Definitions*
κ	*Constant determined by system parameters.*
$\beta_{i,b}$	*Fast fading gain with exponential distribution.*
$\Gamma_{i,b}$	*Slow fading gain with log-normal distribution.*
$L_{i,b}$	*Distance between CUE i and the eNB b.*
$L_{i,j}$	*Distance between CUE i and the receiver of DUE j.*
α	*Pathless exponent.*
$g_{j,j}^{(i)}$	*Channel gain of D2D pair j on i-th channel.*
$g_{i,b}^{(i)}$	*Channel gain from CUE i to the eNB b on i-th channel.*
$h_{j,b}^{(i)}$	*Interference gain of the links, from DUE-TX j to eNB b on i-th channel*
$h_{i,j}^{(i),B}$	*Interference gain of the links, from CUE i in eNB B to DUE-RX j on i-th channel.*
$h_{th}^{(i)}$	*Threshold interference gain between the D2D links on i-th channel.*
σ_N^2	*The energy of the additive white Gaussian noise (AWGN) on each channel*
$\xi_{i,min}^{c,b}$	*The minimum SINR requirements of CUE i in eNB b.*
$\xi_{j,min}^{d}$	*The minimum SINR requirements of DUE j.*
$\xi_i^{c,b}$	*The SINR of CUE i in eNB b.*
ξ_j^d	*The SINR of DUE j.*
$P_{max}^{c,b}$	*The maximum transit power of CUE in eNB b.*
P_{max}^d	*The maximum transit power of DUE.*
$P_i^{c,b}$	*Transmit power of CUE i in eNB b.*
P_j^d	*Transmit power of DUE j.*

utilizes a continuous variable to represent power control strategy (how much transmission power should be assigned to D2D transmitter for the potential D2D), and a binary variable to represent the resource allocation decision (which D2D pair can share the same spectrum resource with CUE). Which means standard convex optimization methods cannot be used. In the following section, we will solve the overall throughput optimization problem by dividing the original problem into three steps.

5.3 Optimal Resource Allocation

In this section, we will focus on how to allocate resource reuse between cellular users and D2D users in order to maximize the total throughput after the introduction of D2D communication. We will solve the overall throughput optimization problem by switch the original one into three subproblems. The first one, where we can find the optima reuse candidate for each D2D pair with minimum-SINR. The second one is the power control for a DUE and its reuse partner, where we assign transmit power to maximize the overall throughput of each user (e.g. CUEs and DUEs). The third one is the resource allocation for multiple D2D pairs, where we find the optimal resource pairing relationship between CUEs and DUEs.

5.3.1 Candidate channel selection of D2D pairs

We will focus on how to assign channel reuse among CUEs and DUEs in this section, where we will find the superior reuse candidate for each D2D pair. Furthermore, the purpose of this step is to decide the initial set of candidate CUEs' channels that can be reused by each DUE. Since the key objective of this chapter is to maximize the overall uplink network throughput taking all the interferences into consideration. We assume that each CUE has already been allocated an orthogonal channel for communication according to certain scheduling policies. Therefore, the interference relationship between co-channel CUEs in other cells is invariant.

The purpose of this stage is to select the initial set of candidate channels that can be reused by each D2D pair. Since the main objective of the proposed algorithm is to maximize the overall uplink network throughput. To increase the throughputs of cellular and D2D users, it is attractive to have higher SINR, which can be realized that having smaller values of $h_{i,j}^{(i),B}$ and $h_{k,j}^{(i)}$ reduces the interference from CUE i to DUE j and from DUE j to DUE k when sharing the same channel i, respectively, resulting in higher ξ_j^d and D2D throughput gain. In order to pack more D2D pairs to reuse the same channel and still satisfy the minimum SINR requirements of both CUE and DUEs. To do so, the interference $h_{k,j}^{(i)}$ should be less than $h_{th}^{(i)}$, which the BS is decide $h_{th}^{(i)}$, depending on the maximum distance allowed between D2D pairs and the threshold distance between other D2D pairs to sharing the same channel i. Thus, the interferences are avoided between

D2D pairs which are expected to reuse the same channel, as following:

$$h_{j,k}^{(i)} = \kappa \beta_{j,k} \Gamma_{j,k} \; L_{j,k}^{-\alpha} < h_{th}^{(i)} \tag{5.12}$$

The jth DUE that has interference less than $h_{th}^{(i)}$, with other DUE k for given constant CUEs and DUEs transmit powers when sharing the same channel i. Consequently, the set of DUEs that initially permitted reusing the ith channel can be selected as the group of DUEs ($\bar{D}_r^{(i)} \subseteq D$) under the condition that the generated accumulated interference on the ith channel attains constraint in the following equation:

$$\sum_{j \in \bar{D}_r^{(i)}} I_{j,B}^{(i)} \leq I_{max,B}^{(i)} \tag{5.13}$$

Where $I_{j,B}^{(i)}$ is the interference gain from the D2D j to the BS for given constant DUEs transmit power. Therefore, the set of candidate channels that can be primarily reused by jth DUE ($D_{r,j} \subseteq C$) can be derived as follows:

$$D_{r,j} \leftarrow i, \quad if\; j \in \; \bar{D}_r^{(i)} \quad \forall i \in C. \tag{5.14}$$

Therefore, the eNB can easily find suitable CUE candidates for a DUE based on all conditions in (5.12) and (5.13) are satisfied.

5.3.2 Optimal Power Allocation

In this section, we will address the problem of how to assign the optimal power allocation for each DUE over the pre-determined set of channels resulted from the candidate channel selection step is computed in the previous section. Therefore, the problem of deciding the optimal power allocation on each channel reused by each D2D pair is formulated as a constrained optimization problem that the sum throughput is maximized while all constraints are satisfied, which can be expressed as:

$$\left.\begin{array}{l}
U(P_j^{d*}) = \arg \max\limits_{P_j^d} \sum\limits_{b\in B_S}\sum\limits_{i\in C}\left[\log_2(1+\xi_i^{c,b}) + \sum\limits_{j\in D}\log_2(1+\xi_j^d)\right] \\
\qquad\qquad\qquad Subject\ to: \\
\xi_i^{c,b} = \dfrac{P_i^{c,b} g_{i,b}^{(i)}}{\sum_{j\in D} P_j^d h_{j,b}^{(i)} + \sigma_N^2} \geq \xi_{i,min}^{c,b}, \qquad \forall i \in C, \forall b \in B_S \\
\xi_j^d = \dfrac{P_j^d g_{j,j}^{(i)}}{\sum_{B\in B_S}\sum_{i\in C} P_i^{c,B} h_{i,j}^{(i),B} + \sum_{k\in D, k\neq j} P_k^d h_{k,j}^{(i)} + \sigma_N^2} \geq \xi_{j,min}^d,\ \forall j \in D \\
\qquad 0 \leq P_i^{c,b} \leq P_{max}^{c,b} \qquad \forall i \in C \\
\qquad 0 \leq P_j^d \leq P_{max}^d \qquad \forall j \in D
\end{array}\right\} \quad (5.15)$$

In this section, we will focus on the D2D power allocation optimization.

1. D2D-Rate Maximization

This problem is formulated as a constrained optimization problem that maximizing DUE sum-rate as follows:

$$\left.\begin{array}{c}
U\left(P_j^{d*}\right) = \max\limits_{P_j^d} \sum\limits_{b\in B_S}\sum\limits_{i\in D_{r,j}}\sum\limits_{j\in D}\log_2\left(1+\dfrac{P_j^d g_{j,j}^{(i)}}{\tilde{I}_j^d}\right) \\
Subject\ to: \\
\xi_j^d = \dfrac{P_j^d g_{j,j}^{(i)}}{\tilde{I}_j^d} \geq \xi_{j,min}^d,\ \forall j \in D \\
0 \leq P_j^d \leq P_{max}^d, \qquad \forall j \in D
\end{array}\right\} \quad (5.16)$$

We can solve the problem by Lagrangian dual optimization. The Lagrangian function of above problem is defined as follows:

$$\left.\begin{array}{rl}
L\left(P_j^d, \vec{\lambda}, \vec{\mu}\right) = & \sum\limits_{b\in B_S}\sum\limits_{i\in D_{r,j}}\sum\limits_{j\in D}\log_2\left(1+\dfrac{P_j^d g_{j,j}^{(i)}}{\tilde{I}_j^d}\right) \\
& -\sum\limits_{j\in D}\lambda_j\left(P_j^d g_{j,j}^{(i)} - \tilde{I}_j^d \xi_{j,min}^d\right) \\
& -\sum\limits_{j\in D}\mu_j\left(P_j^d - P_{max}^d\right)
\end{array}\right\} \quad (5.17)$$

Where $\vec{\lambda} = [\lambda_1, \dots\dots\dots, \lambda_k]^T \succeq 0$, and $\vec{\mu} = [\mu_1, \dots\dots\dots, \mu_k]^T \succeq 0$ denote the Lagrange multiplier vectors. By using Karush-Kuhn-Tucker (KKT) conditions [88], the optimal solution of (5.17) can be found to obtain the optimal power allocation. So, for each DUE j, the optimal power can be derived as:

$$P_j^{d*} = \left[\frac{1}{(\lambda_k \, g_{j,j}^{(i)} + \mu_k) \ln 2} - \frac{\tilde{I}_j^d}{g_{j,j}^{(i)}} \right] \tag{5.18}$$

Using the sub-gradient method, the Lagrange multipliers are iteratively updated until convergence as follows:

$$\left. \begin{aligned} \lambda_k^{t+1} &= \lambda_k^t - \alpha \left(\tilde{I}_j^d \, \xi_{j,min}^d - P_j^d \, g_{j,j}^{(i)} \right) \\ \mu_k^{t+1} &= \mu_k^t - \beta \left(P_{max}^d - P_j^d \right) \end{aligned} \right\} \tag{5.19}$$

Let t denotes the update time, α and β are the step sizes for Lagrangian factors update.

