Resource Allocation for D2D Communication Systems

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Declaration

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Most materials contained in the chapters of this thesis have been previously published in research articles written by the author of this work (Miaomiao Liu), who appears as lead (first) author in all of them. The research has been supervised and guided by Dr. Li Zhang, and she appears as a co-author on these articles. All the materials included in this document is of the author's entire intellectual ownership.

A) Details of the publications which has been used (e.g. titles, journals, dates, names of authors):

In Chapter 3:
"Joint Power and Channel Allocation for Relay-Assisted Device-to-Device Communications," *2018 15th International Symposium on Wireless Communication Systems (ISWCS), IEEE, 2018*, **Published**. Co-author: Li Zhang.
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"Graph Colour-based Resource Allocation for Relay-Assisted D2D Underlay Communications," **Submitted** to *IET Communication.* Co-authors: Li Zhang.

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"Resource Allocation for D2D Underlay Communications with Proportional Fairness using Iterative-based Approach," **Submitted** to *IEEE Access,*, 2019. Co-author: Li Zhang.

B) Details of the work contained within these publications which is directly attributable to Miaomiao Liu:
With the exceptions detailed in section C, the published work is entirely attributable to Miaomiao Liu: the literature review necessary to construct and originate the ideas behind the published manuscripts, the novel ideas presented in the papers and all the work necessary in the editing process of the manuscripts.

C) Details of the contributions of other authors to the work:
Dr. Li Zhang is the co-author for all the publications listed above. These publications have been written under her supervision, benefiting from excellent technical advice and editorial, patient guidance and valuable feedback.

You You performed proofreading to the final drafts of the paper that his name appeared on.

I wish to dedicate this thesis to my beloved parents, my daring sibling and my sister-in-law.

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Abstract

The rapid growth of mobile traffic has motivated the development of enabling technologies for enormous network capacity enhancement in future wireless networks. Device-to-Device (D2D) communication is considered as a key technique to meet the increasing demand of high data rate and capacity. With D2D communication, user equipments (UEs) in close proximity can communicate with each other directly without going through the base station (BS), which reduces the traffic load in the core network. In addition, due to the short-range communication links, D2D communication can also improve the system energy efficiency (EE). Moreover, for the dense networks, which will be deployed in the future, D2D communication improves the system spectral efficiency significantly because of the spectrum reuse.

However, D2D communication may generate interference to the existing cellular networks if not designed properly. In this thesis, we investigated the resource allocation problem for D2D underlay communication aiming to maximize network performance (such as the overall throughput or system fairness), while guaranteeing the quality of service (QoS) requirements for both cellular and D2D links. Novel efficient resource allocation algorithms with low complexity and acceptable system performance were proposed.

Firstly, two heuristic algorithms with low computational complexity were proposed to solve the resource allocation problem aiming to maximize the overall throughput. Secondly, a joint mode selection, relay selection and resource allocation problem was optimally solved by an efficient algorithm. Thirdly, a more general and uninvestigated D2D communication scenario, where the channels are simultaneously allocated to both cellular and D2D links, was considered. An efficient Graph Colour-based Resource Allocation (GCRA) algorithm was proposed to achieve the close-to-optimal performance with low complexity.

Finally, the system fairness was investigated for D2D-based Vehicle-to-Vehicle (V2V) communication. In vehicular communication, due to the mobility of vehicles, message loss is inevitable. The situation that one or a few vehicles take all

the loss must be avoided because they may become invisible to their surrounding vehicles and cause serious safety concerns. Therefore, we proposed a novel resource allocation scheme aiming to enhance the system fairness to make sure all users have the same priority to access the system resource.

Contents

List of Abbreviations

2-D	2-Dimensional
3-D	3-Dimensional
3GPP	3rd Generation Partnership Project
5G	Five Generation
AF	Amplify-and-Forward
ACI	Adjacent Carrier Interference
BS	Base Station
BnB	Branch-and-Bound
CUEs	Cellular Users
CM	Cellular Mode
CA	Channel allocation
CSI	Channel State Information
CNN	Chaining Neural Network
D2D	Device-to-Device
DM	D2D Mode
DUR	D2D Receiver
DUT	D2D Transmitter
DF	Decode and Forward
D-R	DUT to Relay node
D.C.	Difference of Convex functions programming
eICIC	enhanced Inter-Cell Interference Coordination
EE	Energy Efficiency
GAs	Genetic Algorithms
GCRS	Graph-Colouring Based Resource Allocation
GOAL	schemes Graph-coloring resOurce ALlocation
H2H	Human-to-Human
IDs	Identifications

ILP	Integer linear Programming
INS	Interference Negligible Distance
I2-DA	Iterative 2-Dimensional Assignment
JMRC	Joint Mode, Relay selection and Channel allocation
JACMSPA	Joiny Admission Control, Mode Selection, and Power Allocation
LTE-A	Long Term Evolution-Advanced
LP	Linear Programming
mm-wave	Millimetre Wave
MIMO	Multiple-Input Multiple-Output
MINP	Mixed Integer Linear Programming
M2M	Machine-to-Machine
MINLP	Mixed-Integer Non-Linear Programming
MCSs	Modulation and Coding Scheme
MSMAP	Mode Selection and Modulation and coding schemes Assignment subProblem
NLP	Nonlinear Programming
NP-Hard	Non-deterministic Polynomial-time Hardness
NE	Nash Equilibrium
OPA	Optimal Power Allocation
OAA	Outer Approximation Approach
PSO	Particle Swarm Optimization
Proposed HA1	Proposed Heuristic Algorithm 1
Proposed HA2	Proposed Heuristic Algorithm 2
PF	Proportional Fairness
PA	power allocation
QoS	Quality of Service
RM	Relay Mode
RPA	Radio Protocol Architecture
RBR	Relaxation-Based Rounding
RB	Resource Block
SINR	Signal and Interference Noise Ratio
SNR	Signal to Noise Ratio
UEs	User Equipments
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

V2I	Vehicle-to-Infrastructure
V2D	Vehicle-to-Device

List of Symbols

m	Cellular user index
M	The total number of cellular users
$\mathcal{M}$	The set of cellular users
n	D2D pair index
N	The total number of D2D pairs
$\mathcal{N}$	The set of D2D pairs
k	Channel resource index
K	The total number of channel resource
$\mathcal{K}$	The set of channel resource
σ^2	Noise power
α	Pathloss exponent
κ	Rayleigh fading
d_{max}	Maximum distance between D2D pair
p^C_{max}	Maximum cellular transmission power
p^D_{max}	Maximum D2D transmission power
γ^C_{min}	SINR requirements of cellular links
γ^D_{min}	SINR requirements of D2D links

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Chapter 1

Introduction

1.1 Background

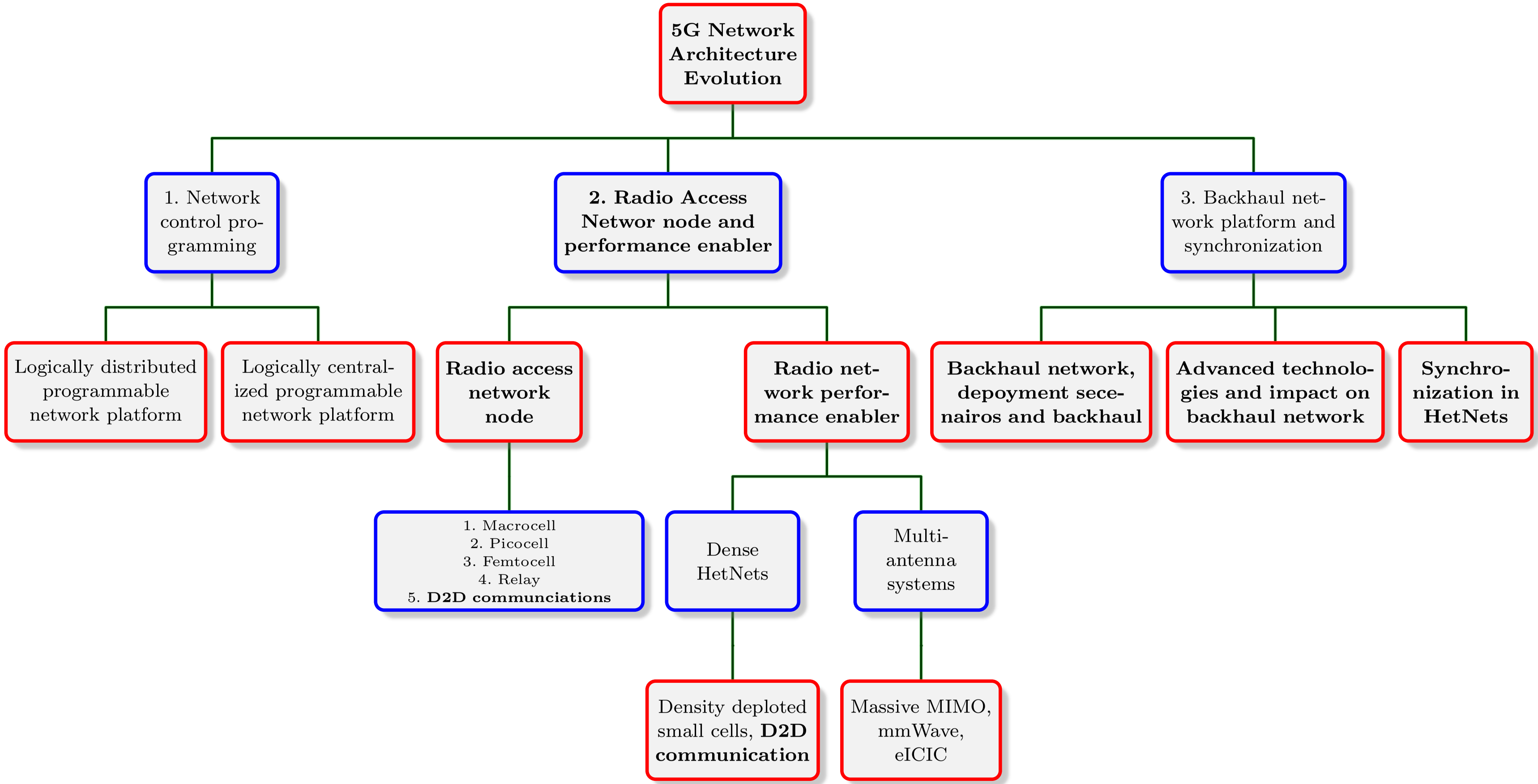
The last two decades has witnessed an unprecedented growth in both mobile broadband traffic and users' demand for faster data access. The number of connected devices is predicted as 50 billion in 2020. To fulfil the increasing demand of users in future daily life, 5G (Fifth Generation) network has been researched to bring 10-100 times higher data rate and number of connections than the existing network such as 4G and Long Term Evolution-Advanced (LTE-A) [1] [2] [3].

As shown in Table 1.1, 5G network is designed with a number of advanced communication techniques such as millimetre wave (mm-wave) communication, enhanced inter-cell interference coordination (eICIC), cooperative communication, multiple-input multiple-output (MIMO), and massive MIMO, smell cells (e.g. picocell eNBs, femtocell eNBs and relay nodes), as well as Device-to-Device (D2D) communication. D2D communication is believed to be able to significantly enhance the system performance in terms of system capacity, coverage, throughput, latency and energy efficiency (EE) [4].

1.2 Introduction of D2D Communications

D2D communication has attracted lots of attention from both academic and industry, and has been studied in the Third Generation Partnership Project (3GPP) Release 12 and 13 [5]. D2D communication allows two D2D-capable user equipments (UEs) in close proximity to perform a direct data transmission without traversing the Base Station (BS) or core network. From the technical perspective, D2D communication provides multiple performance benefits. Firstly, similar to the existing short-range wireless transmission techniques (such as Wi-Fi and Bluetooth), D2D communication can bring high data rate and low end-to-end

Table 1.1: Detailed 5G Network Architectural Evolution Framework [4].



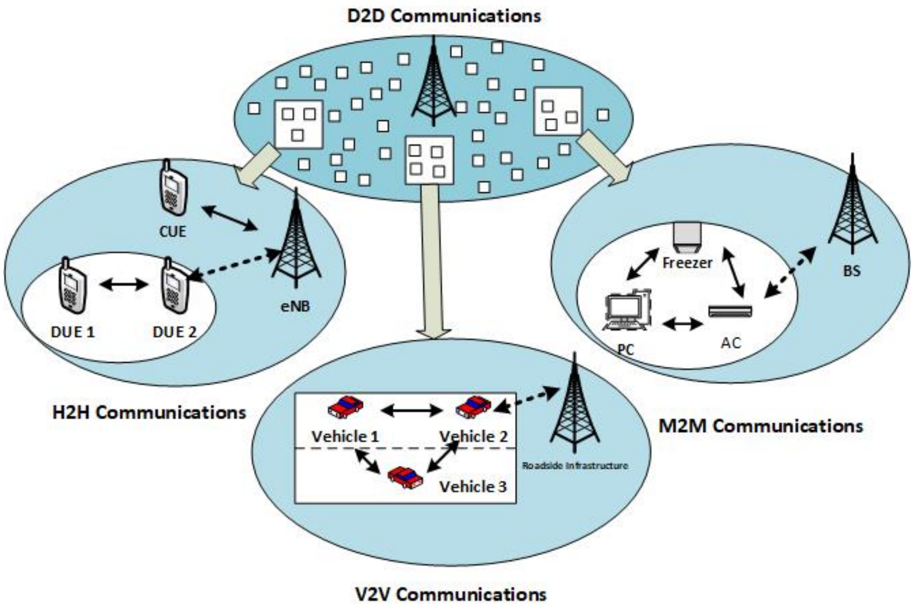


Figure 1.1: The various D2D communication types

delay due to the short-range distance. Moreover, compared to traditional cellular network where all communication must go through the BS even if both users are close to each other, direct communication saves energy and provides higher link quality. Secondly, it is more resource-efficient for D2D UEs. By reusing the channel resource with existing cellular users (CUEs), it can improve radio resource utilization, which is critical for the spectrum scarcity wireless systems. Thirdly, switching from an infrastructure path to a direct path will offload cellular traffic and avoid congestion of backhaul in core network, and this benefits other non-D2D UEs as well. Last but not least, comparing the unlicensed direct communication e.g. Wi-Fi and Bluetooth, D2D communication guarantees the quality of service (QoS) when utilizing the licensed spectrum bands.

Normally, D2D communication is classified into three application scenarios including vehicle-to-vehicle (V2V), machine-to-machine (M2M) and human-to-human (H2H) communication as shown in Figure 1.1. Each type of communication corresponds to a special application. For instance, V2V communication is related to the automotive driving systems, and M2M is related with appliances at home such as air conditioner, fridge oven, and any kinds of cleaners. M2M communication makes our lifestyle more convenient and intelligent. The H2H communication is also called D2D communication in cellular network, which is the direct communication between mobile UEs. In this thesis, we mainly focus on the D2D communication in cellular network. A D2D-based V2V communication system will be investigated in chapter 6.

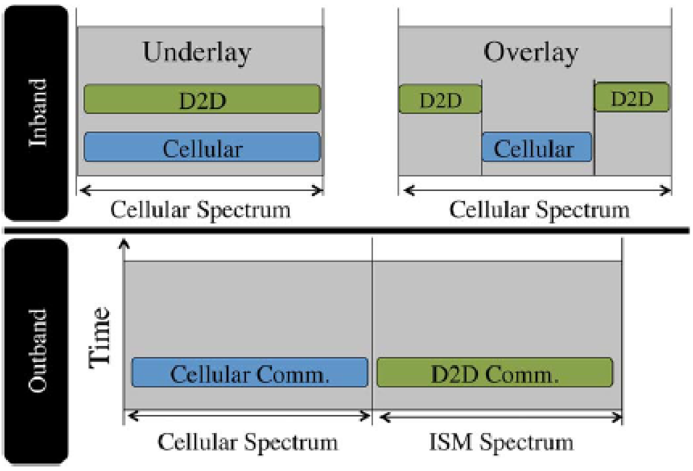


Figure 1.2: The overlay inband, underlay inband, and outband D2D communication

1.2.1 D2D Communications in Cellular Networks

Based on how the spectrum is allocated, D2D communication in cellular network can be classified into two categories: Outband and Inband communication as shown in Figure 1.2. In outband D2D communication, the D2D links exploit unlicensed spectrum. Thus, there is no interference issue between cellular and D2D links. However, using unlicensed spectrum requires an extra interface and usually adopts other wireless technologies (such as WiFi-Direct, ZigBee or Bluetooth). It should be noted that only cellular devices with two wireless interfaces such as LTE and WiFi can use the outband D2D communication, thus users can have simultaneous D2D and cellular communication. Even there is no interference issue between D2D link and cellular link, it may suffer from the uncontrolled nature of unlicensed spectrum.

In inband D2D communication, the D2D links exploit the licensed spectrum or the cellular spectrum. The inband D2D communication is further divided into overlay and underlay categories. In overlay D2D communication, D2D links are given dedicated cellular resource. Similar with the outband D2D communication, overlay inband D2D communication does not have any interference between D2D links and cellular links. In underlay D2D communication, cellular and D2D links share the same spectrum resource. The D2D links reuse the uplink or downlink channel resource of cellular links. Although this spectrum reusing can cause some interference between D2D and cellular links, it can greatly improve the spectrum efficiency of the cellular network. Thus, this thesis is focused on D2D underlay communication.

1.3 Challenges in D2D underlay communication

Despite the benefits that we discussed above, there are also many challenges in D2D underlay communication including D2D pair discovery, mode selection and resource allocation.

1.3.1 D2D pair discovery

The purpose of D2D pair discovery process is to find the potential users that can communicate directly with each other to increase the network capacity and benefit from the close distance communication in terms of low latency and higher throughput. Device discovery not only involves discovering one or more other discoverable UEs within communication range for D2D communications but also involves being discovered by one or more other discovering UEs within communication range for D2D communication [6]. The discovery phase and connection establishment are very similar to WiFi Direct standard defined procedures. The main difference is the addition of an extra phase, which transmits D2D specific message to exchange LTE IDs (Identifications) between D2D users. For more description of this procedure and protocol refer to [7]. Different D2D peers discovery schemes have been presented in literature [8] [9]. The work in [8] proposes a novel communication path setup architecture focusing on the cellular data offloading. Few of the proposed protocols for D2D communication comment on when/how to activate the link. Thus, this remains an open research problem.

D2D pair discovery is the first process before starting the direct transmission [10]. Two UEs candidates can establish the D2D transmission session only after the peer devices discovery is finished. In this thesis, all our works are conducted under assumption that the discovery process has been done and D2D pairs are already established. Our work will focus on solving the following two challenges e.g. mode selection and resource allocation.

1.3.2 Mode selection

The definition of mode selection is firstly introduced in [11], where a novel distance-dependent algorithm is proposed to realize the mode selection process. D2D communication can be further classified to four modes.

1. Cellular mode (CM): This mode is the same as the traditional cellular system, where each user occupies the orthogonal channel resource. The D2D pair communicates with each other through the BS as traditional cellular

users. Thus, there is no interference between any users. This communication mode corresponds to the inband overlay D2D communication.

2. Dedicated mode: the D2D pairs are allocated with dedicated channels which are not currently used by cellular users. Thus, there is no interference between D2D link and cellular link. This communication mode corresponds the outband D2D communication and the overlay inband D2D communication.

3. Direct mode (DM): D2D pair communicates with each other directly by reusing the same channel resources with the cellular link. In some works, it also called reuse mode. To distinguish from the D2D communication via relay, DM is defined. Due to the reuse, there are mutual interference between cellular link and D2D link. In this case, the BS should control the mutual interference by allocating the proper transmission power and channel resource to maintain the QoS of both cellular and D2D links. This communication mode actually corresponds to the inband underlay D2D communication.

4. Relay mode (RM): D2D pair communicates with each other via a relay node and reuses the same channel resource with cellular link. Proper transmission power and channel resource are also required to reduce interference. In this case, the system is also called relay-assisted D2D communication network.

Three communication modes (CM, Dedicate mode and DM) are considered for D2D underlay communication in [12], in which the mode selection is to decide whether two users in proximity should communicate directly or not, and whether to use dedicated channels or reuse channels of cellular users. The mode selection between CM and DM is researched in [13], and between DM and RM for D2D relay-assisted communication is also investigated to enhance the performance of D2D communication in [14] [15] [16]. Due to channel reuse and short range communication, the DM and RM can bring higher system spectrum efficiency and low latency with proper resource allocation strategies. Thus, in this thesis, we mainly study the mode selection between DM and RM communication for relay-assisted D2D underlay communication.

1.3.3 Resource Allocation

In this thesis, the resource allocation includes power allocation and channel allocation. Power allocation is related to control the transmission power of the

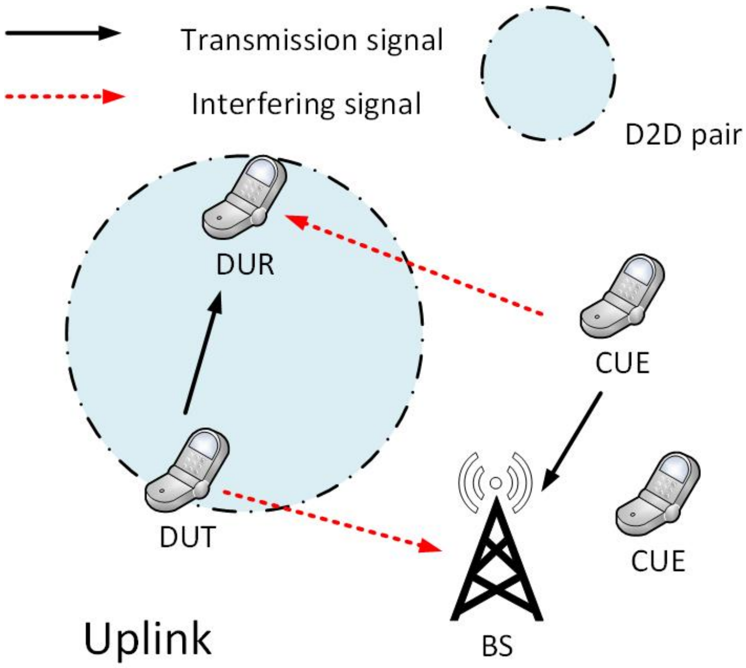


Figure 1.3: D2D communication reuse the cellular uplink resource

cellular link and D2D link to maximize system performance while avoiding harmful mutual interference. Channel allocation is to allocate the appropriate channel resource to enhance the system performance. Normally, there are two kinds of cellular link channel resource that D2D link can share: uplink and downlink channel resource, which are shown in Figure. 1.3 and Figure. 1.4, respectively. CUE means the cellular user equipment, DUT and DUR are the transmitter and receiver of D2D pairs. The BS, CUEs and D2D pair coexist in the cell. Since multiple D2D pairs reusing one channel resource brings more mutual interference between D2D pairs, and this will degrading the benefits of direct communication. Thus, in this paper, we consider one channel resource of cellular link can be reused by only one D2D pair, meanwhile each D2D pair can only reuse the same channel with one CUE.

In Figure. 1.3, the CUE communicates with the BS by using the uplink cellular channel. At the same time, the D2D link chooses to operate at the underlay situation, and it reuses the uplink that the CUE uses. Thus, the interference between these two links (i.e. cellular and D2D links) are generated. More specifically, the DUR will suffer the interference from the CUE while CUE transmitting the signal to the BS. Meanwhile, the BS suffers interference from the DUT.

In Figure. 1.4, the CUE communicates with the BS by using the downlink cellular channel. The D2D pair reuses this downlink channel to communicate with each other. The BS will generate the interference to the DUR when sending

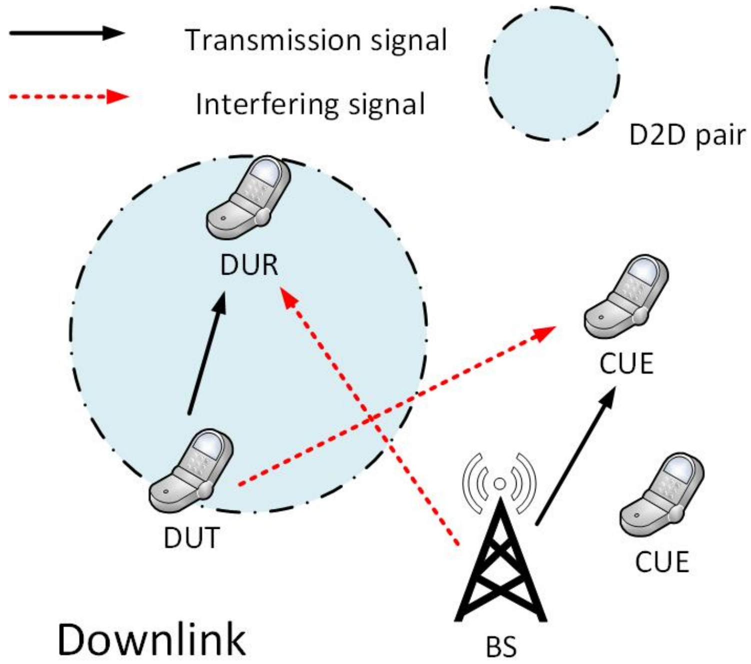


Figure 1.4: D2D communication reuse the cellular downlink resource.

the signal to CUE. And the CUE also receives the interference from DUT.

A joint mode selection and resource allocation scheme based on particle swarm optimization (PSO) is proposed to maximize the system throughput in [17], where the D2D links reuse the downlink resource of cellular users. Since there is more uplink resource than downlink, and the DUR will be affected by larger interference from the BS if the downlink resource is shared, so most of the recent researches focus on the uplink scenario (i.e. Figure 1.3), such as [18] [19] [20] [21], which study the resource allocation strategies while guaranteeing the QoS of communication links. In this thesis, the D2D links will reuse uplinks resources.

1.4 Motivations and objectives

In D2D underlay communication systems, D2D links share the channel resources to improve spectral efficiency. This will inevitably cause mutual interference. Particularly, spectrum should only be reused with D2D links when it improves system throughput without compromising on the QoS of cellular links. Therefore, it is critical to properly select the communication modes and efficiently allocate the system resource for communication links. A number of works have investigated these issues. Authors in [20] investigated the resource allocation problem aiming to maximize overall system throughput. [15] [16] considered the joint mode selection and resource allocation problem aiming to maximize overall system throughput for relay-assisted D2D communication. However, there are still numerous issues that have to be addressed for relay-assisted D2D communication.

1. The existing resource allocation algorithms generally have unaffordable high complexity and is not easy to implement. Thus, the first objective is to find low complexity resource allocation algorithms to facilitate relay-assisted D2D communication.

2. In a practical relay-assisted D2D communication, a relay node should be chosen from a group of nodes to assist the D2D link (defined as relay selection). However, most of the existing works assume that the relay nodes have been pre-selected, and relay selection is rarely researched. The relay selection joint with mode selection and resource allocation problem is not investigated yet and motivates researchers. Thus, the second objective is to investigate the joint problem, and propose a algorithm to efficiently solve it.

3. Joint channel resource allocation for both cellular and D2D links can result in a better system performance [21]. However, none of the existing works simultaneously consider the channel allocation for both cellular and D2D links, and all assume that the channel allocation for cellular link are pre-allocated. Thus, the third objective that follows naturally is to investigate a more general relay-assisted D2D underlay communication, in which the joint channel allocation is considered aiming to enhance overall system throughput. Given that the performance of the exhaustive search method is optimal at the cost of extremely high complexity burden, the main goal is to find a low complexity algorithm, which can be implemented more efficiently.

4. The last objective is driven by the V2V application, where each user should have equal right to access the system resource to avoid serious safety concerns. However, few of the researches focus on the system fairness, and none of them investigate the resource allocation problem while guaranteeing the QoS of links for dynamic communication network. Thus, the objective is to improve the system fairness for D2D-based V2V communication while while guaranteeing the QoS of links with low complexity. The main goal is to propose a novel power allocation algorithm to improve the system fairness, and derive a low complexity algorithm solving the channel allocation problem while guaranteeing the system performance.

1.5 Main Contributions

The research reported in this thesis is focused on the resource allocation techniques for D2D underlay communication. The author of thesis has

- proposed two efficient heuristic algorithms (named Proposed HA1 and Proposed HA2) with low complexity to solve the resource allocation problem aiming to improve the system overall throughput, while guaranteeing the QoS of communication links for D2D underlay communication. The proposed HA1 focuses on reducing the complexity of channel allocation by narrowing the available channel search space for D2D links. The proposed HA2 aims to reduce the complexity of power allocation. Simulation results show that both algorithms can provide acceptable system performance with much lower complexity.

- investigated the joint mode, relay selection and resource allocation problem to maximize the system overall throughput while guaranteeing the power limits and QoS requirements. Then, a low complexity optimal power allocation that maximize the sum data rate when D2D link operates in DM is designed. In addition, a practical mechanism by adding more constraints is proposed to solve the joint problem. Simulation results show that our proposed scheme can achieve better system throughput than the existing schemes.

- modelled the resource reusing relationship among different CUEs, D2D pairs and relay nodes as a colour-based graph to maximize the system throughput while jointly considering the channel allocation for both cellular and D2D links. Then, a Graph Colour-based Resource Allocation (GCRA) algorithm is derived to effectively solve the joint problem with low complexity. In this algorithm, we creatively introduce three individual attributes for each channel resource, and iteratively allocate the resource for each channel. In this way, the computational intensive exhaustive search is no longer needed, and thus the complexity is drastically reduced. Simulation results confirm that the proposed algorithm also achieves the close-to-optimal performance in terms of the network throughput.

- investigated the proportional fairness (PF) scheduling for D2D-based V2V communication aiming at maximizing the system fairness. The author designed a novel power allocation mechanism to improve the system fairness by transforming it into a weighted sum data rate problem. Simulation results reveal that the proposed power allocation can bring higher system fairness than the existing methods. In addition, an efficient channel allocation mechanism which produces the close-to-optimal system fairness is designed via iteratively solving the reduced subproblems. In this way, the overall system complexity is significantly reduced. Extensive numerical studies show that the proposed iterative channel allocation mechanism improves system fairness without degrading overall system throughput.

1.6 Thesis Overview

This thesis comprises seven chapters, the succinct account of each chapter is given below.

Chapter 1 provides the background of D2D communication. Then, the challenges in D2D underlay communication is presented. Moreover, the motivations, objectives and main contributions of this thesis are given.

Chapter 2 presents a number of popular resource allocation techniques such as optimization programming. Moreover, the existing mathematical modellings of resource allocation are explained.

Chapter 3 formulates the joint power and channel allocation problem for relay-assisted D2D communication aiming to maximize the system sum rate while guaranteeing the minimum required SINR (Signal to Interference and Noise Ratio) of both cellular and D2D links. As it is a MINLP (Mixed Integer Non-linear Programming), which can not be solved in polynomial time, we propose two heuristic algorithms (named Proposed HA1 and Proposed HA2) with lower complexity to solve it. Monte-Carlo simulation results show that the performance of the proposed algorithms with acceptable complexity have an acceptable performance comparing with the optimal performance.

In Chapter 4, a joint mode selection, relay selection and resource allocation optimization in relay-assisted D2D communication is proposed. We maximize the overall system throughput while guaranteeing the power limits and SINR requirements of all cellular and active D2D links. After decomposing the original design problem into two sub-problems: 1) Optimal Power Allocation (OPA); 2) Joint Mode selection, Relay selection and Channel allocation (JMRC), we then propose the corresponding algorithms to solve them sequentially. Simulation results show that the proposed scheme significantly outperforms the existing schemes.

Chapter 5 shows a more complicated scenario, where not only the mode selection and relay selection but also the channel allocation for both cellular link and D2D link are jointly considered. Since the joint problem is a MINLP problem, we then propose the graph-colouring based resource allocation (GCRA) algorithm to effectively solve it. Simulation results show that the proposed algorithm can not only bring better performance than the existing works but also achieve the close-to-optimal performance with acceptable computational complexity.

In Chapter 6, the mobility feature of users during long-term is considered, which is particularly important for vehicular communication. More importantly, the system fairness is considered when allocating the power and channel resource for both cellular and D2D links. We first formulate the joint power and channel allocation for both cellular and D2D links aiming to maximize the system fairness while guaranteeing the QoS requirements and power limits of communication links. Then, the joint problem is divided into two sub-problems: power allocation and channel allocation for each communication slot, and solved subsequentially by the proposed algorithms. Simulation results show that the proposed scheme can not only achieve fairer system but enhance the system throughput comparing with the existing schemes.

Chapter 7 concludes the thesis and highlights the main contributions. This chapter also outlines some potential areas for further researches.

1.7 List of Publications

1. **M. Liu** and L. Zhang,"Joint Power and Channel Allocation for Relay-Assisted Device-to-Device Communications," **published** in *2018 15th International Symposium on Wireless Communication Systems (ISWCS), IEEE, 2018.* (DOI: 10.1109/ISWCS.2018.8491059)

2. **M. Liu**, L. Zhang, and You You, "Joint Power and Channel Allocation for Underlay D2D Communications with Proportional Fairness," **published** in *2019 15th International Wireless Communications and Mobile Computing Conference (IWCMC),IEEE, 2019.* (DIO: 10.1109/IWCMC.2019.8766723)

3. **M. Liu** and L. Zhang,"Joint Relay Selection and Resource Allocation for Relay-Assisted D2D Underlay Communications," **published** in *2019 22nd Wireless Personal Multimedia Communications (WPMC2019).* **Received** the **Best Student Paper Award.**

4. **M. Liu** and L. Zhang, "Resource Allocation for D2D Underlay Communications with Proportional Fairness using Iterative-based Approach," **submitted** to *IEEE Access.*

5. **M. Liu** and L. Zhang, " Graph Colour-based Resource Allocation for Relay-Assisted D2D Underlay Communications," **submitted** to *IET Communication.*

Chapter 2

Resource Allocation Techniques

This thesis focuses on the resource allocation for D2D underlay communications. In order to control the mutual interference between cellular and D2D links, effective resource allocation techniques such as optimization programming, graph theory and game theory have attracted intensive interest.

Graph theory can provide efficient tools for modelling and analysing various types of interactions, relations, and dynamics in different networks, and thus it has been widely used to solve the resource management problems [22]. Authors in [21] formulate the channel assignment problem by using the graph-based approach, in which each link corresponds to a vertex and each channel assignment is represented by a hyper-edge. An iterative rounding algorithm is proposed to solve the resulting graph-based problem and can attain almost the same system sum-rate as the optimal algorithm. Game theory offers a set of mathematical tools to study the complex interactions among interdependent rational players and to predict their choices of strategies. A game theory model can be developed to study the interaction between cellular networks. The interaction between cellular users and D2D users can be treated as competing with each other or coordinating with each other to achieve their certain goals individually or together [23]. In [23], multiple D2D links can reuse more than one channel resource. Although this will bring high spectrum efficiency, the mutual interference not only between cellular and D2D links but also among D2D links will occur. And this will degrade the benefits of D2D links.

The optimization programming is a function to be maximized and minimized while satisfying the constraints. The function that being optimized is referred to as the objective function. The variables in the objective function are denoted as the design variables, which can be real or discrete numbers, binary or integer types. Since the optimization programming technique on power allocation and channel allocation aspects will be applied in Chapter 3- 6, so this chapter is devoted to explain the optimization techniques in details.

2.1 Optimization Programming

According to the properties of whether the objective function and constraints are linear or nonlinear, and the variables are integer or continues, the optimization problem can be classified as many types such as linear programming (LP), integer linear programming (ILP), nonlinear programming (NLP), mixed integer linear programming (MINP), MINLP.

A number of researches have been looked into this. The joint mode selection, MCS (modulation and coding scheme), channel allocation and power control is studied in [13]. In order to solve it effectively, authors decouple it into two subproblems: RAP (Resource block Allocation subProblem) and MSMAP (Mode Selection and Modulation and coding schemes Assignment subProblem), which are solved by Lagrangian relaxation and tabu search methods, respectively. In [24], the Joiny Admission Control, Mode Selection, and Power Allocation (JACMSPA) falls into a class of MINLP that are generally NP-hard. The outer approximation approach (OAA) based linearisation technique is applied to solve the joint problem. The proposed OAA gives guaranteed ε-optimal results with finite convergence. A resource allocation scheme involving several D2D multicast groups is proposed in [25]. The proposed method is divided into two steps: 1) channel resource are allocated while ensuring the minimum throughput of the D2D multicast groups and the QoS of cellular links; 2) the power allocation is solved by convex optimization after being transformed into an approximation Shannon capacity form. The two-step power allocation is proposed in [20], where the admission control is first to perform, secondly the optimal power for both cellular and D2D links are calculated. It also proved that the maximum system throughput can be achieved when at least one of the users (i.e. cellular and D2D users) transmits at its maximum power. The channel allocation is transformed as a maximum weight bipartite matching problem, which can be solved by the well-known *Hungary* algorithm in [20]. Works in [12] consider the joint mode selection and resource allocation, where three communication modes are considered for D2D users: CM, dedicated mode and DM. Then, the joint optimization is decomposed into two subproblems: power control and joint mode selection and channel assignment. The joint mode selection and channel assignment is NP-hard, so a low-complexity algorithm according to the network load is developed. Based on the assumption that the cellular transmission powers are fixed, authors in [26] use the convex approximation technique to formulate the joint power allocation into a solvable convex optimization problem.

In addition, there are also many works on improving system energy efficiency (EE) for D2D underlay communications in recent years. Utilising the properties of fractional programming, [27] and [28] transform the original non-convex EE problem into an equivalent optimization problem with subtractive form, which is solved by an iterative approach. Authors in [29] propose three channel allocation algorithms: dual-based, BnB (Branch-and-Bound) and RBR (Relaxation-based Rounding) algorithms with different computational complexity levels. The dual decomposition and relaxation approaches are used to solve the EE problem in dual-based algorithm and BnB and RBR algorithms, respectively.

In this thesis, the power allocation is a continuous variable. The mode selection and the channel allocation are binary variables. The existing mathematical modellings of power and channel allocation are explained in the following subsection.

