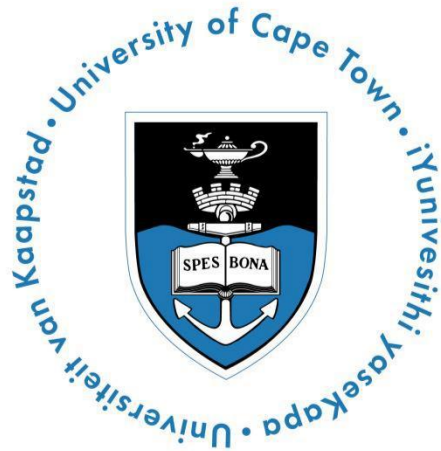


# Interference Management of Inband Underlay Device-to-Device Communication in 5G Cellular Networks



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This dissertation is submitted in partial fulfilment of the academic requirements

for the degree of

Master of Science in Electrical Engineering

in the Faculty of Engineering and The Built Environment

University of Cape Town

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As the candidate's supervisor, I have approved this dissertation for submission.

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## Declaration

I declare that this dissertation is my own work. All the sources used have been indicated and acknowledged in the references. This dissertation has been submitted to the Turnitin module and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

I am presenting the dissertation for examination for the Master of Science in Electrical Engineering Degree. This work has not been submitted to any other university for any other degree or examination.

Signed by candidate

---

Sharon Ampomaa Boamah

21/10/2020

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Date

## **Dedication**

*In loving memory of my grandmother and friend, Madam Sophia Dufie Appiah, in fulfilment of your last memory of me before you joined your Maker.*

## **Acknowledgement**

Firstly, I am thankful to God for the strength and grace bestowed on me throughout the duration of this master's programme.

I would like to express my fervent gratitude to my supervisor, Mr. Neco Ventura on his guidance and constructive criticisms in my research work. I am grateful for the willingness to support me with issues outside academic work.

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Finally, I would like to thank my parents for their unwavering love, financial support, encouragement and prayers. I would also like to appreciate my family and friends for the love and motivation.

## Abstract

The explosive growth of data traffic demands, emanating from smart mobile devices and bandwidth-consuming applications on the cellular network poses the need to drastically modify the cellular network architecture. A challenge faced by the network operators is the inability of the finite spectral resources to support the growing data traffic. The Next Generation Network (NGN) is expected to meet defined requirements such as massively connecting billions of devices with heterogeneous applications and services through enhanced mobile broadband networks, which provides higher data rates with improved network reliability and availability, lower end-to-end latency and increased energy efficiency. Device-to-Device (D2D) communication is one of the several emerging technologies that has been proposed to support NGN in meeting these aforementioned requirements. D2D communication leverages the proximity of users to provide direct communication with or without traversing the base station. Hence, the integration of D2D communication into cellular networks provides potential gains in terms of throughput, energy efficiency, network capacity and spectrum efficiency.

D2D communication underlaying a cellular network provides efficient utilisation of the scarce spectral resources, however, there is an introduction of interference emanating from the reuse of cellular channels by D2D pairs. Hence, this dissertation focuses on the technical challenge with regards to interference management in underlay D2D communication. In order to tackle this challenge to be able to exploit the potentials of D2D communication, there is the need to answer some important research questions concerning the problem. Thus, the study aims to find out how cellular channels can be efficiently allocated to D2D pairs for reuse as an underlay to cellular network, and how mode selection and power control approaches influence the degree of interference caused by D2D pairs to cellular users. Also, the research study continues to determine how the quality of D2D communication can be maintained with factors such as bad channel quality or increased distance.

In addressing these research questions, resource management techniques of mode selection, power control, relay selection and channel allocation are applied to minimise the interference caused by D2D pairs when reusing cellular channels to guarantee the Quality of Service (QoS) of cellular users, while optimally improving the number of permitted D2D pairs to reuse channels. The concept of Open loop power control scheme is examined in D2D communication underlaying cellular network. The performance of the fractional open loop power control

components on SINR is studied. The simulation results portrayed that the conventional open loop power control method provides increased compensation for the path loss with higher D2D transmit power when compared with the fractional open loop power control method.

Furthermore, the problem of channel allocation to minimise interference is modelled in two system model scenarios, consisting of cellular users coexisting with D2D pairs with or without relay assistance. The channel allocation problem is solved as an assignment problem by using a proposed heuristic channel allocation, random channel allocation, Kuhn-Munkres (KM) and Gale-Shapley (GS) algorithms. A comparative performance evaluation for the algorithms are carried out in the two system model scenarios, and the results indicated that D2D communication with relay assistance outperformed the conventional D2D communication without relay assistance.

This concludes that the introduction of relay-assisted D2D communication can improve the quality of a network while utilising the available spectral resources without additional infrastructure deployment costs. The research work can be extended to apply an effective relay selection approach for a user mobility scenario.

# Table of Contents

<b>Declaration</b> .....	iv
<b>Dedication</b> .....	v
<b>Acknowledgement</b> .....	vi
<b>Abstract</b> .....	vii
<b>Table of Contents</b> .....	ix
<b>List of Tables</b> .....	xii
<b>List of Figures</b> .....	xiii
<b>List of Acronyms</b> .....	xv
<b>1 Introduction</b> .....	1
<b>1.1 Background</b> .....	2
<b>1.2 Research Motivation</b> .....	4
<b>1.3 Problem Definition</b> .....	5
<b>1.4 Research Question</b> .....	6
<b>1.5 Dissertation Objectives</b> .....	6
<b>1.6 Scope and Limitation</b> .....	7
<b>1.7 Publication</b> .....	8
<b>1.8 Dissertation Organisation</b> .....	8
<b>2 Literature Review</b> .....	10
<b>2.1 Introduction</b> .....	10
<b>2.2 Overview of Device-to-Device Communication</b> .....	10
<b>2.2.1 Classification of Device-to-Device Communication</b> .....	12

2.3	<b>Related Works</b> .....	15
2.4	<b>Conclusion</b> .....	24
3	<b>Analytical System Model for Device-to-Device Communication</b> .....	25
3.1	<b>Introduction</b> .....	25
3.2	<b>System Model and Assumptions</b> .....	26
3.3	<b>Channel Model</b> .....	27
3.3.1	<b>Path loss</b> .....	28
3.3.2	<b>Shadowing</b> .....	30
3.3.3	<b>Multipath Fading</b> .....	30
3.4	<b>Channel Gain Measurements</b> .....	31
3.5	<b>Performance Metrics</b> .....	32
3.6	<b>Conclusion</b> .....	33
4	<b>Performance Evaluation of Fractional Power Control in Uplink Device-to-Device Communication</b> .....	34
4.1	<b>Introduction</b> .....	34
4.2	<b>Notations</b> .....	35
4.3	<b>System Model</b> .....	36
4.4	<b>Problem Formulation</b> .....	36
4.5	<b>Simulation Results and Discussion</b> .....	40
4.6	<b>Conclusion</b> .....	44
5	<b>Uplink Interference Management for Device-to-Device Communication Underlying Cellular Networks</b> .....	45
5.1	<b>Introduction</b> .....	45

5.2	Notations .....	47
5.3	System Model .....	48
5.4	Problem Formulation and Methodology.....	49
5.5	Simulation Parameters, Results and Discussions.....	56
5.5.1	Scenario 1 (Without Relay) .....	57
5.5.2	Scenario 2 (With Relay).....	60
5.6	Conclusion .....	65
6	Interference Minimisation for Uplink Channel Reuse in Device-to-Device Communication Underlying Cellular Networks – A Stable Matching Approach.....	66
6.1	Introduction.....	66
6.2	Concept of Matching Theory .....	67
6.2.1	Matching Theory Classifications .....	68
6.3	Notations .....	69
6.4	System Model .....	69
6.5	Problem Formulation and Methodology.....	70
6.6	Simulation Parameters and Results Discussion .....	79
6.7	Conclusion .....	82
7	Conclusion and Future Work .....	83
7.1	Conclusion .....	83
7.2	Recommendations for Further Study .....	87
	References.....	88

## List of Tables

Table 4.1: Summary of Notations .....	35
Table 4.2: Simulation Parameters .....	40
Table 5.1: Summary of Notations .....	47
Table 5.2: Simulation Parameters .....	56
Table 6.1: Summary of Notations .....	69
Table 6.2: Simulation Parameters .....	79

## List of Figures

Figure 1.1: Some Key Enabling Technologies for 5G.....	2
Figure 1.2: The disruptive capabilities of 5G [10].....	3
Figure 2.1: Traditional Cellular Communication versus Device-to-Device Communication .	10
Figure 2.2: Classification of D2D communication based on spectrum usage .....	13
Figure 3.1: System Model of D2D Communication Underlying Cellular Network .....	26
Figure 3.2: Path loss, Shadowing and Multipath [48] .....	28
Figure 3.3: Channel gain links of cellular UEs coexisting with D2D pairs and relay-assisted D2D pairs .....	31
Figure 4.1: The system model of D2D communication underlying cellular network .....	36
Figure 4.2: Transmit power spectral density for Fractional OLPC scheme .....	41
Figure 4.3: Impact on SINR per user when $P_o$ is constant and $\alpha$ is varied.....	42
Figure 4.4: Impact on SINR per user when $P_o$ is varied and $\alpha = 0.6$ .....	43
Figure 4.5: Impact on SINR per user when $P_o$ is varied and $\alpha = 0.8$ .....	43
Figure 5.1: System Model for D2D communication - (a) Without relay (b) With relay .....	48
Figure 5.2: Performance comparison of the proposed algorithms in relation to average interference as interference threshold varies.....	57
Figure 5.3: Performance comparison of the proposed algorithms in relation to the permitted number of D2D users as interference threshold varies .....	58
Figure 5.4: Performance of the proposed algorithms in relation to the average interference caused by permitted D2D pairs as the SINR threshold varies .....	59

Figure 5.5: Performance of the proposed algorithms in relation to the number of permitted D2D pairs as the SINR threshold varies .....	60
Figure 5.6: Interference threshold Versus Average interference caused by permitted users...	61
Figure 5.7: Interference threshold Versus Number of permitted users.....	62
Figure 5.8: SINR threshold Versus Average interference caused by permitted users.....	63
Figure 5.9: SINR threshold Versus Average number of permitted users .....	63
Figure 5.10: Performance comparison of the proposed relay selection algorithm .....	64
Figure 6.1: System Model for D2D communication underlying cellular network .....	70
Figure 6.2: A bipartite graph with one-to-one matching .....	74
Figure 6.3: Flow chart of stable matching algorithm.....	76
Figure 6.4: Performance comparison of proposed algorithms in relation to the permitted number of D2D users .....	80
Figure 6.5: Performance comparison of the proposed algorithms in relation to the average interference caused by permitted D2D users .....	81
Figure 6.6: The system sum rate with varying number of permitted D2D pairs .....	82

## List of Acronyms

1G	First Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G-PPP	Fifth Generation Infrastructure Public Private Partnership
AWGN	Additive White Gaussian Noise
BS	Base Station
CAPEX	Capital Expenditure
CDF	Cumulative Distributive Function
CLPC	Closed Loop Power Control
CLT	Central Limit Theorem
CM	Cellular Mode
CQI	Channel Quality Indicator
CSI	Channel State Information
CUE	Cellular User Equipment
D2D	Device-to-Device
dB	Decibels
DM	Dedicated Mode

eMBB	Enhanced Mobile Broadband
eNB	evolved Node B
EPC	Evolved Packet Core
FDD	Frequency Division Duplexing
GS	Gale-Shapley
IMT-A	International Mobile Telecommunications-Advanced
IoTs	Internet of Things
ITU	International Telecommunication Union
KM	Kuhn-Munkres
LOS	Line-of-Sight
LTE	Long Term Evolution
LTE-A	LTE-Advanced
M2M	Machine-to-Machine
mMTC	Massive Machine-Type Communication
NGNs	Next Generation Networks
NLOS	Non-line-of-sight
NNS	Nearest Neighbour Search
OFDMA	Orthogonal Frequency Division Multiple Access
OLPC	Open Loop Power Control
OPEX	Operational Expenditure

PDF	Probability Density Function
PSD	Power Spectral Density
QOE	Quality of Experience
QoS	Quality of Service
RSRP	Reference Symbol Received Power
RSS	Received Signal Strength
SINR	Signal-to-Interference-Noise-Ratio
SM	Shared Mode
SNR	Signal-to-Noise-Ratio
UEs	User equipment
uRLLC	Ultra Reliable and Low Latency Communication
V2X	Vehicle-to-everything
VNI	Virtual Networking Index
WiFi	Wireless Fidelity
WLANs	Wireless Local Area Networks

# Chapter 1

## 1 Introduction

In the past decades, millions of devices communicate in the traditional way, by relying solely on the base station (BS) or evolved Node B (eNB). Although this state-of-the-art paradigm provides strong mobility management for seamless wireless services, it may not be efficient for spectrum utilisation, energy consumption and transmission latency [1]. This inefficiency becomes extreme when cellular communication occurs between short-range users. It is envisioned that data traffic will increase 1,000-fold in the next decade [2]. This is as a result of the development of bandwidth and data consuming applications, with exponentially increasing smart user terminals. According to the Cisco Virtual Networking Index (VNI) report, devices that connect to the network are growing faster than the global human population. New devices with increased capabilities and intelligence are introduced and adopted in the markets every year, thereby contributing to the acceleration in the increase in the average number of devices and connections per household. The increasing growth in the number of Machine-to-Machine (M2M) applications in areas such as transportation, healthcare monitoring, video surveillance and smart meters is also a major contributing factor to the growth of devices and connections [3]. Billions of devices are expected to connect to the Next Generation Networks (NGNs), where these connections are heterogeneous, with demands of extremely higher throughput, lower latencies and improved system capacity [4].