2. Sum-Rate Maximization

Note that the sum-rate of cellular users over RBs in cellular mode, prior to the D2D pair entering the system, is given by:

$$R_C = \sum_{i \in C} \log_2 \left(1 + \frac{P_i^{c,b} \, g_{i,b}^{(i)}}{\sigma_N^2} \right) \tag{5.20}$$

We estimate the expected D2D throughput gain, defined as the difference between the maximum expected sum-rate of the system and the maximum sum-rate of the partner CUE without D2D, given by:

$$\left. \begin{aligned} U\left(P_j^{d*}\right) = \max_{P_j^d} \sum_{b \in B_S} \sum_{i \in C} \sum_{j \in D} \\ \left[\log_2(1 + \xi_i^{c,b}) + \log_2(1 + \xi_j^d) - \log_2(1 + \frac{P_i^{c,b} \, g_{i,b}^{(i)}}{\sigma_N^2}) \right] \end{aligned} \right\} \tag{5.21}$$

Given these SINR threshold constraints, we can approximate the capacity in higher SINR cases by removing the term '1' from the logarithm functions for all term, and after some mathematical manipulations can be derived as:

$$U\left(P_j^{d*}\right) = \max_{P_j^d} \sum_{b\in B_S} \sum_{i\in C} \sum_{j\in D} \log_2 \left(\frac{P_j^d \; g_{j,j}^{(i)} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d} \right) \tag{5.22}$$

Where $\tilde{I}_i^c = \sum_{j\in D} P_j^d \; h_{j,b}^{(i)} + \sigma_N^2$ is the total interference at CUE i. Since the transmit power for all CUEs are assumed to be fixed, so the overall uplink network throughput can be maximized by determining the optimal power allocation for each DUE-TX on each channel that maximizes the DUEs sum-rate while maintaining the required QoS for both CUEs and DUEs. This problem is formulated as a constrained optimization problem that Sum-Rate Maximization, which is equivalent to:

$$\left.\begin{aligned}
U\left(P_j^{d*}\right) = \arg \quad & \max_{P_j^d} \sum_{b\in B_S} \sum_{i\in C} \sum_{j\in D} \log_2 \left(\frac{P_j^d \; g_{j,j}^{(i)} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d} \right) \\
& Subject\, to: \\
& \xi_i^{c,b} = \frac{P_i^{c,b} \; g_{i,b}^{(i)}}{\tilde{I}_i^c} \geq \xi_{i,min}^{c,b}, \qquad \forall i \in C, \forall b \in B_S \\
& \xi_j^d = \frac{P_j^d \; g_{j,j}^{(i)}}{\tilde{I}_j^d} \geq \xi_{j,min}^d, \qquad \forall j \in D \\
& 0 \leq P_i^{c,b} \leq P_{max}^{c,b}, \qquad \forall i \in C \\
& 0 \leq P_j^d \leq P_{max}^d, \qquad \forall j \in D
\end{aligned}\right\} \tag{5.23}$$

We can solve the problem by Lagrangian dual optimization. The Lagrangian of above problem is defined as:

$$\begin{aligned}L\left(P_j^d, \vec{\lambda}, \vec{\beta}, \vec{\nu}, \vec{\mu}\right) = &\sum_{b \in B_S} \sum_{i \in C} \sum_{j \in D} \log_2 \left(\frac{P_j^d g_{j,j}^{(i)} * \sigma_N^2}{\tilde{I}_i^c * \tilde{I}_j^d} \right) \\ &- \sum_{i \in C} \lambda_i \left(P_i^{c,b} g_{i,b}^{(i)} - \tilde{I}_i^c \xi_{i,min}^{c,b} \right) \\ &- \sum_{j \in D} \beta_j \left(P_j^d g_{j,j}^{(i)} - \tilde{I}_j^d \xi_{j,min}^d \right) \\ &- \sum_{i \in C} \nu_i \left(P_i^{c,b} - P_{max}^{c,b} \right) \\ &- \sum_{j \in D} \mu_j \left(P_j^d - P_{max}^d \right) \end{aligned} \tag{5.24}$$

Where $\vec{\lambda} = [\lambda_1, \dots \dots \dots, \lambda_k]^T \succeq 0$, $\vec{\beta} = [\beta_1, \dots \dots \dots, \beta_k]^T \succeq 0$, $\vec{\nu} = [\nu_1, \dots \dots \dots, \nu_k]^T \succeq 0$, and $\vec{\mu} = [\mu_1, \dots \dots \dots, \mu_k]^T \succeq 0$ are vectors of dual variables. By using Karush-Kuhn-Tucker (KKT) conditions [88], the optimal solution of (5.24) can be found to obtain the optimal power allocation. So, for each DUE j, the optimal power can be derived as:

$$P_j^{d*} = \left[\frac{1}{\sum_{b \in B_S} \sum_{i \in C} \sum_{j \in D} \left(\frac{h_{j,b}^{(i)}}{\tilde{I}_i^c} \right) + \left(\beta_k \, g_{j,j}^{(i)} + \mu_k \right) \ln 2} \right] \tag{5.25}$$

So, using the sub-gradient method, the Lagrange multipliers are iteratively updated until convergence as in the previous section.

5.3.3 Resource Allocation for Multiple D2D Pairs

In the above, we have discussed how to find reuse candidates for a D2D pair with a targeted QoS requirement and the optimal power allocation schemes for it and the reuse partners. Now, we can find the optimal reuse partner for a D2D pair when more than one partner users are available. Given the maximum achievable throughput for each D2D pair when reusing each cellular channel. Therefore, when there are multiple admissible D2D pairs, the problem of finding the optimal reuse channel for each D2D pair is maximum the D2D throughput gain which can be expressed as:

$$\left.\begin{array}{c} U=\max\limits_{\rho_{i,j}}\sum\limits_{i\in D_{r,j}}\sum\limits_{j\in D}\rho_{i,j}\log_2(1+\xi_j^d) \\ Subject\ to: \\ \sum\limits_{i}\rho_{i,j}\leq 1,\ \rho_{i,j}\in\{0,1\}\,,\ \forall j\in D \end{array}\right\} \tag{5.26}$$

To reuse the resource between one CUE and multiple DUEs, the genetic algorithm (GA) is more suitable than the bipartite matching approach. Therefore, GA is applied in the third phase to solve (5.26) similar in [95].

5.3.4 Optimal Resource Allocation Algorithm

Algorithm 5.1 solves the resource allocation problem in (5.5). The proposed algorithm requires interference values from the D2D transmitters to the BS $I_{j,B}^{(i)}$, the interference limits of each ith channel at BS, $I_{max,B}^{(i)}$, and the interference from DUE j to DUE k when sharing the same ith channel, $h_{j,k}^{(i)}$. The proposed algorithm 5.1 is executed in three steps. In the first step, the candidate set of channels that can be initially reused by each DUE is determined, the complexity of this step is $\mathcal{O}\left(M(M-1)*N\right)$. In the second step, the optimal power allocation for each DUE j on each ith channel is calculated, the complexity of this step is $\mathcal{O}\left(M*N\right)$. The third step is, however, the resource allocation for multiple D2D pairs based on genetic algorithm, the genetic algorithm-based scheme is developed to select a suitable reuse partner for each D2D pair so as to maximize the D2D throughput, the complexity of this step is $\mathcal{O}\left((M*N)*log(N)\right)$. Therefore, the computational complexity of the proposed algorithm is $\mathcal{O}\left(M^2*N\right)$, which is a polynomial complexity. Flow chart of this optimal resource allocation scheme is illustrated in Figure (5.2).

Algorithm 5.1 Optimal Resource Allocation Algorithm

```
Input: $C$: The set of active CUEs and $D$: The set of DUEs.
Initialization : $\begin{cases} D_{r,j} = \emptyset,\ \bar{D}_r^{(i)} = \emptyset,\ \rho_{i,j} = 0, \quad \forall i \in C\ \&\ \forall j \in D, \\ \qquad \lambda,\ \beta,\ \nu,\ \mu \quad \text{and set } t = 0. \end{cases}$
 1: First step: Channel Selection
 2: while $C \neq \emptyset \ \ \& \ \ D \neq \emptyset$ do
 3:     for $i \in C$ do
 4:         for $j \in D$ do
 5:             for $k \in D\ \ \&\ \ k \neq j$ do
 6:                 Calculate $h_{j,k}^{(i)}$ by using eq. (5.12).
 7:                 if $(h_{j,k}^{(i)} < h_{th}^{(i)})$ then
 8:                     $\bar{D}_r^{(i)} \leftarrow j\ \ \&\ \ k$
 9:                 end if
10:             end for
11:         end for
12:         if $(\sum_{j \in \bar{D}_r^{(i)}} I_{j,B}^{(i)} \leq I_{max,B}^{(i)})$ then
13:             Set $D_{r,j} = D_{r,j} \cup i$.
14:         else
15:             $\bar{D}_r^{(i)} \leftarrow \bar{D}_r^{(i)} \backslash j$,        // Remove $jth$ DUE from the set $\bar{D}_r^{(i)}$ //
16:         end if
17:     end for
18: end while
19: Second step: Power Control
20: repeat
21: for $\forall$ DUE $j \in D$ & $\forall$ CUE $i \in D_{r,j}$ do
22:     Calculate $(P_j^{d*})$ using eq. (5.18) or (5.25).
23: end for
24:      Update $\lambda, \beta, \nu, \mu$ and $t = t + 1$.
25: until convergence or $t_{max}$.
26: for $\forall$ DUE $j \in D$ & $\forall$ CUE $i \in D_{r,j}$ do
27:         According to formula (5.2) & (5.4),  calculate $\xi_i^{c,b}$ & $\xi_j^d$.
28:     if $(\xi_i^{c,b} \geq \xi_{i,min}^{c,b})\ \ \&\ \ (\xi_j^d \geq \xi_{j,min}^d)$ then
29:             Set $\rho_{i,j} = 1$.
30:     end if
31: end for
32: Third step: Resource Allocation
33: for $\forall$ DUE $j \in D$ & $\forall$ CUE $i \in D_{r,j}$ do
34:     Formulate the GA to do resource allocation.
35:     Generate the first random population. repeat
36:     i. Calculate the fitness value of each individual using (5.26) and save the best solution.
37:     ii. Apply the selection process on the parents to select parents of the next offspring.
38:     iii. Produce a new generation by applying the crossover operator on selected parents.
39:     iv. Apply mutation to enrich the new generation with new solutions.
40:     v. Calculate the fitness of the new offspring and update the best solution if any.
41:     until termination criteria are met.
42: end for
43: Find the best fitness value and the corresponding best individual $G^*$ in the last generation.
44: Each DUE $j$ corresponding best individual $G^*$, will reuse corresponding subchannel for its transmission
    with $P_j^{d*}$ calculated in step 22.
```