2.2 Power Allocation

Allocating the transmission power for communication links affects the mutual interference directly [13] [16]. Decreasing the transmission power of the BS or increasing the transmission power of the D2D transmitter can both increase the quality of D2D links. To achieve the desired performance of D2D underlay networks, proper power control is essential. In this subsection, the power allocation problem when D2D pair operates in DM and RM are discussed, respectively.

2.2.1 Power allocation in Direct Mode

In DM, D2D pair communicates with each other directly by reusing the channel resource with cellular link shown in Figure. 1.3, where each D2D link can only reuse one channel resource with one cellular link, and each cellular link is allocated one channel resource. The main goal is to allocate the transmission power for both cellular link and D2D link (denoted as p_c, p_d) to maximize the sum throughput. Specifically, the power allocation becomes an optimization problem with power limits and QoS requirement constraints. In order to solve this optimization problem, [20] shows a two-step process to obtain the feasible power allocation. Therefore, the SINRs of cellular link and D2D link can be expressed as

$$\gamma_c = \frac{p_c h_{cB}}{\sigma^2 + p_d h_{dB}}, \tag{2.1}$$

$$\gamma_d = \frac{p_d h_{dd}}{\sigma^2 + p_c h_{cd}}, \tag{2.2}$$

respectively, where h_{cB} is the channel gain from the cellular user to the BS, h_{dd} is the signal channel gain between D2D pair. h_{cd} is the interfering channel gain from the cellular link to the D2D receiver, and h_{dB} is the interfering channel gain from the D2D receiver to the BS. σ^2 is the noise power. In addition, the channel gain is modelled as

$$h_{a,b} = d_{a,b}^{-\alpha} \kappa,$$

where $d_{a,b}$ is the distance between node a and b, α is the pathloss exponent; κ is the Rayleigh fading gain.

Mathematically, the optimization problem is expressed as

$$(p_c^*, p_d^*) = \arg\max_{(p_c, p_d)} \{\log_2(1 + \gamma_c) + \log_2(1 + \gamma_d)\} \tag{2.3}$$

s.t.

$$\gamma_c \geq \gamma_{min}^C, \tag{2.3a}$$

$$\gamma_d \geq \gamma_{min}^D, \tag{2.3b}$$

$$0 \leq p_c \leq p_{max}^C, \tag{2.3c}$$

$$0 \leq p_d \leq p_{max}^D, \tag{2.3d}$$

where p_c^* and p_d^* are the optimal transmission power for cellular and D2D transmitters. γ_{min}^C and γ_{min}^D are the minimum SINR requirements for cellular link and D2D link. p_{max}^C and p_{max}^D are the maximum transmission power for cellular link and D2D link. Constraints (2.3a) and (2.3b) guarantee the minimum SINR requirements for both cellular and D2D links. Constraints (2.3c) and (2.3d) restrict the maximum transmission power of cellular and D2D transmitter.

[20] proposes a Two-step power allocation:

Step1: Admission control

Constrains (2.3a)-(2.3b) mean that a D2D pair can share resource with an existing cellular user only when both their SINR requirements are satisfied. Let $L_{c,d}$ denote the distance between cellular user and D2D transmitter, and $L_{c,d}^{min}$ denote the minimum distance between cellular user and D2D transmitter. Then, the following proposition is used to select the reuse candidate for D2D pair.

Proposition 2.1 *A cellular user is a reuse candidate of a D2D pair, if* $L_{c,d} \geq L_{c,d}^{min}$*, where* $L_{c,d}^{min}$ *is given by*

$$L_{c,d}^{min} = \begin{cases} [\frac{\kappa\gamma_{min}^C\gamma_{min}^D p_{max}^C}{(p_{max}^C h_{cB}-\gamma_{min}^C\sigma^2)\beta-\gamma_{min}^C\gamma_{min}^D\sigma^2}]^{\frac{1}{\alpha}}, & \text{if } \frac{p_{max}^C h_{cB}}{\sigma^2+p_{max}^D h_{dB}} \leq \gamma_{min}^C, \\ [\frac{\kappa\gamma_{min}^C\gamma_{min}^D(\sigma^2+p_{max}^D h_{d,B})}{h_{cB}(p_{max}^D h_{dd}-\gamma_{min}^D\sigma^2)}]^{\frac{1}{\alpha}}, & \text{if } \frac{p_{max}^D h_{dd}}{\sigma^2+p_{max}^C h_{cd}} \geq \gamma_{min}^D. \end{cases} \tag{2.4}$$

where $\beta = \frac{h_{dd}}{h_{dB}}$ *represents the D2D channel gain advantage over traditional user to BS link.*

Proof 2.1 *See proof in [20] .* ■

Accordingly, the BS can easily determine whether the cellular link and D2D pair can reuse the same channel resource while guaranteeing both their SINR requirements. If $L_{c,d} \geq L_{c,d}^{min}$, the D2D pair get the permission from the BS to access the cellular link.

Step2: Optimal power control

In this step, the transmission power is allocated to both the D2D transmitter and the cellular user to maximize the sum throughout.

Proposition 2.2 *Denoting* $f(p_c, p_d) = \{\log_2(1+\gamma_c) + \log_2(1+\gamma_d)\}$*, the optimal power vector* (p_c^*, p_d^*) *in* (2.3) *can be expressed as follows,*

$$(p_c^*, p_d^*) = \begin{cases} \underset{(p_c,p_d)\in\mathcal{P}_1}{\arg\max} f(p_c, p_d), & \text{if } \frac{p_{max}^C h_{cB}}{\sigma^2+p_{max}^D h_{dB}} \leq \gamma_{min}^C, \\ \underset{(p_c,p_d)\in\mathcal{P}_2}{\arg\max} f(p_c, p_d), & \text{if } \frac{p_{max}^C h_{cB}}{\sigma^2+p_{max}^D h_{dB}} > \gamma_{min}^C \text{ and } \frac{p_{max}^D h_{dd}}{\sigma^2+p_{max}^C h_{cd}} < \gamma_{min}^D, \\ \underset{(p_c,p_d)\in\mathcal{P}_3}{\arg\max} f(p_c, p_d), & \text{if } \frac{p_{max}^C h_{cB}}{\sigma^2+p_{max}^D h_{dB}} > \gamma_{min}^C \text{ and } \frac{p_{max}^D h_{dd}}{\sigma^2+p_{max}^C h_{cd}} \geq \gamma_{min}^D, \end{cases} \tag{2.5}$$

where

$$\begin{aligned} \mathcal{P}_1 &= \{(p_{max}^C, p_1), (p_{max}^C, p')\}, \\ \mathcal{P}_2 &= \{(p_3, p_{max}^D), (p_4, p_{max}^D)\}, \\ \mathcal{P}_3 &= \{(p_{max}^C, p_1), (p_{max}^C, p_{max}^D), (p_4, p_{max}^D)\}, \\ p_1 &= \frac{(p_{max}^C h_{cd}+\sigma^2)\gamma_{min}^D}{h_{dd}}, \\ p' &= \frac{p_{max}^C h_{c,B}-\gamma_{min}^C\sigma^2}{\gamma_{min}^C h_{d,B}}, \\ p_3 &= \frac{p_{max}^D h_{dd-\gamma_{min}^D\sigma^2}}{\gamma_{min}^D h_{cd}}, \\ p_4 &= \frac{(p_{max}^D h_{dB}+\sigma^2)\gamma_{min}^C}{h_{cB}}. \end{aligned} \tag{2.6}$$

Proof 2.2 *See proof in [20] .* ■

It is obvious that at least one user needs to transmit at their peak power to maximize the overall throughput. This is an important conclusion and will be used in our proposed method in chapter 4.

2.2.2 Power Allocation in Relay Mode

Relay-assisted communications has attracted enormous research interest in the past decade, and shown to improve the transmission rate and/or diversity order of wireless links [30] [31] [32].

Relay strategies typically fall into two categories: amplify-and-forward (AF) and decode-and-forward (DF). In AF, the relay simply amplifies the source signal linearly; whereas, in DF, the relay fully decodes, re-encodes and retransmits the source codeword. Since the noise will be amplified in AF, the DF relaying strategy is applied in many works.

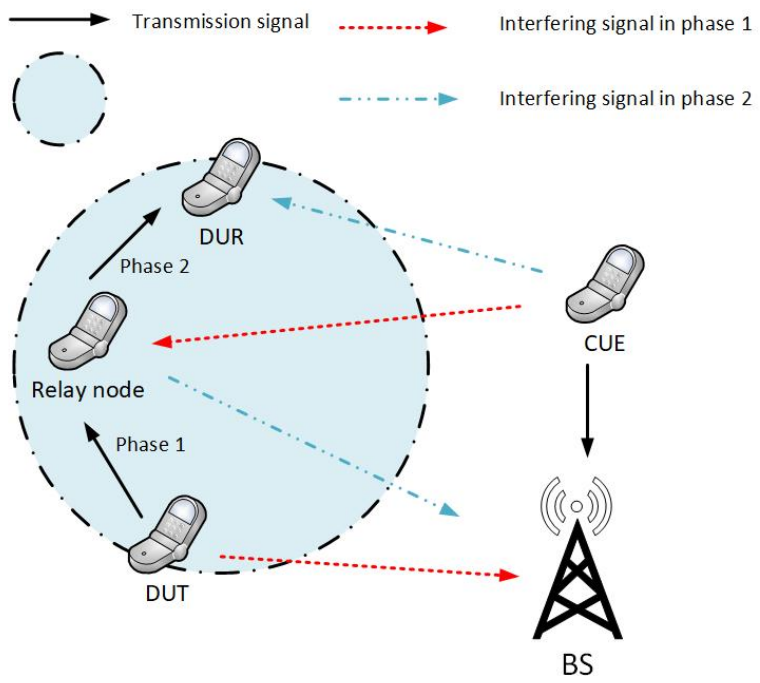


Figure 2.1: The D2D communications in relay mode.

In RM, the D2D pair communicates with each other via a relay node. In fact, the relay-assisted D2D communications can be extended to two-hop and multi-hop D2D communications [1]. In multi-hop D2D communications, there are more than one relay nodes assisting the D2D communications along with the multiple intervals [33] [34]. In two-hop communications, each communication period is divided into two equal intervals corresponding to the DUT to relay (D-R) communication phase and relay to DUR (R-D) communication phase, as shown in Figure 2.1. Specifically, in the first interval, the CUE produces interference to the relay node, and in the second interval, the interference at the BS is from the relay

[1]In some work, the direct D2D communications is also called one-hop D2D communications.

node instead of the DUT. In this thesis, two-hop relay-assisted D2D communication is selected and the multi-hop relay-assisted D2D communication will be our future work. In relay-assisted D2D communications, the relay nodes can be the idle UEs. As relay nodes involving, extra transmission power are consumed.

Let p_r be the transmission power of relay node to support the D2D link. Then, the SINRs of cellular link in the first and the second communication phases can be expressed as

$$\gamma_{c1} = \frac{p_c h_{cB}}{\sigma^2 + p_d h_{dB}}, \tag{2.7}$$

$$\gamma_{c2} = \frac{p_c h_{cB}}{\sigma^2 + p_r h_{rB}}, \tag{2.8}$$

where h_{rB} is the interfering channel gain from relay node to the BS.

Moreover, the SINRs of D2D link achieved on the D-R and R-D links in the first and second communications phases can be shown as

$$\gamma_{d1} = \frac{p_d h_{dr}}{\sigma^2 + p_c h_{cr}}, \tag{2.9}$$

$$\gamma_{d2} = \frac{p_r h_{rd}}{\sigma^2 + p_c h_{cd}}, \tag{2.10}$$

where h_{cr} is the interfering channel gain from the CUE to the relay node, h_{rd} is the signal channel gain from the relay node to the DUR, h_{rB} is the interfering channel gain from the relay node to the BS.

Thus, the data rates of cellular and D2D links can be written, respectively, as

$$R_c = \frac{1}{2}\log_2(1+\gamma_{c1}) + \frac{1}{2}\log_2(1+\gamma_{c2}), \tag{2.11}$$

and

$$R_d = \frac{1}{2}\log_2(1+\min\{\gamma_{d1},\gamma_{d2}\}). \tag{2.12}$$

Here, the $\frac{1}{2}$ means this transmission needs two communication intervals.

The power allocation problem tries to allocate the proper transmission power for CUE, relay node and DUT (i.e. p_c, p_r and p_d) aiming to maximize the sum data rate, which can be expressed as

$$(p_c^*, p_d^*, p_r^*) = \arg\max_{(p_c,p_d,p_r)}\{R_c + R_d\} \tag{2.13}$$

s.t.

$$\gamma_{c1}, \gamma_{c2} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.13a}$$

$$\gamma_{d1}, \gamma_{d2} \geq \gamma_{min}^D, \tag{2.13b}$$

$$0 \leq p_c \leq p_{max}^C, \tag{2.13c}$$

$$0 \leq p_d \leq p_{max}^D, \tag{2.13d}$$

$$0 \leq p_r \leq p_{max}^R, \tag{2.13e}$$

where p_c^*, p_d^* and p_r^* are the optimal transmission power for CUE, DUT and relay node.

Proposition 2.3 *If problem* (2.13) *is feasible then at optimality at least one node (DUT, relay node, or CUE) uses maximum transmission power and* $\gamma_{d1} = \gamma_{d2}$ *[16].*

Proof 2.3 *If no node uses maximum transmit power at optimality, we can increase the powers of all nodes by a scaling factor* $\alpha \geq 1$ *until one node reaches its maximum transmit power. Hence, total data rate of cellular link and D2D link increase, which contradicts with the assumption. Therefore, at least one node uses maximum power at optimality.*

At optimality of problem (2.13)*, if* $\gamma_{d1} \geq \gamma_{d2}$*, we can decrease* p_d *while maintaining* $\gamma_{d1} \geq \gamma_{d2}$*, which leads to the increase of* R_d*. Hence, the objective value of problem* (2.13) *can be improved. We can prove similarly if* $\gamma_{d1} < \gamma_{d1}$*. Therefore,* $\gamma_{d1} = \gamma_{d2}$ *at optimality.* ■

Accordingly, the problem (2.13) can be further formulated as

$$\begin{aligned}(p_c^*, p_d^*, p_r^*) &= \arg\max_{(p_c,p_d,p_r)} \frac{1}{2}\{\log_2(1+\gamma_{c1}) + \log_2(1+\gamma_{c2}) + \log_2(1+\gamma_{d1})\} \\ &= \arg\max_{(p_c,p_d,p_r)} \{(1+\gamma_{c1})(1+\gamma_{c2})(1+\gamma_{d1})\} \\ &= \arg\max_{(p_c,p_d,p_r)} f(p_c, p_d, p_r)\end{aligned} \tag{2.14}$$

s.t.

$$\frac{p_d h_{dr}}{\sigma^2 + p_c h_{cr}} = \frac{p_r h_{rd}}{\sigma^2 + p_c h_{cd}}, \tag{2.14a}$$

$$\frac{p_d h_{dr}}{\sigma^2 + p_c h_{cr}} \geq \gamma_{min}^D, \tag{2.14b}$$

$$\frac{p_c h_{cB}}{\sigma^2 + p_d h_{dB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.14c}$$

$$\frac{p_c h_{cB}}{\sigma^2 + p_r h_{rB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.14d}$$

$$0 \leq p_c \leq p_{max}^C, \tag{2.14e}$$

$$0 \leq p_d \leq p_{max}^D, \tag{2.14f}$$

$$0 \leq p_r \leq p_{max}^R, \tag{2.14g}$$

where $f(p_c, p_d, p_r) = (1 + \frac{p_c h_{cB}}{\sigma^2 + p_d h_{dB}})(1 + \frac{p_c h_{cB}}{\sigma^2 + p_r h_{rB}})(1 + \frac{p_d h_{dr}}{\sigma^2 + p_c h_{cr}})$. Constraint (2.14a) is based on **Proposition** 2.3.

From **Proposition** 2.3, it can be verified that problem (2.14) will achieve its optimum when $p_c = p_{max}^C$ or $p_d = p_{max}^D$, or $p_r = p_{max}^R$. Therefore, three cases are considered as follows.

Case 1: $p_c = p_{max}^C$

We define $f_c(p_c, p_d, p_r) = f(p_c, p_d, p_r)|_{p_c = p_{max}^C}$, problem (2.14) is equivalent to

$$\max_{(p_d, p_r)} f_c(p_c, p_d, p_r) \tag{2.15}$$

s.t.

$$\frac{p_d h_{dr}}{\sigma^2 + p_{max}^C h_{cr}} = \frac{p_r h_{rd}}{\sigma^2 + p_{max}^C h_{rd}}, \tag{2.15a}$$

$$\frac{p_d h_{dr}}{\sigma^2 + p_{max}^C h_{cr}} \geq \gamma_{min}^D, \tag{2.15b}$$

$$\frac{p_{max}^C h_{cB}}{\sigma^2 + p_d h_{dB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.15c}$$

$$\frac{p_{max}^C h_{cB}}{\sigma^2 + p_r h_{rB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.15d}$$

$$0 \leq p_d \leq p_{max}^D, 0 \leq p_r \leq p_{max}^R. \tag{2.15e}$$

Constraint (2.15a) suggests that p_d can be expressed as a linear function of p_r i.e.

$$p_d = \frac{h_{rd}(\sigma^2 + p_{max}^C h_{cr})}{h_{dr}(\sigma^2 + p_{max}^C h_{rd})} p_r. \tag{2.16}$$

Therefore, the objective function in (2.15) is expressed as a function of p_r, which is a ratio between one cubic polynomial and one quadratic polynomial:

$$f_c = \frac{\zeta_c(p_r)}{g_c(p_r)} = \frac{a_{c3}p_r^3 + a_{c2}p_r^2 + a_{c1}p_r + a_{c0}}{b_{c2}p_r^2 + b_{c1}p_r + b_{c0}}, \tag{2.17}$$

where the coefficients $a_{c3}, a_{c2}, a_{c1}, a_{c0}, b_{c2}, b_{c1}$ and b_{c0} can be obtained by the Matlab *expand* function. $\zeta_c(p_r)$ denotes the cubic polynomial function of p_r when CUE transmits at its maximum power. $g_c(p_r)$ denotes the quadratic polynomial function of p_r when CUE transmits at its maximum power.

Moreover, constraints (2.15b)-(2.15e) imply that $p_r \in [P_r^{min}, P_r^{max}]$, where P_r^{min} and P_r^{max} are the upper and lower bounds of p_r. Hence, the problem (2.15) is simplified into

$$\max_{p_r \in [P_r^{min}, P_r^{max}]} \frac{\zeta_c(p_r)}{g_c(p_r)}. \tag{2.18}$$

Problem (2.18) is a fractional optimization problem, and its associated parametric problem $z_r(\eta_r, p_r)$ with a given parameter η_r is

$$z_r(\eta_r, p_r) = \max_{p_r \in [P_r^{min}, P_r^{max}]} \{\zeta_c(p_r) - \eta_r g_c(p_r)\}. \tag{2.19}$$

The *Dinkelbach* method is used to solve this problem, and is described in the following subsection.

Case 2: $p_d = p_{max}^D$ **or** $p_r = p_{max}^R$

Since the problem (2.14) is similar when $p_d = p_{max}^D$ and $p_r = p_{max}^R$, so only $p_r = p_{max}^R$ is presented.

When $p_r = p_{max}^R$, problem (2.14) is transformed into

$$\max_{(p_c,p_d)} f_r(p_c, p_d, p_r) \tag{2.20}$$

s.t.

$$\frac{p_d h_{dr}}{\sigma^2 + p_c h_{cr}} = \frac{p_{max}^R h_{rd}}{\sigma^2 + p_c h_{cd}}, \tag{2.20a}$$

$$\frac{p_c h_{cB}}{\sigma^2 + p_d h_{dB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.20b}$$

$$\frac{p_{max}^R h_{rd}}{\sigma^2 + p_c h_{rd}} \geq \gamma_{min}^D, \tag{2.20c}$$

$$\frac{p_c h_{cB}}{\sigma^2 + p_{max}^R h_{rB}} \geq \frac{1}{2}\gamma_{min}^C, \tag{2.20d}$$

$$0 \leq p_c \leq p_{max}^C, 0 \leq p_d \leq p_{max}^D, \tag{2.20e}$$

in which $f_r(p_c, p_d, p_r) = f_r(p_c, p_d, p_r)|_{p_r = p_{max}^R}$. The first constraint (2.20a) suggests that p_d can be expressed as a linear function of p_c, i.e.

$$p_d = \frac{p_{max}^R h_{rd}(\sigma^2 + p_c h_{cr})}{h_{dr}(\sigma^2 + p_c h_{cd})}. \tag{2.21}$$

Substituting this p_d to the second constraint in (2.20b) leads to the following inequality:

$$d_{r2}p_c^2 + d_{r1}p_c + d_{r0} \geq 0, \tag{2.22}$$

where $d_{r2} > 0, d_{r0} < 0$. This inequality corresponds to $p_c \in [p_{c1}, +\infty)$, and p_{c1} is the positive root of equation $d_{r2}p_c^2 + d_{r1}p_c + d_{r0} = 0$.

In addition, the remaining constraints in (2.20c) and (2.20e) lead to $p_c \in [P_c^{min}, P_c^{max}]$. Define

$$\mathbf{D}_c = [\max\{P_c^{min}, p_{c1}\}, P_c^{max}] \tag{2.23}$$

as the feasible set of p_c for problem (2.20). P_c^{min} and P_c^{max} are the upper and lower bound of p_c.

Finally, substituting p_d as a function of p_c in (2.21) to the objective function in (2.20), it becomes

$$f_r = \frac{\zeta_r(p_c)}{g_r(p_c)} = \frac{a_{r4}p_c^4 + a_{r3}p_c^3 + a_{r2}p_c^2 + a_{r1}p_c + a_{r0}}{b_{r2}p_c^2 + b_{r1}p_c + b_{r0}}, \tag{2.24}$$

which is a ratio between one quartic polynomial and one quadratic polynomial. $a_{r4}, a_{r3}, a_{r2}, a_{r1}, a_{r0}, b_{r2}, b_{r1}$ and b_{r0} are the coefficients. $\zeta_r(p_c)$ and $g_r(p_c)$ are the quartic and quadratic polynomial function of p_c when relay node transmits at its maximum transmission power.

Moreover, (2.20) is further simplified as:

$$\max_{p_c \in \mathbf{D}_c} \frac{\zeta_r(p_c)}{g_r(p_c)}, \tag{2.25}$$

and its associated problem (i.e. $z_c(\eta_c, p_c)$) with an given parameter η_c is formulated as

$$z_c(\eta_c, p_c) = \max_{p_c \in \mathbf{D}_c} \{\zeta_c(p_c) - \eta_c g_c(p_c)\}. \tag{2.26}$$

The *Dinkelbach method*, which is described in Section 2.2.3 is employed to solve it.

2.2.3 Dinkelbach Method

The *Dinkelbach method* proposed by W. Dinkelbach in [35] is the most popular method to solve the fractional programming. It has been proved in [36] that the *Dinkelbach method* is an effective method to solve a class of MINLP problems. The mathematical details of the *Dinkelbach method* and its working process are presented below with a numerical example.

Mathematical background of Dinkelbach Method

Non-linear fractional programming problem is an optimization problem with a general format

$$\max_{p} f = \frac{\zeta(p)}{g(p)} \tag{2.27}$$

s.t.

$$p \in \mathbf{D},$$

where $\mathbf{D}$ is the feasible closed and bounded set of the variable power p; $\zeta(p)$ and $g(p)$ are continuous and $g(p) > 0$ for all $p \in \mathbf{D}$. Hence the non-linear fractional programming problem has a solution when $\mathbf{D}$ is not empty.

Proposition 2.4 *[35] A necessary and sufficient condition for*

$$\eta^* = \frac{\zeta(p^*)}{g(p^*)} = \max_{p \in \mathbf{D}} \frac{\zeta(p)}{g(p)} \tag{2.28}$$

is

$$z(\eta^*, p) = z(\eta^*, p^*) = \max_{p \in \mathbf{D}} [\zeta(p) - \eta^* g(p)] = 0,$$

where η^* and p^* denote the optimal value and solution of (2.28)*.*

Proof 2.4 *Let p^* be an optimal solution to non-linear fractional problem. Then $\eta^* = \frac{\zeta(p^*)}{g(p^*)} \geq \frac{\zeta(p)}{g(p)}$ for all $p \in \mathbf{D}$. This implies*

$$\zeta(p) - \eta^* g(p) \leq 0, \forall p \in \mathbf{D} \tag{2.29}$$

$$\zeta(p^*) - \eta^* g(p^*) = 0 \tag{2.30}$$

Define

$$\begin{aligned} z(\eta^*, p) =& \max_{p \in \mathbf{D}} [\zeta(p) - \eta^* g(p)] \\ =& \zeta(p^*) - \eta^* g(p^*) \\ =& z(\eta^*, p^*) \\ =& 0 \end{aligned} \tag{2.31}$$

Hence, p^* is the solution to the reduced non-linear fractional problem when $\eta = \eta^*$.

To establish the converse, let p^* be an optimal solution to the reduced nonlinear fractional problem i.e. $\zeta(p^*) - \eta^* g(p^*) = 0$. Then,

$$\zeta(p) - \eta^* g(p) \leq \zeta(p^*) - \eta^* g(p^*) = 0, \forall p \in \mathbf{D}.$$

This implies

$$\frac{\zeta(p)}{g(p)} \leq \eta^*, \forall p \in \mathbf{D}, \tag{2.32}$$

$$\frac{\zeta(p^*)}{g(p^*)} = \eta^*. \tag{2.33}$$

It follows from relations between (2.32) *and* (2.33) *that p^* is an optimal solution to the nonlinear fractional problem and*

$$\eta^* = \frac{\zeta(p^*)}{g(p^*)} = \max_{p \in \mathbf{D}} \frac{\zeta(p)}{g(p)}.$$

■

The *Dinkelbach method* is described in Table 2.1, which has three steps.

Step 1: Initialization: Set $\eta = 0$ and proceed to *Step 2*.
Step 2: Use a suitable convex algorithm to find a $p' \in \mathbf{D}$ that maximize $[\zeta(p) - \eta g(p)]$, then calculate $z(\eta, p') = \zeta(p') - \eta g(p')$.
Step 3: If $z(\eta, p') \leq \epsilon$, where ϵ is a small value which approaches zero, the iteration is terminated with $p^* = p'$, then p^* is an appropriate optimal solution to the fractional problem. Otherwise, if $z(\eta, p') > \epsilon$, then go to *Step 2* with updated $\eta = \frac{\zeta(p')}{g(p')}$.

It should be noted that the related problem with a given η in *Step 2* will be solved by a suitable convex algorithm. The choice of the convex algorithm depends on the type of the problem. As discussed in Section 2.1, the optimization problems can be classified to different types such as LP, ILP, NLP, MILP, and

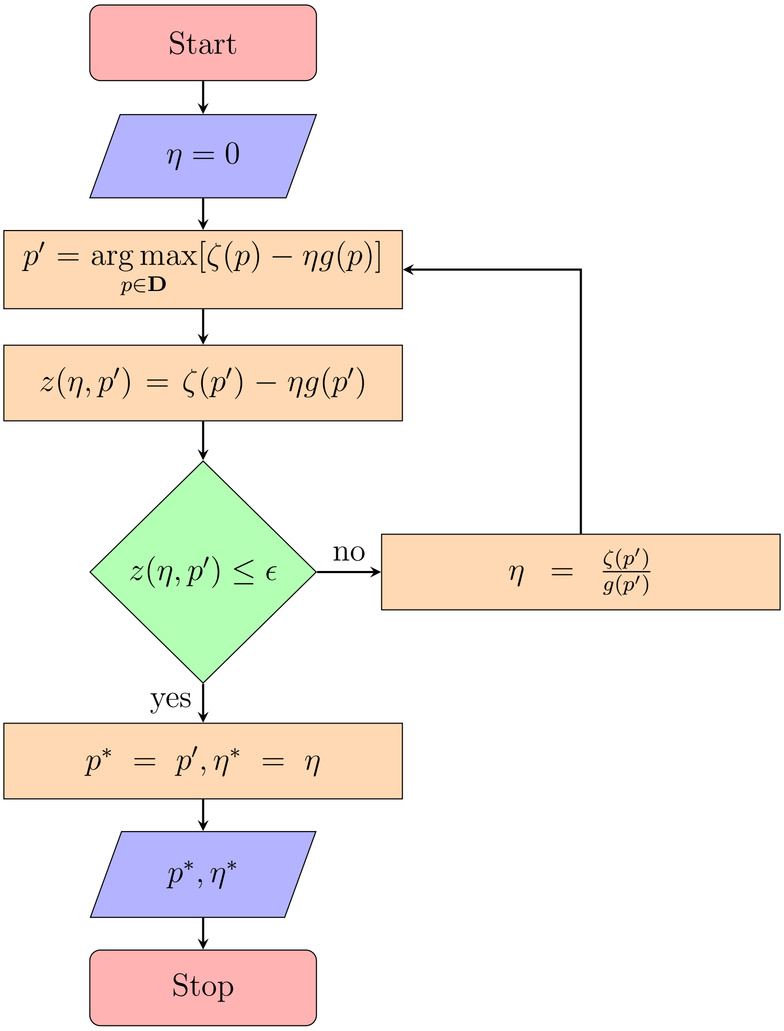


Table 2.1: The procedure of the Dinkelbach method

MINLP, according to the property of the objective function, the linear or non-linear constraints, and the integer or continues variables [37]. Therefore, solvers must be selected according to the specific optimization problem. In this thesis, we apply different existing functions in the Matlab Optimization Tootbox [1] as the solvers.

A numerical example

$$\max Z = \frac{2p_1 + 2p_2 + 1}{p_1^2 + p_2^2 + 3} \tag{2.34}$$

s.t.

$$p_1 + p_2 \leq 3, \tag{2.35}$$

$$p_1, p_2 \geq 0, \tag{2.36}$$

where $p = (p_1, p_2)^T$, $\zeta(p) = 2p_1 + 2p_2 + 1$, $g(p) = p_1^2 + p_2^2 + 3$, and $\mathbf{D} = (p : p_1 + p_2 \leq 3, p_1, p_2 \geq 0)$. Clearly, $g(p) > 0$, choose $\epsilon = 0.01$.

Iteration 1:

Step 1: To start the algorithm, let $\eta = 0$.

Step 2: Now the problem becomes

$$\max_{p \in \mathbf{D}} 2p_1 + 2p_2 + 1, \tag{2.37}$$

which is a linear programming problem and can be solved by the *simplex* method (i.e. *linprog* function in Matlab). The optimal solution of this linear program is $p' = [3 \quad 0]^T$. Thus, $z(\eta, p') = \zeta(p') - \eta g(p') = \zeta(p') = 2 \times 3 + 2 \times 0 + 1 = 7$.

Step 3: Since $z(\eta, p') > \epsilon$ (i.e. 7 >0.01), η is computed using the formula

$$\eta = \frac{\zeta(p')}{g(p')} = \frac{2p_1 + 2p_2 + 1}{p_1^2 + p_2^2 + 3} = \frac{2 \times 3 + 2 \times 0 + 1}{3^2 + 0^2 + 3} = \frac{7}{12},$$

and go back to *Step 2*.

Iteration 2:

Step 2: Substituting $\eta = \frac{7}{12}$, $\zeta(p)$ and $g(p)$ in the formula, the problem becomes

$$\begin{aligned} \max_{p \in \mathbf{D}} Z =& 2p_1 + 2p_2 + 1 - \frac{7}{12}(p_1^2 + p_2^2 + 3) \\ =& -\frac{7}{12}p_1^2 - \frac{7}{12}p_2^2 + 2p_1 + 2p_2 - \frac{9}{12}, \end{aligned} \tag{2.38}$$

[1] https://uk.mathworks.com/products/optimization.html

which is the quadratic programming problem. The *quadprog* function in Matlab is applied to obtain the optimal solution $p' = [3/2 \quad 3/2]^T$. Calculating

$$z(\eta, p') = \zeta(p') - \eta g(p') = (2p_1 + 2p_2 + 1) - \frac{7}{12}(p_1^2 + p_2^2 + 3) = \frac{21}{8}.$$

Step 3: Since $z(\eta, p') > \epsilon$ (i.e.$\frac{21}{8} > 0.01$), η is computed using the formula

$$\eta = \frac{\zeta(p')}{g(p')} = \frac{14}{15},$$

and go back to *Step 2*.

Iteration 3:

Step 2: The new objective function is obtained as given below by substituting the value of $\eta = \frac{14}{15}$, $\zeta(p)$ and $g(p)$,

$$\begin{aligned} \max_{p \in \mathbf{D}} Z =& 2p_1 + 2p_2 + 1 - \frac{14}{15}(p_1^2 + p_2^2 + 3) \\ =& -\frac{14}{15}p_1^2 - \frac{14}{15}p_2^2 + 2p_1 + 2p_2 - \frac{9}{5}. \end{aligned} \tag{2.39}$$

Similarly, applying the *quadprog* function, the optimal solution of this quadratic programming is $p' = [15/14 \quad 15/14]^T$. Calculating

$$z(\eta, p') = \zeta(p') - \eta g(p') = (2p_1 + 2p_2 + 1) - \frac{14}{15}(p_1^2 + p_2^2 + 3) = \frac{13}{35}.$$

Step 3: Since $z(\eta, p') > \epsilon$ (i.e. $\frac{13}{35} > 0.01$), η is computed using the formula

$$\eta = \frac{\zeta(p')}{g(p')} = \frac{518}{519},$$

and go back to *Step 2*.

Iteration 4:

Step 2: The new objective function is given below by substituting the value of $\eta = \frac{518}{519}$, $\zeta(p)$ and $g(p)$,

$$\begin{aligned} \max_{p \in \mathbf{D}} Z =& 2p_1 + 2p_2 + 1 - \frac{518}{519}(p_1^2 + p_2^2 + 3) \\ =& -\frac{518}{519}p_1^2 - \frac{518}{519}p_2^2 + 2p_1 + 2p_2 - \frac{345}{173}. \end{aligned} \tag{2.40}$$

The optimal solution is $p' = [1.0019 \quad 1.0019]$. Calculating

$$z(\eta, p') = \zeta(p') - \eta g(p') = (2p_1 + 2p_2 + 1) - \frac{14}{15}(p_1^2 + p_2^2 + 3) = 0.0096.$$

Step 3: $0.0096 > 0.01$. η is computed using the formula

$$\eta = \frac{\zeta(p')}{g(p')} = 1,$$

and go back to *Step 2*.

Iteration 5:

Step 2:

The new objective function is obtained as given below by substituting the value of $\eta = 1$, $\zeta(p)$ and $g(p)$,

$$\begin{aligned} \max_{p \in \mathbf{D}} Z =& 2p_1 + 2p_2 + 1 - (p_1^2 + p_2^2 + 3) \\ =& -p_1^2 - p_2^2 + 2p_1 + 2p_2 - 2. \end{aligned} \tag{2.41}$$

The optimal solution is $p' = [1 \quad 1]$. Calculating the

$$z(\eta, p') = \zeta(p') - \eta g(p') = (2p_1 + 2p_2 + 1) - (p_1^2 + p_2^2 + 3) = 0.$$

Step 3: $0 < 0.01$, iterations stop. The optimal solution is $p^* = p' = [1 \quad 1]$, and the optimal value is $\eta^* = \frac{\zeta(p^*)}{g(p^*)} = 1$. This satisfies the **Proposition** 2.4.

2.3 Channel Allocation

In order to maintain the QoS of communication links, D2D link should share the same channel resource with the cellular link which causes acceptable mutual interference. In this thesis, we define spectrum allocation as channel allocation unless it is otherwise specified. The well-known *Hungary* method (also called *Kuhn-Munkres* method in some works) is an optimization algorithm that solves the special assignment problem in polynomial time [38]. It has been applied to solve channel resource allocation problem for D2D links in [16] [20] [26] [27] [39].

The *Hungary* method will be explained below with an example. Assuming that there are 4 cellular channels (CH_1, CH_2, CH_3, CH_4) and 4 D2D links ($D2D_1$, $D2D_2$, $D2D_3$, $D2D_4$) in D2D communications networks. The channels will be assigned to four different D2D links to improve the sum throughput. Each D2D

Table 2.2: Data rate matrix (bit/s/Hz)

	$D2D_1$	$D2D_2$	$D2D_3$	$D2D_4$
CH_1	5	12	19	3
CH_2	7	18	9	19
CH_3	10	2	6	15
CH_4	9	3	4	17

link can only reuse one channel and each channel is only assigned to one D2D link. The data rate in bit/s/Hz on each channel when different D2D links allocated to are given in Table 2.2.

Thus, the channel assignment problem can be mathematically formulated as

$$\max \sum_{m=1}^{M} \sum_{n=1}^{N} w_{m,n} x_{m,n} \tag{2.42}$$

s.t.

$$\sum_{n=1}^{N} x_{m,n} = 1, \forall m = 1, 2, ...M, \tag{2.42a}$$

$$\sum_{m=1}^{M} x_{m,n} = 1, \forall n = 1, 2, ...N, \tag{2.42b}$$

$$x_{m,n} = \{0, 1\}, \forall m = 1, 2, ...M, \forall n = 1, 2, ...N, \tag{2.42c}$$

where $w_{m,n}$ is the data rate on channel m when D2D link n occupies. The binary variable

$$x_{m,n} = \begin{cases} 1, \text{if cellular channel } m \text{ is assigned to D2D link } n, \\ 0, \text{if cellular channel } m \text{ is not assigned to D2D link } n. \end{cases} \tag{2.43}$$

Constraint (2.42a) shows that each D2D link is assigned to only one channel, and constraint (2.42b) shows that each channel is assigned to only one D2D link. Constraint (2.42c) means that the variables are binary.