The recent existing Fourth Generation (4G) network is unable to support the current trend for “anytime, anywhere” high-speed connectivity for users. The evolution of the cellular network from the First Generation (1G) towards the Fifth Generation (5G) network is mainly driven by the need to support these forecast rising demands. The Fifth Generation cellular network is expected to be heterogenous and is depicted by factors such as the existence of different types of radio access technologies, user interactions, user applications, devices and multi-layer networks [5]. 5G is envisioned to not only provide an enhanced mobile broadband capacity, but also efficient support for all traffic types, flexible and cost-efficient network deployments, energy efficient and agile radio access technologies, backward compatibility with legacy services and communication systems and their future enhancements. There is the need for a drastic change in the existing cellular network architecture to meet these 5G requirements which include higher data rates, lower end-to-end latency, consistent Quality of Experience

(QoE) for users, massive connection and traffic density, enhanced spectrum efficiency, improved communication reliability and cost-efficient services. Figure 1.1 outlines a few of the key enabling technologies for the 5G network.

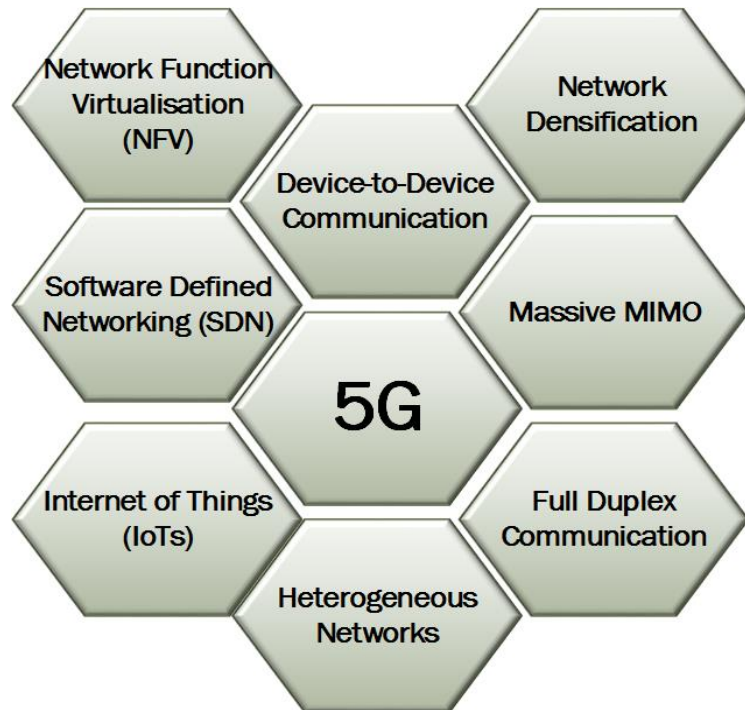


Figure 1.1: Some Key Enabling Technologies for 5G

A key challenge in supporting the enormous traffic demands associated with the proliferating connectivity of devices in 5G is as a result of the unavailability of spectral resources. However, the discrepancy between spectrum allocation and spectrum use suggest that spectrum access is a more significant problem than the physical scarcity of spectrum as a result of its underutilisation [6]. One of the straightforward approaches in fulfilling 5G requirements for higher data rates demands is to exploit spectral resource management techniques, of which Device-to-Device (D2D) communication is seen as an emerging paradigm that would complement and enhance the next generation 5G network.

## 1.1 Background

In the late 2000s, the Third Generation (3G) network was introduced to support broadband and multimedia services, making use of both circuit and packet switching. Bluetooth and Wireless Local Area Networks (WLANs) were introduced in this generation to support direct communication. However, these technologies introduce interference and are not able to meet

up with the Quality of Service (QoS) requirements of cellular users since they operate in unlicensed bands. The 4G network was deployed because users in the cellular network were close to saturation, and this was driven by the demand for broadband multimedia services. The 4G network utilises an exclusive packet switching to provide data, voice and multimedia services. 3GPP further deployed Long Term Evolution (LTE) and LTE-Advanced (LTE-A) standards to help the 4G network meet the set International Mobile Telecommunications-Advanced (IMT-Advanced) requirements of the International Telecommunication Union (ITU) [7],[8]. LTE-A introduced D2D communication and was mainly intended for public safety services.

Beyond the current 4G network is the proposed 5G network, which was expected to be deployed in 2020. The 5G network has received much momentum, while earning the interest of the industry and the research academia. Hence, it is foreseen as a mobile communication system that will interconnect the society with unlimited access to information and data sharing anywhere and at any time by anyone or anything. Also, the 5G cellular network is expected to address the challenges faced in 4G and perform better by providing a longer battery life span for the mobile devices, higher data rates, higher network capacity, higher spectral efficiency, lower cost of deployment and lower end-to-end latency [9] as shown in Figure 1.2.

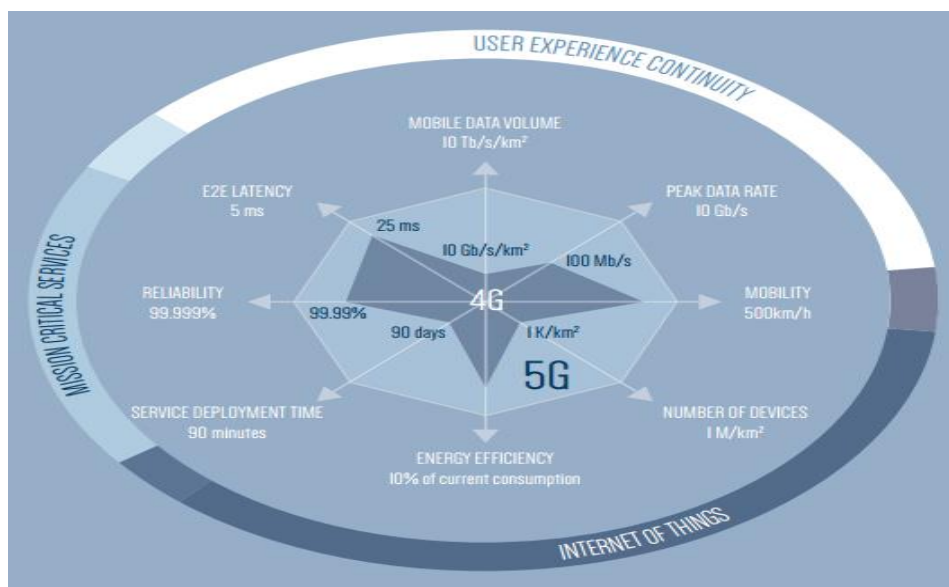


Figure 1.2: The disruptive capabilities of 5G [10]

The Fifth-Generation cellular network is foreseen to support a broad variety of use cases that are expected to be supported by diverse QoS requirements. The Fifth Generation Infrastructure

Public Private Partnership (5G-PPP) has categorised these use cases of 5G into Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communication (mMTC) and Ultra Reliable and Low Latency Communication (uRLLC) [11]. These use cases have different applications and performance requirements: ranging from high-speed entertainment application in a vehicle to mobility on demand for connected users on the network, from delay-sensitive video applications to an ultra-low latency requirement and from best effort applications to reliable and ultra-reliable ones such as safety and health [5],[12].

## 1.2 Research Motivation

In conventional cellular communication, cellular users communicate with each other via the base station, also called the evolved Node B. This method of communication is flawed and does not scale with the expected rise in user and traffic demand for the next decade. 5G is expected to address these issues of the existing 4G networks by employing approaches such as increasing of cellular resources, evolving to software-oriented network architecture, increasing the number of base stations and adopting efficient spectrum utilisation methods. Increasing bandwidth is possible through additional spectral resources, thereby enhancing the capacity of the network. However, increasing spectral resources require the deployment of additional hardware, consequently raising the Capital Expenditure (CAPEX) of the network. To further improve network performance, network densification is accomplished by increasing the number of antennas and the density of base stations in a geographical area [13]. However, extreme densification of base stations increases Operational Expenditure (OPEX) and CAPEX, with a requirement for an elaborate site planning.

Besides the use of cell splitting approaches to improve network capacity, D2D communication is a suggested approach to efficiently utilise spectral resources and address the challenges in the high-density networks. D2D communication is the direct communication between proximate users with or without traversing through the base station. Qualcomm carried out the first attempt to introduce D2D communication in cellular networks by implementing FlashLinQ [4]. FlashLinQ is a synchronous peer-to-peer wireless network architecture that leverages the parallel channel access provided by the Orthogonal Frequency Division Multiple Access (OFDMA) to enable node discovery, link management, channel allocation and power control [14]. The Third Generation Partnership Project (3GPP) standardisation group is another

organisation that got involved with D2D communication by specifying its functionalities in the LTE Release 12 towards public safety communications [15].

However, the application of LTE proximity-based services has not been limited to public safety services, but enhanced from Release 12 to Release 16, accompanied by extensive improvement in the D2D communication functionalities with the introduction of other applications in conventional cellular services, D2D relaying, Vehicle-to-everything (V2X) communication, Internet of Things and maritime communications [16]. D2D communication provides several benefits to both network operators, and as well as the users of the networks by taking advantage of the proximity of users and frequency reuse gains. D2D communication leverages short-range communication and single hop transmission to provide network users with higher data rates, lower power consumption and lower transmission delay. Also, the reuse of resources of cellular users by D2D users potentially leads to an increase in spectrum efficiency, thereby enhancing the capacity of the network. D2D communication also helps to extend the coverage area of networks and offloads data traffic from the base station, consequently reducing network congestion.

### **1.3 Problem Definition**

Despite the benefits of D2D communication, there are some concerns associated with its implementation in cellular networks. D2D communication underlying cellular networks provides effective utilisation of spectral resources, but it faces the challenge of interference caused by D2D users. This dissertation focuses on the issue of interference that is caused by the D2D users to cellular users, when simultaneously sharing the same resources. Due to interference, increasing the capacity of a network, as well as maintaining the QoS for cellular and D2D users remains a challenge that needs to be addressed, especially in cases where D2D users are densely underlying cellular users.

Hence, interference management techniques are important in D2D communication to mitigate the degradation of cellular networks. This dissertation delves deeper into the potentials of D2D communication as an underlay to cellular networks and focuses on exploiting interference management techniques to guarantee the QoS of cellular users. In addition, when considering the mobility of users and channel propagation conditions, the practicality of D2D communication becomes limited, due to the increasing distance between potential D2D pairs, thereby affecting the quality of the D2D communication link. Thus, this dissertation will also

consider relay-assisted D2D communication to enhance the performance of D2D communication when D2D pairs are far from each other, or the channel quality is poor for direct communication.

## **1.4 Research Question**

In order to tackle the defined problems in D2D communication, the research questions which arise are summarised as follows:

1. If the channel resources of cellular users can be shared with D2D pairs in D2D communication, how can these channels be efficiently allocated to D2D pairs for reuse with minimal interference to the cellular users, while guaranteeing an optimal number of permitted D2D pairs?
2. How can mode selection and power control minimise the interference caused by D2D users to cellular users, when they share or reuse resources belonging to cellular users?
3. When direct communication is impossible because of an increasing distance or poor channel link between D2D pairs, relay-assisted communication becomes an alternative approach to enhance the performance of D2D communication. How can the optimal relay node be selected among other optional relay nodes to assist in D2D communication for effective coordination of interference?

## **1.5 Dissertation Objectives**

Interference mitigation can be achieved by introducing an optimal resource allocation approach to ensure proper utilisation of cellular resources. However, there are cases where the transmission power of users exceeds the allocated transmission power for the request channel, causing battery drainage and interference in the network. Hence, in this dissertation, we focus on using effective interference approaches to enhance the performance of D2D communication when underlying cellular networks.

The objectives of this research are summarised as follows:

- To present the existing literature on interference management approaches implemented in D2D communication underlying cellular networks, and highlighting on the benefits and drawbacks.

- To develop an interference minimisation algorithm, that employs efficient mode selection, power control and channel allocation techniques.
- To propose a relay selection approach that will optimally select the best relay node to reduce interference and improve performance of D2D communication.
- To implement the proposed algorithms and carry out a comparative performance evaluation in the conventional D2D communication and relay-assisted D2D communication network model scenarios.