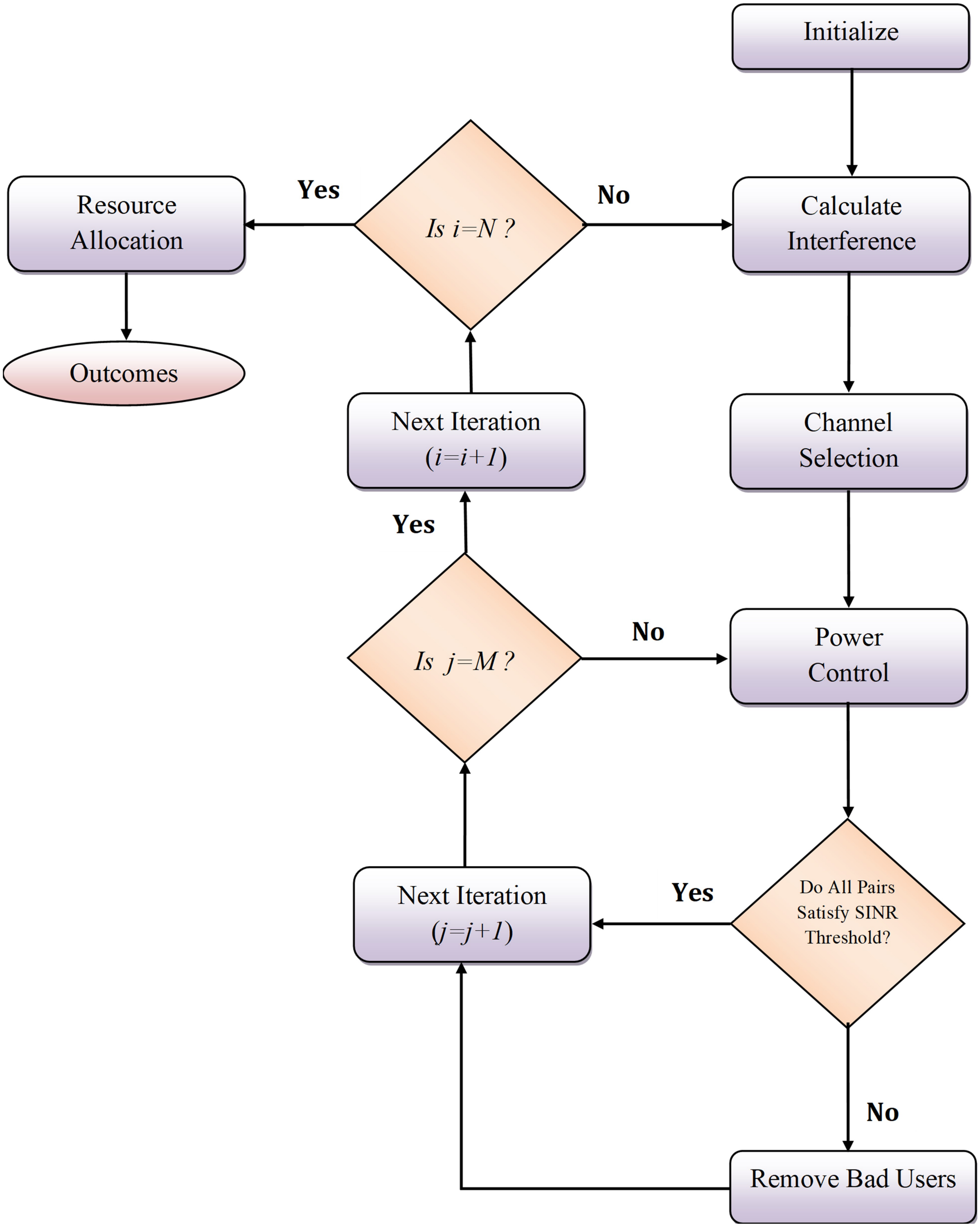


Figure 5.2: Flowchart of the proposed optimal resource allocation algorithm for the D2D communication.

5.4 Performance Analysis

In our simulation, we consider two cells each with a radius of 500m, which are neighbours for each other, where DUEs share uplink resources with CUEs. Where the CUEs are uniformly distributed in all cells. We adopt the clustered distribution model for D2D pairs, in which the transmitter (DUE-Tx) and the receiver (DUE-Rx) of each D2D pair are uniformly distributed in a cluster with radius r; and clusters are uniformly distributed in all cells so that the transmitter and the receiver of each pair may be situated in the same cell or different cells. The snapshot for the distribution of CUEs and DUEs in a multi-cell networks in the simulation scenario is shown in Figure (5.3). The used parameters values are: Uplink bandwidth = 5MHz, channel bandwidth =180 KHz, $P_{max}^{c,b} = P_{max}^{d}$ =24 dBm, noise power σ_N^2 = -114 dBm, pathloss exponent α=4 and SINR requirement for DUEs and CUEs are uniform distributed from 0 to 10 dB.

To evaluate the performance of the proposed resource allocation scheme, we consider two metrics that are used to evaluate the efficiency: access rate defined as the ratio of the number of accessed DUEs and the total number of DUEs; and D2D throughput gain defined as the maximum increased throughput brought by the accessed DUEs. Moreover, we compare our scheme with two proposed power allocation algorithms based on sum-rate maximization and D2D-rate maximization, respectively. In addition, the performance of the proposed algorithm is compared with the exhaustive search method as an optimal solution, the heuristic scheme offered in [38] and the random search approach (referred to as random search), in terms of the D2D throughput gain.

Figure(5.4) shows the D2D throughput gain for the proposed algorithm in comparison with the other algorithms, under different numbers of DUEs ($r_{max}^{Tx-Rx} = 20m$) and versus the maximum distance between DUE-TX and DUE-RX, $r(m)$. It can be observed that the proposed method outperforms the other comparable algorithms and also obtains a solution close to that of the exhaustive search.

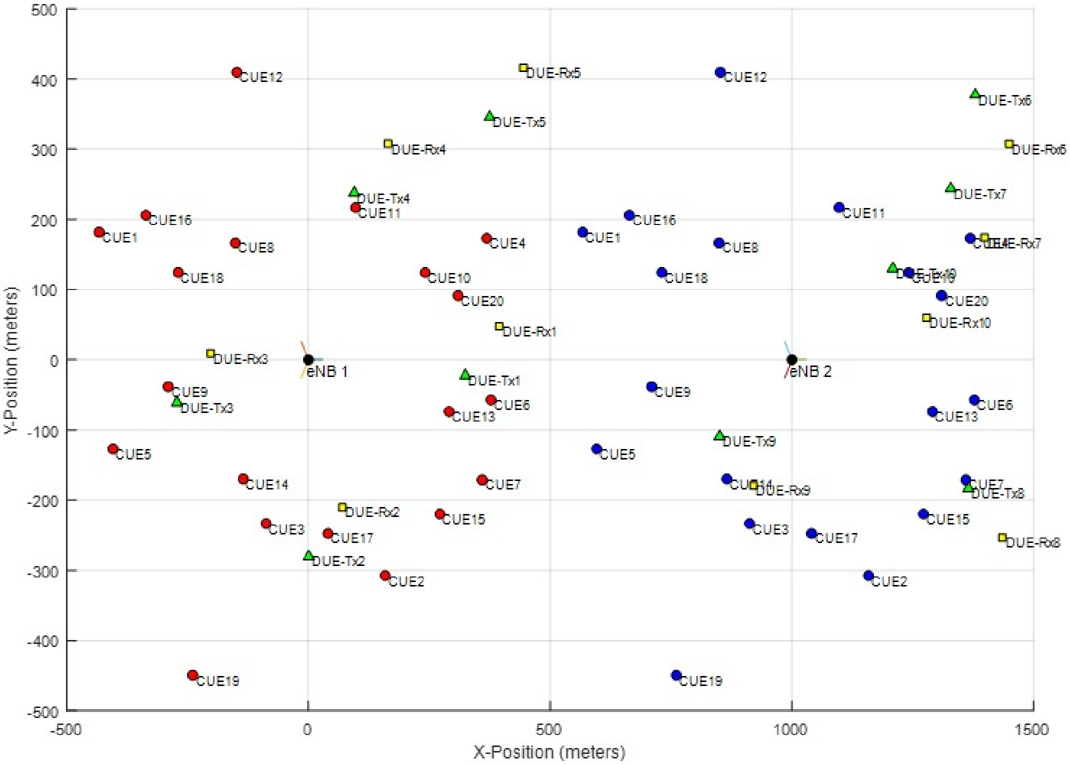
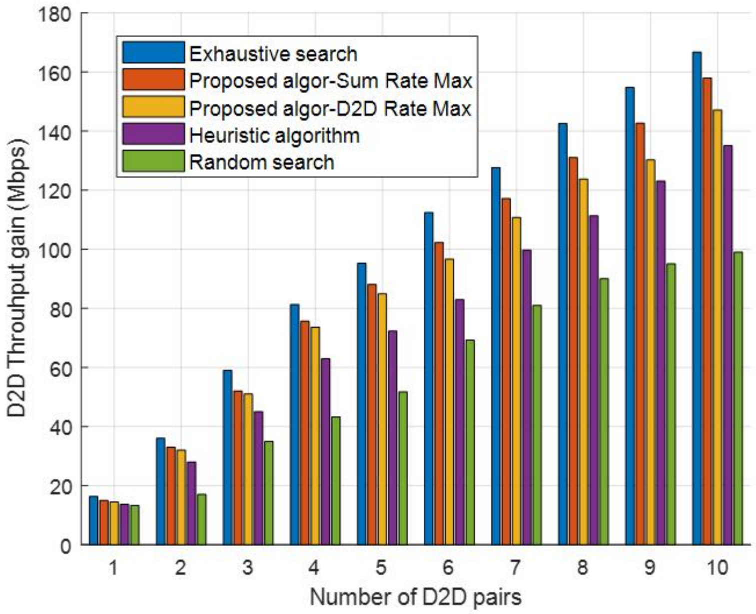


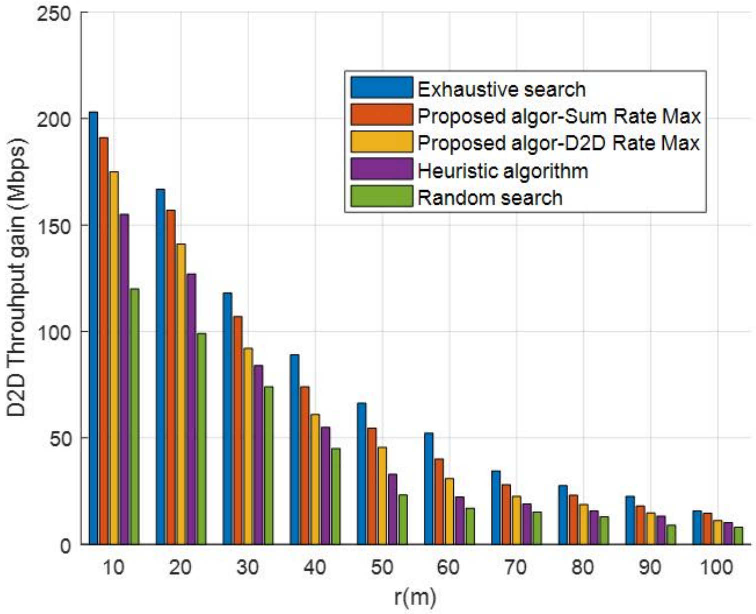
Figure 5.3: Topology of D2D Communications in multi-cell networks.