Based on theorem 2.3.1, the *Hungary* method can find the optimal assignment for the above problem with following five steps [40]:

Theorem 2.3.1 *If a number is added to or subtracted from all of the entries of any one row or column of a weight matrix, then on optimal assignment for the resulting weight matrix is also an optimal assignment for the original weight matrix.*

Table 2.3: Maximum data rate matrix

	$D2D_1$	$D2D_2$	$D2D_3$	$D2D_4$
CH_1	5	12	19	3
CH_2	7	18	9	19
CH_3	10	2	6	15
CH_4	9	3	4	17

Step 1 Subtract the smallest entry in each row from all the entries of its row.

Step 2 Subtract the smallest entry in each column from all the entries of its column.

Step 3 Draw lines through appropriate rows and columns so that all the zero entries of the cost matrix are covered and the minimum number of such lines is used.

Step 4 Test for Optimality: (i) If the minimum number of covering lines is M, an optimal assignment of zeros is possible and we are finished. (ii) If the minimum number of covering lines is less than M, an optimal assignment of zeros is not yet possible. In that case, proceed to *Step 5*.

Step 5 Determine if the smallest entry is not covered by any line. Subtract this entry from each uncovered elements, and then add it to each elements that covered by two lines. Return to *Step 3*.

More explanation and the Matlab function that implements this method can be found in [41]. After this, the maximum total data rate is calculated as 64 (i.e. 19+18+10+17=64) bit/s/Hz, with $D2D_3$ occupying CH_1, $D2D_2$ occupying CH_2, $D2D_1$ occupying CH_3, and $D2D_4$ occupying CH_4 assignment, as shown in Table 2.3.

The *Hungary* method was proposed by *Harold Kuhn* in 1995 with lower complexity $O(\max\{M, N\}^3)$ than the Brute-Force method which has $O(M!)$ complexity. Note that in practice, most of the matching problem have unequal dimensions (i.e. $M \neq N$). The weight matrix should be transformed into the square matrix [42] by adding ($|M - N|$) virtual nodes. Moreover, the *Hungary* method with the five-step process is proposed to find the minimum total cost matrix, so to maximize the total sum data rate matrix in this thesis should be adjusted before applying the *Hungary* method.

2.4 Summary

In this chapter, the resource allocation techniques (i.e. optimization programming, graph theory and game theory) with their literature reviews are given. The background of the optimization programming are detailed. In addition, the mathematical modellings of power and channel allocation are presented. Specifically, the power allocation is further considered under two cases: power allocation in DM and in RM. The channel allocation is investigated as the job assignment problem. The,, the well-known *Hungary* method is explained.

Chapter 3

Joint Power and Channel Allocation for Relay-Assisted D2D Communications based Heuristic Algorithms

3.1 Introduction

As explains in Section 1.2, D2D communications can operate in two basic modes: underlay and overlay, which means the D2D user shares the spectrum with the cellular user in orthogonal or non-orthogonal way [43]. The most important aspect of D2D communications is that it can improve the network capacity greatly by spectrum reusing between D2D and cellular users [44], [45]. The resource reusing is based on the criteria that it would not bring harmful interference to the cellular users. Many researchers already work on resource allocation for D2D communications underlay cellular system [18], [20], [26], [27], [28], [46], [47]. In [18], the centralized and decentralized methods are proposed to solve the resource allocation problem. Assuming global CSI, the resource allocation problem is formulated as a non-convex optimization problem, which is solved using convex approximation techniques. On the other hand, by exploiting the decentralized network structure with only local CSI at each node, the Stackelberg game model is then adopted to devise a distributed resource allocation scheme. The Nash equilibrium (NE) and the uniqueness of the solution are presented, and an iterative algorithm is proposed to solve the problem. Two reuse cases i.e. downlink and uplink interference scenarios are considered in [46]. An alternative greedy heuristic algorithm which can lessen the interference to primary cellular network is proposed by utilizing channel gain information. [47] aims to minimize the power consumption while meeting users' data rate requirements. They present an effective algorithm to solve the joint mode selection and resource allocation problem.

However, the D2D transmitter and receiver may not be able to perform direct D2D communications due to long separation distance or poor channel conditions [33]. In such cases, network-assisted transmission through relays could enhance the performance of D2D communication, which is referred to as relay-assisted D2D communications, as discussed in Chapter 2.

3.1.1 Related Works and Motivations

The resource allocation problem for relay-assisted D2D communications has been studied recently [14], [15], [16]. The radio protocol architecture (RPAs) for relay mode are first proposed in [14]. After that, a joint mode selection, radio resource and power allocation problem is formulated, where D2D links have dedicated channel, and there is no interference between any communication links. Moreover, a heuristic approach is proposed to make the joint allocation decisions. Authors in [15] considered the joint mode selection (between DM and RM) and channel assignment problem aiming to maximize the overall network throughput while guaranteeing the QoS of both cellular and D2D links. Authors in [48] propose a greedy algorithm based on game theory to allocate channel resource for each link, but they do not consider the power allocation, instead they assume that the transmission power of the links is constant. Authors in [49] assume that the transmission power of cellular links are constant at the maximum transmitter value. Then, the optimal power allocation of D2D links is performed by a closed-form solution. However, the system complexity of the above existing works grow exponentially with the number of cellular and D2D links. This will become a serious issue in the future networks as the number of connected devices is predicted as 7.33 billion in 2023 [50].

3.1.2 Main Contributions

Two efficient heuristic algorithms (named Proposed HA1 and Proposed HA2) with low complexity are proposed to solve the resource allocation problem while guaranteeing the QoS of communications links. Proposed HA1 focuses on reducing the complexity of channel allocation by narrowing the available channel search space for D2D links. Proposed HA2 aims to reduce the complexity of power allocation. Firstly, the best reuse pairs between cellular and D2D links while minimizing the interference on cellular links are figured out. Then, the optimal power resource is allocated to each reuse pair. In this way, the number of channels considered in power allocation procedure is greatly decreased, hence system computational complexity is reduced. Simulation results show that the Proposed HA1 and the Proposed HA2 can provide acceptable system performance with much lower complexity.

3.1.3 Chapter Organization

This chapter is organized as follows. Section 3.2 introduces the system model for relay-assisted D2D communications and the problem formulation. Section 3.3 illustrates our proposed solutions. Simulation results and complexity analysis are shown in Section 3.4. Section 3.5 concludes this chapter.

3.2 System Model and Problem Formulation

3.2.1 System Model

A single cell system with a BS in the central, where M CUEs in the set $\mathcal{M} = \{1, ...m, ...M\}$, N D2D pairs in the set $\mathcal{N} = \{1, ...n, ...N\}$ and N corresponding relay nodes in the set $\mathcal{R} = \{r_1, ...r_n, ..., r_N\}$ is shown in Figure 3.1. We assume that each cellular link has been pre-allocated an uplink channel. And each D2D link operates in RM (i.e. relay mode) with the support of a corresponding relay node. Note that mode selection is not considered in this chapter, instead efficiently allocating the channel resource to D2D links is the main focus. Without loss of generality, the channel index in this chapter is ignored, and use symbols (m, n, r_n) to denote the CUEs, the D2D pair and the relay node, respectively.

We also assume that each D2D link can only reuse one channel resource of cellular link, and each channel resource of cellular link is assigned to at most one D2D link. D2D link n is supported by relay node r_n in the set $\mathcal{R}$. We denote $\boldsymbol{\chi}$ as a binary channel allocation decision matrix, where the binary variable

$$\chi_{mn} = \begin{cases} 1 & \text{D2D link } n \text{ resues the channel resource of cellular user } m, \\ 0 & \text{otherwise.} \end{cases} \tag{3.1}$$

h_{ab} is denoted as the channel gain from the transmitter of link or relay node a to the receiver of the link or relay node b.

The DF relaying strategy is employed i.e. each communication period is divided into two equal intervals corresponding to the DUT to relay node communication phase (phase 1) and relay node to DUR communication phase (phase 2) as discussed in Chapter 2. In addition, D2D communications in phase 1 and phase 2 use the same cellular channel resource.

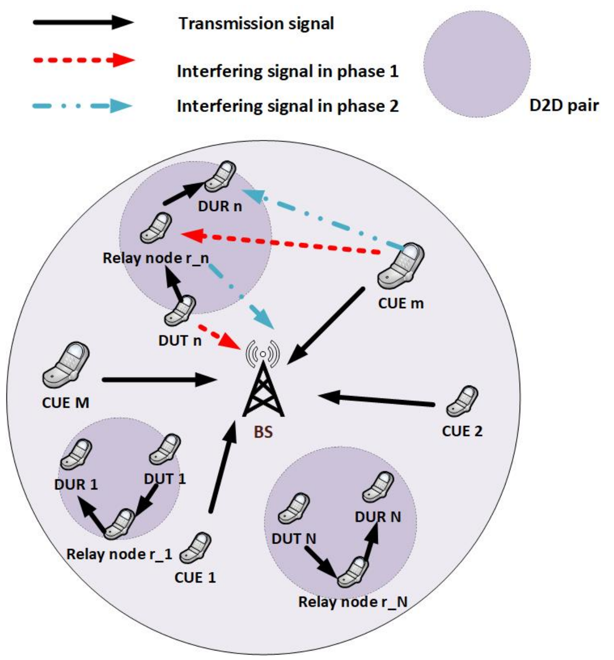


Figure 3.1: A Single Cell System with M cellular links, N D2D links and corresponding N relay nodes.

In phase 1, when D2D link n reuses the channel resource of cellular link m, the SINRs of cellular link m i.e. γ_{mn}^{C1} and D2D link n i.e. γ_{mn}^{D1} are expressed as

$$\gamma_{mn}^{C1} = \frac{p_m^C h_{mB}}{\sigma^2 + p_n^D h_{nB}}, \tag{3.2}$$

$$\gamma_{mn}^{D1} = \frac{p_n^D h_{nr_n}}{\sigma^2 + p_m^C h_{mr_n}}, \tag{3.3}$$

in which p_m^C and p_n^D are the transmission power of cellular link m and D2D link n, respectively. The script B in h_{mB} and h_{nB} is denoted as the BS. h_{mB} is the signal channel gain from the CUE m to the BS, and h_{nB} is the interfering channel gain from the DUT n to the BS. Moreover, h_{nr_n} is the signal channel gain between the DUT n to relay node r_n, and the h_{mr_n} is the interfering channel gain from CUE m to relay node r_n. σ^2 denotes the noise power.

In phase 2, the SINRs of cellular link m i.e. γ_{mn}^{C2} and D2D link n i.e. γ_{mn}^{D2} are expressed as

$$\gamma_{mn}^{C2} = \frac{p_m^C h_{mB}}{\sigma^2 + p_n^R h_{r_nB}}, \tag{3.4}$$

$$\gamma_{mn}^{D2} = \frac{p_n^R h_{r_nn}}{\sigma^2 + p_m^C h_{mn}}, \tag{3.5}$$

in which p_n^R is the transmission power of the relay node r_n. h_{r_nB} is the interfering channel gain from relay node r_n to the BS, h_{r_nn} is the signal channel gain from relay node r_n to DUR n, h_{mn} is the interfering channel gain from CUE m to DUR n. We denote the transmission power vector as $p_{mn} = [p_m^C, p_n^D, p_n^R]$, while D2D link n reuses the same channel resource with cellular link m. Thus, the data rate in bits per second per hertz (i.e. normalized by the channel bandwidth) of cellular link m and D2D link n can be expressed as

$$R_{mn}^C = \frac{1}{2}\log_2(1+\gamma_{mn}^{C1}) + \frac{1}{2}\log_2(1+\gamma_{mn}^{C2}), \tag{3.6}$$

$$R_{mn}^D = \frac{1}{2}\log_2(1+\min\{\gamma_{mn}^{D1}, \gamma_{mn}^{D2}\}). \tag{3.7}$$

Moreover, when cellular link does not experience any co-channel interference from D2D link, the maximum throughput could be achieved while cellular link transmits with its maximum power (i.e. p_{max}^C). Thus, the data rate of cellular link m without reusing is:

$$R_m^0 = \log_2(1+\frac{p_{max}^C h_{mB}}{\sigma^2}). \tag{3.8}$$

3.2.2 Problem Formulation

In this section, we formulate the joint power and channel allocation problem for relay-assisted D2D communications, which aims to maximize the sum data rate of all communication links while guaranteeing the required minimum SINRs of cellular and D2D links.

The joint optimization problem is expressed as

$$\max_{P,\boldsymbol{\chi}}\{\sum_{m=1}^{M}(1-\sum_{n=1}^{N}\chi_{mn})R_m^0 + \sum_{m=1}^{M}\sum_{n=1}^{N}\chi_{mn}R_{mn}^C + \sum_{n=1}^{N}\sum_{m=1}^{M}\chi_{mn}R_{mn}^D\} \tag{3.9}$$

s.t.

$$\gamma_{mn}^{C1} \geq \frac{1}{2}\gamma_{min}^C, \gamma_{mn}^{C2} \geq \frac{1}{2}\gamma_{min}^C, \forall m \in \mathcal{M}, \tag{3.9a}$$

$$\gamma_{mn}^{D1} \geq \gamma_{min}^D, \gamma_{mn}^{D2} \geq \gamma_{min}^D, \forall n \in \mathcal{N}, \tag{3.9b}$$

$$0 \leq p_m^C \leq p_{max}^C, \forall m \in \mathcal{M}, \tag{3.9c}$$

$$0 \leq p_n^D \leq p_{max}^D, \forall n \in \mathcal{N}, \tag{3.9d}$$

$$0 \leq p_n^R \leq p_{max}^R, \forall r_n \in \mathcal{R}, \tag{3.9e}$$

$$\sum_{n=1}^{N}\chi_{mn} \leq 1, \forall m \in \mathcal{M}, \tag{3.9f}$$

$$\sum_{m=1}^{M}\chi_{mn} = 1, \forall n \in \mathcal{N}, \tag{3.9g}$$

$$\chi_{mn} \in \{0,1\}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \tag{3.9h}$$

in which P is the power allocation matrix. γ^C_{min} and γ^D_{min} are the minimum SINR requirements of cellular and D2D links, respectively. $p^C_{max}, p^D_{max}, p^R_{max}$ are the maximum transmission power of CUE, DUT and relay node. Constraints (3.9a) and (3.9b) show the minimum SINR requirement of each link in all transmission intervals. Constraints (3.9c)-(3.9e) express the limited transmission power of individual cellular, D2D and relay node transmitter, respectively. Constraint (3.9f) shows that each cellular link can only be shared by no more than one D2D link, and constraint (3.9g) shows that each D2D link can only reuse one cellular link's resource. The final constraint (3.9h) shows the value of resource allocation indicators are binary.

3.3 Proposed Solutions

The design problem (3.9) with constraints (3.9a)-(3.9h) is a MINLP problem, which is NP-hard. It implies that there is no known polynomial-time algorithm for finding all the feasible power and channel allocation. In order to solve the above design problem efficiently, the HA1 and HA2 with low complexity are proposed in this subsection. The main idea is to divide the original design problem into two sub-problems (i.e. power allocation and channel allocation) firstly, and then solve them separately. Specifically, in the Proposed HA1, the optimal power for each communication link is first allocated when the channel resource of cellular link m reused by D2D link n. Then, the channel resource for each D2D link is assigned by using the proposed channel allocation algorithm. To further reduce the system computational complexity, in the Proposed HA2 we first allocate the channel resource for each D2D link while minimizing the interference in cellular link by using the proposed channel allocation algorithm. Then, the optimal transmission power for both cellular and D2D links is allocated.

3.3.1 The Proposed HA1

In Proposed HA1, the power allocation for each reuse pair is firstly investigated. The power allocation problem is expressed as following:

$$\begin{aligned}(p^{C*}_m, p^{D*}_n, p^{R*}_n) &= \underset{(p^C_m, p^D_n, p^R_n)}{\arg\max}\,(R^C_{mn} + R^D_{mn}) \\ &= \underset{(p^C_m, p^D_n, p^R_n)}{\arg\max}\{\frac{1}{2}\log_2(1+\gamma^{C1}_{mn}) + \frac{1}{2}\log_2(1+\gamma^{C2}_{mn}) \\ &\quad + \frac{1}{2}\log_2(1+\min\{\gamma^{D1}_{mn}, \gamma^{D2}_{mn}\})\}\end{aligned} \tag{3.10}$$

s.t. constraints(3.9a)-(3.9e), which can be solved by the power allocation in RM algorithm as described in Section 2.2.2. Then, the optimal data rate of cellular and D2D links i.e. R_m^{C*} and R_n^{D*} are obtained. Note that R_m^{C*} and R_n^{D*} are achieved under the assumption that if D2D link n reuses the channel resource of cellular link m.

After considering all the power allocation possibilities, the channel allocation in (3.9) becomes a job assignment problem:

$$\max_{\boldsymbol{\chi}} \quad \sum_{m=1}^{M} \sum_{n=1}^{N} \Pi_{mn} \chi_{mn}, \tag{3.11}$$

s.t. constraints(3.9f)-(3.9h), where $\Pi_{mn} = (R_m^{C*} + R_n^{D*} - R_m^0)$ and R_m^0 is obtained according to (3.8). Link n is one D2D link in the set of all D2D links (i.e. $\mathcal{N}$) and link m is one of the cellular link in the set of all cellular links (i.e. $\mathcal{M}$), so the value of Π_{mn} may be different with varying m and n. Moreover, $\Pi_{mn} > 0$ means that when D2D link n reuses the resource of cellular link m, it can help increase the total data rate. If $\Pi_{mn} < 0$, allowing D2D link n to reuse the resource of cellular link m results in the decrease of the system data rate. Thus, in the matching problem (3.11), if $\Pi_{mn} < 0$, the optimal solution will give the result $\Pi_{mn} = 0$ to implement the following proposed channel allocation algorithm.

Here, the channel resource is sequentially allocated by applying the proposed channel allocation algorithm, as described in Algorithm 1. Denote the available channel resource as Ω_{avail}. We first select the channel resource of cellular link m^* which can produce the maximum data rate gain i.e. Π_{mn} by comparing with all possible channel resource reuse scenarios. Then, the selected channel resource of cellular link m^* is removed from the Ω_{avail}. In this way, the search space of Ω_{avail} for the next D2D link is reduced. The above step is repeated until all D2D links are allocated. Note that the different initialization of this algorithm will bring in different simulation results. Thus, we assume that the

3.3.2 The Proposed HA2

To further reduce the complexity, the channel resource for D2D links is first allocated, the transmit power is then assigned. Considering the worst situation that D2D link transmits at its maximum power i.e. p_{max}^D, the D2D link will choose the reuse channel resource that cause the minimum interference to that cellular link.

The interference on cellular link m when it is reused by the D2D link n is denoted as $i_{mn} = p_{max}^D(h_{nm} + h_{r_n m}), \forall m \in M, \forall n \in N$. Again, the design problem

Algorithm 1 The proposed channel allocation algorithm

1: Input
The set of cellular link $\mathcal{M}$
The set of D2D link $\mathcal{N}$
The optimal sum rate matrix Π_{mn}
2: Output
The set of channel resource of cellular links shared by D2D links: Ω
3: Initialization: $\Omega = \phi$, $\Omega_{avail} = \mathcal{M}$
4: **for all** $n \in N$, $m \in \Omega_{avail}$ **do**
5: $\quad m^* = arg \max_{n \in N, m \in \Omega_{avail}} \Pi_{mn}$
6: $\quad \Omega_n = \Omega_n \cup \{m^* | m^* \in \Omega_{avail}\}$
7: $\quad \Omega_{avail} = \Omega_{avail} - m^*$
8: $\quad \Omega = \{\Omega_n | n \in N\}$
9: **end for**

becomes the following job assignment problem,

$$\min_{\chi} \quad \sum_{m=1}^{M} \sum_{n=1}^{N} i_{mn} \chi_{mn}, \tag{3.12}$$

s.t. constraints(3.9f)-(3.9h).

The proposed channel allocation algorithm as shown in Algorithm 1 is applied to solve problem in (3.12). After that, each D2D link is allocated its own reuse channel resource with a certain cellular link. Thus, the original problem is reduced to the power allocation problem for each reuse pair:

$$\max_{(p_m^C, p_n^D, p_n^R)} \sum_{m=1}^{N} \sum_{n=1}^{N} (R_{mn}^C + R_{mn}^D), \tag{3.13}$$

s.t.

$$\gamma_{mn}^{c1} \geq \frac{1}{2}\gamma_{min}^C, \gamma_{mn}^{c2} \geq \frac{1}{2}\gamma_{min}^C, \forall n \in \mathcal{N}, \tag{3.13a}$$

$$\gamma_{mn}^{d1} \geq \gamma_{min}^D, \gamma_{mn}^{d2} \geq \gamma_{min}^D, \forall m \in \Omega, \tag{3.13b}$$

$$0 \leq p_m^C \leq p_{max}^C, \forall m \in \Omega, \tag{3.13c}$$

$$0 \leq p_n^D \leq p_{max}^D, \forall n \in \mathcal{N}, \tag{3.13d}$$

$$0 \leq p_n^R \leq p_{max}^D, \forall n \in \mathcal{N}, \tag{3.13e}$$

which can be solved by the power allocation using the RM algorithm as described in Section 2.2.2. Note that, after the channel allocation, the number of candidate channel resource decreases, which is actually equal to the number of D2D links N. It means we only need to solve N times selected power allocation problem in the Proposed HA2. In this way, the complexity of the power allocation is further reduced.

Table 3.1: Simulation Parameters

Cell Radius C (m)	500
Maximum distance between D2D pairs d_{max} (m)	(20,...,200)
Number of cellular links M	10
Number of D2D links N ($N \leq M$)	(1,..,9)
Maximum cellular transmission power p^C_{max}(dBm)	24
Maximum D2D transmission power p^D_{max} (dBm)	24
Maximum relay node transmission power p^R_{max} (dBm)	24
QoS requirements of cellular links γ^C_{min} (dB)	5
QoS requirements of D2D links γ^D_{min} (dB)	15
Noise power σ^2 (dBm)	-110
Pathloss exponent for DUT-Relay-DUR links $\alpha 1$	3
Pathloss exponent for other communications $\alpha 2$	4

3.4 Simulation Results and Complexity Analysis

In this section, the Monte Carlo simulation is applied to evaluate the performance of the proposed algorithms. We consider a single cellular network with a radius C, where the BS is located in the centre of the cell, cellular users and relay nodes are distributed uniformly in the cell. Each D2D transmitter and receiver are located randomly whose distance to its relay node varies within d_{max}. The channel gain is modelled as $h_{a,b} = d_{a,b}^{-\alpha}\kappa$ for all communication links, where $d_{a,b}$ is the distance between node a and b, α is the pathloss exponent[1]; κ represents the Rayleigh fading. The simulation parameters as summarized in TABLE 3.1, are chosen according to [16] for the purpose of comparison.

The complexity of our proposed algorithms are analysed for power and channel allocation as shown in Table 3.2[2] in term of the total number of cellular links M and that of D2D links N. In the Proposed HA1, we first solve MN power allocation problem with complexity of $O(1)$, which means the power allocation

[1]To demonstrate the benefit that relay can bring us, we choose different pathloss exponent value for D2DT to Relay nodes and Relay nodes to D2DR links.

[2]MN means we solved MN times problems. It is exhaustive search.

Table 3.2: Complexity Comparison

Resource allocation algorithms	Power allocation	Channel allocation
Tuong2017 [16]	MN	M^3
Proposed HA1	MN	$MN - \frac{N(N-1)}{2}$
Proposed HA2	N	$MN - \frac{N(N-1)}{2}$

complexity is $O(MN)$. And the complexity of the proposed channel allocation algorithm is expressed as

$$\underbrace{M + (M-1) + (M-2) + \quad ... \quad + (M-N+1)}_{N} = O\Big(MN - \frac{N(N-1)}{2}\Big).$$

Therefore, the total complexity of the Proposed HA1 is

$$O\Big(MN + (MN - \frac{N(N-1)}{2})\Big) = O\Big(2MN - \frac{N(N-1)}{2}\Big).$$

In the Proposed HA2, after completing the channel allocation, we only need to solve N power allocation problem with $O(1)$ complexity. Therefore, the total complexity of Proposed HA2 is

$$O\Big(\Big(MN - \frac{N(N-1)}{2}\Big) + N\Big),$$

which is less than $O\Big(2MN - \frac{N(N-1)}{2}\Big)$. Moreover, the complexity of the well-known *Hungary* method is $O(M^3)$ as discussed in section 2.3. Thus, the complexity of the Proposed HA1 and the Proposed HA2 are significantly less than that of algorithms in [16], as shown in Figure 3.2, where the algorithm in [16] is referred as *Tuong2017*. And the the complexity of the Proposed HA2 is less than that of the Proposed HA1.

Figure 3.3 shows the system sum data rates of the *Tuong2017*, the Proposed HA1 and the Proposed HA2 with varying maximum distance between D2D transmitter and receiver d_{max}. In *Tuong2017*, authors get the optimal performance by searching all the possible power combinations in the search space and applying the *Hungary* method to get the optimal channel allocation. From Figure 3.3 , we can see that the performance of the Proposed HA1 and Proposed HA2 are 93% and 80% close to the optimal performance obtained in *Tuong2017*, but requiring notable lower complexity. As d_{max} increases, the system sum data rate decreases dramatically. That is because the data rate that contributed by the D2D links reduces with the increase of d_{max}. In addition, when d_{max} is large, the D2D transmitter will increase its transmission power to maintain its QoS. This will cause

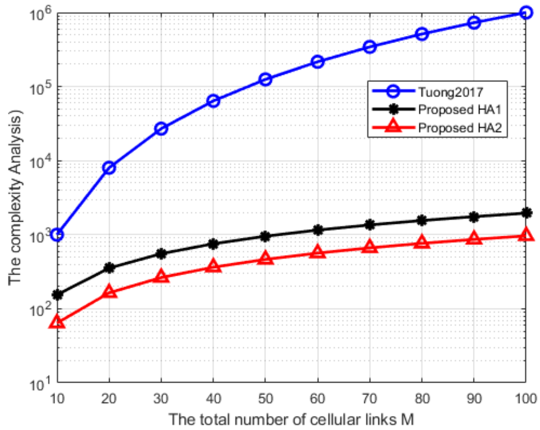


Figure 3.2: The comparison of complexity between different algorithms when $N = 10$.

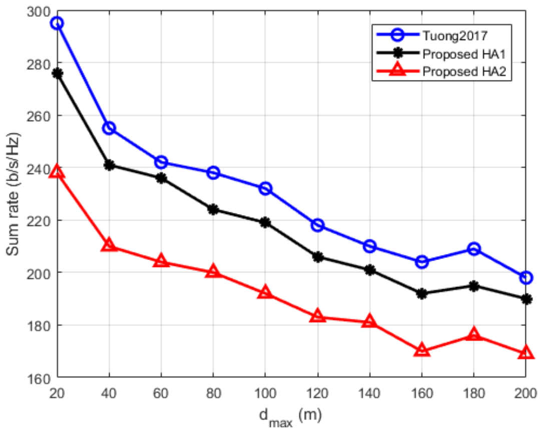


Figure 3.3: System sum data rate VS. d_{max} with different algorithms ($M = 10, N = 6$).

larger interference to the cellular links and thereby reduce the system sum data rate.

Figure 3.4 shows that the system sum data rate increases dramatically with the number of D2D links increases. That is because more D2D links will increase overall data rate. We can also see that the performance of the Proposed HA1 is close to the optimal performance when number of D2D links is small. From the above results, although the performance of the two proposed algorithms (Proposed HA1 and HA2) are worse than the optimal performance, the complexity of the proposed algorithms are significant lower, and this is important for the future network which has massive number of connected devices.

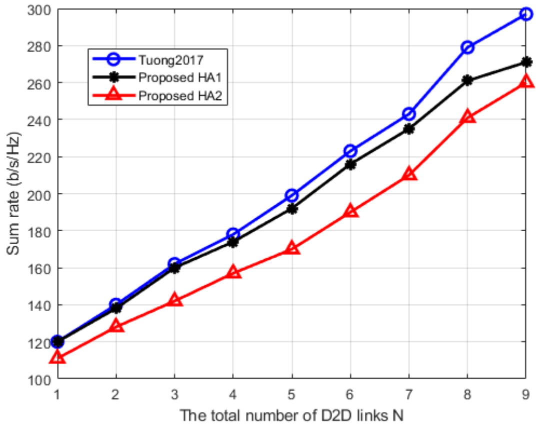


Figure 3.4: System sum data rate with different number of D2D links under different algorithms ($M = 10, d_{max} = 100m$).

3.5 Summary

In this chapter, we have developed low complexity efficient power and channel allocation algorithms for relay-assisted D2D communications underlay cellular systems. We first formulated the design problem as a MINLP, which can not be solved in polynomial time. We then proposed two algorithms (the Proposed HA1 and the Proposed HA2) with lower computational complexity. Simulation results show that the Proposed HA1 and Proposed HA2 can produce acceptable performance with significantly lower complexity.

Chapter 4

Joint Mode Selection, Relay Selection and Resource Allocation for Relay-Assisted D2D Underlay Communications

4.1 Introduction

As defined in Chapter 2, a D2D pair communicates with each other directly is named as direct mode (DM), and the D2D pair communicates with each other via the relay node is named as the relay mode (RM). In this chapter, D2D links can operate in either DM or RM. The mode selection is to choose the transmission mode between DM and RM. Moreover, when operating in RM, relay selection is required to choose a relay node to assist its communications.

4.1.1 Related Works and Motivations

Recently, there are some researches on joint mode, relay selection and resource allocation problem for relay-assisted D2D communications [14]. A joint mode selection, channel assignment and power allocation for D2D underlay cellular communicants system is studied in [16], in which the mode selection is determined by comparing the performance offered by different communication modes for each D2D communication link. Moreover, the relay selection is ignored, where one relay node is pre-set for each D2D link. Although relay selection scheme is investigated in [51] [49], they do not consider the mode selection and the D2D links always operate in RM. The joint mode selection, relay selection and resource allocation is considered in [15], and Genetic Algorithm (GA) is applied to solve the joint problem, which is insufficient to achieve the close-to-optimal system performance.

The existing works show that power allocation and channel allocation are dependent on each other. Various transmission power on different channel will effect the channel allocation, and different channel allocation can also effect the optimal power allocation on each channel. Only considering all the reuse possibilities in both power and channel allocation can lead to the optimal system performance. Thus, in this chapter, we mainly focus on achieving the optimal system performance for relay-assisted D2D underlay communications while guaranteeing the QoS of all cellular and active D2D links. To the best of our knowledge, this is the first work on joint mode selection, relay selection and resource allocation for relay-assisted D2D communication aiming to achieve the optimal system performance.

4.1.2 Main Contributions

The main contributions of this chapter are as follows:

- The joint mode selection, relay selection and resource allocation problem aiming to maximize the overall network throughput is formulated, subject to power and SINR constraints for both cellular and active D2D links.

- In order to solve the above joint problem efficiently, we decompose our optimization problem into two subproblems: *OPA* and *JMRC*, which are then solved sequentially. Specifically, we considered all the reuse possibilities between cellular user and D2D pairs in power allocation, which is exhaustive research. Then, after channel allocation, this resource allocation algorithm yields the optimum results.

- The *OPA* is further divided into *OPA*-I and *OPA*-II for two cases i.e. D2D links operate in DM and RM. Power allocation in these two cases can be optimally solved by the proposed *OPA*-I algorithm and the existing algorithm in [16] as discussed in Section 2.2.2.

- Based on the above optimal power allocation while considering all the reuse possibilities between cellular and D2D link, the *JMRC* is linearised into an ILP by introducing auxiliary variables. Then, the *JMRC* problem is solved directly by standard linear programming methods such as simplex method and Balas method.

Simulation results show that our proposed scheme outperforms the existing schemes.

4.1.3 Chapter Organization

The rest of this chapter is organized as follows. Section 4.2 introduces the system model for relay-assisted D2D communications. Section 4.3 shows the problem formulation and decomposition. The proposed algorithms are explained in section 4.4. Simulation results and analysis are presented in section 4.5. Section 4.6 concludes this chapter.

4.2 System model and Problem formulation

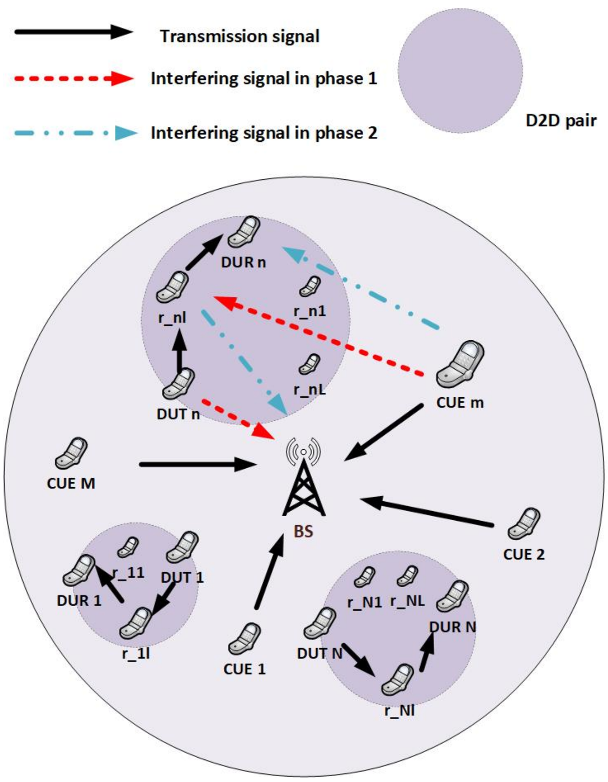


Figure 4.1: A Single Cell System with M cellular links, N D2D links and the corresponding relay nodes.

The spectrum sharing relay-assisted D2D communications underlay cellular networks is shown in Figure 4.1, which has M cellular links, N D2D links. We use $\mathcal{M} = \{1, ...m, ...M\}$ and $\mathcal{N} = \{1, ...n, ...N\}$ to denote the index sets of cellular links and D2D links, respectively. Each D2D link has L corresponding relay nodes, which can be denoted $\mathcal{L}_n = \{r_{n1}, r_{n2}..., r_{nl}, ..., r_{nL}\}$, where $n = 1, .., N$. The relay node set of all D2D links is $\mathcal{R} = \{\mathcal{L}_1, ...\mathcal{L}_n, ...\mathcal{L}_N\}$. Note that each relay node set $\mathcal{L}_n$ is independent with each other. We consider a fully loaded cellular network, in which M active cellular links occupy the M orthogonal channels and there is no spare spectrum. Moreover, we assume that each D2D link can only reuse no more than one cellular link channel resource, and each relay node can only support one D2D link. We denote $h_{a,b}$ as the channel gain from the transmitter of link or relay node a to the receiver of the link or the relay node b. Each D2D link can operate in either DM or RM.

4.2.1 Direct Mode

When D2D link n operates in DM, the D2D transmitter communicates directly with its D2D receiver. Thus, the SINRs of cellular link m (i.e. $\gamma^{(d)}_{C_{m,n}}$) and D2D links n (i.e. $\gamma^{(d)}_{D_{m,n}}$) are expressed as

$$\gamma^{(d)}_{C_{m,n}} = \frac{p^{(d)}_{C_m} h_{m,B}}{\sigma^2 + p^{(d)}_{D_n} h_{n,B}}, \tag{4.1}$$

$$\gamma^{(d)}_{D_{m,n}} = \frac{p^{(d)}_{D_n} h_{n,n}}{\sigma^2 + p^{(d)}_{C_m} h_{m,n}}, \tag{4.2}$$

where $p^{(d)}_{C_m}$ and $p^{(d)}_{D_n}$ are the transmit power of cellular link m and D2D link n in DM, respectively [1]. $h_{m,B}$ is the signal channel gain between cellular link m transmitter and the BS, and $h_{n,B}$ is the interfering channel gain from the transmitter of D2D link n to the BS. $h_{n,n}$ is the signal channel gain between D2D link n transmitter and receiver, and $h_{m,n}$ is the interfering channel gain from cellular link m transmitter to D2D link n receiver, respectively. σ^2 denotes the noise power. Therefore, the data rates in bits per second per hertz (i.e. normalized by the channel bandwidth) of cellular link m and D2D link n are expressed as

$$R^{(d)}_{C_{m,n}} = \log_2(1 + \gamma^{(d)}_{C_{m,n}}), \tag{4.3}$$

$$R^{(d)}_{D_{m,n}} = \log_2(1 + \gamma^{(d)}_{D_{m,n}}), \tag{4.4}$$

The total data rate of cellular link m and D2D links n in DM is

$$R^{(d)}_{m,n} = R^{(d)}_{C_{m,n}} + R^{(d)}_{D_{m,n}}. \tag{4.5}$$

4.2.2 Relay Mode

When D2D link n operates in RM, D2D link n selects relay node r_{nl} when it reuses the same channel resource with cellular link m. As discussed in Chapter 2, the DF relaying strategy is employed, where each communication period is divided into two equal intervals corresponding to the D2D transmitter to relay node

[1] Here, the superscript (d) means DM, and (r) means RM for the next subsection.

communication phase (phase 1) and relay node to D2D receiver communication phase (phase 2). Also, we assume that communications in phase 1 and phase 2 use the same cellular channel resource.