## 1.6 Scope and Limitation

In this research work, an additional transmission mode is explored, that is the relay-assisted D2D communication. Hence, three transmission modes are considered namely cellular transmission mode, D2D transmission mode and relay-assisted D2D transmission mode within a single cell environment. The issue of interference associated with D2D communication underlying cellular networks is addressed in this dissertation. The focus of this research work is to develop an optimal mode selection, power control and channel allocation algorithms to help in minimising interference that is introduced when D2D users share the same resources with cellular users, as well as guarantee QoS requirements of cellular users and permit an optimal number of D2D pairs for communication. It is assumed that the system model is a Frequency Division Duplexing (FDD) based cellular network and each D2D or relay-assisted D2D link reuses only one uplink cellular channel. The presented work in this dissertation admits D2D pairs to simultaneously reuse the uplink channels of cellular users since uplink channels are mostly underutilised and most likely generate less significant interference compared with the downlink cellular channels.

It is assumed in this work that the spectrum access by cellular users is based on Orthogonal Frequency Division Multiple Access, hence we avoid the issue of co-channel interference between cellular users. This study aims to implement an admission control channel allocation and power control approaches with transmission mode selection and relay selection algorithms as a simulation using the MATLAB simulation environment to mitigate the interference caused by D2D pairs to cellular users. The performance of these proposed schemes will be evaluated using performance metrics, constituting the average interference caused by D2D users, number of permitted D2D pairs, Signal-to-Interference-Noise-Ratio (SINR) of D2D receivers, transmit power spectral density of D2D pairs and sum rate. However, mobility of users is not considered

in this work since we are focusing on an instance of a static indoor scenario with less or no movement.

## 1.7 Publication

- Sharon Boamah and Neco Ventura, “Interference Management of Inband Underlay D2D Communication in 5G Cellular Networks”, in *Proc. Southern Africa Telecommunications Networks and Applications Conference (SATNAC), Hermanus, South Africa, 02-05 Sept. 2018.*
- Sharon Boamah and Neco Ventura, “Uplink Interference Management for Device-to-Device Communication Underlying Cellular Networks”, in *Proc. Southern Africa Telecommunications Networks and Applications Conference (SATNAC), Durban, South Africa, 01-04 Sept. 2019, ISBN: 978-0-6398415-0-2.*
- Sharon Boamah and Neco Ventura, “Interference Minimization for Uplink Channel Reusing in Device-to-Device Communication Underlying Cellular Networks”, in *Proc. IEEE AFRICON, Accra, Ghana, 25-27 Sept. 2019, ISBN: 978-1-7281-3289-1.*

## 1.8 Dissertation Organisation

The remaining chapters of this document are organised as follows:

Chapter 2 introduces an in-depth overview of D2D communication, highlighting the benefits, applications, classification based on spectrum usage and involvement of the base station. The chapter finally investigates the existing literature for interference minimisation approaches in D2D communication underlying cellular networks.

Chapter 3 presents the analysis of the system model scenarios, assumptions and the models considered for the channel design. This chapter further takes into account the types of channel gain measurements that arise from the system model scenarios. Finally, the performance metrics regarded for the evaluation of the proposed schemes are discussed.

In Chapter 4, the performance of fractional open loop power control scheme in D2D communication underlying cellular network is evaluated. The mathematical equations for the open loop power control scheme are derived. The simulation results showed that the transmit power spectral density is directly proportional to the path loss when the path loss compensation

factor is varied, and the initial power is fixed. The conventional open loop power control provided the highest transmit power spectral density when compared with the fractional open loop power control by fully compensating for the path loss by allowing D2D pairs to transmit at the highest power. The effect of fractional open loop power control parameters on the SINR experienced by users is evaluated.

Chapter 5 models a channel allocation problem in two system model scenarios, where a mode selection algorithm is proposed to determine the transmission modes of the users and a power control problem is formulated with its feasible solutions obtained using an optimising tool. Also, interference minimisation problem is formulated and solved as an assignment problem using proposed channel reuse allocation algorithms. The performances of the proposed algorithms are compared. The outcome of the simulation indicated that the proposed heuristic algorithm performed close to the Kuhn-Munkres (KM) algorithm. Furthermore, the system model scenario with relay assistance performed better than the system model scenario without relay assistance.

Chapter 6 discusses the overview of matching theory and its application in wireless communication for resource allocation. The channel allocation problem is formulated as a matching problem, and the Gale-Shapley (GS) algorithm is used to solve the channel allocation problem. A performance comparison analysis conducted on the outcome of the simulation indicates that the Gale-Shapley algorithm performed slightly lower than the Kuhn-Munkres algorithm.

Chapter 7 summarises the entire dissertation, provides conclusion and suggestions for future work. The conclusion reflects the solutions to the earlier discussed research questions of the identified research problem, and the contributions derived from extensive literature review on interference management in D2D communication underlying cellular networks. The chapter further provides future work as a recommendation for the extension of the current research work.

## Chapter 2

### 2 Literature Review

#### 2.1 Introduction

In this chapter, a survey emphasising on the importance of the integration of D2D communication into cellular networks is provided. The benefits, applications and classification of D2D communication is presented. This chapter finally discusses the related works regarding the interference management approaches in D2D communication.

#### 2.2 Overview of Device-to-Device Communication

As network operators are struggling to support the rising traffic demands with the limited available spectral resources, this struggle will become significant in the 5G cellular networks. Hence, Device-to-Device communication has been introduced as a technology to help 5G cellular networks meet their requirements and support their associated use cases. D2D communication is anticipated to complement the traditional cellular communication by leveraging the physical proximity of users in the network and allowing direct communication between these users without traversing the base station, as shown in Figure 2.1.

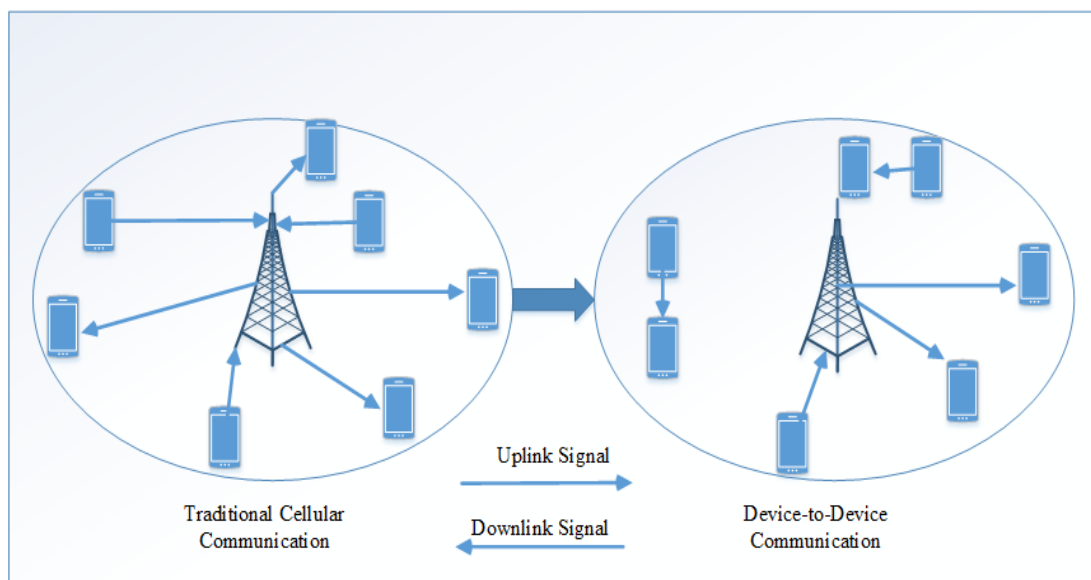


Figure 2.1: Traditional Cellular Communication versus Device-to-Device Communication

In traditional cellular communication, nearby or distant devices communicate through the base station while D2D communication allows nearby users to communicate directly with each other, hence offloading traffic on the base station. D2D communication supports users communicating over short distances, thereby providing benefits such as increased throughput, reduced delay and a low transmit power with improved energy efficiency. The spectrum reuse capability of D2D communication enables proper utilisation of these finite spectral resources.

In view of the several merits associated with D2D communication, it comes along with different applications as follows:

- **Traffic Offloading:** D2D communication can be applied in a scenario where devices are within communication range of the base station and utilise licensed spectrum to reduce load on the base station. This can be achieved by allowing users within the proximity of each other to communicate directly with each other rather than traversing through the base station.
- **Emergency Services:** D2D communication is applicable in scenarios where there is no coverage for cellular communication. This vital role can be seen in instances where natural disasters such as earthquake and flood partially or completely destroy the cellular radio infrastructure. D2D communication can be used as a fallback to provide a temporal local connectivity through the autonomous establishment of communication sessions by proximate devices without assistance from a central entity, the base station.
- **Cellular Coverage Extension:** In a situation where cellular users at the edge or outside of the cell coverage area experience poor signal quality with increased channel fading, D2D communication becomes applicable. A cellular user within the coverage of the cell with a stronger signal strength and proximate to another cellular user outside the coverage area, may act as a relay to the out-of-coverage user through the establishment of D2D communication links.
- **Local data services:** D2D communication plays an important role when applied in context-aware services and applications through unicast, groupcast and broadcast transmission. These applications require location discovery and communication with neighbouring devices, and the availability of such functionality helps to reduce cost of communication among devices [17]. Examples of these applications includes online gaming, advertisements and local promotions from restaurants or stores to nearby users and information sharing of popular contents among users in proximity [18].

## 2.2.1 Classification of Device-to-Device Communication

D2D communication can be categorised based on the level of involvement of the base station and the spectrum usage. These categorisations are further described below in the following subsections.

### 2.2.1.1 Classification based on the involvement of base station

In D2D communication, the base station may either have full, partial or no control over the communication between devices. The involvement of the base station is classified in [19] as:

- i. **Direct Communication with base station assisted controlled link:** The transmitting and receiving User Equipment (UEs) within the communication range of each other communicate directly with partial involvement of the base station. The partial involvement of the base station makes it possible to manage interference and security issues. Hence it is considered for use in this research work.
- ii. **Direct Communication with device assisted controlled link:** The transmitting and receiving UEs within the communication range of each other communicate directly without the involvement of the base station. The devices themselves are responsible for performing roles such as link establishment and resource management, hence suitable for emergency services.
- iii. **Device Relaying with base station assisted controlled link:** Devices at cell edge or with poor coverage communicate with a base station by using other devices to relay information to the base station. The base station may have partial or full control in the establishment of the relay link. Device relaying with base station assisted controlled link is considered in this research work in support of relay-assisted D2D communication.
- iv. **Device Relaying with device assisted controlled link:** The source and destination devices communicate with each other through a relay device. The devices themselves are responsible for link establishment, authentication and resource management without an involvement of the base station.

### 2.2.1.2 Classification based on spectrum usage

D2D communication can be classified into two main divisions based on how spectrum is accessed as Inband and Outband D2D communication.

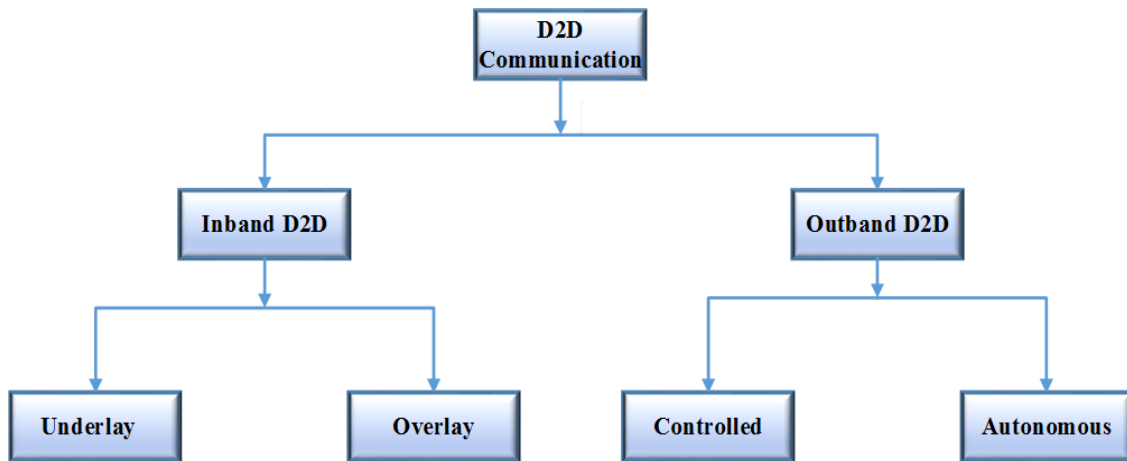


Figure 2.2: Classification of D2D communication based on spectrum usage

These divisions with their respective subdivisions are further discussed into details in the subsections below. The classification of D2D communication based on spectrum usage is shown in Figure 2.2.

- i. **Inband D2D communication:** This type of communication involves the use of licensed spectrum. The base station has partial or total control of the D2D pairs and performs roles such as peer discovery, link establishment based on Channel State Information (CSI) and resource allocation [20]. The motivation for the use of Inband D2D communication is the provision of high control over the licensed spectrum. Inband D2D communication can be divided into:
  - a. **Overlay:** In overlay D2D communication, fixed portions of cellular resources are allocated to D2D pairs for communication hence avoiding the issue of interference. However, this type of communication does not support efficient utilisation of spectral resources.
  - b. **Underlay:** In underlay D2D communication, D2D pairs share the same resources with cellular users. Although underlay D2D communication ensures proper utilisation of spectral resources, it introduces challenges associated with interference management and resource allocation between D2D pairs and cellular users.