The performance of the proposed algorithm at various minimum SINR requirements for CUEs and DUEs is shown in Figure (5.5). The access rate and D2D throughput gain are enhanced, when the SINR requirements are reduced. This is because low SINR requirements for users will lead to an increase in the maximum allowable interference for CUEs. Therefore, more DUEs will allow being admitted and sharing the same channels with CUEs and consequently, the access rate and D2D throughput gain are increased.

Figure (5.6) illustrates the effect of varying cell radius on algorithm efficiency. As shown in the figure, the system performance will enhance when increasing the cell radius, because the average distance of the interference links is expanded which resulting in a decrease in the interference on both CUEs and DUEs. This will allow for admit more DUEs and will hence achieve higher throughput as well as the access rate.

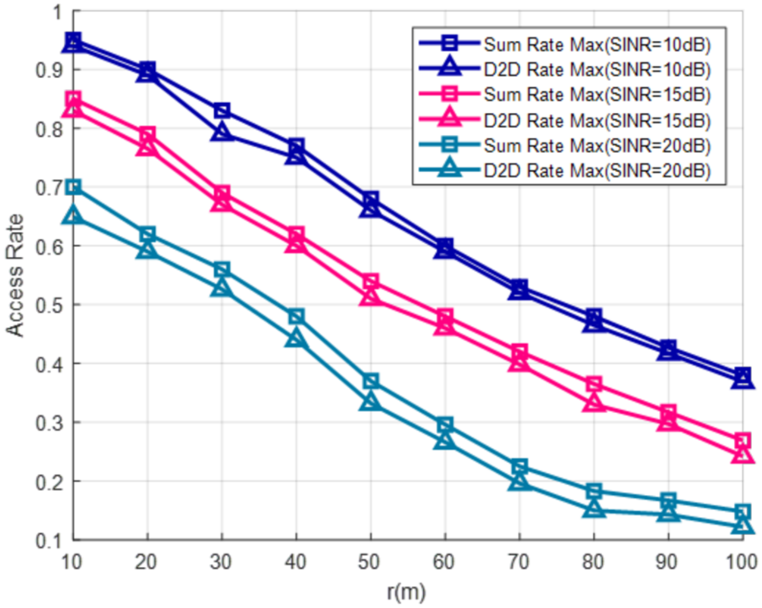


(a) D2D throughput gain

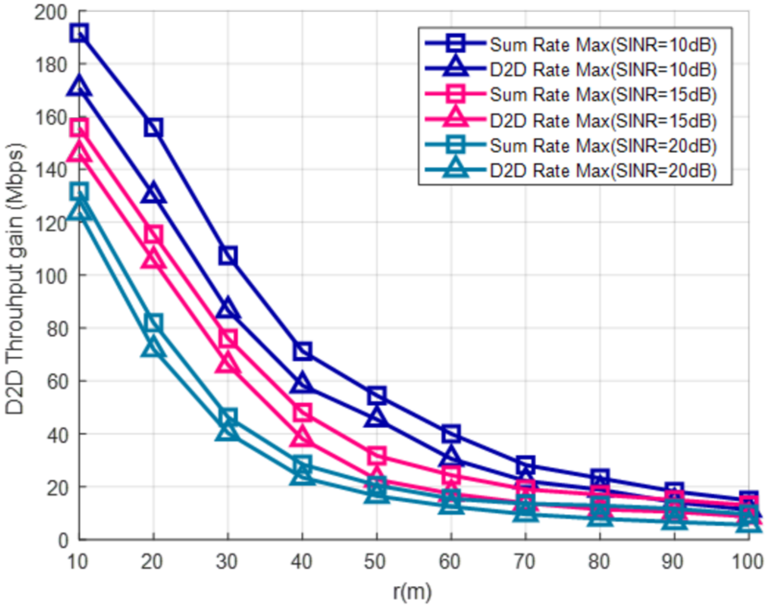


(b) D2D throughput gain

Figure 5.4: D2D throughput gain for different number of D2D pairs and versus maximum distance between DUE-TX and DUE-RX of a D2D pairs, when cell radius= 0.5 Km, CUEs=20 and SINR=10 dB.



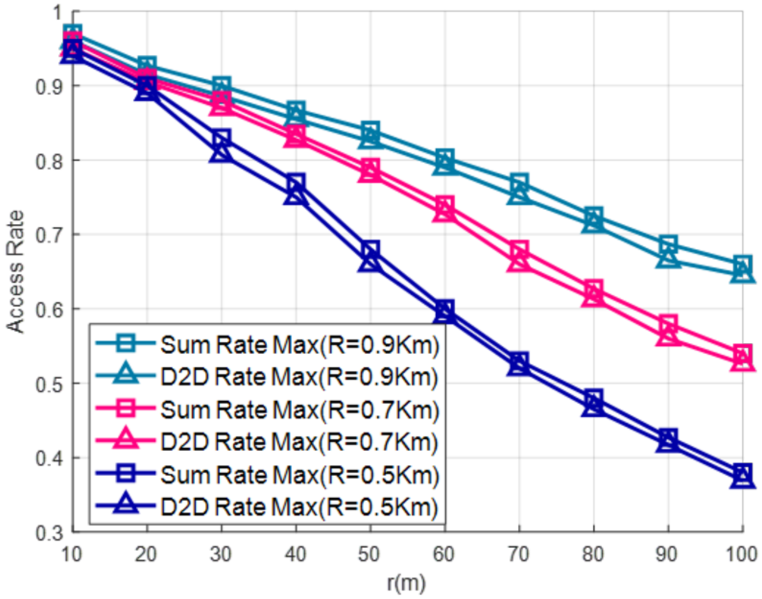
(a) Access rate



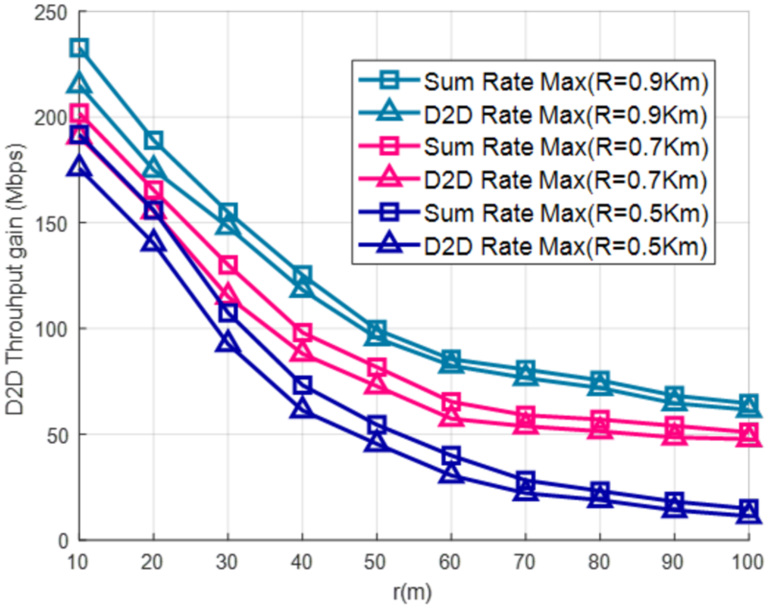
(b) D2D throughput gain

Figure 5.5: Access rate and D2D throughput gain at various minimum SINR, when cell radius= 0.5 Km, CUEs=20 and DUEs=10.

The effect of different maximum transmit power is illustrated in Figure (5.7). It is realized that the performance of the proposed algorithm declines with the decrease of the



(a) Access rate



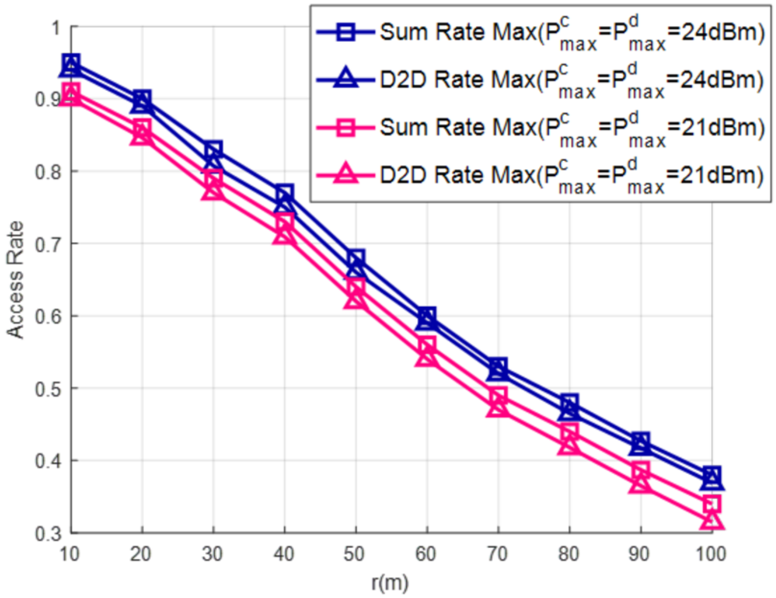
(b) D2D throughput gain

Figure 5.6: Access rate and D2D throughput gain with varying the cell radius, when SINR=10 dB, CUEs=20 and DUEs=10.

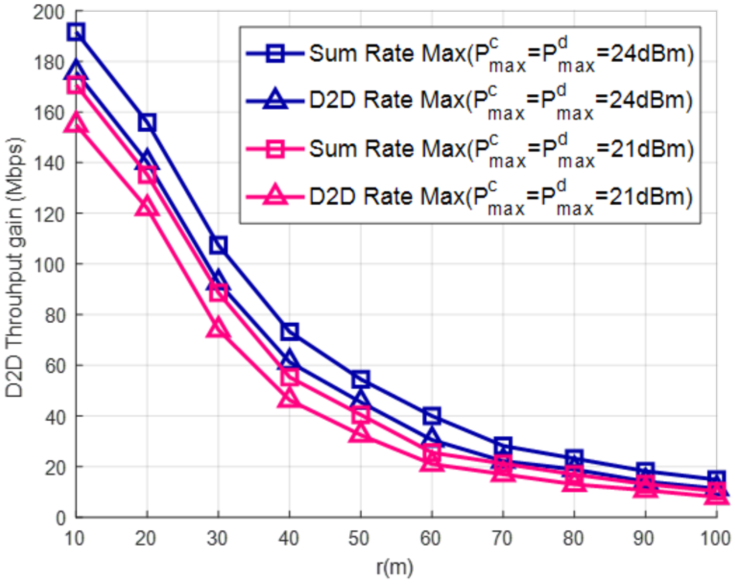
maximum transmits power of CUEs and DUEs, and the degradation becomes fast when the maximum distance between DUE-TX and DUE-RX is large while the increase of the maximum transmit power will enhance the system performance. On other hand, when the maximum distance between DUE-TX and DUE-RX is small, the channel gain of the D2D link is high and the SINR requirement of the DUE can be easily satisfied. Then, the main obstacle for DUE access is to satisfy the minimum SINR of the regular CUE.