In phase 1, the SINRs of cellular link m and D2D link n can be expressed as

$$\gamma^{(r)}_{C1_{m,n,r_{nl}}} = \frac{p^{(r)}_{C_m} h_{m,B}}{\sigma^2 + p^{(r)}_{D_n} h_{n,B}}, \tag{4.6}$$

$$\gamma^{(r)}_{D1_{m,n,r_{nl}}} = \frac{p^{(r)}_{D_n} h_{n,r_{nl}}}{\sigma^2 + p^{(r)}_{C_m} h_{m,r_{nl}}}. \tag{4.7}$$

Similarly, in phase 2, the SINRs of cellular link m and D2D link n can be expressed as

$$\gamma^{(r)}_{C2_{m,n,r_{nl}}} = \frac{p^{(r)}_{C_m} h_{m,B}}{\sigma^2 + p^{(r)}_{R,r_{nl}} h_{r_{nl},B}}, \tag{4.8}$$

$$\gamma^{(r)}_{D2_{m,n,r_{nl}}} = \frac{p^{(r)}_{R,r_{nl}} h_{r_{nl},n}}{\sigma^2 + p^{(r)}_{C_m} h_{m,n}}, \tag{4.9}$$

where $p^{(r)}_{C_m}$, $p^{(r)}_{D,n}$ and $p^{(r)}_{R,r_{nl}}$ are the transmit power of cellular link m, D2D link n and relay node r_{nl} in RM, respectively. $h_{n,r_{nl}}$ and $h_{m,r_{nl}}$ are the signal channel gain from D2D link n transmitter to relay node r_{nl} and the interfering channel gain from cellular link m transmitter to relay node r_{nl}, respectively. The signal channel gain from relay node r_{nl} to D2D link n receiver is denoted as $h_{r_{nl},n}$. The data rates of cellular link m and D2D links n RM can be expressed as

$$R^{(r)}_{C_{m,n,r_{nl}}} = \frac{1}{2}\log_2(1 + \gamma^{(r)}_{C1_{m,n,r_{nl}}}) + \frac{1}{2}\log_2(1 + \gamma^{(r)}_{C2_{m,n,r_{nl}}}), \tag{4.10}$$

$$R^{(r)}_{D_{m,n,r_{nl}}} = \frac{1}{2}\log_2(1 + \min\{\gamma^{(r)}_{D1_{m,n,r_{nl}}}, \gamma^{(r)}_{D2_{m,n,r_{nl}}}\}). \tag{4.11}$$

Thus, the sum data rate of cellular link m and D2D link n via relay node r_{nl} are

$$R^{(r)}_{m,n,r_{nl}} = R^{(r)}_{C_{m,n,r_{nl}}} + R^{(r)}_{D_{m,n,r_{nl}}}. \tag{4.12}$$

In addition, the data rate of cellular link m without being reused can be expressed as

$$R^0_{C,m} = \log_2(1 + \frac{P^C_{max} h_{m,B}}{\sigma^2}), \tag{4.13}$$

where p^C_{max} is the maximum transmit power of cellular link.

4.3 Problem Formulation and Decomposition

Problem in Chapter 3 only solved the resource allocation problem, without considering the mode and relay section. In this section, the joint mode selection, relay selection and resource allocation problem is formulated, which aims to maximize the sum data rate of all communication links while guaranteeing the required minimum SINRs and power limits of cellular and active D2D links. The problem can be expressed as

$$\max_{\boldsymbol{\chi},\boldsymbol{\rho},P}\{\sum_{m=1}^{M}\{(1-\sum_{n=1}^{N}\chi_{mn})(1-\sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{m,n,r_{nl}})R_{C,m}^{0}+\sum_{n=1}^{N}(\chi_{mn}R_{mn}^{(d)}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}R_{m,n,r_{nl}}^{(r)})\}\} \tag{4.14}$$

s.t.

$$\gamma_{C_{m,n}}^{(d)} \geq \gamma_{min}^{C}; \gamma_{C1_{m,n,r_{nl}}}^{(r)}, \gamma_{C2_{m,n,r_{nl}}}^{(r)} \geq \frac{1}{2}\gamma_{min}^{C}, \forall m \in \mathcal{M}, \tag{4.14a}$$

$$\gamma_{D_{m,n}}^{(d)}, \gamma_{D1_{m,n,r_{nl}}}^{(r)}, \gamma_{D2_{m,n,r_{nl}}}^{(r)} \geq \gamma_{min}^{D}, \forall n \in \mathcal{N}, \tag{4.14b}$$

$$0 \leq p_{C_m}^{(d)}, p_{C_m}^{(r)} \leq P_{max}^{C}, \forall m \in \mathcal{M}, \tag{4.14c}$$

$$0 \leq p_{D_n}^{(d)}, p_{D,n}^{(r)} \leq P_{max}^{D}, \forall n \in \mathcal{N}, \tag{4.14d}$$

$$0 \leq p_{R,r_{nl}}^{(r)} \leq P_{max}^{D}, \forall r_{nl} \in \mathcal{R}, \tag{4.14e}$$

$$\{\sum_{m=1}^{M}(\chi_{mn} + \sum_{l=1}^{L}\rho_{m,n,r_{nl}})\} \leq 1, \forall n \in \mathcal{N}, \tag{4.14f}$$

$$\{\sum_{n=1}^{N}(\chi_{mn} + \sum_{l=1}^{L}\rho_{m,n,r_{nl}})\} \leq 1, \forall m \in \mathcal{M}, \tag{4.14g}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{m,n,r_{nl}} \leq 1, \forall r_{nl} \in \mathcal{R}, \tag{4.14h}$$

$$\chi_{mn}, \rho_{m,n,r_{nl}} \in \{0,1\}, \forall m \in \mathcal{K}, \forall n \in \mathcal{N}, \forall r_{nl} \in \mathcal{R}, \tag{4.14i}$$

where P is the power matrix. $\boldsymbol{\chi}$ and $\boldsymbol{\rho}$ are the binary channel allocation decision matrices for D2D in DM and RM, respectively. $\chi_{mn} = 1$ if D2D link n operates in DM by reusing the same channel resource of cellular link m, otherwise, $\chi_{mn} = 0$. $\rho_{m,n,r_{nl}} = 1$ if D2D link n selects relay node r_{nl} by reusing the same channel resource with cellular link m, otherwise, $\rho_{m,n,r_{nl}} = 0$. γ_{min}^{C} and γ_{min}^{D} are the minimum SINR requirements of cellular and D2D links, respectively. p_{max}^{D} is the maximum transmission power of D2D and relay transmitters. Constraints (4.14a)-(4.14b) show the minimum SINR requirement of each link in all transmission intervals. Constraints (4.14c)-(4.14e) express the limited transmission power of cellular, D2D links and relay transmitter, respectively. Constraint (4.14f) shows that each D2D link can reuse no more than one channel and can operate in DM or RM. Constraint (4.14g) shows either in DM or RM, each channel resource of cellular link can only be shared by no more than one D2D link, and constraint (4.14h) shows that each D2D link can only be served by no more than one relay node. The final constraint (4.14i) means the value of channel allocation indicators are binary.

The above design problem in (4.14) is a MINLP, which is an NP-hard problem. In order to solve it efficiently, we decompose it into two sub-problems: *OPA* and *JMRC*. For each reuse pair (i.e. one cellular link and one D2D link reuse a certain channel resource), the *OPA* can be further divided to *OPA*-I and *OPA*-II, respectively, corresponding to the scenarios that D2D link operate in DM and D2D link operate in RM. Both *OPA*-I and *OPA*-II problems aim to maximize the sum data rate on the channel that cellular and D2D links reuse by allocating the appropriate transmission power.

In case that D2D link operates in DM, the *OPA*-I problem is

$$\max_{(p_{C,m}^{(d)}, p_{D,n}^{(d)})} \quad R_{mn}^{(d)} \tag{4.15}$$

s.t.

$$\gamma_{C_{m,n}}^{(d)} \geq \gamma_{min}^{C}, 0 \leq p_{C_m}^{(d)} \leq P_{max}^{C}, \tag{4.15a}$$
$$\gamma_{D_{m,n}}^{(d)} \geq \gamma_{min}^{D}, 0 \leq p_{D_n}^{(d)} \leq P_{max}^{D}. \tag{4.15b}$$

In case that D2D operates in RM, the *OPA*-II problem is

$$\max_{(p_{C,m}^{(r)}, p_{D,n}^{(r)}, p_{R,r_{nl}}^{(r)})} \quad R_{m,n,r_{nl}}^{(r)} \tag{4.16}$$

s.t.

$$\gamma_{C1,m}^{(r)}, \gamma_{C2,m}^{(r)} \geq \frac{1}{2}\gamma_{min}^{C}; \gamma_{D1,n}^{(r)}, \gamma_{D2,n}^{(r)} \geq \gamma_{min}^{D}, \tag{4.16b}$$
$$0 \leq p_{C_m}^{(r)} \leq P_{max}^{C}, 0 \leq p_{D,n}^{(r)}, p_{R,r_{nl}}^{(r)} \leq P_{max}^{D}. \tag{4.16d}$$

The $R_{mn}^{(d)}$ and $R_{m,n,r_{nl}}^{(r)}$ are the sum data rates that can be achieved due to the reuse. The optimal sum data rates named $R_{mn}^{(d)*}$ and $R_{m,n,r_{nl}}^{(r)*}$ for D2D operates in DM and RM cases will be obtained by applying the corresponding algorithms, which will be discussed in section 4.4. Note that both the above cases based on the assumption that if D2D link n reuses the same channel resource with cellular link m. To achieve the optimal system performance, each D2D link $n \in \mathcal{N}$ should be paired with all the cellular link $m \in \mathcal{M}$. This means that the optimal power allocation problem will be repeated MN times for each mode ($2MN$ times in total).

After considering all these possibilities, the *JMRC* problem becomes

$$\max_{\boldsymbol{\chi},\boldsymbol{\rho}} \sum_{m=1}^{M}\{\{(1-\sum_{n=1}^{N}\chi_{mn})(1-\sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{m,n,r_{nl}})R^{0}_{C,m} + \sum_{n=1}^{N}(\chi_{mn}R^{(d)*}_{m,n}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}R^{(r)*}_{m,n,r_{nl}})\}\} \quad (4.17)$$

s.t. constraints (4.14f)-(4.14i). Note that $R^{0}_{C,m}$ can be calculated according to (4.13), and the only unknown variables become binary i.e. χ_{mn} and $\rho_{m,n,r_{nl}}$.

4.4 The Proposed Optimal Algorithms

In this section, the *OPA* and *JMRC* problems are solved subsequently.

4.4.1 The OPA Algorithm

In this subsection, two algorithms for *OPA*-I problem and *OPA*-II problem are investigated, respectively. Then, $R^{(d)*}_{mn}$ and $R^{(r)*}_{m,n,r_{nl}}$ can be obtained accordingly.

The OPA-I Algorithm

It has been proved in Section 2.2.1 that at least one user (CUE or DUT) transmits at its maximum power can lead to the maximum total data rate of all cellular and D2D links. Accordingly, a simpler power allocation is proposed as follows.

Ω_{mn} is defined as the feasible set of problem in (4.15), $\Omega1_{mn}$ and $\Omega2_{mn}$ are the feasible sets when cellular and D2D users transmit its maximum power, respectively. Then, we have the following proposition.

Proposition 4.1 *If the problem in (4.15) is feasible, its optimal power allocation solution belongs to the set* $\Omega_{mn} = \Omega1_{mn} \cup \Omega2_{mn}$*; otherwise,* $\Omega_{mn} = \phi$.

We first assume that $p^{(d)}_{C,m} = P^{C}_{max}$, then problem in (4.15) becomes

$$\begin{aligned}(P^{C}_{max}, p^{(d)*}_{D,n}) &= \arg\max_{(P^{C}_{max}, p^{(d)}_{D,n})} R^{(d)}_{m,n} \\ &= \arg\max_{(P^{C}_{max}, p^{(d)}_{D,n})} f(P^{C}_{max}, p^{(d)}_{D,n})\end{aligned} \quad (4.18)$$

s.t.

$$\frac{P^{C}_{max}h_{m,B}}{\sigma^2 + p^{(d)}_{D_n}h_{n,B}} \geq \gamma^{C}_{min}, \frac{p^{(d)}_{D_n}h_{n,n}}{\sigma^2 + P^{C}_{max}h_{m,n}} \geq \gamma^{D}_{min}, \quad (4.18a)$$

$$0 \leq p^{(d)}_{D,n} \leq P^{D}_{max}, \quad (4.18b)$$

in which $f(P_{max}^{C}, p_{D,n}^{(d)}) = (1 + \frac{P_{max}^{C} h_{m,B}}{\sigma^2 + p_{D_n}^{(d)} h_{n,B}})(1 + \frac{p_{D_n}^{(d)} h_{n,n}}{\sigma^2 + P_{max}^{C} h_{m,n}})$.

According to constraints (4.18a) and (4.18b), the continuous closed feasible set of $p_{D,n}^{(d)}$ is denoted as $[p_{low,D,n}^{(d)}, p_{up,D,n}^{(d)}]$. The lower and upper bounds $p_{low,D,n}^{(d)}$ and $p_{up,D,n}^{(d)}$ are calculated as

$$p_{low,D,n}^{(d)} = \max\{0, \frac{\gamma_{min}^{D}(\sigma^2 + P_{max}^{C} h_{m,n})}{h_{n,n}}\}, \tag{4.19}$$

$$p_{up,D,n}^{(d)} = \min\{P_{max}^{D}, \frac{(P_{max}^{C} h_{m,B} - \gamma_{min}^{C}\sigma^2)}{h_{n,B}\gamma_{min}^{C}}\}. \tag{4.20}$$

Note that the problem in (4.18) is feasible only when $p_{low,D,n}^{(d)} \leq p_{up,D,n}^{(d)}$ holds.

When problem in (4.18) is feasible, the optimal value of $f(P_{max}^{C}, p_{D,n}^{(d)})$ can be obtained by solving the equation

$$f'(P_{max}^{C}, p_{D,n}^{(d)}) = 0,$$

which always has two negative solutions, i.e.

$$-\frac{h_{m,B}P_{max}^{C} + \sigma^2}{h_{n,B}} \quad \text{and} \quad -\frac{h_{m,n}P_{max}^{C} + \sigma^2}{h_{n,n}}.$$

It means these two roots do not belong to the feasible set, and the function $f(P_{max}^{C}, p_{D,n}^{(d)})$ is monotonous in this feasible set. Thus, the optimal value of $f(P_{max}^{C}, p_{D,n}^{(d)})$ is achieved at the boundary points $p_{low,D,n}^{(d)}$ or $p_{up,D,n}^{(d)}$.

Therefore, $\Omega 1_{mn}$ can be expressed as

$$\Omega 1_{mn} = \{(P_{max}^{C}, p_{low,D,n}^{(d)}), (P_{max}^{C}, p_{up,D,n}^{(d)})\}. \tag{4.21}$$

If (4.18) is not feasible, we then set $\Omega 1_{mn} = \phi$.

When D2D link transmits its maximum power, if $p_{low,C,m}^{(d)} \leq p_{up,C,m}^{(d)}$ holds, where $p_{low,C,m}^{(d)}$ and $p_{up,C,m}^{(d)}$ are the lower and upper bounds of $p_{C,m}^{(c)}$, we have

$$\Omega 2_{mn} = \{(p_{low,C,m}^{(d)}, P_{max}^{D}), (p_{up,C,m}^{(d)}, P_{max}^{D})\}. \tag{4.22}$$

Otherwise, $\Omega 2_{mn} = \phi$. The derivation of $\Omega 2_{mn}$ is similar and hence is omitted.

After that, Ω_{mn} is obtained according to Proposition 4.1. If $\Omega_{mn} = \phi$ (i.e. $\Omega 1_{mn} = \phi$ and $\Omega 2_{mn} = \phi$), we set the optimal data rate $R_{mn}^{(d)*}$ as Q, where Q is a sufficiently small value meaning that cellular link m can not reuse the same channel with D2D link n. Otherwise, the optimal power solution $(p_{C,m}^{(c)*}, p_{D,n}^{(d)*})$ can be determined by comparing at most 4 possible solutions in Ω_{mn}, which maximizes (4.15) i.e.

$$(p_{C,m}^{(c)*}, p_{D,n}^{(d)*}) = \arg\max_{(p_{C,m}^{(d)}, p_{D,n}^{(d)}) \in \Omega_{mn}} R_{mn}^{(d)}. \tag{4.23}$$

Meanwhile, $R_{mn}^{(d)*}$ is obtained by substituting the optimal power solution into (4.5).

The OPA-II Algorithm

The *OPA*-II problem can be solved by the algorithm in [16] using the same proposition that at least one user (CUE or DUT or relay node) transmits at its maximum power can lead to the optimal system sum data rate.

Thus, three cases (*Case1:* $p^{(r)}_{C_m} = P^C_{max}$, *Case2:* $p^{(r)}_{D_n} = P^D_{max}$, *Case3:* $p^{(r)}_{R_{r_{n,l}}} = P^D_{max}$) are considered to get the feasible power solution set. . By applying the algorithm explained in Section 2.2.1, the optimal power allocation i.e. $(p^{(r)*}_{C,m}, p^{(r)*}_{D,n}, p^{(r)*}_{R,r_{nl}})$ and the optimal sum data rate i.e. $R^{(r)*}_{m,n,r_{nl}}$ can be obtained.

4.4.2 The JMRC Algorithm

The relay selection is realized by selecting the relay node r^*_{nl} for the D2D link n, which produces the maximum sum data rate i.e. $R^{(r)*}_{m,n,r^*_{nl}}$. It experiences the exhaustive searching. Based on the above *OPA* which considers all the reuse possibilities for both DM and RM cases, the *JMRC* is further simplified into a joint mode selection and channel allocation problem, which can be expressed as

$$\max_{(\boldsymbol{\alpha},\boldsymbol{\beta})}\{\sum_{m=1}^{M}\{(1-\sum_{n=1}^{N}\alpha_{mn})R^0_{C,m} + \sum_{n=1}^{N}\alpha_{mn}(\beta_n R^{(d)*}_{m,n} + (1-\beta_n)R^{(r)*}_{m,n,r^*_{nl}})\}\} \tag{4.24}$$

s.t.

$$\sum_{m=1}^{M}\alpha_{mn} \le 1, \forall n \in \mathcal{N}, \tag{4.24a}$$

$$\sum_{n=1}^{N}\alpha_{mn} \le 1, \forall m \in \mathcal{M}, \tag{4.24b}$$

$$\alpha_{mn}, \beta_n \in \{0,1\}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \tag{4.24c}$$

where $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are channel allocation matrix and mode selection vector, respectively, where

$$\alpha_{mn} = \begin{cases} 1 & \text{if D2D link } n \text{ reuses the channel } m, \\ 0 & \text{otherwise.} \end{cases} \tag{4.25}$$

$$\beta_n = \begin{cases} 1 & \text{if D2D link } n \text{ operates in DM}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.26}$$

Constraint (4.24a) shows that each D2D link can reuse no more than one channel, and constraint (4.24b) shows that each channel resource of cellular link can be shared by no more than one D2D link. Constraint (4.24c) shows the channel allocation matrix and mode selection vector are binary. These three constraints are equivalent to constraints (4.14f), (4.14g) and (4.14i).

Algorithm 2 : Proposed Joint Optimization Algorithm

Power Allocation:
for all $m \in \mathcal{M}, n \in \mathcal{N}$ **do**
  if $p_{low,D,n}^{(d)} \leq p_{up,D,n}^{(d)}$ **then**
    $\Omega 1_{mn}$ can be obtained according to (4.21)
  else
    $\Omega 1_{mn} = \phi$
  end if
  if $p_{low,C,m}^{(d)} \leq p_{up,C,m}^{(d)}$ **then**
    $\Omega 2_{mn}$ can be obtained according to (4.22)
  else
    $\Omega 2_{mn} = \phi$
  end if
  Obtain Ω_{mn} according to Proposition 4.1
  if $\Omega_{mn} = \phi$ **then**
    $R_{mn}^{(d)*} = Q$
  else
    Obtain $R_{mn}^{(d)*}$ by substituting the $(p_{C,m}^{(d)*}, p_{D,n}^{(d)*})$ into (4.5), where $(p_{C,m}^{(d)*}, p_{D,n}^{(d)*})$ can be obtained according to (4.23)
  end if
end for
for all $m \in \mathcal{M}, n \in \mathcal{N}, l \in L$ **do**
  Obtain $R_{m,n,r_{nl}}^{(r)*}$ by solving *OPA*-II problem in (4.16) using the algorithm in [16]
end for
Obtain $R_{C,m}^{0}, \forall m \in \mathcal{M}$ according to (5.13)
JMRC:
Relay Selection
for all $m \in \mathcal{M}, n \in \mathcal{N}$ **do**
  Get $R_{m,n,r_{nl}^{*}}^{(r)*} = \max_{r_{nl} \in L_n} \{R_{m,n,r_{nl}}^{(r)}\}$
end for
Then, problem in (4.27) **can be solved by the standard linear programming method.**

Problem in (4.24) is an INLP, where the only non-linear expressions are the multiplications of two binary variables (i.e. $\alpha_{mn}\beta_n$ and $\alpha_{mn}(1-\beta_n)$). According to [52], (4.24) can be linearised by introducing two auxiliary variables μ_{mn}, υ_{mn}, where

$$\mu_{mn} = \alpha_{mn}\beta_n,$$

$$\upsilon_{mn} = \alpha_{mn}(1-\beta_n),$$

respectively. In this way, problem in (4.24) becomes an ILP, which is expressed as

$$\max_{(\boldsymbol{\mu},\boldsymbol{\upsilon})}\{\sum_{m=1}^{M}\{(1-\sum_{n=1}^{N}\alpha_{mn})R_{C,m}^{0}+\sum_{n=1}^{N}(\mu_{mn}R_{mn}^{(d)*}+\upsilon_{mn}R_{m,n,r_{nl}^{*}}^{(r)*})\}\} \tag{4.27}$$

s.t.

$$\mu_{mn} \le \alpha_{mn}, \mu_{mn} \le \beta_n, \tag{4.27a}$$

$$\mu_{mn} \ge \alpha_{mn} + \beta_n - 1, \tag{4.27b}$$

$$\upsilon_{mn} \le \alpha_{mn}, \upsilon_{mn} \le (1-\beta_n), \tag{4.27c}$$

$$\upsilon_{mn} \ge \alpha_{mn} - \beta_n, \tag{4.27d}$$

where constraint (4.27a) ensures that μ_{mn} will be 0 if either α_{mn} or β_n are 0, constraint (4.27b) makes sure that μ_{mn} takes 1 if both α_{mn} and β_n are 1. Similarly, constraints (4.27c) ensures that υ_{mn} be 0 if either α_{mn} or $(1-\beta_n)$ is 0, constraint (4.27d) makes sure that υ_{mn} takes 1 if both α_{mn} and $(1-\beta_n)$ are 1. In this way, problem in (4.27) can be effectively solved by the standard ILP methods in [53] (e.g. simplex method and Balas method).

Algorithm 2 describes the proposed joint optimization algorithm. The power allocation is conducted by considering all the reuse possibilities between cellular and D2D links in both DM and RM from *Step 2-Step 22*. Based on the results in RM, the relay selection is implemented as shown in *Step 26-Step 28*. After that, the *JMRC* is linearised and solved in *Step 29*.

4.5 Simulation Results and Analysis

In this section, the *Monte Carlo* simulation is implemented to evaluate the performance of the proposed design. We consider a single cellular network with a radius C, where the BS is located in the centre of the cell, and the cellular users are uniformly distributed. Each D2D transmitter and receiver are uniformly distributed in a randomly located cluster with radius d_{max}, along with the associated relay nodes which uniformly distributed in its concentric cluster with radius $2d_{max}$. The

Table 4.1: Simulation Parameters

Cell Radius C (m)	500
Maximum distance between D2D pairs d_{max} (m)	200 (if fixed)
Number of cellular links M	20
Number of D2D links N ($N \leq M$)	10
Number of relay nodes for each D2D links L	4
Maximum cellular transmission power p^C_{max}(dBm)	20
Maximum D2D transmission power p^D_{max}(dBm)	20 (if fixed)
SINR requirements of cellular links γ^C_{min} (dB)	10 (if fixed)
SINR requirements of D2D links γ^D_{min} (dB)	15
Noise power σ^2 (dBm)	-110
Pathloss exponent for DUT-Relay-DUR links $\alpha 1$	3
Pathloss exponent for other communications $\alpha 2$	4

channel gain is modelled as $h_{a,b} = d_{a,b}^{-\alpha}\kappa$ for all communication links, where $d_{a,b}$ is the distance between node a and b, α is the pathloss exponent[1]; κ represents the Rayleigh fading. The simulation parameters as summarized in TABLE 4.1, are chosen according to [16] and [20] for the purpose of comparison.

The joint optimization is referred as the *Proposed Scheme*. The scheme proposed in *Tuong2017* and *Feng2013* have the same system scenario, where one D2D can only reuse one channel resource. Thus, this two existing works are used for comparison.

Scheme in Tuong2017: Authors solve the joint mode selection and resource allocation problem for D2D underlay cellular communications without considering the relay selection [16].

Scheme in Feng2013: Authors consider the power and channel allocation for D2D underlay cellular communications on DM considering neither the mode selection nor the relay selection [20].

Figure 4.2 shows the overall system sum rate for varying maximum distance between D2D pair d_{max} in three different schemes. From Figure 4.2, we can see that with the increase of d_{max} the system sum rate decreases moderately in the

[1]To demonstrate the benefit that relay can bring us, we will choose different pathloss exponent value for D2DT to Relay nodes and Relay nodes to D2D links.

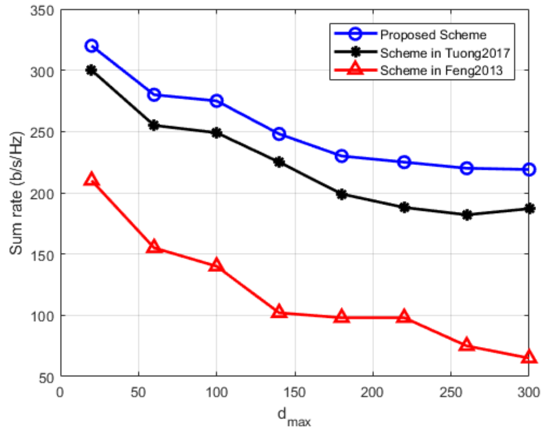


Figure 4.2: The network system sum rate with varying d_{max}.

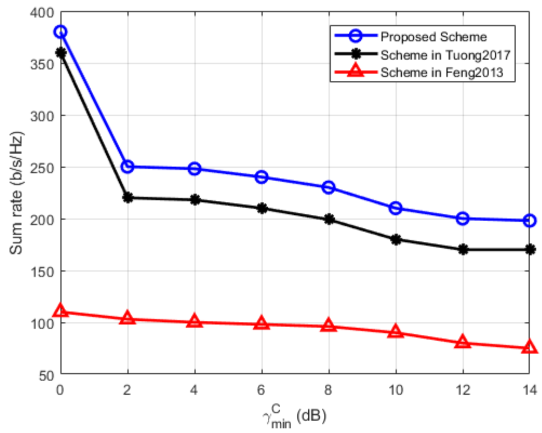


Figure 4.3: The network sum data rate with r varying γ^{C}_{min}.

Proposed Scheme and the *Scheme in Tuong2017* but dramatically in the *Scheme in Feng2013*. The reason is that as d_{max} becomes large, the D2D link data rate decreases due to the large pathloss, which leads to the reduction of the system data rate. However, relay-aided D2D communication is applied when d_{max} is larger. Thus, the system sum data rate decreases moderately in the *Proposed Scheme* and *Scheme in Tuong2017*, as shown in Figure 4.2. Moreover, the performance of the proposed method outperforms *Scheme in Feng2013* and *Scheme in Tuong2017*.

Figure 4.3 shows the system sum rate for varying minimum SINR requirements of cellular link. We can see that the system sum data rate decreases moderately as the increase of γ^{C}_{min} in these three schemes. This is because that γ^{C}_{min}, the cellular link tends to increase its transmission power, but D2D link (include relay node) tends to decrease its transmission power to maintain the QoS of cellular communications. It means that the D2D link transmits at lower power level, and suffers more interference from the cellular link. This results in the decrease of

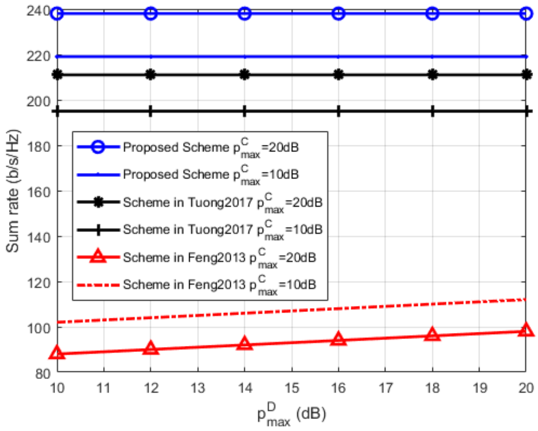


Figure 4.4: The network sum data rate with varying p^C_{max}.

system sum data rate. Due to the assistance of relay node assistance, the performance of the proposed method outperforms *Scheme in Feng2013* and *Scheme in Tuong2017*.

Figure 4.4 shows the system sum rate for varying maximum D2D transmission power p^D_{max} in different schemes with different maximum cellular transmission power p^C_{max}. Figure 4.4 shows that the performance in the *Proposed Scheme* and the *Scheme in Tuong2017* stay stable and increase slightly in the *Scheme in Feng2013* as the increase of p^D_{max}. It reveals that both D2D transmitter and relay node do not need to transmit at their maximum power to maximize the system performance in the *Proposed Scheme* and the *Scheme in Tuong2017*. Moreover, larger p^C_{max} leads to better system performance in these two schemes. According to the OPA-II algorithm in section 2.2.2, we believe that only considering *Case 1* (i.e. the cellular link transmits at its maximum power) is enough for us to attain the optimal system performance, thus this will dramatically reduce the power allocation computational complexity.

However, either increase of p^D_{max} or decrease of p^C_{max} will result in better performance for the *Scheme in Feng2013* as shown in Figure 4.4, because of the improved performance of D2D links. But the performance of the *Scheme in Feng2013* is always worse than that of the *Proposed Scheme*.

The system sum rate of the proposed scheme is always better than the existing methods, because of the additional consideration of the relay and mode selection. However, this brings high computational complexity.

4.6 Summary

In this chapter, we have formulated the joint mode selection, resource allocation and relay selection problem as a MINLP, which is NP-hard. Then, the algorithms are proposed to optimally solve the optimization problem. Specifically, we allocate the transmission powers for all reuse possibilities between D2D and cellular links for both DM and RM cases. Based on the results of power allocation, we then linearise the channel allocation into ILP by adding auxiliary variables. After that, channel allocation can be solved effectively by standard INP method. The simulation results show that the proposed scheme significantly outperforms the existing schemes.

Chapter 5

Graph Colour-based Resource Allocation for Relay-Assisted D2D Underlay Communications

5.1 Introduction

5.1.1 Related Works and Motivations

Moreover, most of the above works focus on a simple case that the channel allocation of cellular link is pre-allocated, none of them jointly consider the mode selection, relay selection and resource allocation for both cellular and D2D links. Thus, in this chapter, a more general case for relay-assisted D2D underlay network is investigated, where the channel resource is jointly allocated to both cellular and D2D links, meanwhile D2D links can operate in either DM or RM. The relay nodes are generally idle users, which have the potential to support the D2D communication links.

However, this leads to a complicated problem and require significantly high computational complexity. Graph theory has a lot of applications both in mathematics and in everyday life in general. It can provide efficient tools for modelling and analysing various types of interactions, relations, and dynamics in different networks, and thus it has been widely used to solve the resource management problems [22]. Authors in [21] formulate the channel assignment problem by using a graph-based approach, in which each link corresponds to a vertex and each channel assignment is represented by a hyper-edge. An iterative rounding algorithm is proposed to solve the resulting graph-based problem and can attain almost the same system sum-rate as the optimal algorithm. Authors in [54] consider the resource allocation under the more complex scenario that each D2D link can acquire multiple channel resource and each channel resource can be occupied as multiple D2D links. An interference graph-based joint power and channel allocation problem is formulated in [55], where each channel can be allocated to multiple communications links and each communication link can acquire multiple channels for its own data transmission. After that authors propose a joint resource allocation heuristic algorithm that effectively solve above interference graph-based problem, which leads to a near-optimal system performance with low computational complexity. The Graph-Colouring Based Resource Allocation schemes are applied in [56] to solve a more complex scenarios, where the concept of full-duplex cellular network is investigated, and the UEs are allowed to communicate between each other by reusing the spectrum resources of cellular uplinks and downlinks. [57] first formulates the resource allocation problem as MINLP, then proposes the heuristic Graph-coloring resOurce ALlocation (GOAL) algorithm based on a graph-coloring approach. Two concepts: INS (interference negligible distance) and SNR (signal to noise ratio) are introduced to support the GOAL algorithm.

5.1.2 Main Contributions

Therefore, we formulate the resource reusing relationship among different CUEs, D2D pairs and relay nodes as a colour-based graph and propose a GCRA algorithm to effectively obtain a closed-to-optimal solution with low complexity. Instead of associating each attribute with an individual communication link in some existing schemes [55] [56], we creatively introduce three individual attributes for each channel resource, namely cellular link attribute, channel assignment attribute and power allocation attribute. These newly defined attributes can help the iterative procedure of the proposed GCRA algorithm guaranteeing the near-optimal performance. Simulation results confirm that the proposed algorithm achieves the closed-to-optimal performance in terms of the network throughput with much lower complexity, in comparison with the optimal resource sharing solution obtained via the optimization programming (such as the exhaustive search method).

5.1.3 Chapter Organization

The rest of this chapter is organized as follows. Section 5.2 introduces the system model for relay-assisted D2D communications. Section 5.3 shows the problem formulation. The proposed algorithm is explained in Section 5.4. The optimal power allocation is shown in 5.5. Simulation results and complexity analysis are presented in Section 5.6. Section 5.7 concludes this chapter.

5.2 System model

The spectrum sharing relay-assisted D2D underlay network is shown in Figure5.1, where M CUEs in the set $\mathcal{M} = \{1, 2, ...m, ...M\}$, and N D2D links in the set $\mathcal{N} = \{1, 2, ...n, ...N\}$. Each D2D pair includes a DUT and a DUR. $\mathcal{R} = \{1, 2, ..., r, ..., R\}$ is the set of relay nodes and $\mathcal{K} = \{1, 2, ...k, ...K\}$ is the set of channels. A fully loaded cellular network is considered, in which M active cellular links occupy the K orthogonal channels and no spare spectrum for D2D links. Each D2D link can only reuse no more than one channel resource and each relay node can only support one D2D link. Moreover, each D2D link can operate in either DM or RM case, which will be analysed in the following subsections, respectively. h_{ab} is denoted as the channel gain from the transmitter of link or relay node a to the receiver of the link or relay node b.

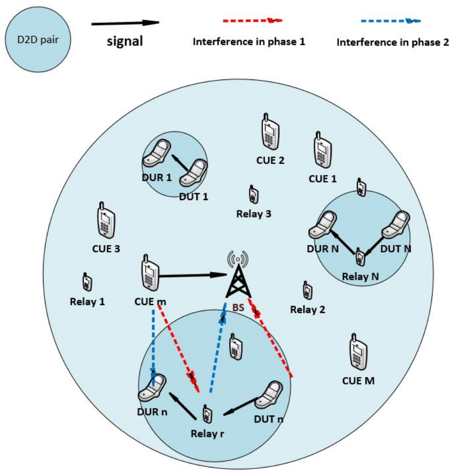


Figure 5.1: A single cell system with M cellular links, N D2D links and R relay nodes.

5.2.1 Direct Mode

In DM case, the D2D pair n communicates with each other directly. The SINRs of cellular link m and D2D links n on channel k can be expressed as

$$\gamma^k_{C_{m,n}} = \frac{p^k_{C_{m,n}} h^k_{m,B}}{\sigma^2 + p^k_{D_{m,n}} h^k_{n,B}}, \tag{5.1}$$

$$\gamma^k_{D_{m,n}} = \frac{p^k_{D_{m,n}} h^k_{n,n}}{\sigma^2 + p^k_{C_{m,n}} h^k_{m,n}}, \tag{5.2}$$

in which $p^k_{C_{m,n}}$ and $p^k_{D_{m,n}}$ are the transmission power of CUE m and DUT n on channel k in DM. $h^k_{m,B}$ is the signal channel gain between CUE m and the BS, and $h^k_{n,B}$ is the interfering channel gain from DUT n to the BS on channel k. $h^k_{n,n}$ and $h^k_{m,n}$ are the signal channel gain between D2D pair n and the interfering channel gain from CUE m to DUR n on channel k. The data rates in bits per second per hertz of cellular link m and D2D link n on channel k are expressed as

$$R^k_{C_{m,n}} = \log_2(1 + \gamma^k_{C_{m,n}}), \tag{5.3}$$

$$R^k_{D_{m,n}} = \log_2(1 + \gamma^k_{D_{m,n}}). \tag{5.4}$$

Therefore, the total data rates on channel k in DM is

$$R^k_{m,n} = R^k_{C_{m,n}} + R^k_{D_{m,n}}. \tag{5.5}$$

5.2.2 Relay Mode

When D2D link n operates in RM, D2D link n selects relay node r and shares the same channel k with the cellular link m. Again, the DF relaying strategy is employed, where each communication period is divided into two equal intervals phase 1 (i.e. D-R) and phase 2 (i.e. R-D). Also, we assume that communications in phase 1 and phase 2 use the same channel resource.