- ii. **Outband D2D communication:** This type of communication involves the use of unlicensed spectrum, where the coordination and management of radio resources are done by either the base station or the D2D devices. Interference between cellular and D2D users is avoided in outband D2D communication. A major drawback in this type of communication is the uncontrollable inter-system interference due to the presence of other communicating entities such as Wireless Fidelity (WiFi) and Bluetooth, hence the use of outband D2D by network operators may not provide a stable controllable environment leading to congestion and poor QoS experience, thereby affecting overall network throughput [20]. Outband D2D communication can be divided into [20]:
  - a. **Controlled:** In controlled outband D2D communication, the base station is responsible for synchronising D2D users in space, time and frequency. The base station has total control of all D2D links activities. Controlled Outband D2D communication satisfies the QoS requirement of cellular communication, with an improvement in the overall system throughput. However, this type of communication introduces high signalling overhead in the process of managing D2D activities.
  - b. **Autonomous:** In autonomous outband D2D communication, the base station has partial control over the activities of D2D users. Also, the D2D users can independently establish communication session and control radio resource allocations. Although autonomous outband D2D communication provides lesser signalling overheads, it introduces significant interference among D2D users and high implementation complexities.

Thus, this dissertation focuses on Inband Underlay D2D communication to address the issue of interference arising from the reuse of cellular channels by D2D pairs, limiting the associated potential of providing controllable interference with highly efficient spectrum utilisation.

Although the integration of D2D communication into cellular networks provides several benefits such as reduced power consumption, lower transmission latency, higher data rate and improved utilisation of spectrum, interference is one of the key issues that needs to be addressed in order to exploit the full potentials of D2D communication. The cellular architecture has thereby evolved into a two-tier cellular network, that is the macro cell and device tier with the integration of D2D communication. The macro cell tier involves communication between the

base station and cellular UEs, whereas the device tier involves communication among D2D devices. The two types of interference in the two-tier cellular network architecture are briefly outlined as follows:

- **Co-tier Interference:** This type of interference occurs between D2D pairs that belong to the same tier in a network. Co-tier interference is introduced when the same radio resources are assigned to more than one D2D pairs. Despite the reuse direction (uplink or downlink) of resources, interference is produced from a D2D transmitter to other D2D receivers of D2D pairs that have been assigned the same cellular resource. The co-tier interference caused by a D2D transmitter to its neighbouring receivers can be minimised through optimal channel allocation and D2D users pairing algorithms.
- **Cross-tier Interference:** This type of interference occurs when one or more D2D pairs share the same channel belonging to cellular users. In the cross-tier interference, the source and receiver of interference vary depending on the reuse direction of the cellular resources, either uplink or downlink. The two types of interferences that arise are [21]:
  1. **Interference from D2D pairs to cellular network:** When D2D pairs share the same uplink channel resources belonging to cellular users, then the source of interference becomes the D2D transmitter, and the target of the interference becomes the cellular base station. Accordingly, in the same instance, cellular users become the source of interference to the D2D receivers.
  2. **Interference from the cellular network to D2D pairs:** When D2D pairs share the same downlink channel resources of cellular users, then the base station becomes the source of interference to D2D receivers. In the same case, the D2D transmitters become the source of interference to cellular users.

## 2.3 Related Works

Device-to-Device communication has attracted a lot of attention from researchers and industries, mainly because of its rising potentials. Several approaches have been proposed to tackle interference in D2D communication underlying cellular networks and a few of these approaches based on mode selection, power control, radio resource allocation and relay selection are reviewed as follows.

Mode selection is crucial in minimising interference, and it can be performed by the base station or the UEs based on selection criteria such as path loss, distance, the channel quality of

the cellular and D2D links and interference [18]. Several works in literature have been done on mode selection and a few are discussed.

The authors in [22] addressed the issue on how D2D pairs can select either cellular or D2D communication mode based on the distance between the two communicating D2D pairs. The authors derived an optimal D2D mode selection threshold that minimises the power of D2D transmitters. The authors discovered that the mode selection threshold is inversely proportional to the square root of the base station density and uniformly increases with the path loss exponent.

In [23], the authors considered an underlay spectrum sharing approach and developed a framework that uses stochastic geometry for power control and mode selection of UEs in an uplink cellular network. The modelled mode selection scheme is based on a biasing factor that accounts for the quality of the cellular and D2D links and controls the extent to which D2D communication is allowed in a network. Potential D2D UEs are permitted to use D2D communication only if the biased D2D link quality is as good as the cellular uplink quality. The shortcoming of [22], [23] is that the authors considered only distance as a mode selection criterion which may not provide an efficient solution to the mode selection problem.

In [24], the authors investigated several power control schemes in combination with mode selection between cellular communication and D2D communication mode. Path loss is the main measurement parameter used in this work for mode selection. The D2D transmission mode is preferred when the path loss between two user equipment is smaller than the path loss between the base station and any of the two-user equipment. Although the path loss dependent mode selection is a simple straightforward approach, the results obtained showed that it is not an optimal scheme for mode selection. Aside the method of mode selection, power control is another approach that has been applied to handle the minimisation of interference in D2D communication underlying cellular networks.

Power control is used to allocate power values to all transmitting user equipment to improve system performance by achieving target QoS, including SINR through the adjustment of transmit power values of UEs sharing the same channel. It is particularly necessary to optimally assign power for transmission, especially in the case of uplink channel transmissions due to near-far effect and co-channel interference [4].

With regards to uplink power control schemes, the authors in [25] proposed a combined open and closed loop power control schemes. These combined algorithms used the fractional power control component of the Open Loop Power Control (OLPC) scheme and the conventional closed loop component in the Closed Loop Power Control (CLPC) scheme. The results indicated that the parameters that affect the transmit power of users are path loss factor and power offset.

The authors in [26],[27] presented a survey of power control schemes for LTE uplink channel in a cellular network setting. These papers focused on the 3GPP LTE power control mechanism and compared its performance to two reference mechanisms, thus, the OLPC and CLPC. The authors performed a detailed survey on the conventional and fractional open loop schemes by considering mean cell throughput, SINR distribution, and cell edge throughput as performance indicators. In [26], the fractional open loop scheme allows users with good radio conditions to obtain a better received SINR, yielding a high mean user throughput while the conventional closed loop power control scheme guides all users to obtain the same received SINR. Hence, users with good radio conditions that can achieve better received SINR are affected, leading to a lower mean user throughput. The simulation results in [27] showed that the fractional power control scheme provided 20% increase in mean cell throughput by maintaining almost the same cell edge throughput. It is also observed that the fractional OLPC method provides a lower transmit power distribution leading to lower interference levels and an improvement in system performance, compared to the conventional OLPC method. In the conventional CLPC method, all the users within a cell are given the same SINR threshold resulting in a reduced mean cell throughput. However, the authors in [25] - [27] considered only cellular network settings for the implementation of the uplink power control scheme.

Taking into account a D2D communication underlaying cellular network scenario, the authors in [28] considered a single cell comprising of a cellular UE and a D2D pair, where the D2D pair shares the same channel with the cellular UE. Subsequently, the authors analysed a cellular and D2D SINR distribution using LTE uplink fractional open loop power control scheme. Also, the interference from D2D pair to a cellular user and base station decreases since the transmit power of the D2D pair is reduced. To the best of our knowledge, there are few works done in relation to the application of uplink power control schemes in a D2D communication underlaying cellular network.

In view of power control optimisation schemes, the authors in [29] proposed centralised and distributed power control algorithms in a one-cell random network to mitigate interference. In the centralised approach, optimal power values are derived to maximise coverage probability of cellular users while scheduling as many D2D pairs as possible. In the distributed approach, the authors proposed an on-off power control and truncated channel inversion power control algorithms. The results showed that although the centralised approach improve network performance, efficiency is reduced because of the channel estimation error. Also, despite the derivation of overall network gains in terms of sum rate, the distributed approach failed to provide reliable cellular communication.

In [30], the authors proposed a centralised and dynamic power control mechanism to reduce the interference caused when D2D pairs reuse resources belonging to cellular users while improving the performance of cellular systems. The proposed mechanism periodically adjusts the power values of the transmitting D2D UEs to exclude cellular UEs whose channels are being reused by D2D pairs from the coverage areas of these D2D pairs. The simulation results showed that the proposed dynamic power control minimises interference from D2D pairs to cellular UEs and improves the average throughput of the cellular network. The drawback in [29] and [30] is that the authors considered a stand-alone power control approach without regarding the option for other joint approaches to obtain optimal solutions. Apart from the method of power control, radio resource allocation is an approach that can be utilised to minimise the interference introduced in D2D communication underlying cellular networks.

The efficient allocation of radio resources to D2D pairs is necessary for minimal interference to cellular users while increasing network capacity. The different modes of radio resource allocation for D2D communication underlying cellular networks are as follows [31]:

- Cellular Mode (CM): This mode allows UEs to communicate via the base station and is used when UEs are far from the base station or in cases when it is not suitable for D2D communication. CM ensures effective management of interference, however it is characterised with inefficient utilisation of spectral resources.
- Dedicated Mode (DM): In this mode, a portion of the radio resources belonging to cellular users are allocated to UEs for D2D communication. DM provides better interference management as the Cellular Mode but guarantees higher gains concerning throughput, network capacity, power consumption and spectrum efficiency.

- Shared Mode (SM): This mode supports single and/or multiple D2D UEs to reuse resources belonging to single and/or multiple cellular users. SM is most efficient with respect to throughput, network capacity, power consumption and spectrum efficiency. However, the SM introduces interference among D2D UEs and Cellular User Equipment (CUEs). This mode can also be referred to as the Underlay or Non-Orthogonal Mode.

Consequently, a few of the research works on radio resource allocation methods are presented. The authors in [32] introduced an interference-aware resource allocation scheme to mitigate intra-cell interference when the uplink channels belonging to cellular UEs are reused by D2D UEs. The D2D UEs help the base station to obtain local awareness of the radio environment. The base station then uses this local information to perform an interference-aware channel allocation for the cellular and D2D links. The proposed mechanism provided efficient information for managing interference and simultaneously causes minimal disruption to the operation of cellular communication. The results obtained in this work portrayed significant improvement in the SINR gain performance when compared with the uncoordinated resource allocation scheme.

The authors in [33] proposed a distance-based resource allocation scheme to deal with the interference that cellular UEs experience from D2D UEs, while guaranteeing the reliability of D2D links. In this work, the base station utilised the proposed resource allocation scheme to select the best cellular UE for channel reusing by D2D UE to mitigate the interference from cellular link to the D2D link. The numerical results showed that the proposed scheme outperforms a previously proposed distance-based resource allocation scheme with regards to the outage probability of D2D links.

The authors in [34] focused on optimising system throughput while meeting the QoS requirements of the D2D and cellular UEs. The resource allocation problem is formulated as a mixed-integer linear programming problem. The authors proposed the Gale-Shapley and minimum weight stable matching algorithms to solve the resource allocation problem to obtain a stable matching that optimises system throughput.

In [35], the authors considered a cognitive radio network where a set of secondary users opportunistically access the vacant licensed spectrum belonging to the primary users. The authors in this work used the Gale-Shapley algorithm to obtain a stable spectrum allocation.

The transmission rate of the secondary users and channels are considered as the utility function, and the channel allocation problem is formulated as a one-to-one matching problem.

The interference introduced when D2D pairs share the same channel with cellular UEs needs to be coordinated and effective channel allocation is a method to help manage the interference. Hence, an interference aware channel allocation scheme based on Hungarian algorithm is proposed in [36],[37] to guarantee the priority of cellular communication. This scheme also focused on increasing the number of permitted D2D pairs while minimising the interference caused to cellular UEs when cellular channels are shared with D2D pairs. The simulation results showed that the proposed methods significantly increase the number of permitted communicating D2D pairs and the proposed heuristic algorithm had performance closer to the optimal Hungarian algorithm. However, the drawback in [32] - [37] is that the authors failed to consider other joint interference minimisation approaches for optimal solutions. The next approach to be discussed is the research works on relay selection methods to reduce interference in underlay relay-assisted D2D communication in cellular networks.

The need for the integration of relays in D2D communication emerges when the distance between the communicating D2D pair is too big for communication or when the channel condition is bad. A major challenge is how to efficiently select UEs to act as relays and consequently minimise the effect of interference in D2D communication underlying cellular networks. In [38], the authors introduced a relay node to assist in D2D communication. A relay selection rule based on interference constraints is proposed to determine UEs in a communicating D2D pair that require the assistance of a relay node. The authors then applied the Kuhn-Munkres and Greedy algorithms as the two selection approaches to select a relay for relay-assisted D2D communication. The presented selection rule provided an improved sum-rate, and the KM algorithm performed slightly better than the Greedy algorithm. Similar to some of the previously discussed research works, the authors regarded relay selection as a stand-alone approach to minimise interference without considering other joint interference minimisation schemes.