5.5 Conclusion

In this chapter, joint channel assignment, optimal power allocation and resource allocation process have been formulated as an optimization problem to maximize the overall network throughput while guaranteeing the QoS requirements for both CUEs and DUEs in uplink multi-cell D2D communications underlaying cellular networks. The case of more than one DUE sharing the same channel is considered. To solve this problem, the algorithm is proposed based on three stages; candidate channel selection for DUEs in addition to the power allocation that is solved using Lagrange dual decomposition and the resource allocation for multiple D2D pairs based on a genetic algorithm. The simulation results have indicated that the proposed algorithm can offer near-optimal performance and outperforms the algorithms in the literature, in achievable throughput and access rate.



(a) Access rate



(b) D2D throughput gain

Figure 5.7: Access rate and D2D throughput gain for different maximum transmit powers, when cell radius= 0.5 Km, SINR=10 dB, CUEs=20 and DUEs=10.

Chapter 6

An Efficient Resource Allocation for D2D Communications Underlaying in HetNets

6.1 Introduction

With the exponential development of mobile multimedia platforms and the number of mobile communication applications, the need for spectrum capacity in system networks is increasing. Conventional D2D communications is to allow mobile devices in close proximity to communicate directly without passing through a base station under the control of cellular system, and consider as one of the key technologies of future wireless communication networks. It has major effects in alleviating base station load, maximising bandwidth performance, increasing system throughput and reducing transmission delay. However, due to the limitations of spatial distance in D2D communication and channel link quality, D2D communication cannot be performed, in addition to the interference problem when reusing spectrum resources with mobile phone users, it can effectively improve D2D communication quality, mitigate interference, and network throughput [5,9,10].

The main objectives of this chapter are to address the resource allocation of D2D communications and femtocells in cellular networks using an optimal resource allocation scheme. We propose to work with D2D communications and femtocells since both are promising techniques regarding the improvement of cellular system capacity. In order to do better use of the cellular spectrum and minimize the interferences, we propose developing an optimal resource allocation of D2D communications and femtocells underlaying networks. Therefore, we propose to design incentives and motivate D2D communications and femtocells to cooperate between them and covers a scenario of the coexistence of D2D communications and femtocells with heterogeneous networks (HetNets) to improve the overall throughput of the cellular network.

In this chapter, we formulate the optimization problem which aims at maximizing the overall network throughput while guaranteeing the QoS requirement for both CUEs, DUEs and FUEs. We considered both D2D communication and femtocell as underlays sharing uplink resources of cellular networks. Since the problem is a non-convex mixed integer programming problem, it is difficult to solve it directly, we propose a joint channel allocation, power control and resource allocation scheme of D2D communications underlaying in HetNets.

6.2 System Model and Problem Formulation

6.2.1 System Model

In this chapter, we consider the UL of an SC-FDMA based multi-tier HetNet which comprises a single macrocell wireless network, embedded with several femtocells FBS deployed over the macrocell tier, and D2D communication tier as shown in Figure (6.1). Suppose that the set of N cellular users CUE, the set of M D2D pairs DUE, and the set of K FBS given by $C = \{1, 2, ..., N\}$, $D = \{1, 2, ..., M\}$ and $F = \{1, 2, ..., K\}$, respectively. Therefore, the K FBS is serving k-th Femto user FUE. In which multiple D2D links and femtocell links coexist in the same uplink resource. Due to severe co-channel interference, the scenario that more than one DUEs or FBSs reusing the same channel usually happens. An orthogonal frequency division multiple access (OFDMA) technique is utilized so that there is no intra-cell interference between the CUEs within the same cell. The base station (BS) can acquire channel state information (CSI) of each communication link.

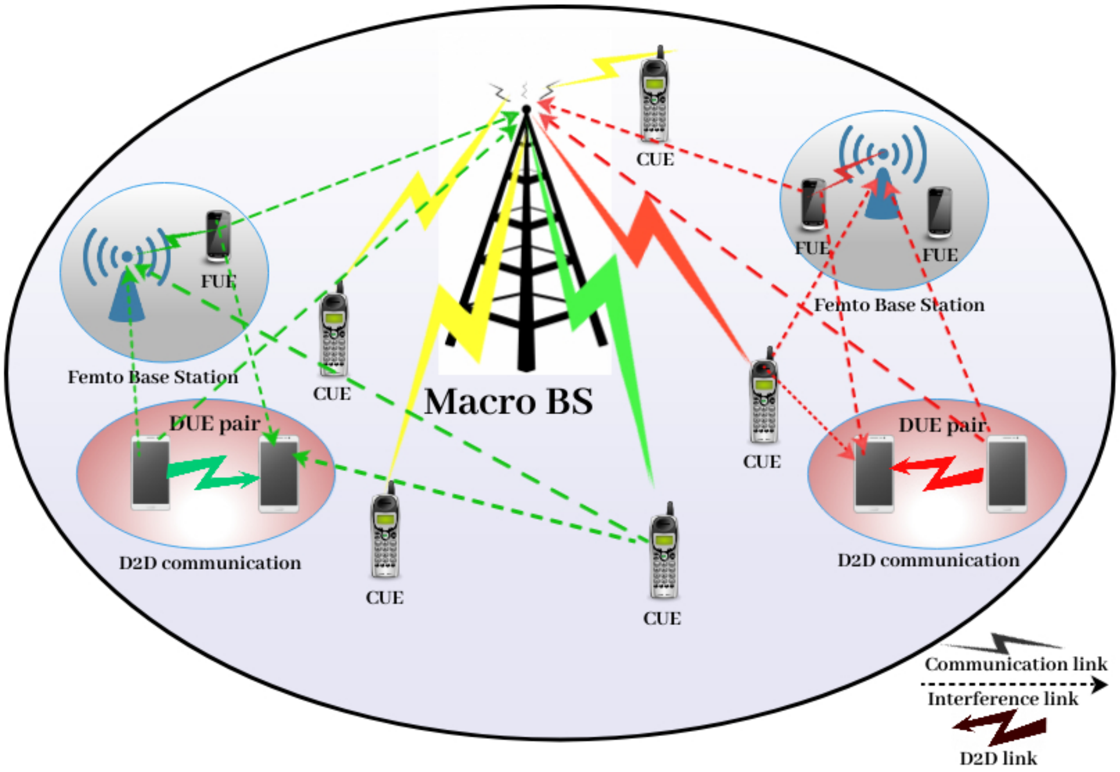


Figure 6.1: System Model of D2D Communications in HetNets.

We consider the fast fading due to multipath propagation and slow fading due to shadowing for the channels between two users, such as our previous work in chapter(3). We define $h_{j,B}$, $h_{i,j}$, and $h_{j,k}$ are interference gains of the links, from the transmitter of DUE j to eNB B, from CUE i to the receiver of D2D pair j, and that from the transmitter of DUE j to FUE k respectively. Due to the coexistence of CUE, DUE and FUE users on the same channel, the signal to interference and noise ratio (SINR) of the CUE i, the DUE

j user and FUE k on the channel i are given respectively by:

$$\xi_i^c = \frac{P_i^c g_{i,B}}{\sum_{j\in D}\omega_{i,j}P_j^d h_{j,B} + \sum_{k\in F}\omega_{i,k}P_k^f h_{k,B} + \sigma_N^2} \tag{6.1}$$

$$\xi_j^d = \frac{P_j^d g_{j,j}}{\sum_{\substack{m\in D\\ m\neq j}} P_m^d h_{m,j} + \sum_{i\in C}\omega_{i,j}P_i^c h_{i,j} + \sum_{k\in F}\omega_{k,j}P_k^f h_{k,j} + \sigma_N^2} \tag{6.2}$$

$$\xi_k^f = \frac{P_k^f g_{k,F}}{\sum_{\substack{z\in F\\ z\neq k}} P_z^f h_{z,F} + \sum_{i\in C}\omega_{i,k}P_i^c h_{i,F} + \sum_{j\in D}\omega_{j,k}P_j^d h_{j,F} + \sigma_N^2} \tag{6.3}$$

where P_i^c, P_j^d, and P_k^f represents the transmitting power of CUE i, DUE j and FUE k, respectively. Let $g_{i,B}$ denotes the channel gain from CUE i to the base station B, $g_{j,j}$ denotes the channel power gain between the transmitter and the receiver of j D2D pair, $g_{k,F}$ denotes the channel power gain between the transmitter k FUE and the FBS, and σ_N^2 is the power of the additive white Gaussian noise (AWGN).

6.2.2 Problem Formulation

Multiple DUEs and FUEs may cause mutual interference when reusing the same CUE's channel. Therefore, our target is to maximize the total throughput of the system under the maximum transmit power and minimum SINR's constraints. And DUEs or FUEs can reuse at most one subchannel resources, respectively. According to the Shannon formula, the objective function and constraints for the optimization problem can be expressed as:

$$\begin{aligned}\max_{\omega_{i,j},\omega_{i,k},\omega_{j,k},P_i^c,P_j^d,P_k^f} R_{overall} = \sum_{i\in C}[\log_2(1+\xi_i^c) + \sum_{j\in D}\omega_{i,j}\log_2(1+\xi_j^d)\\ + \sum_{k\in F}\omega_{i,k}\log_2(1+\xi_k^f)]\end{aligned} \tag{6.4}$$

$Subject\ to:$

$$\xi_i^c \geq \xi_{i,min}^c, \qquad \forall i \in C \tag{6.5}$$

$$\xi_j^d \geq \xi_{j,min}^d, \qquad \forall j \in D \tag{6.6}$$

$$\xi_k^f \geq \xi_{k,min}^f, \qquad \forall k \in F \tag{6.7}$$

$$\sum_i \omega_{i,j} \leq 1,\ \omega_{i,j} \in \{0,1\},\ \forall j \in D \tag{6.8}$$

$$\sum_i \omega_{i,k} \leq 1,\ \omega_{i,k} \in \{0,1\},\ \forall k \in F \tag{6.9}$$

$$0 \leq P_i^c \leq P_{max}^c \quad \forall i \in C \tag{6.10}$$

$$0 \leq P_j^d \leq P_{max}^d \quad \forall j \in D \tag{6.11}$$

$$0 \leq P_k^f \leq P_{max}^f \quad \forall k \in F \tag{6.12}$$

Where $\omega_{i,j}$ (or $\omega_{i,k}$) is the channel reuse indicator for CUE i and DUE j (or the channel reuse indicator for CUE i and FUE k), $\omega_{i,j} = 1$ (or $\omega_{i,k} = 1$) when DUE j reuses the channel of CUE i (or when FUE k reuse the channel CUE i); otherwise, $\omega_{i,j} = \omega_{i,k} = 0$. Constraints (6.5), (6.6), and (6.7) represent the QoS requirements of CUEs DUEs and FUEs, respectively. Constraint (6.8) and (6.9) ensures that DUEs or FUEs can reuse at most one existing CUE's resource. Constraints (6.10), (6.11), and (6.12) guarantee that the transmit powers of CUEs, DUEs and FUEs are within the maximum limit.