In phase 1, the SINRs of cellular link m i.e. $\gamma 1^{k,r}_{C_{m,n}}$ and D2D link n i.e. $\gamma 1^{k,r}_{D_{m,n}}$ can be expressed as

$$\gamma 1^{k,r}_{C_{m,n}} = \frac{p^{k,r}_{C_{m,n}} h^k_{m,B}}{\sigma^2 + p^{k,r}_{D_{m,n}} h^k_{n,B}}, \tag{5.6}$$

$$\gamma 1^{k,r}_{D_{m,n}} = \frac{p^{k,r}_{D_{m,n}} h^k_{n,r}}{\sigma^2 + p^{k,r}_{C_{m,n}} h^k_{m,r}}. \tag{5.7}$$

Similarly, in phase 2, the SINRs of cellular link m $\gamma 2^{k,r}_{C_{m,n}}$ and D2D link n $\gamma 2^{k,r}_{D_{m,n}}$ can be expressed as

$$\gamma 2^{k,r}_{C_{m,n}} = \frac{p^{k,r}_{C_{m,n}} h^k_{m,B}}{\sigma^2 + p^{k,r}_{R_{m,n}} h^k_{r,B}}, \tag{5.8}$$

$$\gamma 2^{k,r}_{D_{m,n}} = \frac{p^{k,r}_{R_{m,n}} h^k_{r,n}}{\sigma^2 + p^{k,r}_{C_{m,n}} h^k_{m,n}}, \tag{5.9}$$

where $p^{k,r}_{C_{m,n}}$, $p^{k,r}_{D_{m,n}}$ and $p^{k,r}_{R_{m,n}}$ are the transmission power of CUE m, DUT n and relay node r on channel k. $h^k_{n,r}$ is the signal channel gain from DUT n to relay node r and $h^k_{m,r}$ is the interfering channel gain from CUE m to relay node r on channel k. The signal channel gain from relay node r to DUR n on channel k is denoted as $h^k_{r,n}$. Therefore, the data rates of cellular link m and D2D links n in RM can be calculated as

$$R^{k,r}_{C_{m,n}} = \frac{1}{2}\log_2(1+\gamma 1^{k,r}_{C_{m,n}}) + \frac{1}{2}\log_2(1+\gamma 2^{k,r}_{C_{m,n}}), \tag{5.10}$$

$$R^{k,r}_{D_{m,n}} = \frac{1}{2}\log_2(1+\min\{\gamma 1^{k,r}_{D_{m,n}}, \gamma 2^{k,r}_{D_{m,n}}\}). \tag{5.11}$$

The total data rate on channel k in RM is

$$R^{k,r}_{m,n} = R^{k,r}_{C_{m,n}} + R^{k,r}_{D_{m,n}}. \tag{5.12}$$

In addition, when cellular links do not experience any co-channel interference from D2D links, the maximum throughput could be achieved when cellular links transmit with their maximum power (i.e. p^C_{max}). Thus, the data rate of cellular link m on channel k without being reused can be calculated as

$$R^k_{C_m} = \log_2(1+\frac{p^C_{max}h^k_{m,B}}{\sigma^2}). \tag{5.13}$$

For convenience, the frequently used symbols in this chapter are listed in TABLE 5.1.

5.3 Problem Formulation

In this section, the joint mode selection, relay selection and resource allocation problem is formulated, which aims to maximize the sum data rate of all communication links while guaranteeing the required minimum SINR of cellular and active D2D links. Three decision variables x^k_m, $y^k_{m,n}$ and $z^{k,r}_{m,n}$ corresponding to cellular links, D2D links and relay nodes are introduced:

$$x^k_m = \begin{cases} 1, & \text{if celluar link } m \text{ exclusively occupies channel } k, \\ 0, & \text{otherwise;} \end{cases} \tag{5.14}$$

$$y^k_{m,n} = \begin{cases} 1, & \text{if D2D link } n \text{ oprates in DM by reusing the same} \\ & \quad \text{channel } k \text{ with cellualr link } m, \\ 0, & \text{otherwise;} \end{cases} \tag{5.15}$$

$$z^{k,r}_{m,n} = \begin{cases} 1, & \text{if D2D link } n \text{ oprates in RM supportted by relay} \\ & \text{node } r \text{ and reuses the channel } k \text{ with cellualr link } m, \\ 0, & \text{otherwise.} \end{cases} \tag{5.16}$$

Table 5.1: The list of symbols

Symbols	**Meanings**
$p^{k}_{C_{m,n}}$	The transmission power of CUE m, when it shares the channel k with D2D pair n in DM
$\tilde{p}^{k}_{C_{m,n}}$	The optimal power of CUE m, when it shares the channel k with D2D pair n in DM
$p^{k}_{D_{m,n}}$	The transmission power of DUT n, when it reuses the channel k with CUE m in DM
$\tilde{p}^{k}_{D_{m,n}}$	The optimal power of DUT n, when it shares the channel k with D2D pair n in DM
$R^{k}_{C_{m,n}}$	The data rate of cellular link m, when it shares the channel k with D2D link n in DM
$R^{k}_{D_{m,n}}$	The data rate of D2D link n, when it reuses the channel k with cellular link m in DM
$R^{k}_{m,n}$	The total data rate on channel k in DM
$\tilde{R}^{k}_{m,n}$	The optimal total data rate on channel k in DM
$p^{k,r}_{C_{m,n}}$	The transmission power of CUE m, when it shares the channel k with D2D link n in RM
$\tilde{p}^{k,r}_{C_{m,n}}$	The optimal power of CUE m, when it shares the channel k with D2D link n in RM
$p^{k,r}_{D_{m,n}}$	The transmission power of DUT n, when it reuses the channel k with cellular link m in RM
$\tilde{p}^{k,r}_{D_{m,n}}$	The optimal power of DUT n, when it shares the channel k with D2D link n in RM
$p^{k,r}_{R_{m,n}}$	The transmission power of relay node r, when it supports D2D link n in RM
$\tilde{p}^{k,r}_{R_{m,n}}$	The optimal power of relay node r, when it supports D2D link n in RM
$R^{k,r}_{C_{m,n}}$	The data rate of cellular link m, when it shares the channel k with D2D link n in RM
$R^{k,r}_{D_{m,n}}$	The data rate of D2D link n, in RM
$R^{k,r}_{m,n}$	The total data rate on channel k, when it reuses the channel k with cellular link m in RM
$\tilde{R}^{k,r}_{m,n}$	The optimal total data rate on channel k in RM

Thus, the joint problem is expressed as

$$\max_{P,X,Y,Z}\{\sum_{k=1}^{K}\sum_{m=1}^{M}(x_m^k R_{C_m}^k + \sum_{n=1}^{N}(y_{m,n}^k R_{m,n}^k + \sum_{r=1}^{R} z_{m,n}^{k,r} R_{m,n}^{k,r}))\} \tag{5.17}$$

s.t.

$$\gamma_{C_{m,n}}^k \geq \gamma_{min}^C; \gamma 1_{C_{m,n}}^{k,r}, \gamma 2_{C_{m,n}}^{k,r} \geq \frac{1}{2}\gamma_{min}^C, \forall m \in \mathcal{M}, \tag{5.17a}$$

$$\gamma_{D_{m,n}}^k, \gamma 1_{D_{m,n}}^{k,r}, \gamma 2_{D_{m,n}}^{k,r} \geq \gamma_{min}^D, \forall n \in \mathcal{N}, \tag{5.17b}$$

$$0 \leq p_{C_{m,n}}^k, p_{C_{m,n}}^{k,r} \leq p_{max}^C, \forall m \in \mathcal{M}, \tag{5.17c}$$

$$0 \leq p_{D_{m,n}}^k, p_{D_{m,n}}^{k,r} \leq p_{max}^D, \forall n \in \mathcal{N}, \tag{5.17d}$$

$$0 \leq p_{R_{m,n}}^{k,r} \leq p_{max}^R, \forall r \in \mathcal{R}, \tag{5.17e}$$

$$\sum_{m=1}^{M}(x_m^k + \sum_{n=1}^{N}(y_{m,n}^k + \sum_{r=1}^{R} z_{m,n}^{k,r})) = 1, \forall k \in \mathcal{K}, \tag{5.17f}$$

$$\sum_{k=1}^{K}(x_m^k + \sum_{n=1}^{N}(y_{m,n}^k + \sum_{r=1}^{R} z_{m,n}^{k,r})) = 1, \forall m \in \mathcal{M}, \tag{5.17g}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M}(y_{m,n}^k + \sum_{r=1}^{R} z_{m,n}^{k,r}) \leq 1, \forall n \in \mathcal{N},, \tag{5.17h}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} z_{m,n}^{k,r} \leq 1, \forall r \in \mathcal{R}, \tag{5.17i}$$

$$x_m^k, y_{m,n}^k, z_{m,n}^{k,r} \in \{0,1\}, \forall k \in \mathcal{K}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall r \in \mathcal{R}, \tag{5.17j}$$

where P is the power allocation matrix. X, Y and Z are the channel allocation matrices. In (5.17), the first term is the sum data rate on channels which are exclusively occupied by cellular links. The second and third terms are the sum data rate of channels while D2D link operating in DM and RM, respectively.

Constraints (5.17a)-(5.17b) show the minimum SINR requirements of each link in all transmission intervals. Constraints (5.17c)-(5.17e) express the limited transmission power of cellular, active D2D and relay node transmitters. Constraint (5.17f) shows that each channel resource can only be either used exclusively by one cellular link or reused by one cellular and one active D2D links. It also reveals that each D2D link can operate in DM or RM. Constraint (5.17g) shows that each cellular link can only use one channel resource, either exclusively or reuse with one active D2D link. Constraint (5.17h) shows that each active D2D link can only reuse no more than one channel resource. Constraint (5.17i) shows that each relay node can support no more than one active D2D link. The final constraint (5.17j) means the value of channel allocation indicator should be binary.

The optimal solution to (5.17) can be obtained through exhaustive search of all possible choices of P, X, Y and Z subject to constraints given from (5.17a)-(5.17j), but it requires extremely high computational complexity. Problem in (5.17) is clearly NP-hard, so we propose a GCRA algorithm to effectively obtain a near-optimal solution with much lower complexity.

5.4 The proposed GCRA algorithm

5.4.1 Graph Construction

To perform the joint resource allocation, relay and mode selection for D2D relay-assisted communication based on a graph colouring approach, we construct the graph corresponding to the network topology. The constraint (5.17h) means that each D2D link can operate in DM or RM. Furthermore, constraint (5.17i) shows that each D2D link can be only supported by one relay node when D2D link operates in RM. To fulfil those constraints, we introduce a virtual relay node R_0 and a virtual D2D link D_0. For convenience, we also define the set $\mathcal{R}_R = \mathcal{R} \cup \{R_0\}$ and $\mathcal{N}_D = \mathcal{N} \cup \{D_0\}$.

In the constructed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, the set of elements is called vertexes $\mathcal{V} = \{V_m, V_n, V_r | \forall m \in \mathcal{M}, \forall n \in \mathcal{N}_D, \forall r \in \mathcal{R}_R\}$, the subsets of $\mathcal{V}$ called edges $\mathcal{E} = \{e = (V_m, V_n, V_r) | \forall m \in \mathcal{M}, \forall n \in \mathcal{N}_D, \forall r \in \mathcal{R}_R\}$ represent the communication relationship between three different kinds of vertexes from different clusters i.e. cellular users, D2D pairs and relay nodes. Moreover, each channel resource is represented by one colour.

We use K colours to dye the vertices in the graph. It is clear that if an edge corresponding to cellular link m, virtual D2D link D_0, and any relay node $\forall r \in \mathcal{R}_R$ is dyed colour k, it means cellular link m uses channel k exclusively. It is because the relay node is active only when it supports an actual D2D link. If an edge corresponding to cellular link m, actual D2D link n, and virtual relay node R_0 is dyed colour k, it means D2D link n operates in DM by reusing channel k with cellular link m. Moreover, if an edge corresponding to cellular link m, actual D2D link n, and actual relay node r is dyed colour k, then D2D link n operates in RM and is supported by relay node r through reusing channel k with cellular link m.

Since a virtual D2D link and a virtual relay node are introduced to make sure every three different nodes are connected by two same-colour edges. So one single virtual D2D link and one single virtual relay node are sufficient. Different scenarios are illustrated in Figure 5.2, where the virtual D2D link D_0 reuses the same channel with cellular link C_1 and C_2, respectively. It means that both cellular link C_1 and C_2 exclusively use the corresponding channel resource. Cellular links (such as C_3, C_m and C_M) reuse the corresponding channel with the actual D2D links (such as D_1, D_n and D_N), respectively. More specifically, D2D link D_1 operates in DM shown by connecting with a virtual relay node. D2D links D_n and D_N operate in RM and are supported by the actual relay nodes R_r and R_3, respectively.

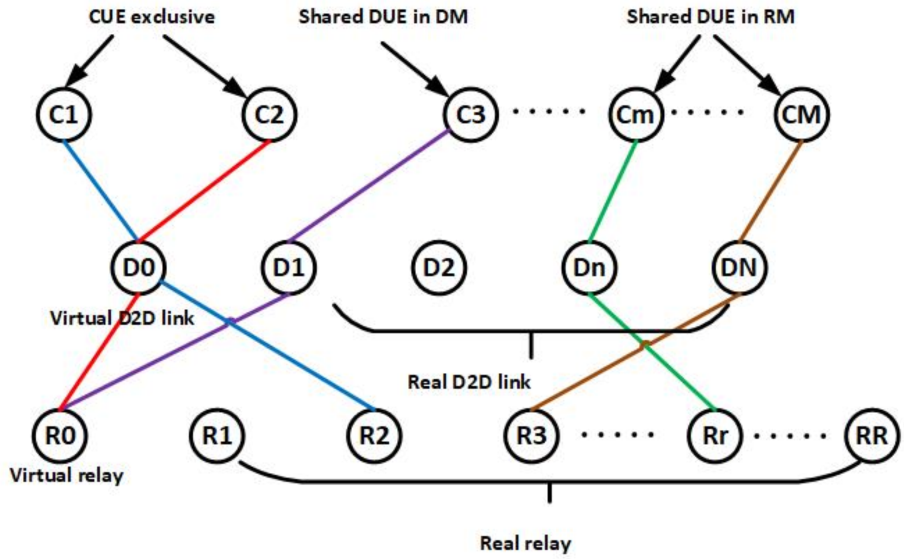


Figure 5.2: Illustrative examples of the channel allocation scenarios.

Each vertex in the constructed graph has one attribute, namely, type, which indicates that it belongs to one group, i,e. $V_m \in \mathcal{M}$ or $V_n \in \mathcal{N}_D$ or $V_r \in \mathcal{R}_R$. Moreover, each colour in the designed graph has three attributes, namely, cellular link attribute, channel assignment vector attribute and power allocation vector attribute.

- The channel link attribute contains two parameters, namely, the cellular vertex list L_k and the current interested vertex index $l_{k,1}$. The term L_k is a vector containing cellular vertex indices, where the cellular vertex index ordered with the signal-to-noise (SNR) at the BS. And the $l_{k,1}$ is the first element of L_k.

- The channel assignment vector a_k is a $1 \times (M + N + R + 2)$ vector, which is denoted as

$$a_k = [a_k(V_m), a_k(V_n), a_k(V_r)|\forall V_m \in \mathcal{M}, \forall V_n \in \mathcal{N}_D, \forall V_r \in \mathcal{R}_R]$$

  indicates the channel k is allocated to this vertexes for data transmission. If V_m, V_n and V_r are chosen from different vertex types to share the same channel k, then $a_k(V_m) = a_k(V_n) = a_k(V_r) = 1$; otherwise, $a_k(V_m) = a_k(V_n) = a_k(V_r) = 0$.

- The power allocation vector

$$p_k = [p_k(V_m), p_k(V_n), p_k(V_r)|\forall V_m \in \mathcal{M}, \forall V_n \in \mathcal{N}_D, \forall V_r \in \mathcal{R}_R]$$

indicates that the transmission power of communication links on channel k. Actually, the power allocation vector and the vertex assignment vector have the potential relationship, e.g. if $p_k(V_m) = p_k(V_n) = p_k(V_r) = 0$, then $a_k(V_m) = a_k(V_n) = a_k(V_r) = 0$, *vice versa*. Note that when the virtual vertex D_0 or R_0 is selected, the corresponding transmission power $p_k(D_0)$ or $p_k(R_0)$ is zero.

5.4.2 GCRA Algorithm

Based on the above colouring-based graph construction, we now start to dye the vertices with colours. In our system, the cellular links always have the high priority to access the channel resource. D2D link becomes active only when its reuse can not only improve the total throughput but also make sure all links satisfy the minimum SINR requirements. To proceed with the proposed GCRA algorithm, we define:

- The set $\mathcal{C}$ represents the unused colour, and its complementary set $\mathcal{C}^*$, i.e. $\mathcal{C}^* = \mathcal{K} - \mathcal{C}$.

- The channel cluster $\mathcal{B}_k = \{V_m, V_n, V_r\}$ represents the set of communication links that share channel k for individual data transmission. Based on this, the colouring circumstance of the whole graph can be represented by a vector $\mathcal{B} = [\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_K]$.

- The throughput value $v_t(\mathcal{B}_k)$ defines the sum of the channel capacity for all communication links that belong to the set $\mathcal{B}_k$, taking the QoS requirement and the mutual relationship among all links into consideration. The value of $v_t(\mathcal{B}_k)$ can be given as

$$v_t(\mathcal{B}_k) = \begin{cases} \tilde{R}^k_{C_m}, & \text{when } V_n = D_0, \\ \tilde{R}^k_{m,n}, & \text{when } V_n \neq D_0, V_r = R_0, \\ \tilde{R}^{k,r}_{m,n}, & \text{when } V_n \neq D_0, V_r \neq R_0, \end{cases} \tag{5.18}$$

where the $\tilde{R}^k_{C_m}$, $\tilde{R}^k_{m,n}$ and $\tilde{R}^{k,r}_{m,n}$ are the optimal transmission data rate on channel k in different scenarios, which will be discussed in section 5.5, subsequently.

- The total network throughput T can be calculated as

$$T = \sum_{k=1}^{K} v_t(\mathcal{B}_k). \tag{5.19}$$

  The basic idea of the graph colouring based algorithm is to iteratively dye the uncoloured vertices and gather them to the corresponding edge set $\mathcal{B}_k$ to maximize the total network throughput T.

As described in Table 5.2, at the beginning of the resource allocation process, the graph that describes the situation of the network is constructed, in which vertices that indicate different communication links are uniformly generated in the area of cellular network. First, each channel's individual information is initialized based on the SNR of the cellular links. All the elements in the vertex assignment and power allocation attributes are initialized as zeros. Next, the unused colour set $\mathcal{C}$ and each channel's cluster set $\mathcal{B}_k$ are initialized as an empty set. And the throughput value $v_t(\mathcal{B}_k)$ is initialized as zero.

In the GCRA algorithm, i.e. colouring process, we first select an unused colour from $\mathcal{C}^*$ and its corresponding current interested vertex index. Then, use this colour to dye the vertex in set $\mathcal{B}_k^{'} = \{V_m, D_0, R_0\}$, and update the throughput value $v_t(\mathcal{B}_k)$. Here the optimal power allocation is considered to obtain the throughput value $v_t(\mathcal{B}_k)$ according to (5.18). Then, an uncoloured vertex V_n is selected to replace D_0, and update the throughput value. If its replacement can not increase the cluster throughput, we then continue replace another type vertex R_0 in $\mathcal{B}_k^{'}$ with uncoloured V_r. After tried all the feasible vertexes choices, we update the throughput value with the largest $v_t(\mathcal{B}_k)$, and colour the corresponding vertexes, which means $a_k(V_m) = a_k(V_n) = a_k(V_r) = 1$ (if vertexes V_m, V_n and V_r are selected). Meanwhile, the power allocation p_k can be obtained. After those vertexes are coloured, all the related information is updated. This iterative procedure will continue until all the colours are used. Finally, the BS reports the obtained solution to the corresponding communication links. The cellular and D2D links can transit data in the allocated channel with permitted transmission power.

As explained in Table 5.2, the reason that the proposed scheme can approach the close-to-optimal network performance is that communication links will be selected only if they have the ability to further improve the network capacity performance.

Table 5.2: The proposed GCRA algorithm

1. Initialization

* Construct the $M+N+R$ vertices, with M cellular vertices, N D2D vertices, and R relay node vertices.

* Initialize each channel's individual attributes i.e. L_k and $l_{k,1}$.

* Initialize each channel's vertex assignment and power allocation vector $a_k = [a_k(1), a_k(2), ..., a_k(M+N+R+2)]$ is zero.

* Initialize each channel's vertex set $\mathcal{B}_k = \phi$, then $v_t(\mathcal{B}_k) = 0$, $\forall k \in \mathcal{K}$.

* Initialize $\mathcal{C} = \phi$, then $\mathcal{C}^* = \mathcal{K}$.

2. REPEAT

-Select an unused colour k from the complement of vertex set $\mathcal{C}$, i.e. $\mathcal{C}^*$, and its corresponding current interested vertex index $V_m = l_{k,1}$.

-Set $\mathcal{B}_k^{'} = \{V_m, D_0, R_0\}$, and store the current value $v_t^{'}(\mathcal{B}_k)$.

Repeat

-select the uncoloured D2D vertex V_n.

-replace D_0 with V_n in $\mathcal{B}_k$, i.e. $\mathcal{B}_k = \{V_m, V_n, R_0\}$.

- update the value of $v_t(\mathcal{B}_k)$ according to (5.18).

- If the value of $v_t(\mathcal{B}_k) \leq v_t^{'}(\mathcal{B}_k)$, then

Repeat

-Select an uncoloured relay vertex V_r to replace R_0 in $\mathcal{B}_k$, i.e. $\mathcal{B}_k = \{V_m, V_n, V_r\}$.

-Update the value of $v_t(\mathcal{B}_k)$ according to (5.18), and record the result.

-Delete the vertex V_r from $\mathcal{B}_k$, recover $\mathcal{B}_k = \{V_m, V_n, R_0\}$ and the value of $v_t(\mathcal{B}_k)$, recover relay vertex to uncoloured state.

Until all the uncoloured relay vertices have been tried or the value of $v_t(\mathcal{B}_k)$ is not greater than that of last cycle.

-Choose the largest result from all the recorded values of $v_t(\mathcal{B}_k)$.

If $v_t(\mathcal{B}_k) \geq v_t^{'}(\mathcal{B}_k)$, colour the corresponding optimum vertex group $\{V_m, V_n, V_r\}^{opt}$ using colour k and set $\mathcal{B}_k = \{V_m, V_n, V_r\}$, else $\mathcal{B}_k = \mathcal{B}_k^{'}$.

-Update the value of $v_t(\mathcal{B}_k)$, and record the result.

-Else record the value of $v_t(\mathcal{B}_k)$

-Delete the vertex V_n from $\mathcal{B}_k$, and recover $\mathcal{B}_k = \{V_m, D_0, R_0\}$ and recover the D2D and relay vertex to uncoloured state.

Until all the uncoloured D2D vertices have been tried or the value of $v_t(\mathcal{B}_k)$ is not greater than that of the cycle.

-Choose the largest result from all the recorded values of $v_t(\mathcal{B}_k)$, and colour the corresponding optimum vertex group $\{V_m, D_0, R_0\}$ or $\{V_m, V_n, R_0\}$ or $\{V_m, V_n, V_r\}$ using colour k. Set $\mathcal{B}_k = \{V_m, D_0, R_0\}$ or $\mathcal{B}_k = \{V_m, V_n, R_0\}$ or $\mathcal{B}_k = \{V_m, V_n, V_r\}$

-Update the value of $v_t(\mathcal{B}_k)$

UNTIL $\mathcal{C}^* = \phi$ or the value of $v_t(\mathcal{B}_k)$ is not greater than that of last cycle. Then $\mathcal{B}$ is obtained and the total $T = \sum_{k=1}^{K} v_t(\mathcal{B}_k)$ converges.

3. The power and channel allocations are given as $[p_1, p_2, ..., p_k]$ and $[a_1, a_2, ..., a_k]$.

5.5 Optimal Power Allocation

In this section, we illustrate the power allocation algorithms for different scenarios as expressed by equation (5.18).

5.5.1 When $V_n = D_0$

In this case, the cellular link exclusively occupies the channel resource. The optimal data rate on channel k can be obtained when the cellular link transmits on its maximum power, which is calculated as

$$\tilde{R}^k_{C_m} = R^k_{C_m}. \tag{5.20}$$

5.5.2 When $V_n \neq D_0, V_r = R_0$

In this case, the cellular link shares the same channel with a D2D link operating in DM. Thus, the power allocation problem can be expressed as

$$(\tilde{p}^k_{C_{m,n}}, \tilde{p}^k_{D_{m,n}}) = \underset{(p^k_{C_{m,n}}, p^k_{D_{m,n}})}{\arg\max} \; R^k_{m,n} \tag{5.21}$$

s.t.

$$\gamma^k_{C_{m,n}} \geq \gamma^C_{min}, \tag{5.21a}$$

$$\gamma^k_{D_{m,n}} \geq \gamma^D_{min}, \tag{5.21b}$$

$$0 \leq p^k_{C_{m,n}} \leq p^C_{max}, \tag{5.21c}$$

$$0 \leq p^k_{D_{m,n}} \leq p^D_{max}. \tag{5.21d}$$

It has been proved that either $\tilde{p}^k_{C_{m,n}}$ or $\tilde{p}^k_{D_{m,n}}$ needs to be equal to the maximum transmit power in order to achieve the optimal sum data rate. The optimal power solution $(\tilde{p}^k_{C_{m,n}}, \tilde{p}^k_{D_{m,n}})$ can be determined by comparing at most 4 possible solutions according to Proposition 4.1. After that, the optimal sum data rate on channel k can be obtained as

$$\tilde{R}^k_{m,n} = \log_2(1 + \frac{\tilde{p}^k_{C_{m,n}} h^k_{m,B}}{\sigma^2 + \tilde{p}^k_{D_{m,n}} h^k_{n,B}}) + \log_2(1 + \frac{\tilde{p}^k_{D_{m,n}} h^k_{n,n}}{\sigma^2 + \tilde{p}^k_{C_{m,n}} h^k_{m,n}}). \tag{5.22}$$

Note that $\tilde{R}^k_{m,n} = 0$ if the solution set is empty, it means that the transmission power of both cellular and D2D links can not meet all the constraints in (5.21), so the cellular and D2D links will not be allowed to share the same channel.

5.5.3 When $V_n \neq D_0, V_r \neq R_0$

In this case, the cellular link shares the same channel with the D2D link operating in RM with relay node r. The power allocation problem can be expressed as

$$(\tilde{p}^{k,r}_{C_{m,n}}, \tilde{p}^{k,r}_{D_{m,n}}, \tilde{p}^{k,r}_{R_{m,n}}) = \underset{(p^{k,r}_{C_{m,n}}, p^{k,r}_{D_{m,n}}, p^{k,r}_{R_{m,n}})}{\arg\max} R^{k,r}_{m,n} \tag{5.23}$$

$$\gamma 1^{k,r}_{C_{m,n}}, \gamma 2^{k,r}_{C_{m,n}} \geq \frac{1}{2}\gamma^{C}_{min}, \tag{5.23a}$$

$$\gamma 1^{k,r}_{D_{m,n}}, \gamma 2^{k,r}_{D_{m,n}} \geq \frac{1}{2}\gamma^{D}_{min}, \tag{5.23b}$$

$$0 \leq p^{k,r}_{C_{m,n}} \leq p^{C}_{max}, \tag{5.23c}$$

$$0 \leq p^{k,r}_{D_{m,n}} \leq p^{D}_{max}, \tag{5.23d}$$

$$0 \leq p^{k,r}_{R_{m,n}} \leq p^{R}_{max}. \tag{5.23e}$$

Since problem in (5.23) involves the power allocation for one relay, one DUT and one CUE on a certain channel resource, we reformulate it in the following concise form where for brevity the channel index k is omitted and the subscript symbols "c", "d", and "r" denote CUE, DUT and relay node, respectively.

From *Proposition 1*, it can be verified that problem (5.23) can achieve its optimum if $p_c = p^C_{max}$ or $p_d = p^D_{max}$ or $p_r = p^R_{max}$. Since cellular links have the higher priority to communicate than D2D links, it has been proved in [58] that only consider $p_c = p^C_{max}$ case is enough to achieve near optimal power allocation.

Thus, the problem in (5.23) is simplified into

$$(p^C_{max}, \tilde{p}_d, \tilde{p}_r) = \underset{(p^C_{max}, p_d, p_r)}{\arg\max}\, f_c(p^C_{max}, p_d, p_r) \tag{5.24}$$

s.t.

$$\frac{p_d h_{dr}}{\sigma^2 + p^C_{max} h_{cr}} = \frac{p_r h_{rd}}{\sigma^2 + p^C_{max} h_{cd}}, \tag{5.24a}$$

$$\frac{p_d h_{dr}}{\sigma^2 + p^C_{max} h_{cr}} \geq \gamma^D_{min}, \tag{5.24b}$$

$$\frac{p^C_{max} h_{cB}}{\sigma^2 + p_d h_{dB}} \geq \frac{1}{2}\gamma^C_{min}, \tag{5.24c}$$

$$\frac{p^C_{max} h_{cB}}{\sigma^2 + p_r h_{rB}} \geq \frac{1}{2}\gamma^C_{min}, \tag{5.24d}$$

$$0 \leq p_d \leq p^D_{max}, 0 \leq p_r \leq p^R_{max}, \tag{5.24e}$$

where $f(p^C_{max}, p_d, p_r) = (1 + \frac{p^C_{max} h_{cB}}{\sigma^2 + p_d h_{dB}})(1 + \frac{p^C_{max} h_{cB}}{\sigma^2 + p_r h_{rB}})(1 + \frac{p_d h_{dd}}{\sigma^2 + p^C_{max} h_{cr}})$. The first constraint in (5.24a) suggests that p_d can be expressed as a linear function of p_r

$$p_d = \frac{h_{rd}(\sigma^2 + p^C_{max} h_{cr})}{h_{dr}(\sigma^2 + p^C_{max} h_{cd})} p_r. \tag{5.25}$$

Therefore, the objective function in (5.24) can be expressed as a function of p_r, which is the ratio between one cubic polynomial and one quadratic polynomial

$$f_r = \frac{\zeta(p_r)}{g(p_r)} = \frac{a_3 p_r^3 + a_2 p_r^2 + a_1 p_r + a_0}{b_2 p_r^2 + b_1 p_r + b_0}, \tag{5.26}$$

where the coefficients $a_3, a_2, a_1, a_0, b_2, b_1$ and b_0 can be obtained by the Matlab *expand* function. Moreover, constraints (5.24b)-(5.24e) imply that $p_r \in [P_r^{min}, P_r^{max}]$, where the P_r^{min} and P_r^{max} are the lower and upper bounds. The optimal solution i.e. $(p_{max}^C, \tilde{p}_d, \tilde{p}_r)$ and the optimal value i.e. $\tilde{R}_{m,n}^{k,r}$ of problem (5.26) can be obtained by applying the *Dinkelbach* method as discussed in section 2.2.2.

5.6 Simulation Results and Complexity Analysis

Monte-Carlo simulations are conducted in this section to evaluate the efficiency of the proposed GCRA scheme. An isolated cell is considered here with radius of $500m$, where the BS is located at the centre. The CUEs and the relay nodes are uniformly distributed. Each D2D pair (includes one DUT and one DUR) are uniformly distributed in a randomly located cluster with radius d_{max}. The channel gain in our proposed model is modelled as $h_{a,b} = d_{a,b}^{-\alpha}\chi$ for all communication links, where $d_{a,b}$ is the distance between node a and b, α is the pathloss exponent[1]; χ represents the Rayleigh fading. The simulation parameters summarized in Table 5.3, are chosen according to [20] for the purpose of comparison.

5.6.1 Simulation Results

We define our joint optimization as the *proposed GCRA* algorithm, and compare it with the following schemes:

Tra-Cellular: In traditional cellular network, the CUEs are allocated orthogonal channel resource to transmit data through the BS directly.

Only-Direct: In [20], the D2D links communicate with each other directly by reusing the channel resources of CUEs. Only DM is considered here.

Optimal-Relay: The optimization programming is applied to obtain the optimal performance of the joint problem. Specifically, for both DM and RM, all the reuse possibilities of CUEs and D2D links on each channel resource are considered in the power allocation process. Then, the channel allocation problem among multiple CUEs and D2D links are solved by the exhaustive search method.

[1]To demonstrate the benefit that relay can bring us, we will choose different pathloss exponent value for DUTs to relay nodes and relay nodes to DURs.

Table 5.3: Simulation Parameters

Maximum distance between D2D pairs d_{max} (m)	300 (if fixed)
Number of channel resource K	20
Number of cellular links M	20
Number of D2D links N ($N \leq M$)	10 (if fixed)
Number of relay nodes R	30
Maximum cellular transmission power P^C_{max}(dBm)	20
Maximum D2D transmission power P^D_{max}(dBm)	20
Maximum relay transmission power P^D_{max}(dBm)	20
SINR requirements of cellular links γ^C_{min} (dB)	10 (if fixed)
SINR requirements of D2D links γ^D_{min} (dB)	15
Noise power σ^2 (dBm)	-110
Pathloss exponent for relay communications $\alpha 1$	3
Pathloss exponent for other communications $\alpha 2$	4

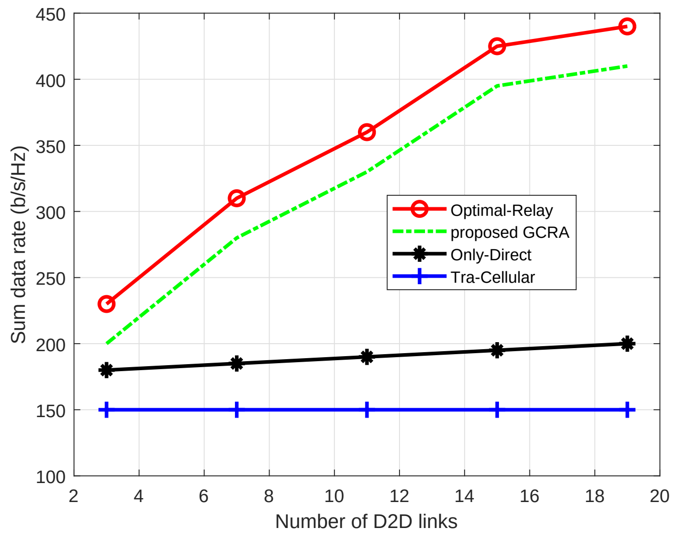


Figure 5.3: The system sum data rate in different schemes with varying N.

Figure 5.3 shows that the system sum data rate achieved by various schemes for different N when $d_{max} = 300$. We observe that the sum data rate increases with the increase of the total number of D2D links for *Only-Direct*, *proposed GCRA* algorithm and *Optimal-Relay* algorithms. That is due to the number of active D2D links increases. Moreover, the *proposed GCRA* algorithm achieves close-to-optimal performance and significantly outperforms the *Only-Direct* and *Tra-Cellular*, which stays unchanged with the increase of N.

Figure 5.4 shows that the system sum data rate of different scheme with varying d_{max} when $N = 10$. As the increase of d_{max}, the sum data rate decrease in all schemes except in the traditional cellular networks. That is because the channel gain between D2D links is decreasing with the increase of d_{max}, and this can lead to the worst system performance in *Only-Direct*, proposed GCRA and *Optimal-Relay* algorithms. As shown in the figure, the proposed GCRA closely approaches the optimal-relay and notably outperforms the other two methods.

Figure 5.5 shows that the system data rate of various scheme for different γ_{min}^{C}. The increase of γ_{min}^{C}, the sum data rate of the *Tra-Cellular* and the *Only-Direct* methods decrease. The sum rates of the *proposed GCRA* and the *Optimal-Relay* scheme also decrease, but moderately with the increase of γ_{min}^{C}. This is because the number of both active cellular links and D2D links decrease with the increase of γ_{min}^{C}. This will lead to low system data rate. Owing to the assistance of relay nodes, high γ_{min}^{C} would not significantly degrade the data rate of D2D links in both *proposed GCRA* and the *Optimal-Relay* schemes.

All the above results show that the proposed algorithm produces notably bet-

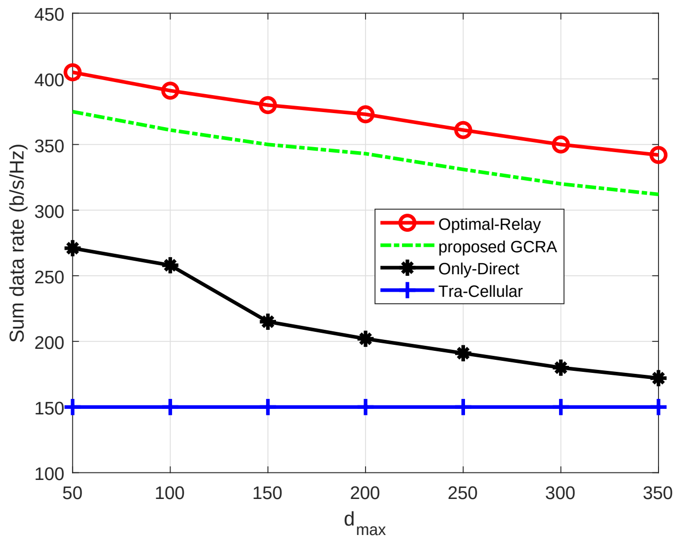


Figure 5.4: The system sum data rate in different schemes with varying d_{max}.

ter performance than the existing works. This is because our proposed scheme not only applies the relay selection for D2D links but also considers the joint channel allocation for both cellular and D2D links. Moreover, thanks to the heuristic channel allocation and the optimal power allocation in each iteration, the proposed GCRA algorithm produces close-to-optimal results.

5.6.2 Complexity Analysis

The computational complexity is analysed by counting the number of operations required in the power and channel allocations. Although the optimal resource allocation includes the power and channel allocations, but the complexity of the power allocation is indeed negligible. Based on the results of power allocations, the complexity of the *Optimal-Relay* scheme with considering all the channel allocation possibilities is $O(MN + MNK + MNKR)^{3.5} = O(MNKR)^{3.5}$.

According to Algorithm 1, the proposed GCRA algorithm is operated iteratively. Different initial states of the graph constructed based on the current investigated network will lead to different numbers of iterations to obtain the final solution. Therefore, we focus on the worst case complexity of GCRA, which can sufficiently verify the efficiency of the proposed algorithm.