It is worth noting that although mode selection, power control, channel allocation and relay selection are effective schemes to manage inter-cell and intra-cell interference, however considering an approach on its own is not very effective to handle the interference introduced in D2D communication underlying cellular networks [21]. Accordingly, the related works on joint interference minimisation approaches are discussed as follows.

Despite the benefits of D2D communication, interference is a major problem requiring attention. Hence, the authors in [39] investigated the case where D2D pairs simultaneously share the downlink channels belonging to cellular UEs, similar to [6]. A power control problem for D2D transmitters is formulated, and the feasible centralised and distributed solutions are obtained to deal with co-channel interference as well as guaranteeing the QoS of D2D and cellular UEs. The authors further proposed a joint dynamic power control and channel re-allocation algorithm that guarantees the priority of cellular UEs. The simulation outcome demonstrated the effectiveness of the presented methods.

In order to efficiently minimise the level of interference when D2D pairs reuse downlink cellular channels, the authors in [40] proposed a joint resource allocation scheme for D2D communication underlaying a cellular network. The resource allocation scheme is based on users' QoS requirements using a Greedy algorithm, and the power control algorithm is performed using the convex optimisation theory to optimally allocate power to D2D transmitters to help balance throughput and interference introduced by D2D pairs. The authors compared the proposed scheme with the Random, Max-CQI and Interf-Min schemes. The random scheme assigns a resource to D2D pair randomly, Max-CQI assigns a resource with maximum Channel Quality Indicator (CQI) to D2D pair, and Interf-Min assigns a resource to D2D pair with minimum interference to cellular UE. The simulation outcome indicates that the presented scheme efficiently guarantees the QoS requirements of the users with improved system throughput. However, the drawback of [39], [40] is that the authors considered the reuse of downlink cellular channels which is more problematic since cellular users are randomly located thereby making it difficult to manage the significant interference introduced by the cellular users.

The authors in [41] applied proper mode selection and power control schemes to alleviate the interference based on the assumptions that instantaneous channel gains are available at the base station. The mode selection is performed for users to transmit either in the cellular mode or D2D mode (reuse or dedicated) using channel gain as constraint whereas power control is performed based on the SINR at the D2D receiver. The analysis showed that the throughput in D2D (reuse or dedicated) mode is significantly higher than in traditional cellular communication mode. However, assigning dedicated channels to D2D pairs is not always the best since it results in wastage of spectral resources.

The authors in [42] worked on allocating uplink resources to maximise the overall system capacity while guaranteeing the SINR of D2D pairs and cellular UEs. The optimisation problem is divided into power control and channel allocation subproblems. The authors proved that the objective function of the power control problem is a convex function to obtain an optimal transmit power and then designed an optimal selection algorithm for channel assignment to D2D pairs. The simulation outcome demonstrated that the presented algorithms provide a rise in the system performance when compared with the random channel assignment scheme. The shortcoming of [39] - [42] is that the authors avoided relay-assisted D2D communication, hence the applicability of D2D communication becomes limited. To the best of our knowledge, relay-assisted D2D communication underlying cellular networks is still in its infancy. As such, the related works on relay-assisted D2D communication that consider joint interference approaches are discussed as follows.

In [43], the authors proposed a two-stages relay selection and resource allocation joint method for a relay-assisted D2D communication when D2D pairs and relay UEs reuse the uplink channels of cellular users. The first stage determines the range of candidate relay UEs through the design of a regional division method that reduces the range of candidate relay UEs and computational complexity. The second stage selects the optimal relay UE from the candidate relay UEs. A centralised method is also designed to maximise the capacity of the cellular and relay-assisted D2D communication links. The analyses showed that, relative to the other two methods, the proposed methods provide increased throughput and reduced computation complexity.

The authors in [44], considered a D2D relaying approach in an instance where several relay UEs are available. A mixed problem of relay selection and resource allocation is formulated, as an optimisation problem and a simplified relay selection and resource allocation scheme is proposed. The authors used system simulation to demonstrate performance, and the D2D relaying UE with power control provided an increased throughput performance for cell edge users.

The authors in [45] considered a relay transmission mode in addition to the existing cellular and D2D transmission modes. In this work, a transmission mode allocation method based on the Hungarian algorithm is presented to increase the total throughput of the cellular network. The proposed algorithm solves the problem of selecting a suitable transmission mode for each anticipated transmission and selecting suitable relay UE for a relay transmission mode. The

simulation outcome portrayed an increase in the performance of the presented algorithm with regards to total system throughput and D2D access rate when compared with the traditional and random allocation schemes. Although the authors in the above discussed related works have performed a great task in tackling the issue of interference in D2D communication underlying cellular network, there are still some gaps that need to be addressed.

As such, there is the need for this study to address some of the highlighted gaps in the related works for improvement. Motivated by the limited research works on the application of uplink power control schemes in D2D communication underlying cellular network, to the best of our knowledge, it is worth mentioning that this dissertation takes into account the implementation of the uplink power control scheme in D2D communication as an underlay in a cellular network. Consequently, owing to the fact that most of the above discussed related works considered a stand-alone approach in tackling the issue of interference in D2D communication underlying cellular networks, this dissertation focuses on utilising joint methods of mode selection, power control and channel allocation to achieve an efficient solution. Hence the problem is formulated as joint problem and further solved by decomposing into separate sub-problems to avoid computational complexity. Also, with few works on relay-assisted D2D communication, the research work is further extended to study the effect of relay UEs on D2D communication in addressing the issue of interference. The contributions of this dissertation are summarised as follows:

- i. Performance Evaluation of Fractional Power Control in Uplink Device-to-Device Communication:* Despite the benefits of higher signal quality and wider network coverage possibilities associated with higher power transmissions, it can lead to a degradation of the cellular network due to the introduction of interference. Accordingly, the Open Loop Power Control scheme is applied in D2D communication underlying cellular networks to analyse the effect of path loss on the transmit power of D2D UEs. Also, the impact of Fractional OLPC scheme on SINR is studied since SINR is a key determinant of the degree of interference experienced by the network users.
- ii. Uplink Interference Management for Device-to-Device Communication Underlying Cellular Networks:* A channel allocation problem is modelled jointly with mode selection, power control and relay selection problems. The joint problem is then disintegrated and solved as individual subproblems to address interference while maximising the number of permitted D2D pairs for the two scenarios namely, D2D

communication and relay-assisted D2D communication as an underlay to cellular networks.

- iii. *Interference Minimisation for Uplink Channel Reuse in Device-to-Device Communication Underlying Cellular Networks – A Stable Matching Approach*: An overview of matching theory and its application in radio resource allocation is carried out. A channel allocation problem is formulated as a matching problem for a cellular network model where D2D and relay-assisted D2D pairs coexist with cellular UEs. The solution to the matching problem is achieved using the Gale-Shapely algorithm and demonstrated near-optimal performances regarding the number of permitted D2D pairs, average interference and the sum rate of the permitted D2D pairs.

## 2.4 Conclusion

In this chapter, an overview of D2D communication consisting of the aspects of merits and different applications is presented. Next, the classification of D2D communication based on the involvement of the base station and the usage of spectrum is discussed. Interference management in D2D communication, with regards to the research work is highlighted as one of the key challenges that requires attention to fully experience the potentials of D2D communication. Hence, a review of related works addressing interference management in D2D communication underlying cellular networks is presented to identify the gaps in these related works.

The research gaps identified are summarised as follows; the reviewed related works mostly considered stand-alone approaches to tackle the issue of interference, with few reviewed works applying uplink power control schemes and relay assistance in D2D communication underlying cellular networks. Consequently, the contributions to address these gaps respectively are provided by formulating the channel allocation problem as a joint method to minimise interference, analysing the effects of the path loss components of the Open Loop power control scheme on the transmit power and SINR of D2D pairs and then evaluating the performance of relay UEs in assisting D2D communication.

## Chapter 3

### 3 Analytical System Model for Device-to-Device Communication

#### 3.1 Introduction

As highlighted in the second chapter, D2D communication is one of the key enabling technologies, anticipated to support the diverse demands of 5G cellular networks by allowing direct communication between proximate UEs with or without traversing through the base station. It is associated with several applications, use cases and numerous benefits to network operators as well as to the mobile network subscribers. Besides, interference is of utmost concern and a challenge in D2D communication. The underlay D2D communication suffers significant network degradation owing to the challenge of interference. Hence there is the need to efficiently manage interference that arises in D2D communication underlying cellular networks.

In Chapter 2, most of the related works considered a stand-alone approach while few considered a joint approach in tackling the issue of interference in D2D communication underlying cellular network. In view of that, the dissertation fills this gap and considers minimising interference from D2D communication as an underlay to cellular networks by employing channel allocation method jointly with mode selection and power control methods. The joint problem is further solved by decomposing the problem into separated sub-problems to avoid increasing computational complexity. Also, the dissertation considers the implementation of uplink power control schemes in D2D communication underlying cellular networks, since there are limited related works. Lastly, the literature review in this research reveals that few works have been done in using relay UEs to assist D2D communication, especially in the aspect of leveraging it to tackle the issue of interference. Hence, the dissertation further considers relay-assisted D2D communication as an additional transmission mode and analyses how the selection of relay UEs can be leveraged to address interference.

The remainder of this chapter is organised as follows. Section 3.2 presents a detailed explanation of the system model to address the research problem discussed in Chapter 1. In addition, the assumptions and considerations for this model are outlined in Section 3.2. The channel modelling is discussed in Section 3.3 by presenting the three main components of fading, thus, path loss, shadowing and multipath fading, considered for this work. The channel

gain measurements are also given in Section 3.4, where we outlined the essence of having prior knowledge of the channels. The types of channel gains used are highlighted, and the assumptions regarded for the channel state information are also presented for this work. In Section 3.5, the performance metrics are discussed. Finally, the conclusion of the chapter is drawn in Section 3.6.

### 3.2 System Model and Assumptions

In this chapter, a single-cell network is considered, in which a base station ( $o$ ) is located at the centre of the cell with a coverage area radius of  $R$ . The system model adopted in this chapter is depicted in Figure 3.1. In the first network model (a), that is the D2D communication, there exist two types of users present in the network, namely cellular users and D2D pairs.

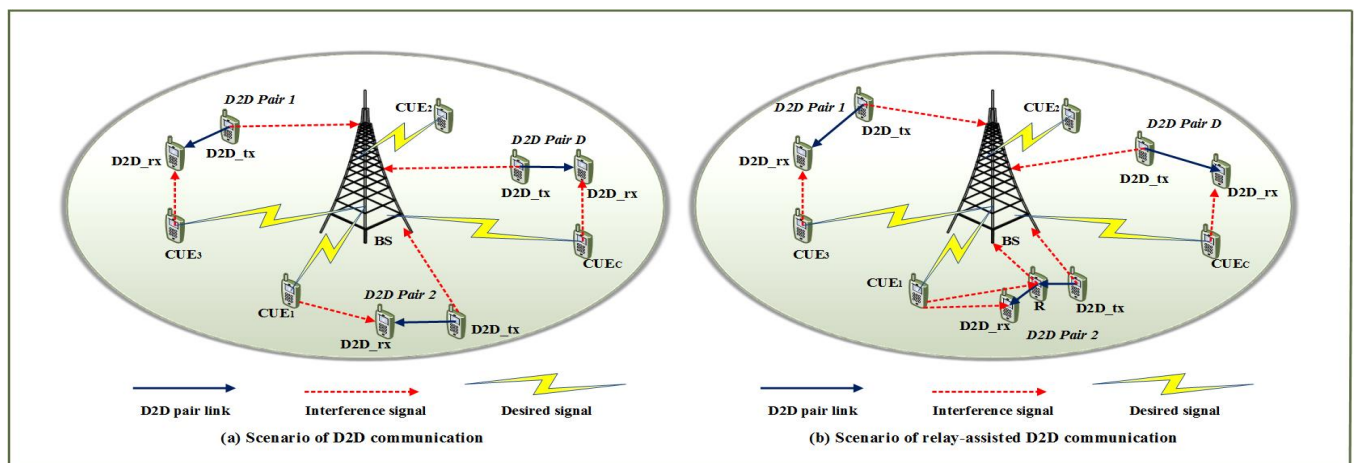


Figure 3.1: System Model of D2D Communication Underlying Cellular Network

The cellular users communicate with the base station. The D2D pairs consist of a transmitting D2D UE and a receiving D2D UE. The D2D pairs communicate directly with each other with less involvement of the base station. In this work, the D2D pairs underlay the cellular network, where cellular users and D2D pairs are regarded as primary users and secondary users, respectively. Also, the introduction of D2D pairs to reuse cellular channels is to complement, rather than degrade the cellular network. Hence, the performances of the cellular users are prioritised in the design of coordination methods in the network.

In the second network model (b), relay UEs are introduced to assist D2D pairs in situations where channel conditions become very bad or when the distance between communicating D2D

pairs increases. The cell in the two network model scenarios is characterised by randomly distributed active users that communicate using cellular uplink channels.