6.3 Proposed Solution

Therefore, the joint optimization problem in Eqs. (6.4)-(6.12) belongs to a non-convex optimization problem (MINLP) which is an NP-hard combinatorial problem and there are no efficient solutions. Furthermore, when the problem size increases, the computational complexity also increases exponentially. In order to solve this problem, we adopt a suboptimal method and decompose the problem into two stages such that the channel selection scheme is solved in the first stage, then, we propose a joint power control and resource allocation algorithm in the second stage, so as to strike a balance between the performance and complexity. The following sub-sections contain the detail discussions of these stages.

6.3.1 Candidate Channels Selection

Assign a subchannel of CUE i to a DUE j and FUE k, which achieves the highest datarate of the system. So, The main objective is to increase the total uplink throughput of the network. To increase the throughput of cellular and D2D users, it is attractive to have higher SINR. Let Π_j^i and Ξ_k^i define the sets of the combined channel gain factor for DUE j and FUE k on ith channel which expressed respectively as follows,

$$\Pi_j^i = \frac{h_{i,B} * h_{j,j}}{h_{i,j} * h_{j,B}}, \qquad \forall i \in C \ \& \ \forall j \in D \tag{6.13}$$

$$\Xi_k^i = \frac{h_{i,B} * h_{k,F}}{h_{i,F} * h_{k,B}}, \qquad \forall i \in C \ \& \ \forall k \in F \tag{6.14}$$

Due to fixed SINR constraint, with the known channel $g_{i,B}$, and for given transmit powers P_j^d, the maximum interference limit for a CUE i at BS B can be expressed as:

$$I_{max,B}^{(i)} = \frac{P_i^c g_{i,b}}{\xi_{i,min}^c} - \sigma_N^2, \ \forall i \in C \tag{6.15}$$

The specific details of the candidate channels selection algorithm are described in Algorithm 6.1. The proposed algorithm 6.1 is executed to determine the candidate set of channels of CUEs that can be initially reused by each DUE and FUEs. The proposed algorithm 6.1 requires the interference values from DUEs to the BS $I_{j,B}^{(i)}$, the interference values from FUEs to the BS $I_{k,B}^{(i)}$, the interference limits of each ith channel at BS, $I_{max,B}^{(i)}$, and the interference from DUE j to FUE k when sharing the same ith channel, $h_{j,k}^{(i)}$.

Algorithm 6.1 : Candidate Channel Selection Algorithm

```
Input: $C$; The set of active CUEs, $D$; The set of DUEs, and $F$; The set of FBSs.
Initialization : $\begin{cases} \zeta^{i}_{j,k} = \emptyset, \;\; \bar{D}^{(i)}_{r} = \emptyset, \;\; \bar{F}^{(i)}_{r} = \emptyset, \\ \forall i \in C, \;\; \forall j \in D \;\; \& \, \forall k \in F, \\ I^{(i)}_{max,B} \text{ for all } i\text{th channels.} \end{cases}$
Output: $\zeta^{i}_{j,k}$, $\bar{D}^{(i)}_{r}$, and $\bar{F}^{(i)}_{r}$.
for all $i \in C$ do
    for $j \in D \;\; \& \;\; k \in F$ do
        Calculate $\Pi_{(1*M)} = \{\Pi^{i}_{j}\}$ using eq. (6.13).
        Calculate $\Xi_{(1*K)} = \{\Xi^{i}_{k}\}$ using eq. (6.14).
        while $\Pi \neq \emptyset \;\; \& \;\; \Xi \neq \emptyset$ do
            Select $jth$ DUE that has highest $\Pi^{i}_{j}$ in $\Pi$
            Select $kth$ FBS that has highest $\Xi^{i}_{k}$ in $\Xi$
            if ( $\sum_{j \in D} I^{(i)}_{j,B} \leq I^{(i)}_{max,B}$) then
                $\bar{D}^{(i)}_{r} \leftarrow j$
                Where $I^{(i)}_{j,B}$ is interference gain from the DUE $j$ on channel $i$ to the BS $B$.
            end if
            if ( $\sum_{k \in F} I^{(i)}_{k,B} \leq I^{(i)}_{max,B}$) then
                $\bar{F}^{(i)}_{r} \leftarrow k$
                Where $I^{(i)}_{k,B}$ is interference gain from the FUE $k$ on channel $i$ to the BS $B$.
            end if
            $\Pi \leftarrow \Pi \backslash \Pi^{i}_{j}$, // Remove $\Pi^{i}_{j}$ from the vector $\Pi$ //
            $\Xi \leftarrow \Xi \backslash \Xi^{i}_{k}$, // Remove $\Xi^{i}_{k}$ from the vector $\Xi$ //
        end while
    end for
    for $j \in \bar{D}^{(i)}_{r} \;\; \& \;\; k \in \bar{F}^{(i)}_{r}$ do
        Calculate $h^{(i)}_{j,k}$ by using
        if ($h^{(i)}_{j,k} < h^{(i)}_{th}$) then
            Set $\zeta^{i}_{j,k} = \zeta^{i}_{j,k} \cup i$.
        else
            $\bar{D}^{(i)}_{r} \leftarrow \bar{D}^{(i)}_{r} \backslash j$, // Remove $jth$ DUE from the set $\bar{D}^{(i)}_{r}$//
            $\bar{F}^{(i)}_{r} \leftarrow \bar{F}^{(i)}_{r} \backslash k$, // Remove $kth$ FUE from the set $\bar{F}^{(i)}_{r}$//
        end if
    end for
end for
```

6.3.2 Optimal Power Allocation

The above-mentioned channel selection scheme for given DUE transmission powers. In order to bunch more D2D pairs in each subchannel and also fulfill the minimum SINR constraints for both CUE and DUEs, a power control scheme must be used. The optimal power allocation may write as follows,

$$P_j^{d*} = \min \left[P_{max}^d, \quad \frac{\xi_{j,min}^d}{\xi_j^d} * P_j^d \right], \quad \forall j \in D \tag{6.16}$$

As seen in (6.16) D2D transmission power is limited by P_{max}^d. On the other hand CUE's do not join in the power control, they transmit with a fixed power.

6.3.3 Joint Resource and Power Allocation

To solves the resource allocation problem Eqs. (6.4)-(6.12). The proposed solution is executed in two algorithms. In Algorithm 6.1, the candidate set of channels that can be initially reused by each DUE and FUEs is determined. In Algorithm 6.2, we proposed a joint power control and resource allocation algorithm. Firstly, we assign the optimal power allocation for each jth DUE on each ith channel. Then, we find the optimal resource pairing relationship between CUEs, DUEs and FUEs, while all constraints are satisfied. The detailed algorithm is shown in Algorithm 6.2.

6.4 Simulation Results and Discussion

6.4.1 Simulation Parameters

In our simulation, we consider a two-tier HetNets consisting of FBSs underlying a MBS, there is one MBS at the center of a circular area and the CUEs are uniformly distributed inside the cell. We adopt the clustered distribution model for D2D pairs, in which the transmitter (DUE-Tx) and the receiver (DUE-Rx) of each D2D pair are uniformly dis-

Algorithm 6.2 : Joint Resource and Power Allocation Algorithm

```
Input: $\zeta^i_{j,k}$: the set of candidate $ith$ channels, $\bar{D}^{(i)}_r$, and $\bar{F}^{(i)}_r$.
Initialization : $\left\{ \xi^c_{i,min},\ \xi^d_{j,min},\ \ \&\ \ \xi^f_{k,min}. \right.$
Output: $\omega_{i,j}, \omega_{i,k}$ and $\omega_{j,k}$
for $\forall$ DUE $j \in D$ do
    Calculate ($P^{d*}_j$ ) using eq. (6.16).
end for
for $\forall$ CUE $i \in \zeta^i_{j,k}$ do
    for $\forall$ DUE $j \in \bar{D}^{(i)}_r$ and $\forall$ FUE $k \in \bar{F}^{(i)}_r$ do
        According to formula (6.1), (6.2) & (6.3), calculate $\xi^c_i, \xi^d_j\ \&\ \xi^f_k$.
        if $(\xi^c_i \geq \xi^c_{i,min})\ \&\ (\xi^d_j \geq \xi^d_{j,min})$ then
            Set $\omega_{i,j} = 1$.
        else if $(\xi^c_i \geq \xi^c_{i,min})\ \&\ (\xi^f_k \geq \xi^f_{k,min})$ then
            Set $\omega_{i,k} = 1$.
        else if $(\xi^d_j \geq \xi^d_{j,min})\ \&\ (\xi^f_k \geq \xi^f_{k,min})$ then
            Set $\omega_{j,k} = \omega_{k,j} = 1$.
        end if
    end for
end for
$\forall$ DUE $j$ has $\omega_{i,j} = 1$, and $\forall$ FUE $k$ has $\omega_{i,k} = 1$ will reuse $i$-th channel.
```

Table 6.1: Simulation Parameters

Parameter	***Value***
System bandwidth	5 MHz
Channel bandwidth	180 kHz
Macro cell radius	500 m
Femto cell radius	50 m
D2D cluster radius	20, 40, 60, 80, 100, 120 m
Noise power (σ^2_N)	-114 dBm
Maximum transmit power for CUE (P^c_{max})	24 dBm
Maximum transmit power for DUE (P^d_{max})	24 dBm
Maximum transmit power for FUE (P^f_{max})	10 dBm
SINR requirement for CUEs, DUEs, FUEs	Uniform distributed 0 to 20 dB
Simulation type	MATLAB

tributed in a cluster with radius r; where DUEs share uplink resources with CUEs. The network topology and exemplary users placement are shown in Figure (6.2). Our simulation parameters are illustrated in Table 6.1.