From the procedure of GCRA, the core idea of solving the resource allocation problem is to iteratively replace the vertexes in channel cluster with the available D2D or relay vertexes, until one available vertex can bring better throughput. Thus, the worst case complexity can be readily calculated considering the case where all the channel cluster tested by all the available D2D and relay vertexes. A

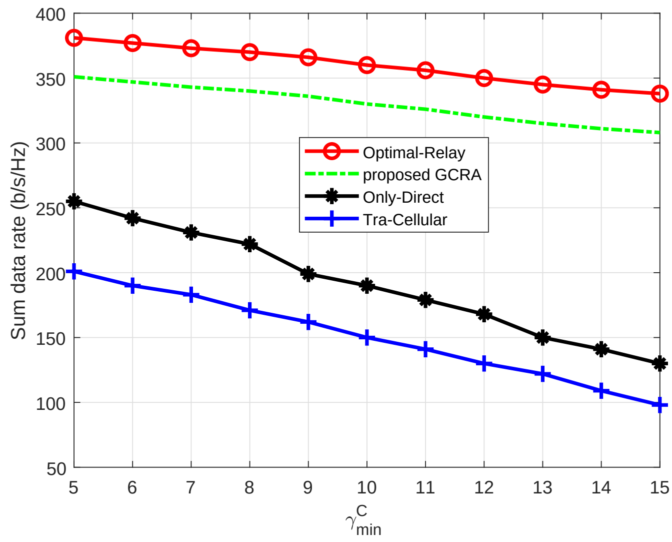


Figure 5.5: The system sum rate with various schemes for different γ^{C}_{min}.

certain channel cluster, a cellular link, the virtual D2D link and the virtual relay link are selected in each iteration. The worst case complexity of the proposed GCRA algorithm can be then given as

$$\begin{aligned} \mathcal{C} =& \mathcal{O}(K(M + \frac{N(N+1)}{2} + \frac{R(R+1)}{2})) \\ =& \mathcal{O}(K(\max\{N, R\}^2)) \\ =& \mathcal{O}(KR^2). \end{aligned} \tag{5.27}$$

Comparing with the complexity of the optimal resource allocation scheme via exhaustive search method, we can conclude that the proposed algorithm can effectively reduce the computational complexity with slightly degraded system performance.

5.7 Summary

In this this chapter, the joint mode selection, relay selection and resource allocation for both cellular and D2D links is formulated. Since the joint optimization is NP-Hard, we then proposed a GCRA algorithm to effectively solve it. Simulation results show that the proposed algorithm can produce the close-to-optimal performance with an acceptable computational complexity.

Chapter 6

Resource Allocation for D2D Underlay Communications with Proportional Fairness using Iterative-based Approach

6.1 Introduction

Most of the above researches focus on improving the total system throughput or EE when allocating the power and channel resource while completely ignoring the fairness aspect. Fairness as an important factor in resource allocation should also been taken into account to ensure all users have equal chance to access the system resource [59]. Generally, the links with good channel condition which can improve the whole system throughput are chosen to communicate. The links with poor channel gain will have lower or no chance to access the channel resource. This will lead to an unfair system and is not acceptable for some applications such as Vehicle-to-Everything (V2X) communications, which is a term that collectively refers to V2V, Vehicle-to-Infrastructure (V2I), and Vehicle-to-Device (V2D) [60] [61]. In V2X emergency communications, due to the mobility of vehicles, message loss is inevitable. The situation that one or a few vehicles take all the loss must be avoided because they may become invisible to their surrounding vehicles and cause serious safety concerns [62–66].

6.1.1 Related works and Motivations

One important aspect of D2D communications is that it can improve the network capacity greatly by spectrum reusing between D2D and cellular links. There have been many works on resource allocation for D2D underlay communications [10] [67]. Lots of works have been investigated aiming at increasing the network throughput for D2D underlay communications [25] [68]. Works in [12] [20] prove that the maximum system throughput can be achieved when at least one of the users transmit at its maximum power. Authors in [12] [20] transform the channel allocation as a maximum weight bipartite matching problem, which can be solved by the well-known *Kuhn-Munkres* algorithm. Authors in [69] formulate the channel allocation by using the graph-based approach, which is solved by an iterative rounding algorithm. Authors in [70] transform the power allocation into a D.C. programming (Difference of Convex functions programming), which can be solved by standard convex algorithm. Based on the assumption that the cellular transmission powers are fixed, authors in [26] use the convex approximation technique to formulate the joint power allocation into a solvable convex optimization problem. In addition, there are also many works on improving system EE for D2D underlay communications in recent years. Utilising the properties of fractional programming, [27] and [28] transform the original non-convex EE problem into an equivalent optimization problem with subtractive form, which is solved by an iterative approach. Authors in [29] propose three channel allocation algorithms: dual-based, BnB and RBR algorithms with different computational complexity levels.

Resource allocation schemes have been proposed in D2D-based V2V communications. Similar with [70], the authors in [64] apply the D.C. programming to obtain the optimal power allocation. And a series of simplification is made leading to a tradeoff between system performance and complexity. A latency and reliability guaranteed resource allocation scheme for V2V communication is proposed in [60] [61]. In [65], authors allocated the transmission power while considering the adjacent carrier interference (ACI) effects to maximize the number of successful links. To maximize the system capacity and reduce the system overhead, a decentralized resource allocation scheme based on the deep reinforcements learning has been introduced for V2V communications in [71]. The EE problem is managed in [66] for V2V communications by applying the concept of the chaining neural network (CNN).

In this chapter, we will propose a novel resource allocation scheme aims to enhance the system fairness and makes sure all users have the same priority to access the system resource. Actually, the system fairness can also be considered in other D2D scenarios, i.e. H2H and M2M. But in this paper, we focus on the V2X communications, where the users have the mobility feature. Generally, the Max-min, Round Robin and Proportional Fairness (PF) schedulers are applied to improve the system fairness. The increase of system fairness can lead to the decrease of throughput, *vice versa*, which is a nature conflict between system throughput and fairness such as the Max-min and Round Robin. The PF scheduler can offer a better tradeoff between system throughput and fairness comparing with other schedulers (e.g. Round Robin and Max-Min schedulers) [72], so the PF scheduler is selected in our proposed scheme.

There are few works on how PF scheme is applied in D2D underlay communications. Authors in [73] optimize the system sum rate while considering the fairness among D2D links. Work in [74] transforms the PF scheduling as an assignment problem by applying *Maclaurin* series expansion. But same transmission powers are allocated to all users and the QoS requirements of the communication links can not be guaranteed. This will lead to harmful interferences between cellular and D2D links. [75] assumes that the system is completely fair when allocating the power for both links, which is unrealistic and may lead to an unfair system. Our work in [58] enhances the system fairness when allocating the transmission power with taking into account the previous average data rates.

The characteristics of above related works are summarized in Table 6.1.1 where CA, PA and Optim are abbreviations of channel allocation, power allocation and Optimization. Note that works in [60] [61] uses the Max-Min scheduler to allocate the channel resource for V2V communications aiming to maximize the system sum rate, which will bring lower system fairness than our works. Similar works have been proved in [75].

6.1.2 Main Contributions

In most of the above works, channel for cellular links is assumed to be pre-allocated. However, joint channel resource allocation for both cellular and D2D links can result in a better system performance [21]. Therefore, to further enhance the system fairness, we consider a more general scheme that the BS needs to simultaneously allocate the channel resource to both cellular and D2D links. In this chapter, we first formulate the joint power and channel allocation for both cellular and D2D links to maximize the system fairness while guaranteeing the QoS requirements and power limits of communication links for all scheduling period[1] ($t = 1$ and $t \geq 2$). Since the above joint problem in each scheduling period is a MINLP problem, we then divide it into two sub-problems: power allocation and channel allocation, and solve them sequentially.

[1]We define that the moment that D2D links are established is the first scheduling period ($t = 1$).

Table 6.1: Summery of related works

Papers	Objective	QoS	Cellular links		Approaches	Mobility
			CA	PA		
[12] [20]	Sum-rate	Yes	No	Yes	Optim	No
[69]	Sum-rate	Yes	Yes	Yes	Optim and Graph-based	No
[70]	Sum-rate	No	No	Yes	Optim	No
[26]	Sum-rate	Yes	No	No	Optim	No
[27]	EE	No	No	Yes	Optim	No
[28]	EE	No	No	Yes	Optim and Game theory	No
[29]	EE	Yes	No	Yes	Optim	No
[73]	Sum-rate	Yes	Yes	Yes	Optim	No
[64]	Sum-rate	Yes	Yes	Yes	Optim	Yes
[60] [61]	Sum-rate	Yes	Yes	Yes	Optim	Yes
[65]	Successful links	Yes	Yes	Yes	Optim	Yes
[71]	Sum-rate	Yes	Yes	Yes	Deep learning	Yes
[66]	EE	Yes	Yes	Yes	CNN	Yes
[74]	PF	No	No	No	Optim	Yes
[75]	PF	Yes	No	Yes	Optim	Yes
[58]	PF	Yes	No	Yes	Optim	Yes
Our works	PF	Yes	Yes	Yes	Optim	Yes

Specifically, the power allocation algorithm for individual scheduling period is proposed. After that, the channel allocation is solved by proposing an iterative technique which projects the 3-dimensional (3-D) assignment problem to a 2-dimensional (2-D) assignment problem. We believe that all the above conducted process in underlay D2D communications can be smoothly applied in the practical V2V communications.

To the best of our knowledge, this is the first work that optimizes the joint power and channel allocation of the mobile cellular and D2D links aiming at maximizing the system fairness. The power allocation is related to control the transmission powers of the cellular link and its reuse D2D link to maximize system fairness while avoiding the harmful mutual interference. The channel allocation is to allocate the appropriate channel resource with the PF scheduler to enhance the system fairness. Our main contributions are summarised as follows.

- We propose the PF scheduling for D2D underlay communications aiming at maximizing the system fairness and deduce it into a solvable form using *Talyor* series.

- When $t = 1$, we model the system fairness as the multiplication of current data rates of cellular and D2D links. The optimal power allocation for D2D link and cellular link which reuses the same channel resource can be obtained by comparing at most 4 potential solutions.

- When $t \geq 2$, we transform the system fairness problem into the maximization of the sum of the ratios of current to average data rates. Similar with $t = 1$, the optimal power allocation for D2D link and its reuse cellular link can be obtained by comparing at most 6 potential solutions.

- Based on the above power allocation results, we introduce the concept of virtual D2D links and model the channel allocation as a 3-D assignment problem. A novel iterative 2-D assignment (*I2-DA*) algorithm is proposed to solve it efficiently. Specifically, in each iteration, we solve a selected 2-D assignment problem by using the *Kuhn-Munkres* method. In this way, the system computational complexity is reduced dramatically.

Simulation results show that our proposed scheme can not only enhance the system fairness but also increase the overall system throughput comparing with the existing schemes. Moreover, the numerical results reveal that our proposed iterative method can produce the close-to-optimal performance with low computational complexity.

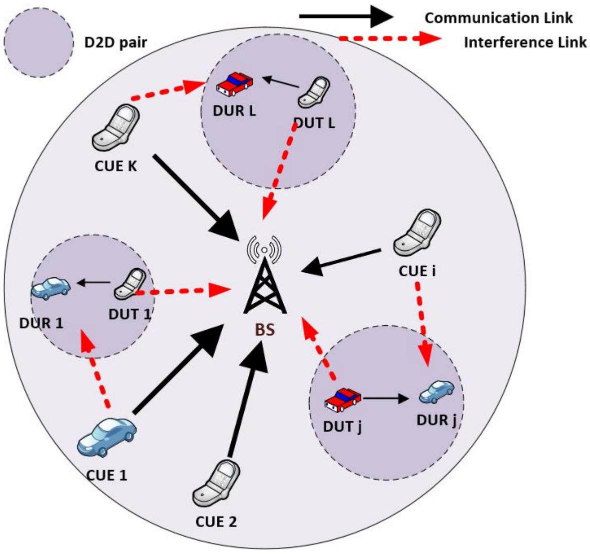


Figure 6.1: The system model of dynamic V2X communications.

6.1.3 Chapter Organization

The rest of chapter is organized as follows. Section 6.2 introduces the system model and the expressions of PF scheduling for D2D underlay communications. Problem formulations and proposed algorithms for $t = 1$ and $t \geq 2$ are shown in section 6.3 and 6.4, respectively. The proposed *I2-DA* algorithm is illustrated in section 6.5. Simulation results and system complexity analysis are presented in section 6.6. Section 6.7 concludes this chapter.

6.2 System model and PF scheduling

6.2.1 System Model

We consider an open air festival scenario occurred within a single cell system with a BS in the centre, where K CUEs in the set $\mathcal{M} = \{1, ...m, ...M\}$, and L predefined and configured D2D pairs in the set $\mathcal{N} = \{1, ...n, ...N\}$. Each D2D pair includes a (DUT) and a (DUR) as shown in Fig. 6.1.

In this chapter, the available channel resource is 2-D, i.e. including both frequency and time domains as shown in Fig. 6.2, where the whole uplink frequency bandwidth is divided into K subbands, with $\mathcal{K} = \{1, ...k, ...K\}$. One subband over one RB time is defined as one resource block (RB). We assume that each RB can be allocated to at most one cellular link and one D2D link. Thus, we ignore the co-channel interference between CUEs and the co-channel interference between D2D links. We also assume that each RB can be allocated to at most one cellular link and one D2D link. In this way, the mutual interference between

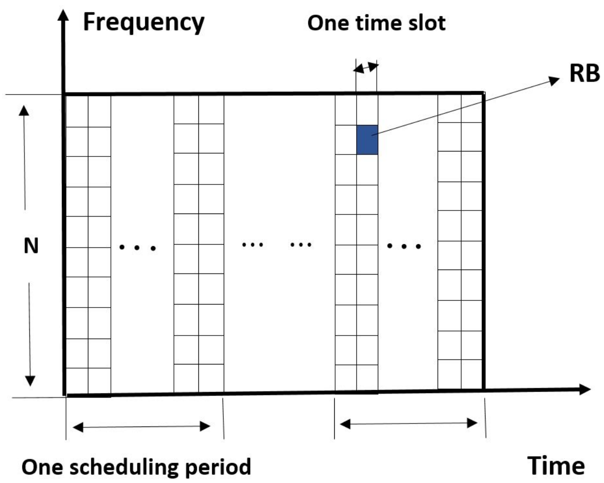


Figure 6.2: The Two-dimensional RBs for channel allocation.

cellular link and D2D link will occur. Moreover, we consider a dense system that there is no spare RBs for D2D links, where D2D links can only reuse the RBs with CUEs. Thus, the total number of RBs can be treated as equal to the number of cellular links (i.e. $N = K$).

In the design of our scheme, we also consider the overhead in practical use. As known, a centralized resource planning and scheduling architecture is considered in our system, where BS has the capability of acquiring the perfect channel state informations (CSIs) of all communication links, which have to be estimated at the receivers and then feed back to the BS. However, due to the mobility of vehicles, it is extremely hard to track the real-time small-scale channel fading coefficients and updating CSIs in every time slot will generate too much overhead and consume excessive bandwidth. Considering the channel coherence time is usually much larger than a time slot even in fast varying scenario [76], it is reasonable to set the scheduling period much longer than the time slot, as shown in Fig. 6.2, such as a few hundred milliseconds. In this way, the CSIs update in every scheduling period instead of every time slot, so the overhead can be greatly reduced. In addition, the investigation in [77] shows that the system performance degradation caused by averaging out the small-scale fading is acceptable. Accordingly, we only consider the large-scale fading phenomenon [64]. Therefore, the channel gain between node a and b on RB c in scheduling period t is modelled as

$$h^t_{a,b,c} = d^{-\alpha}_{a,b}\kappa, \tag{6.1}$$

where κ is the shadow fading gain whose distribution is lognormal. α is the path-loss exponent and $d_{a,b}$ is the distance between node a and b in scheduling period t.

When D2D pair n reuses the same RB k with CUE m, the SINRs of cellular link m and D2D link n on RB k at scheduling period t can be expressed as

$$\gamma^t_{C_{m,n,k}} = \frac{p^t_{C_{m,n,k}} h^t_{m,B,k}}{\sigma^2 + p^t_{D_{m,n,k}} h^t_{n,B,k}}, \tag{6.2}$$

$$\gamma^t_{D_{m,n,k}} = \frac{p^t_{D_{m,n,k}} h^t_{n,k}}{\sigma^2 + p^t_{C_{m,n,k}} h^t_{m,n,k}}, \tag{6.3}$$

in which $p^t_{C_{m,n,k}}$ and $p^t_{D_{m,n,k}}$ are the transmission powers of CUE m and DUT n in scheduling period t on RB k, respectively. $h^t_{m,B,k}$ is the channel gain between CUE m and BS and $h^t_{n,B,k}$ is the interfering channel gain from DUT n to BS in scheduling period t on RB k. $h^t_{n,k}$ is the channel gain between D2D pair n in scheduling period t on RB k. $h^t_{m,n,k}$ is the interfering channel gain from CUE m to DUR n in scheduling period t on RB k. σ^2 is the noise power.

The data rates of cellular link m and D2D link n on RB k can be expressed as

$$r^t_{C_{m,n,k}} = \log_2(1 + \gamma^t_{C_{m,n,k}}), \tag{6.4}$$

$$r^t_{D_{m,n,k}} = \log_2(1 + \gamma^t_{D_{m,n,k}}), \tag{6.5}$$

respectively, where the data rate is calculated in b/s/Hz, which is normalized by channel bandwidth.

When cellular link do not experience any co-channel interference from D2D links, the maximum throughput could be achieved while cellular link transmits with its maximum transmission power (i.e. p^C_{max}). Thus, the data rate of cellular link m on RB k in scheduling period t without reusing can be expressed as[1]

$$r^t_{C_{m,k}} = \log_2(1 + \frac{p^C_{max} h^t_{m,B,k}}{\sigma^2}). \tag{6.6}$$

For convenience, the frequently used symbols in this paper are listed in TABLE 6.2.

6.2.2 PF Scheduling

As mentioned above, a system is fair if it provides equal average data rates to all links over a long-term service and each link is activated only if the minimum SINR requirement is satisfied in every scheduling period. Here, the PF scheduling is used to achieve the system fairness.

[1]We assume that the cellular links without reusing always meet the minimum SINR constraints.

Table 6.2: The list of symbols

Symbols	**Meanings**
$p^t_{C_{m,n,k}}$	The transmission power of CUE m, when it shares the RB k with D2D pair n at scheduling period t
$p^t_{D_{m,n,k}}$	The transmission power of DUT n, when it reuses the RB k with CUE m at scheduling period t
$\gamma^t_{C_{m,n,k}}$	The SINR of cellular link m, when it shares the RB k with D2D pair n at scheduling period t
$\gamma^t_{D_{m,n,k}}$	The SINR of D2D link n, when it reuses the RB k with CUE m at scheduling period t
$r^t_{C_{m,n,k}}$	The data rate of cellular link m, when it shares the RB k with D2D pair n at scheduling period t
$r^t_{D_{m,n,k}}$	The data rate of D2D link n, when it reuses the RB k with CUE m at scheduling period t
$p^{t*}_{C_{m,n,k}}$	The optimal transmission power of CUE m, when it shares the RB k with D2D pair n at scheduling period t
$p^{t*}_{D_{m,n,k}}$	The optimal transmission power of DUT n, when it reuses the RB k with CUE m at scheduling period t
$r^{t*}_{C_{m,n,k}}$	The optimal data rate of cellular link m, when it shares the RB k with D2D pair n at scheduling period t
$r^{t*}_{D_{m,n,k}}$	The optimal data rate D2D link n, when it reuses the RB k with CUE m at scheduling period t
$pd^t_{low,m,n,k}$	The low bound of feasible set $p^t_{D_{m,n,k}}$ when CUE m transmits at it maximum power
$pd^t_{up,i,j,n}$	The up bound of feasible set $p^t_{D_{m,n,k}}$ when CUE m transmits at it maximum power

Definition: A scheduling scheme F is proportional fair if and only if:

$$\sum_{u \in U} \frac{R_u^{(S)} - R_u^{(F)}}{R_u^{(F)}} \leq 0, \tag{6.7}$$

where U is the user set, and $R_u^{(S)}$ and $R_u^{(F)}$ are the average data rates of user u for scheduling scheme S and F, respectively.

According to [78], the PF scheduling scheme F can be expressed as follows

$$F = \arg\max_{S} \sum_{u \in U} \ln R_u^{(S)}. \tag{6.8}$$

This means scheduling F should maximize the sum of logarithmic average user rates. In this work, the scheduling F is related about both the power allocation and the channel allocation. In D2D Underlay communication system, (6.8) can be equally transformed into

$$F = \begin{cases} \arg\max_{S}\{\sum_{m\in\mathcal{M}} \ln r_{m,t}^{(S)} + \sum_{j\in\mathcal{L}} \ln r_{n,t}^{(S)}\}, & \text{for } t = 1, \\ \arg\max_{S}\{\Pi_{m\in\mathcal{M}}(1 + \frac{r_{m,t}^{(S)}}{(t-1)R_{m,t-1}}) \times \Pi_{n\in\mathcal{N}}(1 + \frac{r_{n,t}^{(S)}}{(t-1)R_{n,t-1}})\}, & \text{for } t \geq 2, \end{cases} \tag{6.9}$$

where $r_{m,t}^{(S)}$ and $r_{n,t}^{(S)}$ are the current data rates of CUE m and D2D pair n achieved by scheduling scheme S in scheduling period t, respectively. $R_{m,t-1}^{(S)}$ and $R_{n,t-1}^{(S)}$ are the average date rates of of CUE m and D2D pair n during previous $(t-1)$ scheduling periods. The deviation of (6.9) is given in Appendix A. As seen in (6.9), the scheduling scheme F has different expressions for $t = 1$ and $t \geq 2$. Thus, they will be solved separately in the following sections. Noted that the PF scheduler scheme in $t = 1$ is the initialization of the PF scheduler scheme when $t \geq 2$.

6.3 Joint Power and Channel Allocation for $t = 1$

As shown in section 6.2, the PF scheduler scheme for $t = 1$ is modelled to maximize the sum of the logarithm current data rates for all links while considering the required minimum SINRs and the power limits of all cellular and active D2D links. Since the channel allocation of cellular and D2D links affect each other, we introduce two channel allocation matrices $\mathbf{\Phi}^1$ and $\boldsymbol{\chi}^1$ for cellular and D2D links[1], where

$$\Phi_{m,k}^1 = \begin{cases} 1, & \text{if cellular link } m \text{ occupies RB } k \text{ exclusively}, \\ 0, & \text{otherwise}. \end{cases} \tag{6.10}$$

[1]Here, the superscript 1 means $t = 1$.

$$\chi^1_{m,n,k} = \begin{cases} 1, & \text{if cellular link } m \text{ and D2D link } n \text{ reuse the same RB } k, \\ 0, & \text{otherwise.} \end{cases} \tag{6.11}$$

Then, the problem in (6.9) for $t = 1$ can be reformulated into

$$\begin{aligned}(\boldsymbol{P}^1_*, \boldsymbol{\Phi}^1_*, \boldsymbol{\chi}^1_*) = \underset{(\boldsymbol{P}^1, \boldsymbol{\Phi}^1, \boldsymbol{\chi}^1)}{\arg\max} \{ \sum_{k=1}^{K} \{ (\sum_{m=1}^{M} \Phi^1_{m,k} [\ln r^1_{C_{m,k}}]) \\ + \sum_{m=1}^{M} \sum_{n=1}^{N} \chi^1_{m,n,k} ([\ln r^1_{C_{m,n,k}}] + [\ln r^1_{D_{m,n,k}}]) \} \}\end{aligned} \tag{6.12}$$

s.t.

$$\gamma^1_{C_{m,n,k}} \geq \gamma^C_{min}, 0 \leq p^1_{C_{m,n,k}} \leq p^C_{max}, \forall m \in \mathcal{M}, \tag{6.12a}$$

$$\gamma^1_{D_{m,n,k}} \geq \gamma^D_{min}, 0 \leq p^1_{D_{m,n,k}} \leq p^D_{max}, \forall n \in \mathcal{N}, \tag{6.12b}$$

$$\sum_{k=1}^{K} (\sum_{n=1}^{N} \chi^1_{m,n,k} + \Phi^1_{m,k}) = 1, \forall m \in \mathcal{M}, \tag{6.12c}$$

$$\sum_{k=1}^{K} \sum_{m=1}^{M} \chi^1_{m,n,k} \leq 1, \forall n \in \mathcal{N}, \tag{6.12d}$$

$$\sum_{m=1}^{M} (\sum_{n=1}^{N} \chi^1_{m,n,k} + \Phi^1_{m,k}) = 1, \forall k \in \mathcal{K}, \tag{6.12e}$$

$$\Phi^1_{m,k}, \chi^1_{m,n,k} \in \{0, 1\}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}, \tag{6.12f}$$

in which $\boldsymbol{\Phi}^1$ is a $M \times K$ channel allocation matrix for cellular links. $\boldsymbol{P}^1$ and $\boldsymbol{\chi}^1$ are the $M \times N \times K$ power and channel allocation matrices. $P^1_{m,n,k} = [(p^{1^*}_{C_{m,n,k}}, p^{1^*}_{D_{m,n,k}})]$ is the optimal power allocated to cellular link m and D2D link n when they reuse the RB k in the first scheduling period. γ^C_{min} and γ^D_{min} are the minimum SINR requirements of cellular and D2D links, respectively. p^C_{max} and p^D_{max} are the maximum transmission power of cellular and D2D transmitters. In (6.12), the first term is the sum of logarithm cellular link data rates without reusing, and the second term is the sum of logarithm data rates of the cellular links and D2D links when they reuse the same RB.

Constraints (6.12a) and (6.12b) show that the minimum SINR requirement and power limit of individual cellular link and active D2D link in all transmission intervals. Constraint (6.12c) shows that each cellular link is allocated one RB and constraint (6.12d) indicates that each active D2D link can only reuse no more than one RB. Constraint (6.12e) shows that each RB can be either exclusively allocated to one cellular link or reused by one cellular and one active D2D links.

The final constraint $(6.12f)$ means the value of channel allocation indicators are binary.

In order to solve (6.12) efficiently, we first derive the optimal power allocation on any given RB for any reuse pair of cellular and D2D links, which enables us to determine the data rate of each RB for all possible allocation. Based on the power allocation results, we then transform the original resource allocation into a 3-D channel allocation problem.

6.3.1 Power Allocation for $t = 1$

The power allocation is to allocate the transmission power to one D2D link and one cellular link which share the same RB by optimizing the sum function while meeting their minimum SINR requirements and power limits. Therefore, we will present our proposed optimal power allocation algorithm on one RB basis. This procedure will be repeated for all channel allocation possibilities that cellular and D2D links reuse all different RBs.

Mathematically, when cellular link m reuses the RB k with D2D link n, the power allocation can be simplified as[1]

$$\begin{aligned}(p^{1^*}_{C_{m,n,k}}, p^{1^*}_{D_{m,n,k}}) &= \underset{(p^1_{C_{m,n,k}}, p^1_{D_{m,n,k}})}{\arg\max} \{\ln r^1_{C_{m,n,k}} + \ln r^1_{D_{m,n,k}}\} \\ &= \underset{(p^1_{C_{m,n,k}}, p^1_{D_{m,n,k}})}{\arg\max} \{r^1_{C_{m,n,k}} \times r^1_{D_{m,n,k}}\} \\ &= \underset{(p^1_{C_{m,n,k}}, p^1_{D_{m,n,k}})}{\arg\max} \{\log_2(1+\gamma^1_{C_{m,n,k}}) \times \log_2(1+\gamma^1_{D_{m,n,k}})\} \\ &= \underset{(p^1_{C_{m,n,k}}, p^1_{D_{m,n,k}})}{\arg\max} \{\ln \gamma^1_{C_{m,n,k}} \times \ln \gamma^1_{D_{m,n,k}}\}\end{aligned} \tag{6.13}$$

s.t.

$$\gamma^1_{C_{m,n,k}} \geq \gamma^C_{min}, \gamma^1_{D_{m,n,k}} \geq \gamma^D_{min}, \tag{6.13a}$$

$$0 \leq p^1_{C_{m,n,k}} \leq p^C_{max}, 0 \leq p^1_{D_{m,n,k}} \leq p^D_{max}. \tag{6.13b}$$

Constrain $(6.13a)$ makes sure the SINRs of both cellular and active D2D links satisfy the minimum requirements, which are around 10 (10dB) in most cases. $(6.13b)$ is the transmission power constraints for both links.

It has been proved in [20] that at least one of the cellular and D2D links transmit its maximum power will lead to the optimal performance, it also can be proved that the following lemma holds.

[1] To simplify the expression, we use ln to replace log_2. And this can give us the same simulation results.

Lemma 1: At least one of $p^1_{C_{m,n,k}}$ *and* $p^1_{D_{m,n,k}}$ *needs to reach its maximum value in order to maximize the product in* (6.13).

Proof: See the Appendix B.1. ■

We define $\Omega^1_{m,n,k}$ as the feasible set of problem in (6.13), $\Omega 1^1_{m,n,k}$ and $\Omega 2^1_{m,n,k}$ are the feasible sets when cellular and D2D users transmit the maximum power, respectively. Thus, we have the following proposition.

Proposition 6.1 *If the problem in (6.13) is feasible, its optimal power allocation solution belongs to the set* $\Omega^1_{m,n,k} = \Omega 1^1_{m,n,k} \cup \Omega 2^1_{m,n,k}$*; otherwise, the set is empty* $(\Omega^1_{m,n,k} = \phi)$.

We first assume $p^1_{C_{m,n,k}} = p^C_{max}$, then problem in (6.13) becomes

$$(p^C_{max}, p^{1^*}_{D_{m,n,k}}) = \arg \max_{(p^C_{max}, p^1_{D_{m,n,k}})} f(p^C_{max}, p^1_{D_{m,n,k}}) \tag{6.14}$$

s.t.

$$\frac{p^C_{max} h^1_{m,B,k}}{\sigma^2 + p^1_{D_{m,n,k}} h^1_{n,B,k}} \geq \gamma^C_{min}, \tag{6.14a}$$

$$\frac{p^1_{D_{m,n,k}} h^1_{n,k}}{\sigma^2 + p^C_{max} h^1_{m,n,k}} \geq \gamma^D_{min}, \tag{6.14b}$$

$$0 \leq p^1_{D_{m,n,k}} \leq p^D_{max}, \tag{6.14c}$$

where $f(p^C_{max}, p^1_{D_{m,n,k}}) = \ln(\frac{p^C_{max} h^1_{m,B,k}}{\sigma^2 + p^1_{D_{m,n,k}} h^1_{n,B,k}}) \ln(\frac{p^1_{D_{m,n,k}} h^1_{n,k}}{\sigma^2 + p^C_{max} h^1_{m,n,k}})$.

Constraint (6.14a) shows the minimum SINR requirements of cellular and active D2D links and constraint (6.14c) shows the D2D transmission power should be positive and less than the maximum power (i.e. p^D_{max}).

From constraints (6.14a)-(6.14c), the continuous closed and bounded feasible set of $p^1_{D_{m,n,k}}$ is obtained as $[pd^1_{low,m,n,k}, pd^1_{up,m,n,k}]$, where the lower and upper bounds $pd^1_{low,m,n,k}$ and $pd^1_{up,m,n,k}$ can be calculated as:

$$\begin{aligned} pd^1_{low,m,n,k} &= \max\{0, \frac{\gamma^D_{min}(\sigma^2 + p^C_{max} h^1_{m,n,k})}{h^1_{n,k}}\}, \\ pd^1_{up,m,n,k} &= \min\{p^D_{max}, \frac{(p^C_{max} h^1_{m,B,k} - \gamma^C_{min}\sigma^2)}{h^1_{n,B,k}\gamma^C_{min}}\}, \end{aligned} \tag{6.15}$$

respectively. Note that the set $\Omega 1^1_{m,n,k}$ is valid only when $pd^1_{low,m,n,k} \leq pd^1_{up,m,n,k}$; otherwise, $\Omega 1^1_{m,n,k}$ is empty (i.e. $\Omega 1^1_{m,n,k} = \phi$).

When $\Omega 1^1_{m,n,k}$ is valid, the maximum value of $f(p^C_{max}, p^1_{D_{m,n,k}})$ can be obtained by the solving following equation

$$f'(p^C_{max}, p^1_{D_{m,n,k}}) = (\frac{\ln(\frac{h^1_{m,B,k} p^C_{max}}{h^1_{n,B,k} p^1_{D_{m,n,k}} + \sigma^2})}{p^1_{D_{m,n,k}}} - \frac{h^1_{n,B,k} \ln(\frac{h^1_{n,k} p^1_{D_{m,n,k}}}{h^1_{m,n,k}(p^C_{max})^2 + \sigma^2})}{h^1_{n,B,k} p^1_{D_{m,n,k}} + \sigma^2}) = 0, \tag{6.16}$$

and it always has two roots

$$pd1^1_{m,n,k} = \frac{h^1_{m,n,k} p^C_{max} + \sigma^2}{h^1_{n,k}}, \tag{6.17}$$

$$pd2^1_{m,n,k} = \frac{h^1_{m,B,k} p^C_{max} - \sigma^2}{h^1_{n,B,k}}. \tag{6.18}$$

Combining with (6.15), we can know $pd1^1_{m,n,k} \leq pd^1_{low,m,n,k}$ and $pd2^1_{m,n,k} \geq pd^1_{up,m,n,k}$. It means these two roots (i.e. $pd1^1_{m,n,k}$ and $pd2^1_{m,n,k}$) do not belong to the feasible set, and the $f(p^C_{max}, p^1_{D_{m,n,k}})$ is monotonous. Thus, the maximum value will be found within the bounds $pd^1_{low,m,n,k}$ or $pd^1_{up,m,n,k}$, and the $\Omega 1^1_{m,n,k}$ can be expressed as

$$\Omega 1^1_{m,n,k} = \{(p^C_{max}, pd^1_{low,m,n,k}), (p^C_{max}, pd^1_{up,m,n,k})\}. \tag{6.19}$$

Similarly, $\Omega 2^1_{m,n,k}$ can be expressed as

$$\Omega 1^2_{m,n,k} = \{(pc^1_{up,m,n,k}, p^D_{max}), (pc^1_{up,m,n,k}, p^D_{max})\}, \tag{6.20}$$

where the lower and upper bounds of $p^1_{C_{m,n,k}}$ when D2D link transmit at its maximum power are

$$\begin{aligned} pc^1_{up,m,n,k} &= \max\{0, \frac{\gamma^C_{min}(\sigma^2 + p^D_{max} h^1_{j,B,,n})}{h^1_{m,B,k}}\}, \\ pc^1_{up,m,n,k} &= \min\{p^C_{max}, \frac{(p^D_{max} h^1_{n,k} - \gamma^D_{min}\sigma^2)}{h^1_{m,n,k}\gamma^D_{min}}\}. \end{aligned} \tag{6.21}$$

Then, the $\Omega^1_{m,n,k}$ is obtained according to Proposition 1. After that, the optimal power allocation $(p^{1^*}_{C_{m,n,k}}, p^{1^*}_{D_{m,n,k}})$ can be obtained by comparing at most 4 feasible power pairs in set $\Omega^1_{m,n,k}$, which can maximize (6.13). Therefore, the optimal data rates of cellular link m and D2D link n on RB k can be obtained by

$$\begin{aligned} r^{1^*}_{C_{m,n,k}} &= \log_2(1 + \frac{p^{1^*}_{C_{m,n,k}} h^1_{m,B,k}}{\sigma^2 + p^{1^*}_{D_{m,n,k}} h^1_{n,B,k}}), \\ r^{1^*}_{D_{m,n,k}} &= \log_2(1 + \frac{p^{1^*}_{D_{m,n,k}} h^1_{n,k}}{\sigma^2 + p^{1^*}_{C_{m,n,k}} h^1_{m,n,k}}). \end{aligned} \tag{6.22}$$

In case that $\Omega 1^1_{m,n,k} = \phi$, e.g. the constraints in (6.14) can not be satisfied, we set

$$r^{1^*}_{C_{m,n,k}} = r^{1^*}_{D_{m,n,k}} = Q, \tag{6.23}$$

where Q is an extremely small value, which means RB k is not reused by cellular link m and D2D link n.

6.3.2 Channel Allocation for $t = 1$

After the power allocation considering all the reusing possibilities, the channel allocation is modelled as

$$(\mathbf{\Phi}_*^1, \boldsymbol{\chi}_*^1) = \arg \max_{(\mathbf{\Phi}_1, \boldsymbol{\chi}_1)} \{\sum_{k=1}^{K}\{(\sum_{m=1}^{M} \Phi_{m,k}^1[\ln r_{C_{m,k}}^1]) + \sum_{m=1}^{M}\sum_{n=1}^{N} \chi_{m,n,k}^1([\ln r_{C_{m,n,k}}^{1^*}] + [\ln r_{D_{m,n,k}}^{1^*}])\}\} \tag{6.24}$$

with the same constraints (6.12c)-(6.12f). Note that the $r_{C_{m,n,k}}^{1^*}$ and $r_{D_{m,n,k}}^{1^*}$ can be sequentially obtained from the above power allocations according to (6.22) and (6.23). Although problem in (6.24) can be optimally solved by standard ILP methods (such as interior-point method and Balas method in [79]), it will experience a high exponentially complexity $O(MNK)^{3.5}$. Thus, it is necessary to propose an effective solution.

We now introduce $(M - N)$ virtual D2D links in set $\mathcal{N}_{virt} = \{N + 1, N + 2, ..., K\}$ to construct a new $K \times K \times K$ 3-D channel allocation problem with equal dimensions, i.e. the total number of D2D links is K now and $M = K$. In this way, all the possible channel allocation can be modelled as a single 3-D allocation matrix. Specifically, the cellular link which exclusively uses a particular RB can be treated as sharing its channel with a virtual D2D link. Otherwise, cellular link reuses a RB with an actual D2D link.

In order to distinguish the above actual D2D link index n, we now use the index $l \in \{\mathcal{N}, \mathcal{N}_{virt}\}$ to uniformly indicate the actual and virtual D2D links in the rest of this subsection. Although the new allocation matrix has larger 3-D index than the problem in (6.24), it allows us to apply the proposed low complexity iterative method with a single channel allocation index $\Gamma_{m,l,k}^1$, where $\Gamma_{m,l,k}^1 = 1$, if cellular link m and D2D link l reuse the same RB k, otherwise, $\Gamma_{m,l,k}^1 = 0$.