The uplink cellular channels are orthogonally and equally assigned such that a cellular UE is allocated to only one cellular uplink channel. The D2D pairs reuse the uplink channels belonging to cellular UEs by orthogonally accessing these channels [46]. It is assumed that the number of available uplink channels that is reusable by D2D pairs is the same as the number of cellular UEs. A relay-assisted D2D transmission mode is assumed to be a two-hop communication, consisting of two D2D links, from a transmitter to relay; and from the relay to a receiver. The D2D links are assigned to at most, one channel belonging to a cellular UE and likewise, a channel belonging to a cellular UE is allocated to at most one D2D link for reuse. However, without loss of generality, it is technologically possible that a UE, acting as a relay, receives and transmits in the same channel simultaneously if a full duplex mode is considered [47]. It is assumed that the total number of D2D pairs could be less than or equal to the number of available channels. The base station coordinates resource allocation for cellular UEs as well as the D2D pairs.

It is assumed that the serving base station can obtain full knowledge of the CSI of all communicating devices that are connected to it. When the uplink channels of cellular UEs are shared with D2D pairs, primarily two types of interference are introduced namely;

- Interference caused by D2D pairs to the base station.
- Interference caused by cellular UEs to D2D receiver.

In this work, the focus is to mitigate intra-cell and co-channel interference that arises when D2D pairs share the same uplink channels belonging to cellular UEs. The channel gain between communicating cellular UEs or D2D pair is composed of distance-based path loss, slow fading arising from shadowing and fast fading due to multipath propagation effects.

### **3.3 Channel Model**

The motive behind communication is to transport information through the medium between a transmitter and receiver. Hence, a channel is a medium that separates a transmitting antenna from a receiving antenna. The behaviour of radio signals is dependent on the propagation environment including buildings and other obstructing objects that surround the path of the propagated signal, the distance between the transmitting and receiving antennas and the path(s)

taken by the propagated signal. A distinctive feature of the wireless channel is the fading phenomenon. Fading in wireless communication is the variation of the signal amplitude over time, frequency and geographical location, the latter being the attribute of large scale fading; and is categorised as, large scale fading and small scale fading [48]. The relationship between large scale and small scale fading is illustrated in Figure 3.2.

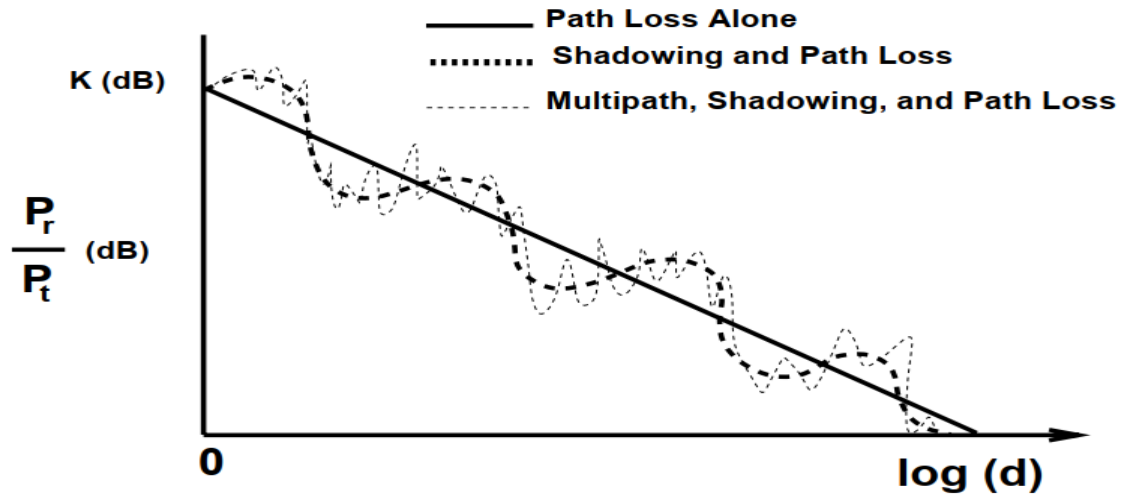


Figure 3.2: Path loss, Shadowing and Multipath [49]

Path loss and shadowing effects fall under large scale fading whereas multipath fading effects fall under small scale fading. However, it is arguable that path loss is part of the fading phenomena; it is rather complementary to fading. Path loss is a deterministic factor that can be obtained from the distance between a transmitter and receiver. Unlike the path loss, shadowing and small scale fading are not deterministic but are random phenomena with effects that can be predicted only by probabilistic distribution. The three key components considered for the channel model are path loss, shadowing and multipath fading.

### 3.3.1 Path loss

Path loss is the power attenuation of a signal as it propagates from a transmitter to a receiver. The free space path loss model is the simplest signal propagation model and has no objects within the path between the transmitter and the receiver. This model is adopted in Line-of-Sight (LOS) environments to measure Received Signal Strength (RSS). The free space path loss model is obtained from the Friis formula in [48], and it is given as:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (3.1)$$

where  $P_r$  represents received power at distance  $d$ ;  $P_t$  is the transmit power;  $G_t$  and  $G_r$  denote the transmit and receive gains of non-isotropic antennas. Additionally,  $\lambda$  is the wavelength of the transmitted carrier;  $d$  denotes the distance in metres between the transmitter and the receiver and  $L$  is the system loss factor that is independent of the propagation environment. The free space path loss is derived from Equation (3.1) by first assuming that there is no loss in the system hardware and finally assuming that there are no antenna gains, given that  $L = 1$  and  $G_t = G_r = 1$  respectively, hence;

$$PL_f = \frac{P_t}{P_r} = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (3.2)$$

However, the free space path loss model is inapplicable for all propagation scenarios encountered in real life. The complexity of signal propagation through a medium makes it challenging to achieve a model that accurately depicts path loss across different types of environments. Therefore, for general tradeoff analysis, it is appropriate to exploit a simple model that represents the essence of signal propagation without falling back on complicated path loss models [50].

In this work, the log-distance path loss model is considered. The log-distance path loss model is a simplified and more generalised form that is constructed by modifying the free space path loss model with the path loss exponent  $\gamma$ , that varies with a change in the environment [48]. This model is expressed as [49]:

$$P_r = P_t \overline{PL}_f(d_0) \left(\frac{d_0}{d}\right)^\gamma \quad (3.3)$$

Converting Equation (3.3) into decibels (dB) gives the log-distance path loss as:

$$PL \text{ dB} = 10 \log \frac{P_t}{P_r} = \overline{PL}_f(d_0) + 10\gamma \log_{10} \frac{d}{d_0} \quad (3.4)$$

where  $d_0$  is a reference distance,  $\overline{PL}_f(d_0)$  is the mean path loss in dB at distance  $d_0$  and  $PL \text{ dB}$  is the log-distance path loss in dB. Irrespective of the fact that the distance between a transmitting and receiving user could be equal to each other, these users may experience different path loss since they have different paths with different obstructions. Hence, it is necessary to take into account the log-normal shadowing model.

### 3.3.2 Shadowing

When a signal is transmitted through a wireless channel, it experiences random variation from objects such as buildings, trees and mountains, blocking the transmitted signal, resulting in random variations in the received power of the transmitted signal at a given distance. This effect of signal attenuation is referred to as Shadowing. The common model is the log-normal shadowing model that has been empirically confirmed to accurately model the variation in received power in outdoor and indoor propagation environments [49]. The path loss then becomes:

$$PL \text{ dB} = \overline{PL}_f(d_0) + 10\alpha \log_{10} \frac{d}{d_0} + X_\sigma \quad (3.5)$$

where  $X_\sigma$  represents a Gaussian random variable with a zero mean and a standardisation of  $\sigma$ . This model allows receivers at the same distance to experience different path loss with varying log-normal distributions.

### 3.3.3 Multipath Fading

Multipath fading occurs when a signal is transmitted over multiple reflective paths, causing variations in the amplitude and phase of the signal, and introducing constructive and destructive interferences. The magnitude of a signal travelling through a channel can be assumed to either vary randomly according to a Rayleigh distribution in a Non-line-of-sight (NLOS) environment for Rayleigh fading models or a Rician distribution in a Line-of-sight environment for Rician fading models. The Rayleigh fading model is appropriate for scattering mechanisms where there are many small reflectors. However, it is adopted primarily because of its simplicity in typical cellular networks with a small number of reflectors [50]. Hence, a Rayleigh fading model is also considered in this dissertation for channel modelling.

With reference to the Central Limit Theorem (CLT), the Rayleigh fading model can be represented by Gaussian random variables,  $X$  and  $Y$ , forming complex Gaussian random variables,  $X + jY$ .  $X$  and  $Y$  are independent and identically distributed Gaussian random variables with a zero mean and equal variance of  $\sigma^2$  [48]. The amplitude of the complex Gaussian random variables,  $R$  is given as:

$$R = \sqrt{X^2 + Y^2} \quad (3.6)$$

where  $R$  is a Rayleigh random variable with a Probability Density Function (PDF) as follows;

$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0, 2\sigma^2 = E|R^2| \quad (3.7)$$

### 3.4 Channel Gain Measurements

It is necessary to perform channel measurements to obtain channel state information, to have prior knowledge of the condition of channels of UEs for better power control and resource allocation, leading to an optimal management of interference. The following channel gains are regarded as shown in Figure 3.3.

Transmitter	$o$	$D2D_{rx}$	$R$
Receiver	$CUE$	$D2D_{tx}$	$R$
	$R$	$R$	$X$

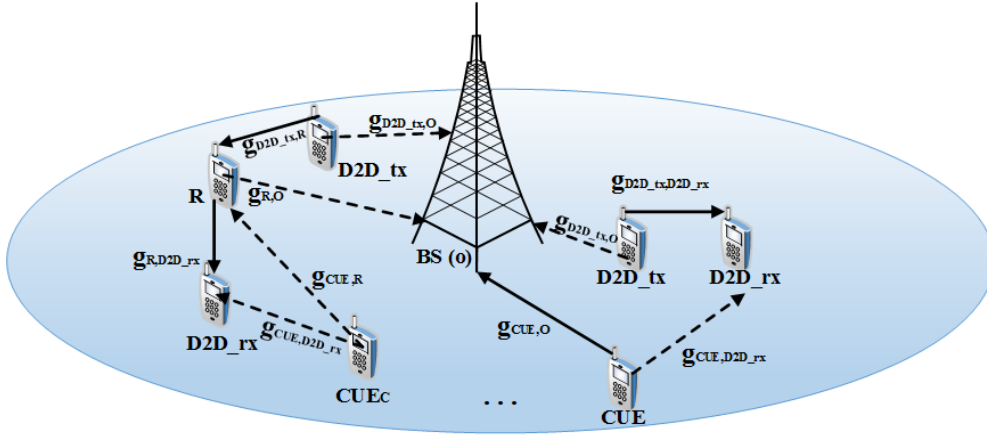
$$\begin{pmatrix} \mathcal{G}_{CUE,o} & \mathcal{G}_{CUE,D2D_{rx}} & \mathcal{G}_{CUE,R} \\ \mathcal{G}_{D2D_{tx},o} & \mathcal{G}_{D2D_{tx},D2D_{rx}} & \mathcal{G}_{D2D_{tx},R} \\ \mathcal{G}_{R,o} & \mathcal{G}_{R,D2D_{rx}} & X \end{pmatrix}$$


Figure 3.3: Channel gain links of cellular UEs coexisting with D2D pairs and relay-assisted D2D pairs

Where;

- $\mathcal{G}_{CUE,o}$  is the channel gain between the cellular UE and base station.
- $\mathcal{G}_{D2D_{tx},D2D_{rx}}$  is the channel gain between the D2D transmitter and the D2D receiver.
- $\mathcal{G}_{D2D_{tx},o}$  is the channel gain between a D2D transmitter and a base station.
- $\mathcal{G}_{CUE,D2D_{rx}}$  represents the channel gain between the cellular UE and the D2D receiver.
- $\mathcal{G}_{D2D_{tx},R}$  is the channel gain between the D2D transmitter and the relay UE.
- $\mathcal{G}_{R,D2D_{rx}}$  is the channel gain between the relay UE and the D2D receiver.

- $g_{R,o}$  is the channel gain between the relay UE and base station.
- $g_{CUE,R}$  represents the channel gain between the cellular UE and relay UE.

The channel links directing to the base station,  $g_{CUE,o}$ ,  $g_{D2D_{tx},o}$  and  $g_{R,o}$  are usually obtained at the base station. Also, it is possible to acquire knowledge of the channels,  $g_{D2D_{tx},D2D_{rx}}$ ,  $g_{D2D_{tx},R}$  and  $g_{R,D2D_{rx}}$ , by the base station during device discovery. The most challenging channel knowledge acquisition is the interference channels,  $g_{D2D_{tx},o}$ ,  $g_{CUE,D2D_{rx}}$ ,  $g_{CUE,R}$  and  $g_{R,o}$ . Therefore, it is assumed that the base station has perfect knowledge of the CSI of cellular UEs and D2D pairs.