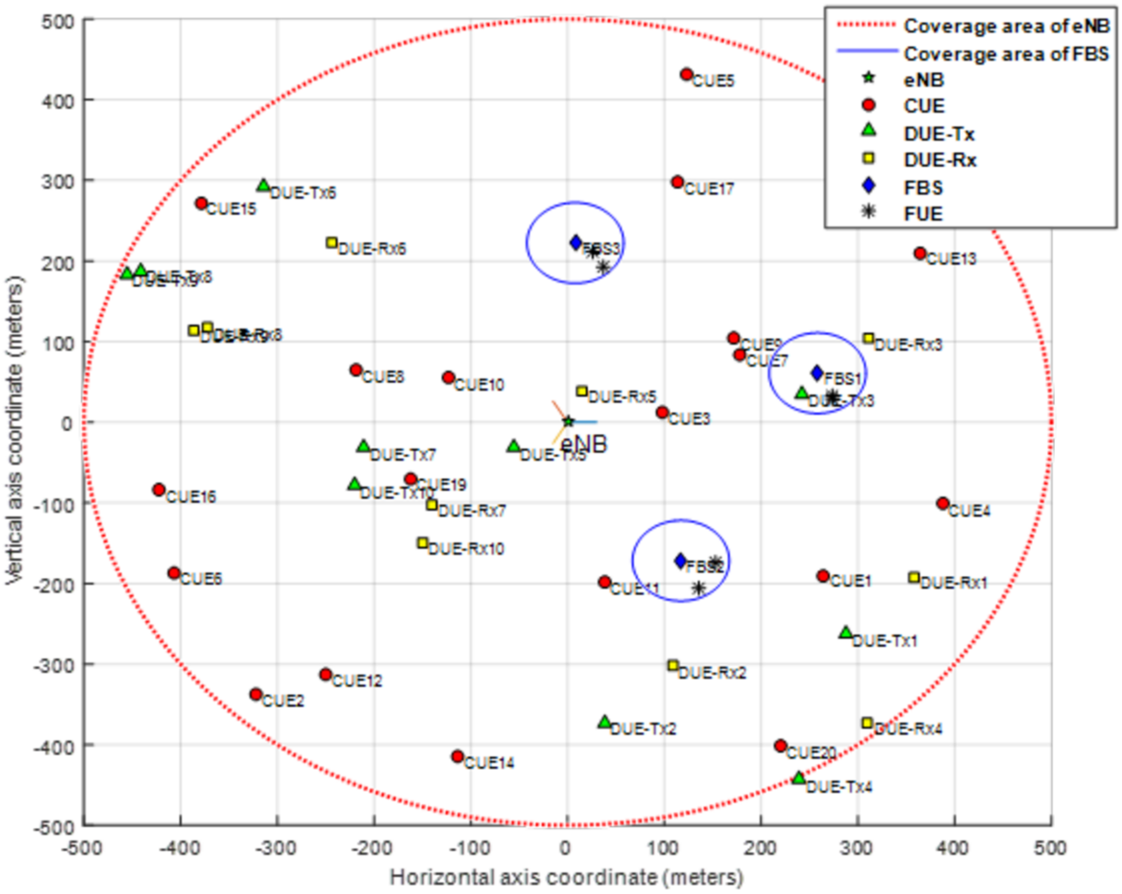


Figure 6.2: Topology of D2D Communications in HetNets.

6.4.2 Simulation Results

The performance of the proposed algorithm is compared with the heuristic algorithm offered in [81] and the random search approach (referred to as random search), in terms of the system throughput gain. Figure (6.3) illustrates the system throughput gain versus D2D radius. It can be observed that the throughput performance of our proposed scheme and the other two scheme decreases with the increase of D2D cluster radius. The reason for that because the channel gain of the D2D link will decrease with the increase of the D2D cluster radius. Hence, the larger transmitting power is required for the D2D communications to satisfy the minimum SINR.

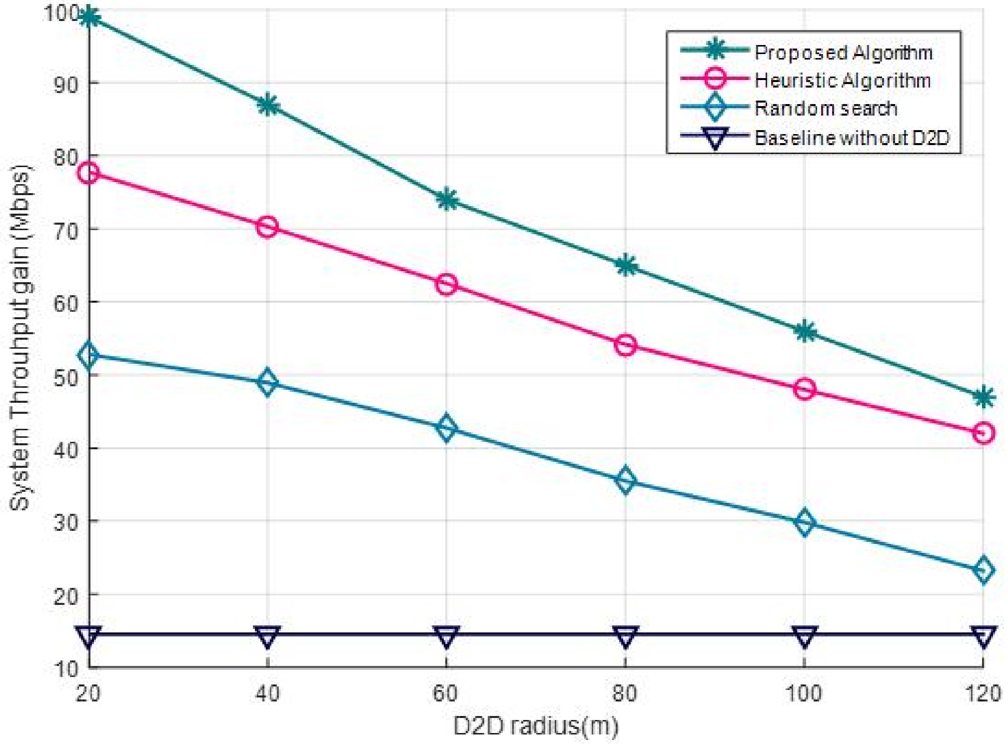


Figure 6.3: System Throughput gain Vs D2D radius when SINR=10 dB, CUEs=20, DUEs=10 and FBSs=5.

Figure (6.4) depicts the comparison of the total number of DUEs with the increasing numbers of CUEs and FUEs when the D2D cluster radius is 60 m. From the figure, it can be observed that when the total number of DUEs increases as well as the CUEs increases, the performance of our proposed algorithm in terms of the system throughput gain increases. This is because in our proposed algorithm the spectrum resources are profoundly reused.

The performance of the proposed algorithm at various minimum SINR requirements for CUEs and DUEs is shown in Figures (6.5) and (6.6). The access rate and the system throughput gain are enhanced, when the SINR requirements are reduced. This is because low SINR requirements for the users will lead to an increase in the maximum allowable interference for CUEs. Therefore, more DUEs and FUEs will allow being admitted and

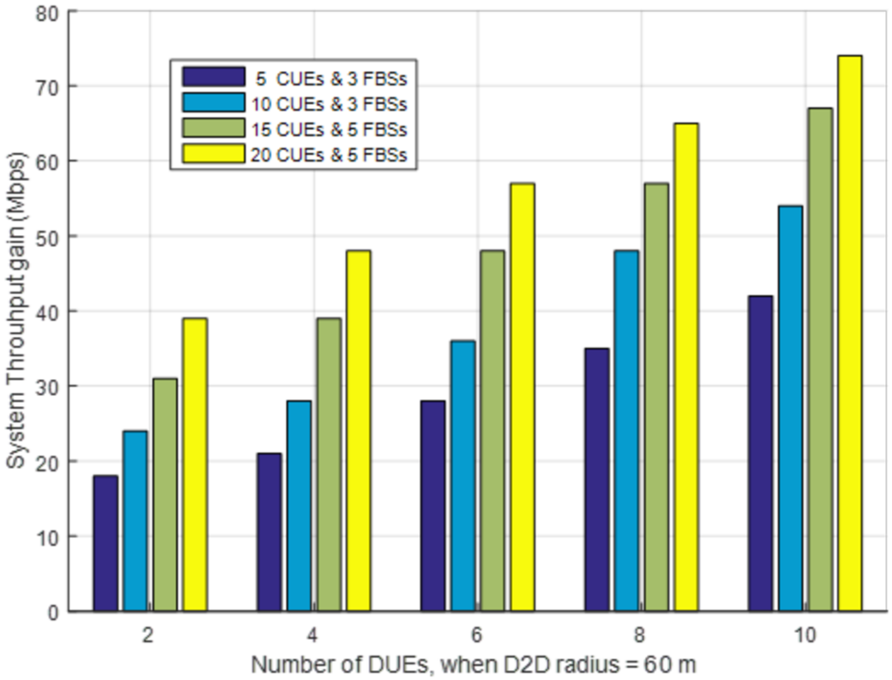


Figure 6.4: System Throughput gain Vs Numbers of DUEs and CUEs.

sharing the same channels with CUEs and consequently, the access rate and D2D throughput gain are increased.

Figure (6.7) shows the access rate and the system throughput gain of different D2D cluster radius versus maximum transmit power. It can be observed that the total throughput performance decreases with the decreases of maximum transmit power. In fact, with the increase P^c_{max} and P^d_{max}, the system throughput increases monotonically due to enhancing the achievable rate for CUEs and DUEs which results in an enhancement of the total throughput of the system, and the degradation becomes fast when the maximum distance between DUE-TX and DUE-RX is large.

6.5 Conclusion

In this chapter, the efficient resource allocation problem with QoS constraints is studied, to maximize the overall throughput of cellular networks. We formulated the overall

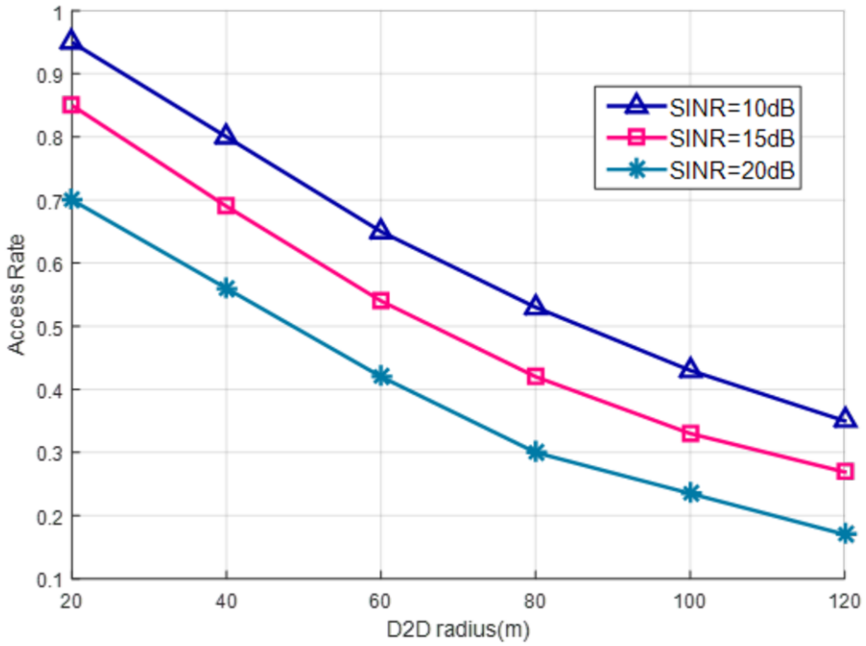


Figure 6.5: Access rate Vs D2D radius when change of the SINR requirements.