Now the problem in (6.24) is restructured into

$$\mathbf{\Gamma}_1^* = \arg \max_{\mathbf{\Gamma}_1} \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{l=1}^{K} \Gamma_{m,l,k}^1 \Psi_{m,l,k}^1 \tag{6.25}$$

s.t.

$$\sum_{k=1}^{K}\sum_{l=1}^{K} \Gamma_{m,l,k}^1 = 1, \forall m \in \mathcal{M}, \tag{6.25a}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} \Gamma_{m,l,k}^1 = 1, \forall l \in \{\mathcal{N}, \mathcal{N}_{virt}\}, \tag{6.25b}$$

$$\sum_{m=1}^{M}\sum_{l=1}^{K} \Gamma_{m,l,k}^1 = 1, \forall k \in \mathcal{K}, \tag{6.25c}$$

$$\Gamma_{m,l,k}^1 \in \{0, 1\}, \forall m \in \mathcal{M}, \forall l \in \{\mathcal{N}, \mathcal{N}_{virt}\}, \forall k \in \mathcal{K}, \tag{6.25d}$$

Algorithm 3 : Joint power and channel allocation algorithm when $t = 1$.

Power Allocation for $t = 1$**:**
for all $m \in \mathcal{M}, n \in \mathcal{N},\ k \in \mathcal{K}$ **do**
  Get $pd^1_{low,m,n,k}$ and $pd^1_{up,m,n,k}$ from (6.15)
  if $pd^1_{low,m,n,k} \leq pd^1_{up,m,n,k}$ **then**
    Get $\Omega1^1_{m,n,k}$ according to (6.19)
  else
    $\Omega1^1_{m,n,k} = \phi$
  end if
  Get $pc^1_{up,m,n,k}$ and $pc^1_{up,m,n,k}$ from (6.21)
  if $pc^1_{up,m,n,k} \leq pc^1_{up,m,n,k}$ **then**
    Get $\Omega2^1_{m,n,k}$ according to (6.20)
  else
    $\Omega2^1_{m,n,k} = \phi$
  end if
  Get $\Omega^1_{m,n,k}$ according to **Proposition 1**
  if $\Omega^1_{m,n,k} = \phi$ **then**
    $r^{1^*}_{C_{m,n,k}} = r^{1^*}_{D_{m,n,k}} = Q$
  else
    $r^{1^*}_{C_{m,n,k}}$ and $r^{1^*}_{D_{m,n,k}}$ can be obtained by (6.22), where $(p^{1^*}_{C_{m,n,k}}, p^{1^*}_{D_{m,n,k}}) = \arg \max\limits_{(p^1_{C_{m,n,k}}, p^1_{D_{m,n,k}}) \in \Omega^1_{m,n,k}} (r^1_{C_{m,n,k}} \times r^1_{D_{m,n,k}})$
  end if
  $r^1_{C_{m,k}} = \log_2(1 + \frac{p^C_{max} h^1_{m,B,k}}{\sigma^2})$
end for
Channel Allocation for $t = 1$:
Based on above power allocation, $r_{m,1}$ and $r_{n,1}$, $\forall m \in \mathcal{M}, \forall n \in \mathcal{N}$ can be obtained by solving problem in (6.25) through our proposed *I2-DA* algorithm in Algorithm 5.
Get $R_{m(n),1} = r_{m(n),1}, m \in \mathcal{M}, n \in \mathcal{N}$.

where

$$\Psi^{1}_{m,l,k} = \begin{cases} [\ln r^{1^*}_{C_{m,n,k}}] + [\ln r^{1^*}_{D_{m,n,k}}], & \text{for } l \in \mathcal{N}, \\ [\ln r^{1}_{C_{m,k}}], & \text{for } l \in \mathcal{N}_{virt}. \end{cases} \tag{6.26}$$

Constraint (6.25a) ensures that each cellular link occupies one RB. Constraint (6.25b) shows each D2D link can reuse one RB with cellular link and constraint (6.25c) means that each RB can be reused by one cellular link and one D2D link. Constraint (6.25d) shows the channel allocation index should be binary. Those three constraints (6.25a)-(6.25c) correspond to the (6.12c)-(6.12e). Moreover, (6.26) makes sure that when $\Gamma^{1}_{m,l,k} = 1$, if $l \in \mathcal{N}$, cellular and the actual D2D links share the same RB, otherwise (i.e. $l \in \mathcal{N}_{virt}$), cellular link occupies the RB exclusively. In this way, problem in (6.25) can be efficiently solved by our proposed *I2-DA* algorithm, which will be presented in Algorithm 5 in section 6.5.

Algorithm 3 presents the operational procedure of the proposed joint power and channel allocation algorithm scheme for $t = 1$. As shown in *Step25* the average data rates of all cellular and actual D2D links are obtained according to (A.3) in Appendix A, and this will be used as the initialization of the subsequent scheduling periods.

6.4 Problem Formulation and Proposed Algorithm for $t \geq 2$

Applying *Maclaurin* theorem, the objective function in (6.9) can be converted to maximize the sum of the ratios of the current data rate to the average data rate for $t \geq 2$ (see Appendix C). Thus, in a given scheduling period t, the joint problem can be expressed as

$$\max_{\boldsymbol{P}^t, \boldsymbol{\Phi}^t, \boldsymbol{\chi}^t} \{\sum_{k=1}^{K} \{\sum_{m=1}^{M} \Phi^{t}_{m,k} \frac{r^{t}_{C_{m,k}}}{R_{m,t-1}} + \sum_{m=1}^{M} \sum_{n=1}^{N} \chi^{t}_{m,n,k} \frac{r^{t}_{C_{m,n,k}}}{R_{m,t-1}} + \sum_{n=1}^{N} \sum_{m=1}^{M} \chi^{t}_{m,n,k} \frac{r^{t}_{D_{m,n,k}}}{R_{n,t-1}}\}\} \tag{6.27}$$

s.t.

$$\gamma^t_{C_{m,n,k}} \geq \gamma^C_{min}, 0 \leq p^t_{C_{m,n,k}} \leq p^C_{max}, \forall m \in \mathcal{M}, \tag{6.27a}$$

$$\gamma^t_{D_{m,n,k}} \geq \gamma^D_{min}, 0 \leq p^t_{D_{m,n,k}} \leq p^D_{max}, \forall n \in \mathcal{N}, \tag{6.27b}$$

$$\sum_{k=1}^{K}(\sum_{n=1}^{N} \chi^t_{m,n,k} + \Phi^t_{m,k}) = 1, \forall m \in \mathcal{M}, \tag{6.27e}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} \chi^t_{m,n,k} \leq 1, \forall n \in \mathcal{N}, \tag{6.27f}$$

$$\sum_{m=1}^{M}(\sum_{n=1}^{N} \chi^t_{m,n,k} + \Phi^t_{m,k}) = 1, \forall k \in \mathcal{K}, \tag{6.27g}$$

$$\Phi^t_{m,k}, \chi^t_{m,n,k} \in \{0,1\}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}, \tag{6.27h}$$

where $\boldsymbol{P}^t$ and $\boldsymbol{\chi}^t$ are the $M \times N \times K$ power and channel allocation matrices in scheduling period t. $\boldsymbol{\Phi}^t$ is the $M \times K$ channel allocation matrix. The channel allocation index $\Phi^t_{m,k} = 1$, if cellular link m occupies RB k exclusively, otherwise, $\Phi^t_{m,k} = 0$ in scheduling period t. $\chi^t_{m,n,k} = 1$, if cellular link m and D2D link n reuse the same RB k, otherwise, $\chi^t_{m,n,k} = 0$ in scheduling period t. In (6.27), the first term is the sum of the ratios for cellular links without reusing; the second term is the sum of the ratios for cellular links with channel reusing, and the last term is the sum of the ratios for all D2D links. Constraints (6.27a)-(6.27h) in scheduling period t are equivalent to (6.12a)-(6.12f) in the first scheduling period.

Problem in (6.27) is to allocate the appropriate transmission power and RBs for links which have high current data rates and low previous average data rates. Similar with the case in $t = 1$, we divide it into two sub-problems: power and channel allocations, then solve them sequentially.

6.4.1 Power Allocation for $t \geq 2$

When D2D link n shares the same RB k with cellular link m, the power allocation in a given scheduling period t is expressed as:

$$\begin{aligned}
(p^{t^*}_{C_{m,n,k}}, p^{t^*}_{D_{m,n,k}}) &= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} \left(\frac{r^t_{C_{m,n,k}}}{R_{m,t-1}} + \frac{r^t_{D_{m,n,k}}}{R_{n,t-1}}\right) \\
&= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} \left\{\frac{\log_2(1+\gamma^t_{C_{m,n,k}})}{R_{m,t-1}} + \frac{\log_2(1+\gamma^t_{D_{m,n,k}})}{R_{n,t-1}}\right\} \\
&= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} \frac{1}{R_{m,t-1}} \{\log_2(1+\gamma^t_{C_{m,n,k}}) + \xi \log_2(1+\gamma^t_{D_{m,n,k}})\} \\
&= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} \log_2\{(1+\gamma^t_{D_{m,n,k}}) \times (1+\gamma^t_{D_{m,n,k}})^{\xi}\} \\
&= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} (1+\gamma^t_{C_{m,n,k}})(1+\gamma^t_{D_{m,n,k}})^{\xi} \\
&= \arg \max_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}})} \left\{\left(1+\frac{p^t_{C_{m,n,k}} h^t_{m,B,k}}{\sigma^2 + p^t_{D_{m,n,k}} h^t_{n,B,k}}\right) \times \left(1+\frac{p^t_{D_{m,n,k}} h^t_{n,k}}{\sigma^2 + p^t_{C_{m,n,k}} h^t_{m,n,k}}\right)^{\xi}\right\}
\end{aligned} \tag{6.28}$$

s.t.

$$\gamma^t_{C_{m,n,k}} \geq \gamma^C_{min}, \quad \gamma^t_{D_{m,n,k}} \geq \gamma^D_{min}, \tag{6.28a}$$

$$0 \leq p^t_{C_{m,n,k}} \leq p^C_{max}, \quad 0 \leq p^t_{D_{m,n,k}} \leq p^D_{max}, \tag{6.28b}$$

where $\xi = \frac{R_{m,t-1}}{R_{n,t-1}}$. Note that the values of $R_{m,t-1}$ and $R_{n,t-1}$ are available in scheduling period t.

We define $\Omega^t_{m,n,k}$ as the feasible set of problem in (6.28). $\Omega 1^t_{m,n,k}$ and $\Omega 2^t_{m,n,k}$ are the feasible sets when cellular and D2D links transmit their maximum powers, respectively. Then, we have the following lemma and proposition.

Lemma 2: At least one of $p^t_{C_{m,n,k}}$ and $p^t_{D_{m,n,k}}$ needs to reach its maximum value to maximize the sum ratios in (6.28).

Proof: See the Appendix B.2.

Proposition 6.2 *If the problem in (6.28) is feasible, its optimal power allocation solution belongs to the set $\Omega^t_{m,n,k} = \Omega 1^t_{m,n,k} \cup \Omega 2^t_{m,n,k}$; otherwise $\Omega^t_{m,n,k} = \phi$.*

As derived in Appendix D, we get set $\Omega 1^t_{m,n,k}$

$$\Omega 1^t_{m,n,k} = \begin{cases} \{(p^C_{max}, pd1^t_{m,n,k})\}, \\ \text{if } \Delta^t_{D,i,j,n} \geq 0, pd1^t_{m,n,k} \in [pd^t_{low,m,n,k}, pd^t_{up,m,n,k}], \\ \{(p^C_{max}, pd^t_{low,m,n,k}), (p^C_{max}, pd^t_{up,m,n,k})\}, \\ \text{if } \Delta^t_{D,i,j,n} \geq 0, pd1^t_{m,n,k} \notin [pd^t_{low,m,n,k}, pd^t_{up,m,n,k}], \\ \{(p^C_{max}, pd^t_{up,m,n,k})\}, \\ \text{if } \Delta^t_{D,i,j,n} < 0. \end{cases} \tag{6.29}$$

and the feasible set $\Omega 2^t_{m,n,k}$

$$\Omega 2^t_{m,n,k} = \begin{cases} \{(pc1^t_{m,n,k}, p^D_{max},)\}, \\ \quad \text{if } \Delta^t_{C,i,j,n} \geq 0, pc1^t_{m,n,k} \in [pc^t_{low,m,n,k}, pc^t_{up,m,n,k}], \\ \{(pc^t_{low,m,n,k}, p^D_{max}), (pc^t_{up,m,n,k}, p^D_{max})\}, \\ \quad \text{if } \Delta^t_{C,i,j,n} \geq 0, pc1^t_{m,n,k} \notin [pc^t_{low,m,n,k}, pc^t_{up,m,n,k}], \\ \{(pc^t_{up,m,n,k}, p^D_{max})\}, \\ \quad \text{if } \Delta^t_{C,i,j,n} < 0. \end{cases} \tag{6.30}$$

The subscript C in (6.30) represents cellular links to distinguish the D2D link D used in (6.29). The deviation of (6.29) and the details of (6.30) are explained in Appendix D .

And we get the feasible set of power allocation as $\Omega^t_{m,n,k} = \Omega 1^t_{m,n,k} \cup \Omega 2^t_{m,n,k}$. Thereby, the optimal power allocation $(p^{t^*}_{C_{m,n,k}}, p^{t^*}_{D_{m,n,k}})$ is performed by comparing at most 6 feasible power pairs in set $\Omega^t_{m,n,k}$, which can maximize (6.28). The optimal data rates of cellular link m and D2D link n on RB k can then be calculated as

$$\begin{aligned} r^{t^*}_{C_{m,n,k}} &= \log_2(1 + \frac{p^{t^*}_{C_{m,n,k}} h^t_{m,B,k}}{\sigma^2 + p^{t^*}_{D_{m,n,k}} h^t_{n,B,k}}), \\ r^{t^*}_{D_{m,n,k}} &= \log_2(1 + \frac{p^{t^*}_{D_{m,n,k}} h^t_{n,k}}{\sigma^2 + p^{t^*}_{C_{m,n,k}} h^t_{m,n,k}}). \end{aligned} \tag{6.31}$$

In case that $\Omega^t_{m,n,k} = \phi$, we set

$$r^{t^*}_{C_{m,n,k}} = r^{t^*}_{D_{m,n,k}} = Q, \tag{6.32}$$

indicating that D2D link n and cellular link m can not reuse the same RB k in scheduling period t.

6.4.2 Channel Allocation for $t \geq 2$

Once the power allocations have been completed, channel allocation can be modelled as

$$\begin{aligned} (\boldsymbol{\Phi}^t_*, \boldsymbol{\chi}^t_*) = \arg\max_{\boldsymbol{\chi}^t} \{ \sum_{k=1}^{K} \{ \sum_{m=1}^{M} \Phi^t_{m,k} \frac{r^t_{C_{m,k}}}{R_{m,t-1}} \\ + \sum_{m=1}^{M} \sum_{n=1}^{N} \chi^t_{m,n,k} \frac{r^{t^*}_{C_{m,n,k}}}{R_{m,t-1}} + \sum_{n=1}^{N} \sum_{m=1}^{M} \chi^t_{m,n,k} \frac{r^{t^*}_{D_{m,n,k}}}{R_{n,t-1}} \} \} \end{aligned} \tag{6.33}$$

with constraints (6.27e)-(6.27h). Again the values of $R_{m(n),t-1}$ are available from previous calculation, so we try to allocate the channel resource for links which can maximize the sum ratios while satisfying the constraints. As explained above, the previous average data rates of all users are considered in both power and channel allocation, and this leads to a higher fairness system than the existing methods.

Similarly, problem in (6.33) can also be restructured into

$$\mathbf{\Gamma}_t^* = \arg\max_{\mathbf{\Gamma^t}} \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{l=1}^{K} \Gamma_{m,l,k}^t \Psi_{m,l,k}^t \tag{6.34}$$

s.t.

$$\sum_{k=1}^{K}\sum_{l=1}^{N} \Gamma_{m,l,k}^t = 1, \forall m \in \mathcal{M}, \tag{6.34a}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} \Gamma_{m,l,k}^t = 1, \forall l \in \{\mathcal{N}, \mathcal{N}_{virt}\}, \tag{6.34b}$$

$$\sum_{m=1}^{M}\sum_{l=1}^{N} \Gamma_{m,l,k}^t = 1, \forall k \in \mathcal{K}, \tag{6.34c}$$

$$\Gamma_{m,l,k}^t \in \{0,1\}, \forall m \in \mathcal{M}, \forall l \in \{\mathcal{N}, \mathcal{N}_{virt}\}, \forall k \in \mathcal{K}, \tag{6.34d}$$

where $\Gamma_{m,l,k}^t = 1$, if cellular link m and virtual D2D link l reuse the same RB k, otherwise, $\Gamma_{m,l,k}^t = 0$. And

$$\Psi_{m,l,k}^t = \begin{cases} \{\frac{r^{t^*}_{C_{m,n,k}}}{R_{m,t-1}} + \frac{r^{t^*}_{D_{m,n,k}}}{R_{n,t-1}}\}, & \text{for } l \in \mathcal{N}, \\ \frac{r^t_{C_{m,k}}}{R_{m,t-1}}, & \text{for } l \in \mathcal{N}_{virt}. \end{cases} \tag{6.35}$$

Constraints (6.34a)-(6.34d) and (6.35) have the same meanings with (6.25a)-(6.25d) and (6.26), respectively. In this way, problem in (6.34) can be then solved by the proposed *I2-DA* algorithm effectively, which will be discussed in the following section.

Algorithm 4 presents the operational procedure of the proposed resource allocation scheme for scheduling period $t \geq 2$. We set $T = 20$, as commonly used for PF scheduling in practical systems [80]. Note that all the following results are presented and analysed in the scheduling period $t = 20$ if not otherwise specified.

In Algorithm 4, the average data rates of all links are initialized by the results obtained from Algorithm 3. The joint power and channel allocation for each subsequent scheduling period is then conducted. Specifically, in each subsequent scheduling period, we divide the problem in (6.27) into two sub-problems: power allocation and channel allocation, and solve them sequentially as discussed above. After that, the current and average data rates of all links in scheduling period t can be obtained as shown in *Step25-26*.

Algorithm 4 : Joint power and channel allocation algorithm when $t \geq 2$.

Initialization:
$R_{m(n),1} = r_{m(n),1}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}$ according to Algorithm 3.
for all t=2:T **do**
  Power Allocation for $t \geq 2$**:**
  for all $m \in \mathcal{M}, n \in \mathcal{N}$, $k \in \mathcal{K}$ **do**
    if $pd^t_{low,m,n,k} \leq pd^t_{up,m,n,k}$ **then**
      $\Omega 1^t_{m,n,k}$ can be obtained according to (6.29)
    else
      $\Omega 1^t_{m,n,k} = \phi$
    end if
    if $pc^t_{low,i,j,n} \leq pc^t_{up,m,n,k}$ **then**
      $\Omega 2^t_{m,n,k}$ can be obtained according to (6.30)
    else
      $\Omega 2^t_{m,n,k} = \phi$
    end if
    Get $\Omega^t_{m,n,k}$ according to Proposition 6.2
    if $\Omega^t_{m,n,k} = \phi$ **then**
      $r^{t^*}_{C_{m,n,k}} = r^{t^*}_{D_{m,n,k}} = Q$
    else
      $r^{t^*}_{C_{m,n,k}}$ and $r^{t^*}_{D_{m,n,k}}$ can be obtained by (6.31), where $(p^{C^*}_{m,n,k}, p^{t^*}_{D_{m,n,k}}) = \arg \max\limits_{(p^t_{C_{m,n,k}}, p^t_{D_{m,n,k}}) \in \Omega^t_{m,n,k}} \{(1 + \gamma^t_{C_{m,n,k}})(1 + \gamma^t_{D_{m,n,k}})^{\xi}\}$
    end if
  end for
  $r^t_{C_{m,k}} = \log_2(1 + \frac{p^C_{max} h^t_{m,B,k}}{\sigma^2})$
  Channel Allocation for $t \geq 2$**:**
  Based on above power allocation, $r_{m,t}$ and $r_{n,t}$, $\forall m \in \mathcal{M}, \forall n \in \mathcal{N}$ can be obtained by solving problem in (6.34) through our proposed *I2-DA* algorithm in Algorithm 5.
  Get $R_{m(n),t}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}$ according to (A.3) in Appendix A.
end for

6.5 I2-DA Algorithm

The 3-D assignment problem can be solved by our proposed iterative three-stage 2-D assignment algorithm. In Stage1, we group the cellular and D2D links[1] which share the same RB as a couple. Then, we reallocate RBs to all the couples to maximize the system performance. Based on these results, the D2D link and its RB are treated as a new couple in Stage2. We then rematch the cellular links with all those new couples. In Stage3, the cellular link and its RB are coupled, then remapping is done between the D2D links with those couples. These three-stage allocation is repeated iteratively for Y iterations. According to our simulation, the convergence is achieved after 3 iterations.

In section 6.3 and 6.4, we have modelled the channel allocation problem in (6.25) for $t = 1$ and (6.34) for $t \geq 2$ as the same 3-D assignment problem, so the scheduling period indices are omitted in this section for brevity. More details of our proposed algorithm is given below.

Initialization: Initialize the allocation matrix as $\mathbf{\Gamma}_{K\times K\times K} = \mathbf{\Gamma}_0^*$. Note that this initial allocation matrix will affect the performance of *I2-DA* algorithm. In this work, we initialise the allocation matrix using the heuristic channel allocation algorithm in [81].

Stage1:

Let index $\tau = m$ denote the cellular and D2D links couple $(m, l) \in \Delta_1$, where $\Delta_1 = \{(m, l)|[\mathbf{\Gamma}_0^*]_{m,l,k} = 1, \forall m, l, k\}$. We adopt a 2-D matching matrix $U_{K\times K} = [q_{\tau,k}]$, where $q_{\tau,k} = 1$ if the RB k is assigned to the reusing couple τ, otherwise, $q_{\tau,k} = 0$. Then, the design problem becomes

$$U^* = \arg\max_{U} \sum_{\tau=1}^{K}\sum_{k=1}^{K} q_{\tau,k}\Psi 1_{\tau,k} \tag{6.36}$$

s.t.

$$\sum_{k}^{K} q_{\tau,k} = 1, \forall \tau; \quad \sum_{\tau}^{K} q_{\tau,k} = 1, \forall k, \tag{6.36a}$$

where $\Psi 1_{\tau,k} = \{\Psi_{m,n,k}|(m, l) \in \Delta_1\}$. Constraint (6.36$a$) shows each cellular link is allocated one RB. This is a 2-D matching problem, which can be solved by the *Kuhn-Munkres* method directly. Now $\mathbf{\Gamma}_1^* = (\Delta_1, U^*)$ is a solution to the 3-D channel allocation problem.

[1]In this section, the D2D links include both the actual and virtual D2D links.

Stage2:

Let $\theta = l$ denote the D2D link and RB couple $(l, k) \in \Delta_2$, where $\Delta_2 = \{(l, k) | [\mathbf{\Gamma}_1^*]_{m,l,k} = 1, \forall m, l, k\}$. We adopt a 2-D matching matrix $Z_{K \times K} = [z_{\theta,m}]$, where $z_{\theta,m} = 1$ if the cellular link m is allocated to the couple θ, otherwise, $z_{\theta,m} = 0$. The design problem is

$$Z^* = \arg\max_{Z} \sum_{\theta=1}^{K} \sum_{m=1}^{M} z_{\theta,m} \Psi 2_{\theta,m} \tag{6.37}$$

s.t.

$$\sum_{\theta}^{K} z_{\theta,m} = 1, \forall m; \quad \sum_{i}^{K} z_{\theta,m} = 1, \forall \theta, \tag{6.37a}$$

where $\Psi 2_{\theta,m} = \{\Psi_{m,l,k} | (l, k) \in \Delta_2\}$. Constraint (6.37$a$) shows that each D2D link reuses one RB with cellular link. Similarly, problem in (6.37) can be solved by the *Kuhn-Munkres* method which returns the solution $\mathbf{\Gamma}_2^* = (\Delta_2, Z^*)$ to the 3-D channel allocation problem.

Stage3:

Let $\upsilon = m$ denote the cellular link and RB couple $(m, k) \in \Delta_3$, where $\Delta_3 = \{(m, k) | [\mathbf{\Gamma}_2^*]_{m,l,k} = 1, \forall m, l, k\}$. We adopt the 2-D matching matrix $S_{K \times K} = [s_{\upsilon,l}]$, where $s_{\upsilon,l} = 1$ if D2D link l is allocated to the couple υ, otherwise, $s_{\upsilon,l} = 0$. The design problem is

$$S^* = \arg\max_{S} \sum_{\upsilon=1}^{K} \sum_{l=1}^{K} s_{\upsilon,l} \Psi 3_{\upsilon,l} \tag{6.38}$$

s.t.

$$\sum_{\upsilon}^{K} s_{\upsilon,l} = 1, \forall l; \quad \sum_{n}^{K} s_{\upsilon,l} = 1, \forall \upsilon, \tag{6.38a}$$

where $\Psi 3_{\upsilon,l} = \{\Psi_{m,l,k} | (m, k) \in \Delta_3\}$. Similarly, as discussed above, constraint (6.38a) indicates each D2D link reuses a RB with cellular link. By solving problem in (6.38), we can obtain $\mathbf{\Gamma}_3^* = (\Delta_3, S^*)$, which is a solution to the 3-D channel allocation problem.

This three-stage procedure will be repeated Y times with the updated $\mathbf{\Gamma}_0^* = \mathbf{\Gamma}_3^*$. After all the iterations, the algorithm can converge to at least a local optimum.

The proof of its convergence can refer to [49].

Algorithm 5 shows the details of the proposed *I2-DA* algorithm. In Algorithm 5, the final current data rates of cellular and actual D2D links are obtained from *Step17-24*. Specifically, the data rates of both active D2D and cellular links can be obtained as shown in *Step21*, when the actual D2D link reuses the same RB with cellular link. Then, the rest of cellular link uses RB exclusively, and the data rate of inactive D2D link is set Q. Meanwhile, in this way, these inactive D2D pairs will have higher priorities to obtain the RBs in the subsequent scheduling periods.

Algorithm 5 : I2-DA Algorithm.

1: **Input**: The $\Psi_{m,n,k}$.
2: **Output**: r_m and r_n, $\forall m \in \mathcal{M}, \forall n \in \mathcal{N}$.
3: **Initialization**: Suppose $\mathbf{\Gamma}_0^*$
4: **for all** y=1:Y **do**
5:     **Stage 1**:
6:     **Get** index τ indicates the pair $(m,l) \in \Delta_1$, $\Delta_1 = \{(m,l)|[\mathbf{\Gamma}_0^*]_{m,l,k} = 1, \forall m,l,k\}$ and $\Psi1_{\tau,k} = \{\Psi_{m,l,k}|(m,l) \in \Delta_1\}$
7:     **Obtain** Q^* by solving problem in (6.36), $\mathbf{\Gamma}_1^* = (\Delta_1, Q^*)$.
8:     **Stage 2**:
9:     **Get** index θ indicates the pair $(n,k) \in \Delta_2$, where $\Delta_2 = \{(n,k)|[\mathbf{\Gamma}_1^*]_{m,l,k} = 1, \forall m,l,k\}$ and $\Psi_{\theta,i}^2 = \{\Psi_{m,l,k}|(l,k) \in \Delta_2\}$
10:     **Obtain** Z^* by solving problem in (6.37), $\mathbf{\Gamma}_2^* = (\Delta_2, Z^*)$.
11:     **Stage 3**:
12:     **Get** index υ indicates the pair $(m,k) \in \Delta_3$, where $\Delta_3 = \{(m,k)|[\mathbf{\Gamma}_2^*]_{m,l,k} = 1, \forall m,l,k\}$ and $\Psi_{\upsilon,l}^3 = \{\Psi_{m,l,k}|(m,k) \in \Delta_3\}$
13:     **Obtain** S^* by solving problem in (6.38), $\mathbf{\Gamma}_3^* = (\Delta_3, S^*)$
14:     Then, go back to Step 5 with updated $\mathbf{\Gamma}_0^* = \mathbf{\Gamma}_3^*$
15: **end for**
16: **Get** $\mathbf{\Gamma}^* = \mathbf{\Gamma}_3^*$.
17: **for all** $[\mathbf{\Gamma}^*]_{m,l,k} = 1, m \in \mathcal{M}, l \in \{\mathcal{N}, \mathcal{N}_{virt}\}, n \in \mathcal{N}$ **do**
18:     **if** $l \in \mathcal{N}$ and $r_{C_{m,l,k}}^* = Q$ **then**
19:         $r_m = r_{C_{m,k}}, r_n = Q$
20:     **else if** $r_{C_{m,l,k}}^* > Q$ **then**
21:         $r_m = r_{C_{m,l,k}}^*, r_n = r_l = r_{D_{m,l,k}}^*$
22:     **else**
23:         $r_m = r_{C_{m,k}}$
24:     **end if**
25: **end for**

Table 6.3: Simulation Parameters

Maximum distance between D2D pairs d_{max} (m)	(20,...,500)
Number of channels K	20
Number of cellular links M	20
Number of D2D links N ($N \leq M$)	15 (if fixed)
Maximum cellular transmission power p^C_{max}(W)	0.5
Maximum D2D transmission power p^D_{max} (W)	0.5
SINR requirements of cellular links γ^C_{min} (dB)	5 (if fixed)
SINR requirements of D2D links γ^D_{min} (dB)	15
Noise power σ^2 (dBm)	-110
Pathloss exponent for all communications α	3

6.6 Simulation Results and Complexity Analysis

6.6.1 Simulation Setup

Monte Carlo simulation is used to evaluate the performance of our proposed algorithms. We consider the test case 9 [82] defined by METIS, which describes an open air festival environmental model. In our system, the entire region is a cell with radius of $500m$. The BS is located in the centre, and the cellular users and D2D transmitters are distributed uniformly in the cell. The D2D receivers are distributed uniformly in a disk centred by the corresponding D2D transmitters with a radius of d_{max}. The cellular users and D2D pairs move in every scheduling period following the random-waypoint mobility model, where users choose their speeds and directions in the range [0 10](m/s) and [0 2π], respectively. Our simulation parameters as summarized in TABLE 6.3, are chosen according to [75] for the purpose of comparison.

We use Jain's fairness index to measure the long-term fairness between different users in terms of their average data rate at scheduling period t, which is expressed as:

$$J_t = \frac{|\sum_{m=1}^{M} R_{i,t} + \sum_{n=1}^{N} R_{j,t}|^2}{(K+L)(\sum_{m=1}^{M} R_{i,t}^2 + \sum_{n=1}^{N} R_{j,t}^2)}. \tag{6.39}$$

J_t takes the values between 0 and 1. Value 1 means completely fair at scheduling period t (i.e. all average data rates are equal), and value 0 means absolutely unfair at time t (i.e. the divergence of all average data rates is very large). The decrease in divergence of all average data rates leads to the increase of J_t.

Power consumption is the total transmit power of all active links in scheduling time $t = 20$, which is equal to:

$$\{\sum_{k=1}^{K}\{\sum_{m=1}^{M}\mathbf{\Phi}_{*}^{t}P_{max}^{C} + \sum_{m=1}^{M}\sum_{n=1}^{N}\boldsymbol{\chi}_{*}^{t}(p_{C_{m,n,k}}^{t^*} + p_{D_{m,n,k}}^{t^*})\}\}. \tag{6.40}$$

6.6.2 Results and Analysis

We label the proposed joint power allocation and the *I2-DA* algorithm scheme as the *Iterative-scheme*, and compare it with the following three schemes.

Existing-scheme: The system fairness is researched in [75], where the RBs of cellular links are pre-allocated. However, the fairness is only considered in channel allocation in $t \geq 2$. Channel allocation in $t = 1$ and power allocation in all scheduling periods are converted to maximize the system throughput without considering system fairness, and results in unfair system.

Improved-scheme [58]: We assume that the RBs of cellular links are pre-allocated as did in [75]. The fairness is taken into account for both power and channel allocation in all scheduling periods. In this way, the *Improved-scheme* produces better performance than the *Existing-scheme* in any scheduling periods. The channel allocation in both the *Existing-scheme* and the *Improved-scheme* are solved by the *Kuhn-Munkres* method.

Optimal-scheme: The power allocation is realized by our proposed optimal power allocation in all scheduling periods. And the standard ILP method is applied to optimally solve the joint cellular and D2D links channel allocation problem.

Note that both the *Existing-scheme* and the *Improved-scheme* assume that the RBs for cellular links have been pre-allocated. The *Optimal-scheme* jointly allocate the RBs for both cellular and D2D links.

Jain's Fairness Index

Fig. 6.3 shows J_t of various schemes for different scheduling periods. It is shown that in any schemes, when scheduling period t is small ($t \leq 10$) J_t increases with the scheduling period t increases. That is because during the first few scheduling periods the links with low average data rates have more chance to improve their current data rates, so the divergence of all links' average data rates is reduced. This increase slows down and converges when $t \geq 10$.

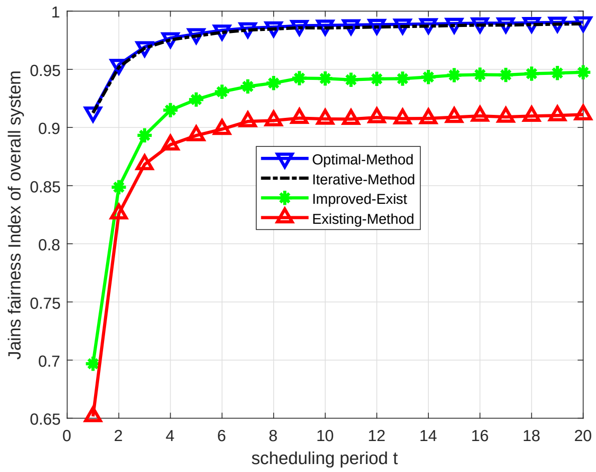
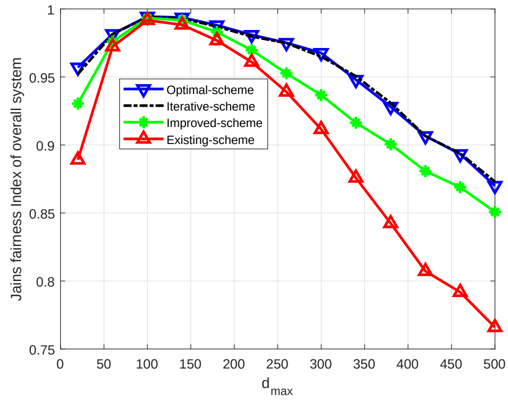


Figure 6.3: Jain's fairness index J_t of overall system versus different scheduling period t with $d_{max} = 20m, L = 10$.

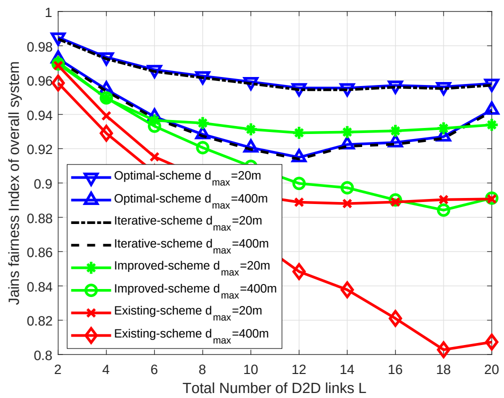
Fig. 6.4 shows the J_t of overall system with various schemes for different parameters. Fig. 6.4 (a) shows the comparison of J_t between various schemes for different d_{max}. We observe that J_t first increases and then decreases with the increase of d_{max} for all schemes. This is because when d_{max} is small, the current data rates of D2D links are larger than that of cellular links due to the short transmission distance. This leads to a large data rate divergence between cellular and D2D links. However, with the increase of d_{max}, the current data rates of D2D links decrease. When $d_{max} = 100m$, the current data rates of D2D and cellular links are close to each other. Therefore, J_t of those various schemes reach the peak values at this point. With the continuous increase of d_{max}, the current data rates of active D2D links become smaller than that of cellular links. In addition, the number of active D2D links also decreases with the increase of d_{max} (can be proved in Fig. 6.5 (a)). Thus, the difference between average data rates of cellular and D2D links increases again, leading to the decrease of J_t.

Fig. 6.4 (b) shows J_t decreases slightly with the increase of L when $d_{max} = 20m$. That is because more D2D links are active with the increase of L, and the active D2D links have higher current data rate than that of cellular links due to the short transmission distance. However, J_t decreases dramatically when $d_{max} = 400m$. That is because more D2D links are inactive when d_{max} is large. Thus, the ratio of active D2D links and inactive D2D links becomes small with the increase of L, leading to high divergence of all links.

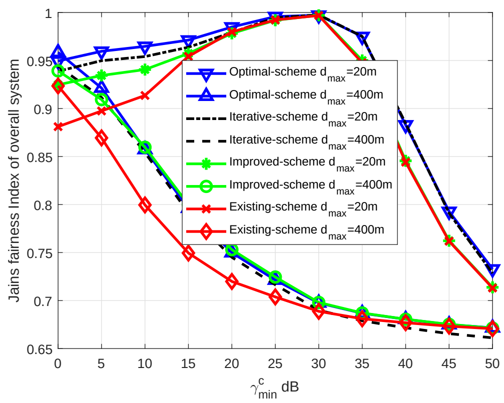
Fig. 6.4 (c) shows the comparison of J_t between various schemes for different γ^C_{min}. With the increase of γ^C_{min}, J_t first increases and then decreases when $d_{max} = 20m$, and decreases dramatically when $d_{max} = 400m$. When $d_{max} = 20m$, the



(a)



(b)



(c)

Figure 6.4: Jain's fairness index J_t of overall system with various schemes: (a) versus different d_{max} when $L = 15$; (b) versus different L with $d_{max} = 20m$ and $d_{max} = 400m$; (c) versus different γ_{min}^{C} with $d_{max} = 20m$ and $d_{max} = 400m$, when $L = 15$.

current data rates of cellular links get close to that of D2D links with the increase of γ_{min}^{C}. Thus, with large number of active D2D links, the divergence of current data rates between cellular and D2D links becomes smaller. After γ_{min}^{C} becomes large enough, the number of active D2D links decreases dramatically as shown in Fig.6.5 (c), which directly results in lower J_t. However, when $d_{max} = 400m$, large γ_{min}^{C} leads to the decrease of active D2D links. This results in the high divergence of current data rates between cellular and D2D links.