### 3.5 Performance Metrics

The performances of the interference coordination schemes considered in the dissertation are evaluated using these key metrics related to the research work.

- Transmit Power Spectral Density (PSD) of D2D pairs: Transmit PSD represents the total power contained in a physical resource block or channel. This parameter is useful in analysing the potential for interference that is experienced by cellular UEs from the reuse of cellular channels by D2D pairs. Most importantly, the transmit PSD of D2D pairs is used in this research work as a metric to analyse the performance of OLPC and Fractional OLPC schemes by considering the path loss compensation and initial power per cellular channel as factors. Hence, the impact of these factors on transmit PSD of D2D pairs is considered to determine how the OLPC and Fractional OLPC schemes compensate for transmitted signal degradation as a result of path loss.
- SINR of D2D receivers: SINR is a key metric in evaluating the performance and QoS experienced by users within a cellular network. It is also used in measuring the degree of interference encountered by users in a cellular network. Accordingly, the performance of the Fractional OLPC is further analysed in this research work by considering the effect of the path loss compensation and initial power per cellular channel factors on the SINR of D2D receivers. Thus, the dependency between the Fractional OLPC factors on the SINR of D2D receivers are studied to determine how these parameters influence the level of interference in a D2D communication underlying a cellular network.

- Average number of permitted D2D pairs (with or without relay assistance): This metric provides an insight on the total number of D2D pairs that can be permitted to reuse the channels belonging to cellular UEs based on designated SINR and interference thresholds. The average number of permitted D2D pairs is considered as a performance metric to analyse how the QoS of cellular users can be guaranteed while efficiently utilising spectral resources. This performance is measured by allowing D2D pairs with minimal interference to cellular users to reuse the uplink cellular channels.
- Average interference: This indicator is considered for performance evaluation since it is the main problem that needs to be addressed in this dissertation and consequently requires performance measurement. Moreover, ineffective management of interference can lead to the degradation of the total network performance, hence the average interference caused by the permitted D2D pairs (with or without relay assistance) is measured by analysing the impact of SINR and interference thresholds. Furthermore, the impact of the selection of idle UEs to act as relays for D2D pairs on the average interference introduced into the cellular network is measured.
- Sum rate: This is an indicator for a successful transfer of information between D2D pairs or cellular UEs, and it is measured in *bits/s/Hz*. Also, high measurements of sum rate indicate good network performance. For this reason, the impact of the permitted D2D pairs (with or without relay assistance) on the total system sum rate is measured to determine how the introduction of D2D communication into cellular network affects the network performance.

### 3.6 Conclusion

In this chapter, the system model scenarios and key assumptions related to D2D communication have been discussed. The fading phenomenon, which is a distinctive feature of wireless communication has been elaborated. The three main components of fading, thus path loss, shadowing and fading are presented, and the types of models in these components, considered for this research work are highlighted. Moreover, the different channel gains employed in this dissertation are discussed, since prior knowledge of the channel provides better interference management. Finally, in this dissertation, the performance measures considered for the study of the performance of the proposed schemes and the importance of the measures are discussed.

## Chapter 4

# 4 Performance Evaluation of Fractional Power Control in Uplink Device-to-Device Communication

### 4.1 Introduction

The previous discussions in Chapter 2 indicate that D2D communication is a feature in the next generation cellular networks, geared towards enhancing spectral utilisation, total system throughput, power consumption, channel capacity and latency through the reuse of cellular resources by D2D pairs. Regardless of the merits of this mode of communication, it is faced with the challenge of interference. It is necessary for network operators to employ the method of uplink power control to limit the power levels of D2D transmitters, thereby improving the performance of the cellular network.

Although OFDMA can be used as the access technique in uplink channels, it is associated with high peak-to-average power ratio, hence an alternative, Single Carrier FDMA which is a modified OFDMA is preferred. Power is an important resource in communication systems that needs to be controlled since it plays an effective role in the network performance. Hence, the standardised 3GPP uplink power control method is defined; composing of open loop and closed loop components [51].

The Open Loop Power Control (OLPC) scheme is mostly regarded in cellular networks because it is associated with low signal overheads, thereby providing simple implementation and low operation costs [52]. Hence, it is important to consider the analysis of the open loop components for efficient radio resource management from the perspective of network operators. This chapter focuses on evaluating the open loop power control scheme in D2D communication underlying cellular networks. The need to obtain a reduced interference level and a required SINR level is interdependent since the intensity of transmit power determines the degree of interference. The objective of this chapter is to analyse the performance of the OLPC scheme in relation to two main indicators, the received signal power and path loss compensation factor. The dependency of the indicators on the SINR of D2D receivers is evaluated to determine how these parameters influence the level of interference in a D2D communication underlying a cellular network.

The remaining sections of this chapter are structured as follows: Section 4.2 highlights the key notations used in this chapter. Section 4.3 presents the system model considered to analyse the power control scheme. Section 4.4 outlines the formulated problem, mathematical expressions for the evaluation of the performance of the OLPC scheme, methodology and simulation parameters considered for the implementation of this scheme. Section 4.5 discusses the simulation outcome and performs a comparative evaluation of the considered indicators to examine the performance of the OLPC scheme. Section 4.6 provides the conclusion of this chapter.

## 4.2 Notations

A few notations used in this chapter are outlined in Table 4.1 as follows:

Table 4.1: Summary of Notations

Symbol	Description
$N_u$	Total number of randomly distributed active users in a single cell
$N$	Total number of transmitters
$M$	Total number of receivers
$P_{n\_d2d}$	D2D transmit power in the uplink channel
$P_{n\_d2d}^{max}$	Maximum D2D transmit power in the uplink channel
$P_o$	Power contained in a channel
$C$	Number of allocated channels per user
$\alpha$	Path loss compensation factor
$PL_{n\_d2d,m\_d2d}$	Estimated uplink path loss between transmitting and receiving D2D link
$\delta_{mcs}$	Cell or UE specific modulation and coding scheme defined in 3GPP. Not considered in this work.
$f(\Delta)$	Closed loop correction function. Not considered in this work.
$SNR_o$	Open loop signal-to-noise ratio (SNR) threshold
$C_o$	Number of channels for which the SNR is reached with the maximum power. It is set to one (1) in this implementation.
$P_{no}$	Noise power in a channel
$\delta^2$	Variance of a Gaussian random variable with a Rayleigh distribution
$P_{OL}$	Open loop transmit power

### 4.3 System Model

A D2D communication underlying cellular network scenario, consisting of cellular UEs and D2D pairs, coexisting in a single cell is considered.  $N_u$  denotes the total number of randomly distributed active users in a single cell and  $o$  represents the base station.  $N_u$  comprises of  $N$  transmitters and  $M$  receivers.  $N = \{1, 2, 3, \dots, n\}$  denotes the set of transmitting UEs and  $M = \{1, 2, 3, \dots, m\}$  represents the set of receiving UEs. Figure 4.1 illustrates the system model of D2D communication underlying a cellular network. As discussed in Chapter 3, the path loss model, the log-normal shadowing model and Rayleigh fading model were considered for designing the channel.

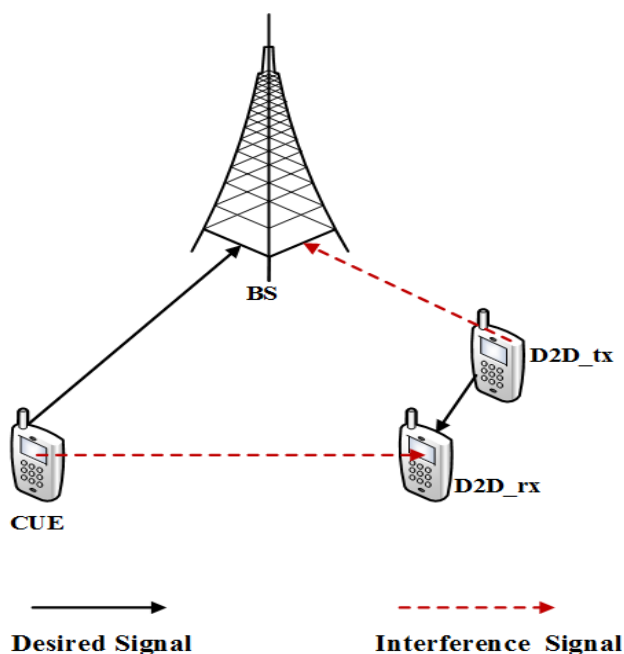


Figure 4.1: The system model of D2D communication underlying cellular network

### 4.4 Problem Formulation

The open loop component utilises the fractional power control scheme to offset slow variations in path loss and shadowing, whereas closed loop component offsets fast variations to improve network performance. The target is to minimise interference introduced when D2D pairs share the uplink channels with cellular users, hence the power of a D2D transmitter is limited in this case. The transmit power of a D2D UE,  $P_{n\_d2d}$  transmitting in the uplink channel is defined in Equation (4.1) from [27] as:

$$P_{n\_d2d} = \min\{P_{n\_d2d}^{max}, P_o + 10 \log(C) + \alpha PL_{n\_d2d,m\_d2d} + \delta_{mcs} + f(\Delta)\} [dBm] \quad (4.1)$$

The parameter  $P_o$  is expressed in Equation (4.2) from [53] as:

$$P_o = \alpha \cdot (SNR_o + P_{no}) + (1 - \alpha)(P_{n\_d2d}^{max} - 10 \cdot \log C_o) [dBm] \quad (4.2)$$

The parameters  $P_o$  and  $\alpha$  are the same for all users within a cell and are signalled from the eNB to the UEs as broadcast. Path loss is calculated at the UE based on the Reference Symbol Received Power (RSRP), to help the UE initially set the transmit power. The closed loop terms,  $\delta_{mcs}$  depends on the modulation and coding scheme selected while  $f(\Delta)$  permits the use of absolute correction value that is signalled by the eNB to a UE after its initial power is set [26]. These closed loop terms are not taken into account and are assumed to be zero [52] in this study because the focus of the research work is on the open loop components. Hence, neglecting  $\delta_{mcs}$  and  $f(\Delta)$  gives the open loop power control scheme for the D2D transmit power, expressed in Equation (4.3) as:

$$P_{OL} = \min(P_{n\_d2d}^{max}, P_o + 10 \log C + \alpha PL_{n\_d2d,m\_d2d}) [dBm] \quad (4.3)$$

The preference of path loss compensation factor values represented as  $\alpha$ , depends on whether a conventional OLPC scheme ( $\alpha = 1$ ) or fractional OLPC scheme ( $0 < \alpha < 1$ ) is considered. In this work, the path loss compensation factor ranging from 0 to 1 is used. The term,  $10 \log C$  can be neglected because the OLPC scheme defines the level of transmit power in a single cellular channel for each D2D pair, where  $C = 1$ . Also, it is assumed that the D2D transmitters take into consideration the power limitation when defining the transmit power level, hence the power limitation,  $P_{n\_d2d}^{max}$  can be neglected [54], [55]. In view of this, the power transmitted across an allocated cellular channel is constant, or in other words, the power spectral density over a transmission bandwidth is constant [26]. Hence, PSD is a measure of the transmit power per channel. This gives the expression for the transmit power spectral density,  $PSD_{n\_d2d}$  in Equation (4.4) as:

$$PSD_{n\_d2d} = P_o + \alpha PL_{n\_d2d,m\_d2d} [dBm] \quad (4.4)$$

The  $PSD_{n\_d2d}$  can also be expressed in  $mW$  as:

$$PSD_{n\_d2d} = P_o (PL_{n\_d2d,m\_d2d}^\alpha) [mW] \quad (4.5)$$

Substituting  $P_o$  with Equation (4.2) in Equation (4.4) gives  $PSD_{n\_d2d}$  as:

$$PSD_{n\_d2d} = \alpha \cdot (SNR_o + P_{no}) + (1 - \alpha)(P_{n\_d2d}^{max} - 10 \cdot \log C_o) + \alpha PL_{n\_d2d,m\_d2d} [dBm] \quad (4.6)$$

The  $PSD_{n\_d2d}$  is linearly dependent on  $P_o$ , whereas  $\alpha$  weighs its dependency with the path loss,  $PL_{n\_d2d,m\_d2d}$ . The parameters  $P_o$  and  $\alpha$  are equal for all users within a cell, while  $\alpha PL_{n\_d2d,m\_d2d}$  varies for each transmitting user within a cell depending on the level of path loss experienced. Accordingly, the analysis is extended to SINR to determine the performance of fractional OLPC technique. The influence of the parameters,  $P_o$  and  $\alpha$  on the Cumulative Distributive Function (CDF) of the SINR of D2D receivers is discussed and evaluated for a better understanding of the fractional OLPC scheme. It is necessary to regard the SINR CDF of D2D receivers because it corresponds to the outage probability of these D2D receivers, thus the probability that a user will experience an unsuccessful communication and is therefore not accepted in the network [56],[57]. Hence the outage probability is the probability when the instantaneous SINR falls below a given SINR threshold,  $\gamma_{th}$ . The SINR CDF is expressed in Equation (4.7) as:

$$F_{\gamma_{n\_d2d,m\_d2d}}(\gamma_{th}) = Pr(\gamma_{n\_d2d,m\_d2d} \leq \gamma_{th}) \quad (4.7)$$