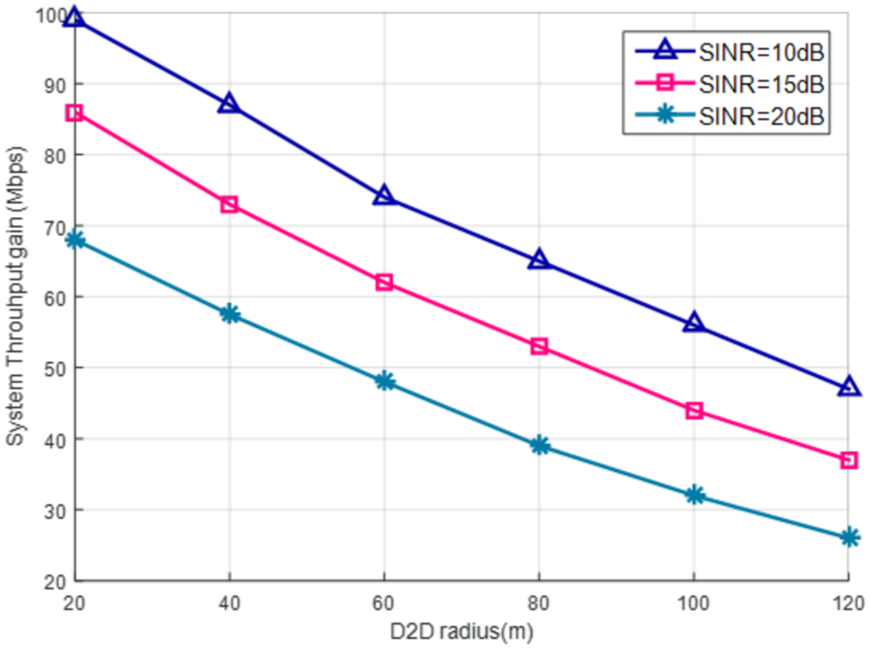
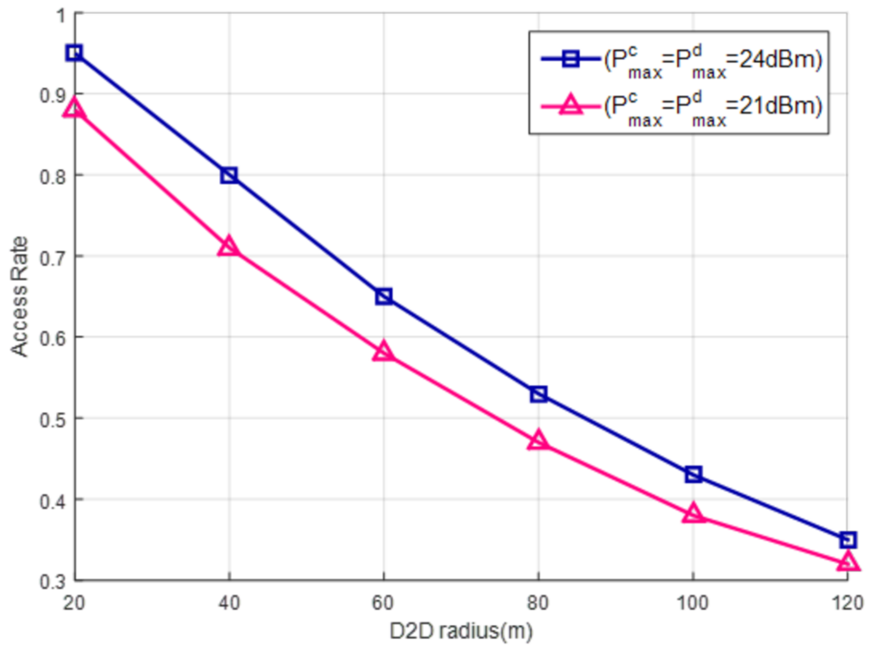
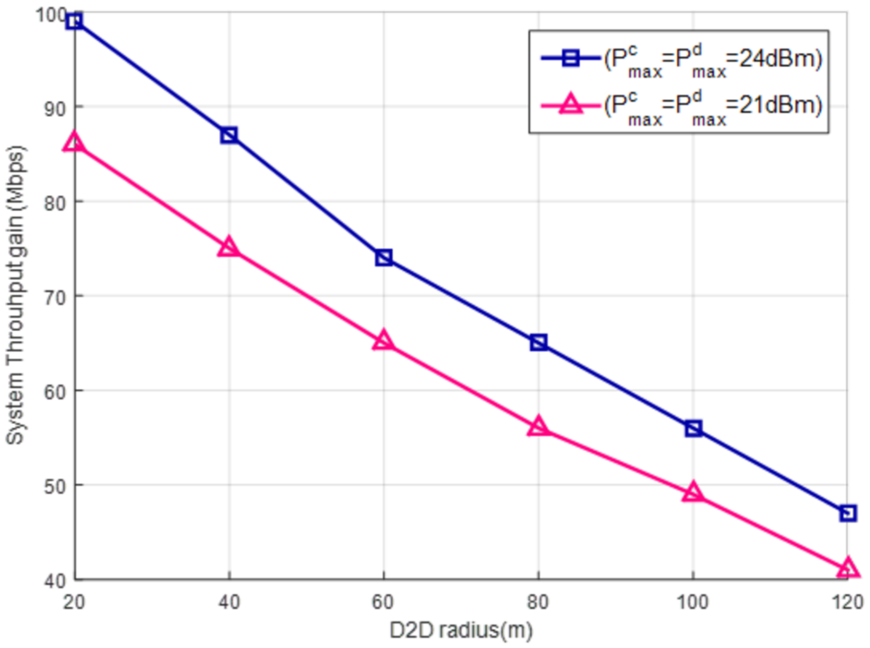


Figure 6.6: System Throughput gain Vs D2D radius when change of the SINR requirements.



(a) Access rate Vs D2D radius



(b) System Throughput gain Vs D2D radius

Figure 6.7: Access rate and system throughput gain Vs D2D radius with different maximum transmit power.

throughput optimization problem, which is a non-convex optimization problem, which usually difficult to find the optimal solution directly. We propose a joint channel section, power control, and resource allocation algorithm for D2D communications underlaying in HetNets. Numerical simulation results demonstrate that the proposed scheme has clear benefits in terms of throughput compared to conventional algorithms.

Chapter 7

Conclusion and Future Work

In this chapter, we summarize the work carried out towards the Ph.D thesis, and discuss the future work.

7.1 Conclusion

Device-to-Device (D2D) communications are seen as a new paradigm that will be implemented in the next generations of mobile networks to provide high performance in a cellular network, improving coverage, provide spectral efficiency, high data rates and offer new peer-to-peer services. This proposal presented investigated resource allocation for D2D communications sharing uplink resources in a fully loaded cellular network. In order to maximize the overall throughput while ensuring the QoS requirements of both CUEs and DUEs. First, the system model is described, and the main problem is formulated as an MINLP problem, which is obviously NP-hard combinatorial problem. This study proposed a joint channel assignment and optimal power allocation algorithm for uplink multi-cell D2D communications underlaying cellular networks. The algorithm is designed to consider both, intra-cell interference and inter-cell interference problems for optimal channel selection and power allocation. In chapter (3) we formulated the optimization problem and then found the solution through two stages: The first stage is the admission control of D2D users while the second one is the power control for each admissible DUE and its reuse partner. In chapter (4) we formulated joint resource management (mode selection, resource block assignment and transmits power control) problem with the constraints of QoS requirements of D2D links. The resource management problem is solved with an RL framework based on MDP. Simulation results show that the method can achieve better performance than other existing methods.

In chapter(5), we proposed a resourced allocation algorithm designed to allow multiple DUEs to reuse the same CUE channel for D2D communications underlaying multi-cell cellular networks with the consideration of the inter-cell and intra-cell interferences. Obviously, under satisfying the QoS requirements of both DUEs and CUEs, the more the number of the allowed accessing DUEs on a single CUE channel is, the higher the spectrum efficiency is, and the higher the network throughput can be achieved. We have proven that the performance of D2D communications in uplink multicell cellular networks fundamentally depends on different system parameters such as; the distance between the transmitter and the receiver of the D2D pair, the numbers of active CUEs and DUEs, cell radius, maximum transmit power for CUEs and DUEs, and the minimum SINR desires for both of CUEs and DUEs.

Integrating Device-to-Device (D2D) communications and Femtocells in Heterogeneous Networks (HetNets) is a promising technology for future cellular networks to satisfy the exponentially growing mobile traffic requirements. So, in the chapter (6), the efficient resource allocation problem with QoS constraints is studied, to maximize the overall throughput of cellular networks. We formulated the overall throughput optimization problem, which is a non-convex optimization problem, which usually difficult to find the optimal solution directly. We propose a joint channel section, power control, and resource allocation algorithm for D2D communications underlaying in HetNets. Numerical simulation results demonstrate that the proposed scheme has clear benefits in terms of throughput compared to conventional algorithms.

7.2 Future Work

Based on our study of D2D communication, there are different statistical models to study and analyze the different requirements to achieve high capacity, improve the overall throughput and Quality of service guarantees for D2D communication. The study conducted in this thesis leads to several interesting new research possibilities:

- The contribution of this work was based on the uplink (UL) resources reuse. One logical extension would be investigating the performance of the proposed solutions in DL resources reuse. Since, the DL reuse scheme is more complicated than the UL reuse scheme due to high interference generated by the BSs to D2D users, which limited D2D performance. As well, base station power control is a challenging task. Also, this thesis neglected the effect of fast fading on the channel models.
- A highly challenging area for resource management relates to D2D communications with high mobility such as, for example, in vehicle-to-vehicle (V2V) communications operating on the licensed spectrum, it would be interesting to consider additional features (e.g., user locations, mobility).
- D2D communications studies have developed and evaluated under the consideration of half-duplex (HD) D2D communications, where a D2D pair can either transmit or receive on the same channel, but not simultaneously.
- In the future analysis of the optimum resource allocation, mm-Wave communication and multi-input multi-output (MIMO) techniques, which are going to be another key feature of future 5G systems. Specifically, the achievements highlight the scenarios when multiple D2D pairs sharing cellular spectrum in enhancing the network capacity while meeting all users' QoS requirements, which should be addressed.
- Finally, machine learning is a powerful tool for solving the problems of resource management. It would be interesting to apply machine learning for D2D communication in HetNets. For example, Game-theoretic approaches and clustering algo-

rithms can be applied for the user association of HetNets with D2D communication, and reinforcement learning can be used when CSI is unknown of mode selection and resource allocation.

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