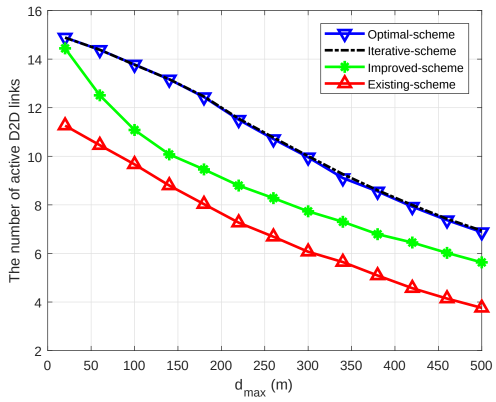
All the above results show clearly that our proposed *Iterative-scheme* produces higher system fairness than that of the *Improved-scheme* and the *Existing-Method* in any scenarios, and approaches the performance of the *Optimal-scheme* closely.

System Sum Rate

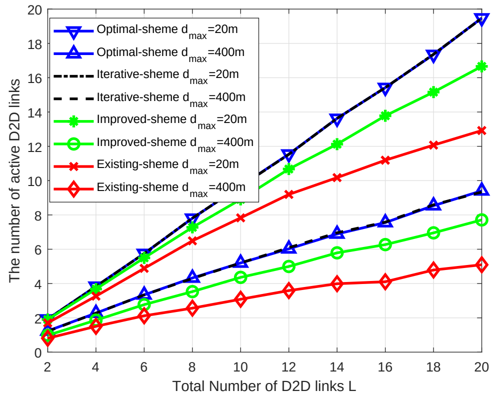
Fig. 6.6 shows the system sum rate in various schemes for different parameters. As shown in Fig. 6.6 (a), with the increase of d_{max}, the system sum rate decreases. This is because the contribution of D2D links' current data rates become smaller with the increase of d_{max} due to the poor channel gain. Also, the number of active D2D links decreases with the increase of d_{max} as shown in Fig. 6.5 (a).

Fig. 6.6 (b) shows that when $d_{max} = 20m$, the system sum data rate increases dramatically for various schemes with the increase of L. Observing this result together with Fig.6.5 (b), we find that when $d_{max} = 20m$, the number of active D2D links increases notably with the increase of L, leading to the dramatical increase in system sum data rate. However, when $d_{max} = 400m$ it decreases slightly for the *Iterative-scheme* and keeps stable for both the *Improved-scheme* and *Existing-Method*. This is because the ratio of active D2D links to inactive D2D links decease. Moreover, the proposed *Iterative-scheme* sacrifices the system sum data rate to maintain the high system fairness,

Fig. 6.6 (c) shows that with the increase of γ_{min}^{C}, the system sum data rate decreases when $d_{max} = 20m$. This is because fewer cellular links can meet the minimum SINR requirement with the increase of γ_{min}^{C}. This results in the decrease of the number of active D2D links as shown in Fig. 6.5 (c). However, the system sum rate first increases slightly and then stays stable with the increase of γ_{min}^{C} when $d_{max} = 400m$. Since we have assumed that cellular links without reusing always meets the QoS requirements, so the the number of cellular links which exclusively use the RBs increase with the increase of the γ_{min}^{C}, leading to the system sum rate increase. In addition, with the continuous increase of γ_{min}^{C}, none of the D2D links is activated. Therefore, the system becomes a pure cellular networks with stable sum data rate.



(a)



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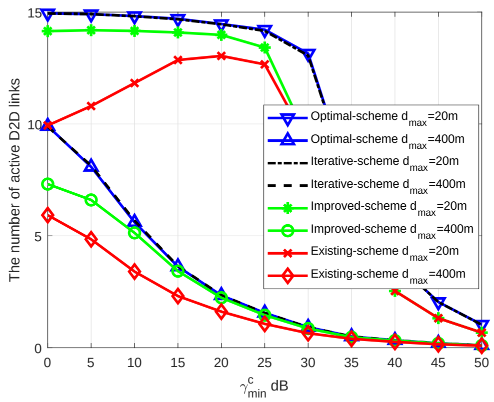
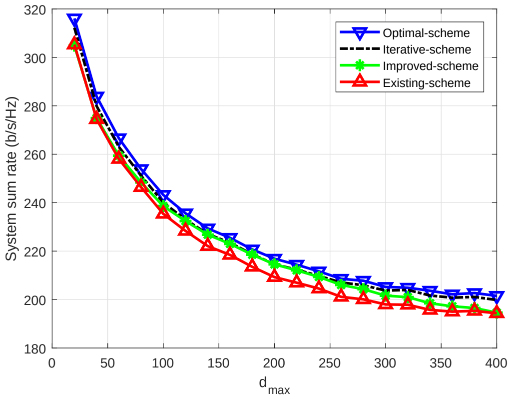
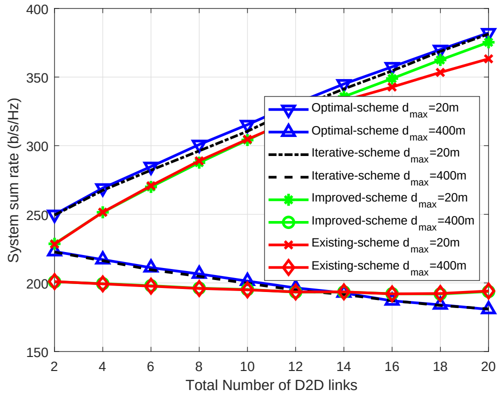


(c)

Figure 6.5: The number of active D2D links with various schemes: (a) versus different d_{max} when $L = 15$; (b) versus different L with $d_{max} = 20m$ and $d_{max} = 400m$; (c) versus different γ^{C}_{min} when $L = 15$ with $d_{max} = 20m$ and $d_{max} = 400m$.



(a)



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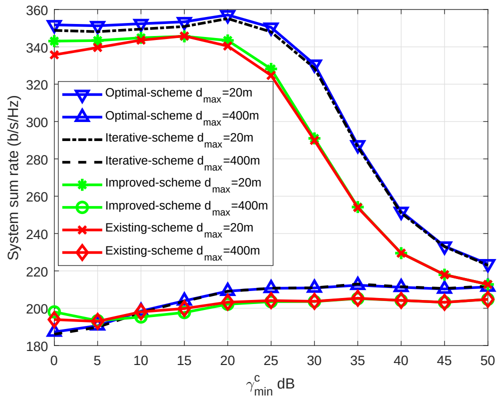


(c)

Figure 6.6: The system sum rate with various schemes: (a) versus different d_{max}; (b) versus different L with $d_{max} = 20m$ and $d_{max} = 400m$; (c) versus different γ^C_{min} with $d_{max} = 20m, d_{max} = 400m$ when $L = 15$.

In summary, the system sum data rate of the *Iterative-scheme* is significantly better than that of both *Improved-scheme* and the *Existing-Method*, and approaches closely to the performance of the *Optimal-scheme*.

Power Consumption

Figure 6.7 shows the power consumption of overall system in various schemes with different parameters. In general, the power consumption of all various schemes decrease with the increase of d_{max} as shown in Figure 6.7 (a). This is because fewer D2D links are activated due to the increase of d_{max}. However, the performance experiences a slight increment during $60m \leq d_{max} \leq 150m$. This is because D2D links tend to consume more power to maintain the QoS requirements with the increase of d_{max}.

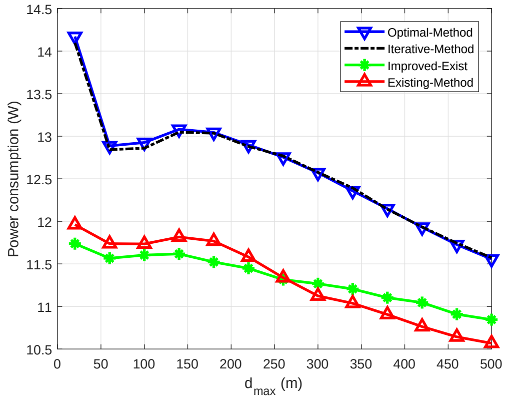
Figure 6.7 (b) shows that the system power consumption increases with the increase of L. The power consumption of *Iterative-scheme* is higher than that of *Improved-scheme* and *Existing-Method* due to the larger number of active D2D links in *Iterative-scheme*. In addition, the *Improved-scheme* has higher power consumption than that of the *Existing-scheme* when d_{max} is large ($d_{max} = 400m$). However, when $d_{max} = 20m$, the *Improved-scheme* has lower power consumption than that of the *Existing-scheme*. This is because instead of maximizing the sum data rate, the *Improved-scheme* aims to maintain the system fairness, which leads to lower power consumption.

From Figure 6.7 (c) we can see that the power consumption decreases with the increase of γ_{min}^C. The power consumption first decreases with the increase of γ_{min}^C, and then converges at $10W$ as shown in Figure 6.7 (c). The power consumption decreases dramatically due to the decrease of active D2D links, which can be confirmed by Fig 6.5 (c). With the continuous increase of γ_{min}^C, the number of active D2D links becomes zero. Thus, the system becomes a pure cellular users network and the total power consumption is equal to $p_{max}^C K(10W)$.

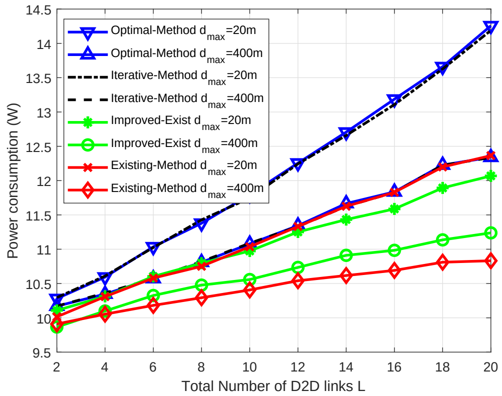
In summary, the proposed *Iterative-scheme* has higher power consumption than the *Improved-scheme* and the *Existing-scheme* due to the large number of active D2D links. In addition, the *Improved-scheme* can bring lower power consumption than the *Existing-scheme* when d_{max} is small.

6.6.3 Complexity Analysis

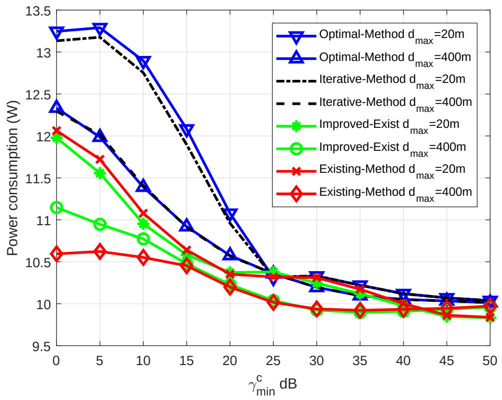
The computational complexity is analysed in terms of number of operations required in the power allocation and channel allocation, but the complexity of the power allocation is to select among a few solutions, so it is indeed negligible in



(a)



(b)



(c)

Figure 6.7: System total power consumption with various schemes (a) versus different d_{max} with $L = 15$; (b) versus various schemes for different L under $d_{max} = 20m$ and $d_{max} = 400m$. (c) versus various schemes for different γ_{min}^{C} under $d_{max} = 20m$ and $d_{max} = 400m$.

this work. Since the computational complexity of the *Kuhn-Munkres* method is $\mathcal{O}(K^3)$ for a 2-D assignment problem, so the complexity of the proposed three-stage *I2-DA* algorithm in each iteration is $\mathcal{O}(3 \times K^3)$. Therefore, the overall complexity is $\mathcal{O}(Y \times 3 \times K^3) = \mathcal{O}(K^3)$. The standard ILP method used in the *Optimal-scheme* requires $O(KLN)^{3.5}$, which is significantly higher than the *I2-DA* algorithm ($\mathcal{O}(KLN)^{3.5} \gg \mathcal{O}(K^3)$), even with a small L value.

6.7 Summary

In this chapter, we first formulated the joint power and channel allocation for D2D underlay communications aiming to maximize the system fairness while guaranteeing the QoS of all cellular and active D2D links. We then divided this optimization problem into two sub-problems: power allocation and channel allocation. The power allocation problem is solved by the proposed optimal power allocation. Based on the optimal power allocation solutions for all possible pairs of cellular and D2D links on any channels, we restructured a 3-D channel allocation with equal dimensions and proposed the *I2-DA* algorithm to efficiently solve the channel allocation with greatly reduced computational complexity. The performance results reveal that the proposed channel allocation algorithm outperforms the existing methods and produces the close-to-optimal performance with low computational complexity. Moreover, numerical results show that the proposed scheme can not only dramatically enhance the system fairness but also improve the system throughput comparing with the existing schemes.

Chapter 7

Conclusions and Future Works

7.1 Conclusions

The works in this thesis have investigated the resource allocation problem for relay-assisted D2D underlay communications. The research was motivated by the challenges that have not been addressed such as joint mode selection, relay selection and resource allocation for relay-assisted D2D comminations and the high computational complexity issue.

The resource allocation (i.e. power and channel allocation) problem aiming to maximize system throughput is formulated in chapter 3, and then two heuristic algorithms are proposed to efficiently solve it. Simulation results show that the heuristic algorithms bring acceptable system performance with low complexity. In chapter 4, a novel system configuration where the relay and mode selection are jointly considered with the resource allocation is examined. To solve this joint problem, we decompose it into two sub-problems, and propose the corresponding algorithms. Specifically, a low complexity power allocation algorithm is proposed for power allocation sub-problem. Based on the power allocation results, the joint mode selection and the channel allocation sub-problem has been linearised by adding two auxiliary variables, and then solved by the standard linear programming method. Simulation results show that the proposed scheme produces higher system throughput than the existing schemes.

Both chapter 3 and 4 assume that the channel allocation of cellular links is pre-allocated, and focus on allocating the channel for D2D links. Thus, to further enhancing the D2D communications performance, a more general system configuration where joint channel allocation for both cellular link and D2D link has been investigated in chapter 5. The exhaustive search is computationally prohibitive in practical application, and a colouring based graph theory algorithm was proposed to effectively solve the joint optimization problem. In colouring based graph theory algorithm, all the communications links are indicated as the vertices, and each channel resource is presented as distinct colour. In the graph, the resource allocation procedure is operated as applying different colours to iteratively dye the vertices. Simulation results show that the proposed graph-based algorithm brings close-to-optimal system performance with low complexity.

The systems in the above three chapters (i.e. chapter 3, 4 and 5) are static, where all problems are considered in one communication slot. Chapter 6 considers the mobility feature of UEs during a practical long-term communications for D2D-based V2V systems. In this system, all users are moving in each communication slot, and the CSI of system is changing. However, links with poor channel gain will have lower or no chance to access the channel resource. This will lead to an unfair system and one or a few vehicles become invisible to their surrounding vehicles. Therefore, it is critical that all communication links should have the same right to access the system resource during long-term communications. The fairness aspect has been considered in chapter 6, while allocating the resource for both cellular and D2D links. Specifically, in each communication slot, the joint power and channel allocation problem was decomposed into two sub-problems, and then solved subsequently. Moreover, similar with chapter 5, the channel allocation for both cellular and D2D links are jointly considered. An iterative algorithm is proposed to efficiently solve the joint channel allocation problem. Simulation results show that the proposed algorithm has brought not only the close-to-optimal system performance but also low system computational complexity. Moreover, numerical results show that the proposed scheme can enhance the system fairness without degrading the system throughput comparing with the existing schemes.

7.2 Future Works

The D2D underlay communication systems analysed in this thesis were based on some simplified assumptions such as the centralized resource allocation scheme with perfect CSIs at each transmitter; the orthogonal uplink resource allocation; a single cell system; two-hop relay communications and so on. The following future research directions related to resource allocation problem in underlay D2D communications remain unexplored challenges.

7.2.1 Decentralized Control

The advantage of centralized system is that the network can easily coordinate and allocate power and channel resource to the users. In this way the harmful interference between D2D and cellular links can be effectively avoided or degraded. Moreover, the BS can easily prioritize the individual transmissions to meet the QoS requirements of the users. However, with additional management tasks in hand by the BS for D2D control, significant overhead is added to its processing. In practice, it is extremely hard to track the real-time small-scale channel fading coefficients. Although some methods have been proposed to reduce the signalling overhead in chapter 6, it is still very hard to be implemented in real systems [83] [84] [85]. Thus, a trade-off of reducing the signalling overhead and maintaining the QoS of both cellular and D2D links in decentralized resource allocation should be investigated.

7.2.2 Full-duplex

Most of the existing works in D2D underlay communications assume that the UEs only occupy the uplink channel resource, which is unrealistic. Normally, the full-duplex radio access technique can further improve the system performance in D2D underlay communications [56] [86]. With the full-duplex communication technology, a wireless node is allowed to simultaneously transmit and receive data on the same frequency band, which leads to an improved system capacity. However, additional consideration of the downlink will also result in the high computational complexity. Therefore, a resource allocation scheme with good trade-off between full-duplex network performance and computational complexity should be devised.

7.2.3 Multiple-Hops for relay-assisted D2D communications

The two-hop relay-assisted D2D communications is researched in most of the existing works. In order to improve the network service quality, the D2D pair with poor channel condition will fall back to other UEs to relay data traffic from the DUT to DUR. Multiple-hope has the potential to dramatically enhance the communications quality and performance [33] [34]. However, since multiple nodes are involved, power allocation problem becomes more complicated. Thus, how to effectively allocate the transmission power for each relay node and the DUT, while guaranteeing the QoS of links should be investigated. In addition, from the viewpoint of relay nodes, they need to consume their own power to help the D2D pair communicating, which is not fair without any payback. Thus, how to reasonably select the relay node for each D2D link perhaps using game theory is also interesting to explore.

Appendix A

The Derivation of (6.9)

A.1 The Derivation of (6.9)

According to (6.8) a PF scheduling F at time slot t should satisfy

$$\sum_{i\in\mathcal{K}}\log R^{(F)}_{i,t}+\sum_{j\in\mathcal{L}}\log R^{(F)}_{j,t}\geq\sum_{i\in\mathcal{K}}\log R^{(S)}_{i,t}+\sum_{j\in\mathcal{L}}\log R^{(S)}_{j,t}, \tag{A.1}$$

which can be simplified as

$$\Pi_{i\in\mathcal{K}}R^{(F)}_{i,t}\times\Pi_{j\in\mathcal{L}}R^{(F)}_{j,t}\geq\Pi_{i\in\mathcal{K}}R^{(S)}_{i,t}\times\Pi_{j\in\mathcal{L}}R^{(S)}_{j,t}, \tag{A.2}$$

where $R^{(S)}_{i,(j),t}$ is the average data rate of cellular user i (or D2D link j) in time slot t with scheduling scheme S, which can be obtained as

$$R^{(S)}_{i,(j),t}=\begin{cases} r^{(S)}_{i(j),t}, & t=1,\\ \frac{(t-1)R_{i,(j),t-1}+r^{(S)}_{i(j),t}}{t}, & t\geq 2,\end{cases} \tag{A.3}$$

where $r^{(S)}_{i(j),t}$ is the current data rate of cellular user i (or D2D link j) in time slot t with scheduling scheme S. $R^{(S)}_{i,(j),t-1}$ is the average data rate of cellular user i (or D2D link j) during previous $(t-1)$ time slot with scheduling scheme S.

For $t=1$, (A.2) can be rewritten as

$$\Pi_{i\in\mathcal{K}}r^{(F)}_{i,1}\times\Pi_{j\in\mathcal{L}}r^{(F)}_{j,1}\geq\Pi_{i\in\mathcal{K}}r^{(S)}_{i,1}\times\Pi_{j\in\mathcal{L}}r^{(S)}_{j,1}. \tag{A.4}$$

From (A.2), we can see in time slot $t=1$, there are no average data rates of cellular and D2D links, we can not employ the proportional fairness algorithm in this time slot. Thus, the cost function is to maximize the sum data rate in logarithm, which is expressed as

$$F=\arg\max_{S}\{\sum_{i\in\mathcal{K}}\ln r^{(S)}_{i,t}+\sum_{j\in\mathcal{L}}\ln r^{(S)}_{j,t}\}.$$

For $t \geq 2$, (A.2) can be rewritten as

$$\Pi_{i\in\mathcal{K}}\frac{(t-1)R_{i,t-1}+r_{i,t}^{(F)}}{t}\times\Pi_{j\in\mathcal{L}}\frac{(t-1)R_{j,t-1}+r_{j,t}^{(F)}}{t}$$
$$\geq \Pi_{i\in\mathcal{K}}\frac{(t-1)R_{i,t-1}+r_{i,t}^{(S)}}{t}\times\Pi_{j\in\mathcal{L}}\frac{(t-1)R_{j,t-1}+r_{j,t}^{(S)}}{t}. \quad \text{(A.5)}$$

By multiplying $\Pi_{i\in\mathcal{K}}\frac{t}{(t-1)R_{i,t-1}}\times\Pi_{j\in\mathcal{L}}\frac{t}{(t-1)R_{j,t-1}}$ on both sides of (A.5), we can obtain

$$\Pi_{i\in\mathcal{K}}(1+\frac{r_{i,t}^{(F)}}{(t-1)R_{i,t-1}})\times\Pi_{j\in\mathcal{L}}(1+\frac{r_{j,t}^{(F)}}{(t-1)R_{j,t-1}})$$
$$\geq \Pi_{i\in\mathcal{K}}(1+\frac{r_{i,t}^{(S)}}{(t-1)R_{i,t-1}})\times\Pi_{j\in\mathcal{L}}(1+\frac{r_{j,t}^{(S)}}{(t-1)R_{j,t-1}}). \quad \text{(A.6)}$$

Thus, the objective function can be expressed as

$$F=\arg\max_{S}\{\Pi_{i\in\mathcal{K}}(1+\frac{r_{i,t}^{(S)}}{(t-1)R_{i,t-1}})\times\Pi_{j\in\mathcal{L}}(1+\frac{r_{j,t}^{(S)}}{(t-1)R_{j,t-1}})\}.$$

And then, the scheduler F for D2D communication underlay network can be expressed as (6.9).

Appendix B

The Proof of Lemmas

B.1 The proof of Lemma 1

Let $\alpha > 1$, we have the following inequality:

$$\begin{aligned}
&\ln(\frac{\alpha p^1_{C_{i,j,n}} h^1_{i,B,n}}{\sigma^2 + \alpha p^1_{D_{i,j,n}} h^1_{j,B,n}}) \times \ln(\frac{\alpha p^1_{D_{i,j,n}} h^1_{j,n}}{\sigma^2 + \alpha p^1_{C_{i,j,n}} h^1_{i,j,n}}) \\
=&\ln(\frac{p^1_{C_{i,j,n}} h^1_{i,B,n}}{\frac{\sigma^2}{\alpha} + p^1_{D_{i,j,n}} h^1_{j,B,n}}) \times \ln(\frac{p^1_{D_{i,j,n}} h^1_{j,n}}{\frac{\sigma^2}{\alpha} + p^1_{C_{i,j,n}} h^1_{i,j,n}}) \\
\geq&\ln(\frac{p^1_{C_{i,j,n}} h^1_{i,B,n}}{\sigma^2 + p^1_{D_{i,j,n}} h^1_{j,B,n}}) \times \ln(\frac{p^1_{D_{i,j,n}} h^t_{j,n}}{\sigma^2 + p^1_{C_{i,j,n}} h^1_{i,j,n}}).
\end{aligned} \tag{B.1}$$

From the inequality, larger α leads to larger multiplication. Therefore, maximum multiplication can be achieved when at least one of $p^1_{C_{i,j,n}}$ and $p^1_{D_{i,j,n}}$ transmit at its maximum power.

B.2 The proof of Lemma 2

Let $\beta > 1$, we have the following inequality:

$$\begin{aligned}
&(1 + \frac{\beta p^t_{C_{i,j,n}} h^t_{i,B,n}}{\sigma^2 + \beta p^t_{D_{i,j,n}} h^t_{j,B,n}}) \times (1 + \frac{\beta p^t_{D_{i,j,n}} h^t_{j,n}}{\sigma^2 + \beta p^t_{C_{i,j,n}} h^t_{i,j,n}})^{\xi} \\
=&(1 + \frac{p^t_{C_{i,j,n}} h^t_{i,B,n}}{\frac{\sigma^2}{\beta} + p^t_{D_{i,j,n}} h^t_{j,B,n}}) \times (1 + \frac{p^t_{D_{i,j,n}} h^t_{j,n}}{\frac{\sigma^2}{\beta} + p^t_{C_{i,j,n}} h^t_{i,j,n}})^{\xi} \\
\geq&(1 + \frac{p^t_{C_{i,j,n}} h^t_{i,B,n}}{\sigma^2 + p^t_{D_{i,j,n}} h^t_{j,B,n}}) \times (1 + \frac{p^t_{D_{i,j,n}} h^t_{j,n}}{\sigma^2 + p^t_{C_{i,j,n}} h^t_{i,j,n}})^{\xi}.
\end{aligned} \tag{B.2}$$

From the inequality, larger β leads to larger weight sum data rates. Therefore, maximum weight sum data rates can be achieved when at least one of $p^t_{C_{i,j,n}}$ and $p^t_{D_{i,j,n}}$ transmits at its maximum power.

Appendix C

C.1

From (6.9), the optimal PF scheduling for $t \geq 2$ can be rewritten as

$$F = \arg\max_{S}\{\sum_{i\in\mathcal{K}} \ln(1+\frac{r_{i,t}^{S}}{(t-1)R_{i,t-1}}) + \sum_{j\in\mathcal{L}} \ln(1+\frac{r_{j,t}^{S}}{(t-1)R_{j,t-1}})\}. \tag{C.1}$$

By applying the *Maclaurin* series expansion, (C.1) can be further expanded as

$$\begin{aligned} F = \arg\max_{S}\{\sum_{i\in\mathcal{K}}\sum_{m=0}^{\infty}\frac{(-1)^m}{(m+1)}(\frac{r_{i,t}^{S}}{(t-1)R_{i,t-1}})^{(m+1)} \\ + \sum_{j\in\mathcal{L}}\sum_{m=0}^{\infty}\frac{(-1)^m}{(m+1)}(\frac{r_{j,t}^{S}}{(t-1)R_{j,t-1}})^{(m+1)}\}, \end{aligned} \tag{C.2}$$

which has infinite number of terms. Since it is different to calculate infinite terms in a practical system and the $(\frac{r_{i,t}^{S}}{(t-1)R_{i,t-1}})$ and $(\frac{r_{j,t}^{S}}{(t-1)R_{j,t-1}})$ will approach to 0 as t increases, so in this work only the first one term is considered to express F (i.e. $m = 0$) [87]. Thus, (C.2) is simplified as

$$\begin{aligned} F &\approx \arg\max_{S}\{\sum_{i\in\mathcal{K}}[\frac{r_{i,t}^{S}}{(t-1)R_{i,t-1}}] + \sum_{j\in\mathcal{L}}[\frac{r_{j,t}^{S}}{(t-1)R_{j,t-1}}]\} \\ &= \arg\max_{S}\{\sum_{i\in\mathcal{K}}\frac{r_{i,t}^{S}}{R_{i,t-1}} + \sum_{j\in\mathcal{L}}\frac{r_{j,t}^{S}}{R_{j,t-1}}\}. \end{aligned} \tag{C.3}$$

Appendix D

The deviation of (6.29) and the details of (6.30)

D.1 The deviation of (6.29)

We assume $p^t_{C_{i,j,n}} = p^C_{max}$, the problem in (6.28) with constraints can be converted into

$$(p^C_{max}, p^{t^*}_{D_{i,j,n}}) = \arg\max_{p^t_{D_{i,j,n}}} f(p^C_{max}, p^t_{D_{i,j,n}}) \tag{D.1}$$

s.t.

$$\frac{p^C_{max} h^t_{i,B,n}}{\sigma^2 + p^t_{D_{i,j,n}} h^t_{j,B,n}} \geq \gamma^C_{min}, \tag{D.1a}$$

$$\frac{p^t_{D_{i,j,n}} h^1_{j,n}}{\sigma^2 + p^C_{max} h^t_{i,j,n}} \geq \gamma^D_{min}, \tag{D.1b}$$

$$0 \leq p^t_{D_{i,j,n}} \leq p^D_{max}, \tag{D.1c}$$

in which $f(p^C_{max}, p^t_{D_{i,j,n}}) = \{(1 + \frac{p^C_{max} h^t_{i,B,n}}{\sigma^2 + p^t_{D_{i,j,n}} h^t_{j,B,n}}) \times (1 + \frac{p^t_{D_{i,j,n}} h^t_{j,n}}{\sigma^2 + p^C_{max} h^t_{i,j,n}})^{\xi}\}$.

According to constraints (D.1a)-(D.1c), we can get the continuous closed and bounded feasible set of $p^t_{D_{i,j,n}}$, which is $[pd^t_{low,i,j,n}, pd^t_{up,i,j,n}]$. The lower and upper bounds $pd^t_{low,i,j,n}$ and $pd^t_{up,i,j,n}$ are expressed as

$$pd^t_{low,i,j,n} = \max\{0, \frac{\gamma^D_{min}(\sigma^2 + p^C_{max} h^t_{i,j,n})}{h^t_{j,n}}\}, \tag{D.2}$$

$$pd^t_{up,i,j,n} = \min\{p^D_{max}, \frac{(p^C_{max} h^t_{i,B,n} - \gamma^C_{min}\sigma^2)}{h^t_{j,B,n}\gamma^C_{min}}\}. \tag{D.3}$$

Problem in (D.1) is feasible only when $pd^t_{low,i,j,n} \leq pd^t_{up,i,j,n}$; otherwise, the set $\Omega 1^t_{i,j,n}$ is empty.

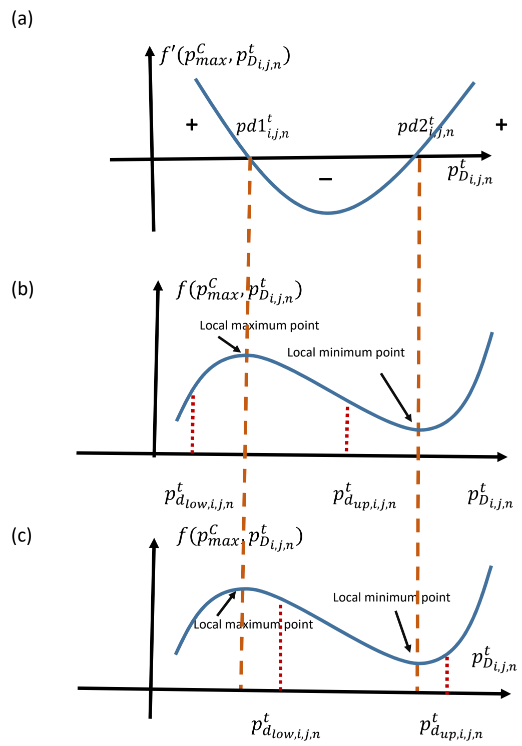


Figure D.1: (a) The graph of $f'(p_{max}^C, p_{D_{i,j,n}}^t)$; (b) The graph of $f(p_{max}^C, p_{D_{i,j,n}}^t)$ when $\Delta_{D,i,j,n}^t \geq 0$ and $pd1_{i,j,n}^t \in [pd_{low,i,j,n}^t, pd_{up,i,j,n}^t]$; (c) The graph of $f(p_{max}^C, p_{D_{i,j,n}}^t)$ when $\Delta_{D,i,j,n}^t \geq 0$ but $pd1_{i,j,n}^t \notin [pd_{low,i,j,n}^t, pd_{up,i,j,n}^t]$.

When problem in (D.1) is feasible, the optimal value of $f(p_{max}^C, p_{D_{i,j,n}}^t)$ can be found by solving the equation

$$f'(p_{max}^C, p_{D_{i,j,n}}^t) = \frac{A_{D,i,j,n}^t (p_{D_{i,j,n}}^t)^2 + B_{D,i,j,n}^t p_{D_{i,j,n}}^t + V_{D,i,j,n}^t}{W_{D,i,j,n}^t} = 0, \tag{D.4}$$

where

$$\begin{aligned} A_{D,i,j,n}^t =& \xi h_{j,n}^t (h_{j,B,n}^t)^2, \\ B_{D,i,j,n}^t =& (\xi - 1) p_{max}^C h_{i,B,n}^t h_{j,B,n}^t h_{j,n}^t + 2\xi h_{j,n}^t \sigma^2 h_{j,B,n}^t, \\ V_{D,i,j,n}^t =& \xi h_{j,n}^t \sigma^2 (\sigma^2 + p_{max}^C h_{i,B,n}^t) - p_{max}^C h_{i,B,n}^t h_{j,B,n}^t (\sigma^2 + p_{max}^C h_{i,j,n}^t), \\ W_{D,i,j,n}^t =& (\sigma^2 + p_{max}^C h_{i,j,n}^t)^{\xi} (\sigma^2 + p_{D_{i,j,n}}^t h_{j,B,n}^t)^2. \end{aligned} \tag{D.5}$$

If $\Delta^t_{D,i,j,n} = (B^t_{D,i,j,n})^2 - 4A^t_{D,i,j,n}V^t_{D,i,j,n} \geq 0$, then (D.4) has two solutions:

$$pd1^t_{i,j,n} = \frac{-B^t_{D,i,j,n} - \sqrt{\Delta^t_{D,i,j,n}}}{2A^t_{D,i,j,n}}, \tag{D.6}$$

$$pd2^t_{i,j,n} = \frac{-B^t_{D,i,j,n} + \sqrt{\Delta^t_{D,i,j,n}}}{2A^t_{D,i,j,n}}, \tag{D.7}$$

as shown in Figure (D.1) (a). Since $A^t_{D,i,j,n}$ is always positive, so $pd1^t_{i,j,n}$ and $pd2^t_{i,j,n}$ are the local maximum and points of function $f(p^C_{max}, p^t_{D_{i,j,n}})$, respectively. If $pd1^t_{i,j,n} \in [pd^t_{low,i,j,n}, pd^t_{up,i,j,n}]$, $pd1^t_{i,j,n}$ is the optimal solution of function $f(p^C_{max}, p^t_{D_{i,j,n}})$ as shown in Figure (D.1) (b). If not, the bounds $pd^t_{up,i,j,n}$ or $pd^t_{low,i,j,n}$ are the optimal solutions. This is because when $pd1^t_{i,j,n} \notin [pd^t_{low,i,j,n}, pd^t_{up,i,j,n}]$, $f(p^C_{max}, p^t_{D_{i,j,n}})$ is a convex function in $[pd^t_{low,i,j,n}, pd^t_{up,i,j,n}]$ as shown in Figure (D.1)(c). Therefore, the optimal solution of $f(p^C_{max}, p^t_{D_{i,j,n}})$ can be either $pd^t_{up,i,j,n}$ or $pd^t_{low,i,j,n}$.

If $\Delta^t_{D,i,j,n} < 0$, it means $f'(p^C_{max}, p^t_{D_{i,j,n}})$ is always positive, so $f(p^C_{max}, p^t_{D_{i,j,n}})$ increase monotonically in $[pd^t_{low,i,j,n}, pd^t_{up,i,j,n}]$ similar as shown in Figure D.1(b) when $t = 1$. Therefore, upper bound $pd^t_{up,i,j,n}$ is the optimal solution.

In summary, after we find out the power feasible set, if the derivation of optimal function has roots, and the left root (i.e. $pd1^t_{i,j,n}$) belongs to the feasible set, the optimal solution will be the left root. If the left root does not belong to the feasible set, the optimal solution will be the lower bound or upper bound points of the feasible set depending which point can bring better sum data rate. Then, if the final derivative of the optimal function has no roots, the solution will be the upper bound of the feasible set.

D.2 The details of (6.30).

Similar, the details of (6.30) are shown below.

$$
\begin{aligned}
pc1^t_{i,j,n} =& \frac{-B^t_{C,i,j,n} - \sqrt{\Delta^t_{C,i,j,n}}}{2A^t_{C,i,j,n}}, \\
A^t_{C,i,j,n} =& \zeta h^t_{i,B,n}(h^t_{i,j,n})^2, \\
B^t_{C,i,j,n} =& (\zeta - 1)p^D_{max}h^t_{j,n}h^t_{i,j,n}h^t_{i,B,n} + 2\frac{R_{j,t-1}}{R_{i,t-1}}h^t_{i,B,n}\sigma^2 h^t_{i,j,n}, \\
V^t_{C,i,j,n} =& \zeta h^t_{i,B,n}\sigma^2(\sigma^2 + p^D_{max}h^t_{j,n}) - p^D_{max}h^t_{j,n}h^t_{i,j,n}(\sigma^2 + p^D_{max}h^t_{i,B,n}), \\
W^t_{C,i,n} =& (\sigma^2 + p^D_{max}h^t_{j,B,n})^\zeta(\sigma^2 + p^t_{C_{i,j,n}}h^t_{i,j,n})^2, \\
\Delta^t_{C,i,j,n} =& (B^t_{C,i,j,n})^2 - 4A^t_{C,i,j,n}V^t_{C,i,j,n}. \\
p^t_{C_{low,i,j,n}} =& \max\{0, \frac{\gamma^C_{min}(\sigma^2 + p^D_{max}h^t_{j,B,n})}{h^t_{i,B,n}}\}, \\
p^t_{C_{up,i,j,n}} =& \min\{p^C_{max}, \frac{(p^D_{max}h^t_{j,n} - \gamma^D_{min}\sigma^2)}{h^t_{i,j,n}\gamma^D_{min}}\}.
\end{aligned}
\tag{D.8}
$$

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