According to Lemma 1 in [58], the CDF of  $\gamma_{n\_d2d,m\_d2d}$  is expressed in Equation (4.8) as:

$$F_{\gamma_{n\_d2d,m\_d2d}}(\gamma_{th}) = 1 - \frac{PSD_{m\_d2d}}{PSD_{m\_d2d} + (\gamma_{th})I} e^{-\frac{N_o(\gamma_{th})}{2\delta^2 PSD_{m\_d2d}}} \quad (4.8)$$

The SINR at a D2D receiver,  $\gamma_{n\_d2d,m\_d2d}$  is given in Equation (4.9) from [27] as:

$$\gamma_{n\_d2d,m\_d2d} = \frac{PSD_{m\_d2d}}{I + N_o} \quad (4.9)$$

Where  $PSD_{m\_d2d}$  represents received power spectral density of a D2D receiver,  $I$  and  $N_o$  denote interference power and thermal noise power density respectively. The received power spectral density,  $PSD_{m\_d2d}$  is expressed in Equation (4.10) as:

$$PSD_{m\_d2d} = \frac{PSD_{n\_d2d}}{PL_{n\_d2d,m\_d2d}} [mW] \quad (4.10)$$

Replacing  $PSD_{n_{d2d}}$  with Equation (4.5) in Equation (4.10) gives:

$$PSD_{m_{d2d}} = P_o (PL_{n_{d2d}, m_{d2d}}^{\alpha-1}) [mW] \quad (4.11)$$

It is obvious from Equation (4.11) that when  $\alpha = 1$  in the conventional OLPC scheme, the received power spectral density becomes equal to  $P_o$  thereby assigning all D2D transmitters with equal power. In the case of  $0 < \alpha < 1$  in the fractional open loop power control scheme, the received power spectral density depends on the path loss of the user. Hence  $PSD_{m_{d2d}}$  varies for each user due to different path loss experienced by the users. Substituting  $PSD_{m_{d2d}}$  in Equation (4.9) with Equation (4.11) gives:

$$\gamma_{n_{d2d}, m_{d2d}} = \frac{P_o (PL_{n_{d2d}, m_{d2d}}^{\alpha-1})}{I + N_o} \quad (4.12)$$

Rewriting Equation (4.12) in dB gives:

$$\gamma_{n_{d2d}, m_{d2d}} = P_o + (\alpha - 1)PL_{n_{d2d}, m_{d2d}} - I - N_o [dB] \quad (4.13)$$

The algorithm for achieving the performance evaluation of the fractional OLPC scheme is summarised below in Algorithm 4.1. Table 4.2 summarises the list of simulation parameters used for the simulation.

---

#### Algorithm 4.1

---

1. **Initialisation:** Setting  $N_u$ ,  $N$  and  $M$  to 0, and obtaining their coordinates.
  2. For all  $(n, m)$  transmissions, perform mode selection for transmission either in cellular or D2D mode.
  3. Setting path loss component to  $0 < \alpha < 1$
  4. *for*  $z = 1: \text{length}(\alpha)$
  5.     Compute the initial power using Equation (4.2)
  6.     Calculate open loop D2D transmit power using,  
 $P_{OL} = \min(P_{max}, P_o + 10 \log C + \alpha(z)PL_{n_{d2d}, m_{d2d}})$
  7.     Compute  $PSD_{n_{d2d}}$  using Equation (4.4)
  8.     Calculate SINR,  $\gamma_{n_{d2d}, m_{d2d}}$ , using Equation (4.12)
  9.     Obtain CDF of SINR,  $\gamma_{n_{d2d}, m_{d2d}}$ , using Equations (4.7) and (4.8)
  10. *end for*
-

Table 4.2: Simulation Parameters

Parameter	Value
Cell radius	300m
Channel bandwidth	10MHz
Thermal Noise	-116dBm
Path loss model for D2D pairs	$148 + 40.6\log_{10}(d[\text{km}])$
Path loss model for cellular link	$128.1 + 37.6\log_{10}(d[\text{km}])$
Distance limitation for D2D link	30m
Maximum transmit power of D2D UE	21dBm
Maximum transmit power of cellular UE	24dBm
Number of Monte Carlo simulation runs	500

#### 4.5 Simulation Results and Discussion

The concept of the fractional open loop power control scheme is further analysed in this section. The simulation of this work is done using MATLAB simulator. Figure 4.2 shows the effect of the path loss compensation factor,  $\alpha$  on the transmit power spectral density,  $PSD_{n,d2d}$  when the compensation factor,  $\alpha$  is varied from 0 to 1. It is observed from Figure 4.2 that the transmit power spectral density,  $PSD_{n,d2d}$  increases as the path loss increases. While maintaining initial power  $P_o$  and varying  $\alpha$ ,  $\alpha = 1$  provides the highest  $PSD_{n,d2d}$  that focuses to compensate for the degradation of a transmitted signal as a result of path loss.

The compensation is done such that a D2D UE transmits with a higher power as path loss increases. Consequently, when  $\alpha = 0.8, 0.6$  or  $0.4$ ,  $PSD_{n,d2d}$  increases as the path loss increases, following the same propensity of  $\alpha = 1$ , where the previous values of  $\alpha$  have higher dispersion distribution of the transmit power spectral density than the subsequent  $\alpha$  values. Hence the contrast in values for  $PSD_{n,d2d}$  at  $40dB$  path loss is lower than that of the  $70dB$  path loss, signifying that users at the edge of the cell experience more path loss than users at the centre of the cell.

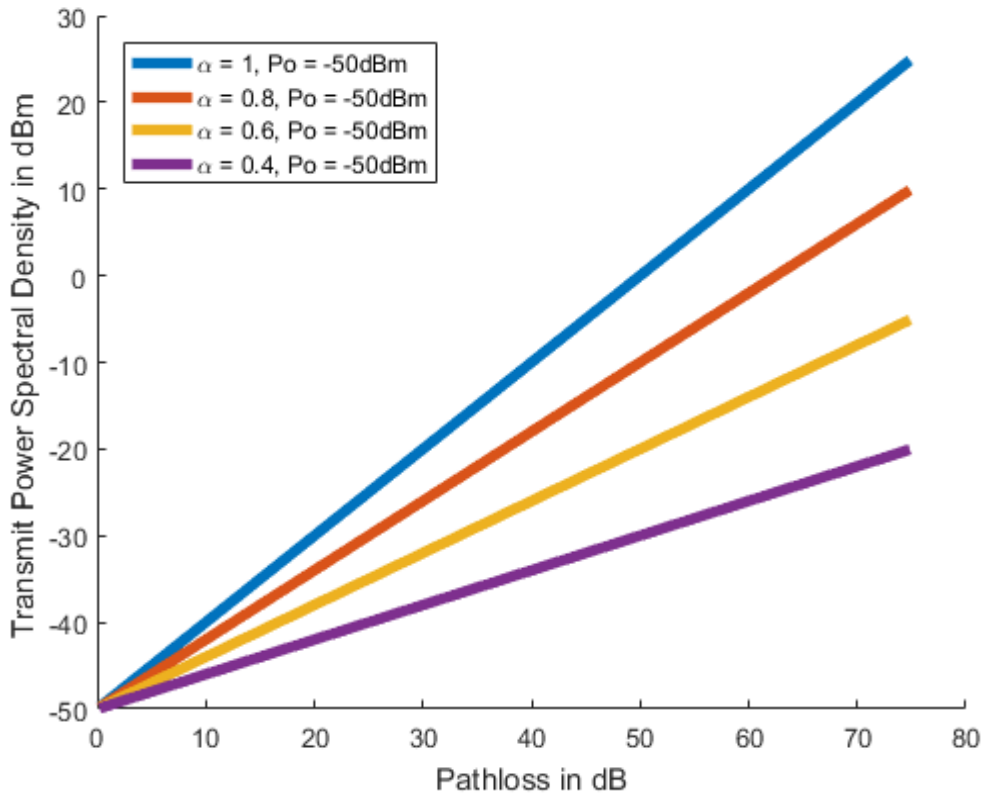


Figure 4.2: Transmit power spectral density for Fractional OLPC scheme

Also, it is noteworthy that when  $\alpha = 0$ , there is no power control and all UEs present in the cellular network therefore transmit with the same power with no compensation for path loss. With regard to  $\alpha = 1$ , D2D UEs are allowed to transmit with a power that completely compensates for the path loss, and this scheme is known as full compensation or conventional OLPC. In the case of  $\alpha$  with values between 0 and 1, compromising is done between no power control and conventional power control where D2D UEs are allowed to transmit at a power that compensates for a fraction of the path loss.

The effect of fractional OLPC parameters on the SINR experienced by D2D receivers are analysed since SINR is one of the key factors that determines the throughput of a UE. The performance of SINR is presented for low, intermediate and high values of  $P_o$  and varying values of  $\alpha$ . Figure 4.3 illustrates the SINR distribution for a fixed initial power  $P_o = -50\text{dBm}$  with contrasting path loss compensation values ranging from  $\alpha = 0.4, 0.6$  to  $0.8$ . It can be observed from Figure 4.3 that the distribution spread of SINR for lower values of  $\alpha$  is wider than the higher values of  $\alpha$ .

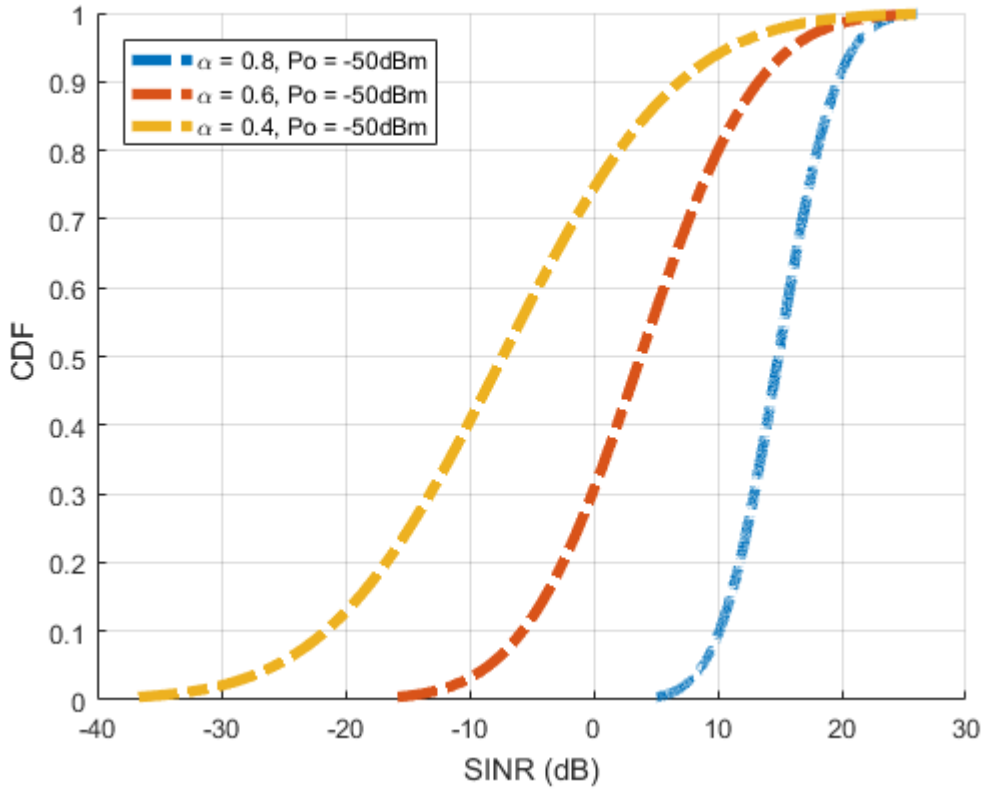


Figure 4.3: Impact on SINR per user when  $P_o$  is constant and  $\alpha$  is varied

A lower value of the path loss compensation component  $\alpha$  leads to a reduction of the power at which a D2D UE is expected to transmit and vice versa, resulting in a reduced SINR with a wider distribution spread that creates a contrast in SINR of users located at the edge or centre of a cell. Hence, the initial power per channel  $P_o$  controls the mean of SINR whereas  $\alpha$  controls the variance of SINR. It can also be deduced from Figure 4.3 that the probability of users with SINR less than  $10dB$  when  $\alpha = 0.4, 0.6$  and  $0.8$  are approximately 94%, 80% and 10% respectively.

The performance of SINR is illustrated in Figures 4.4 and 4.5 where the path loss compensation component is constant,  $\alpha = 0.6, 0.8$  and the initial power per channel is varied between low, mid and high values,  $P_o = -30dBm, -50dBm, -70dBm$ . It is observed that the SINR distribution shifts to the right, demonstrating an increase in the total SINR of users within a cellular network. Accordingly, the lower values of  $\alpha$  has a wider distribution spread of SINR than the higher values.

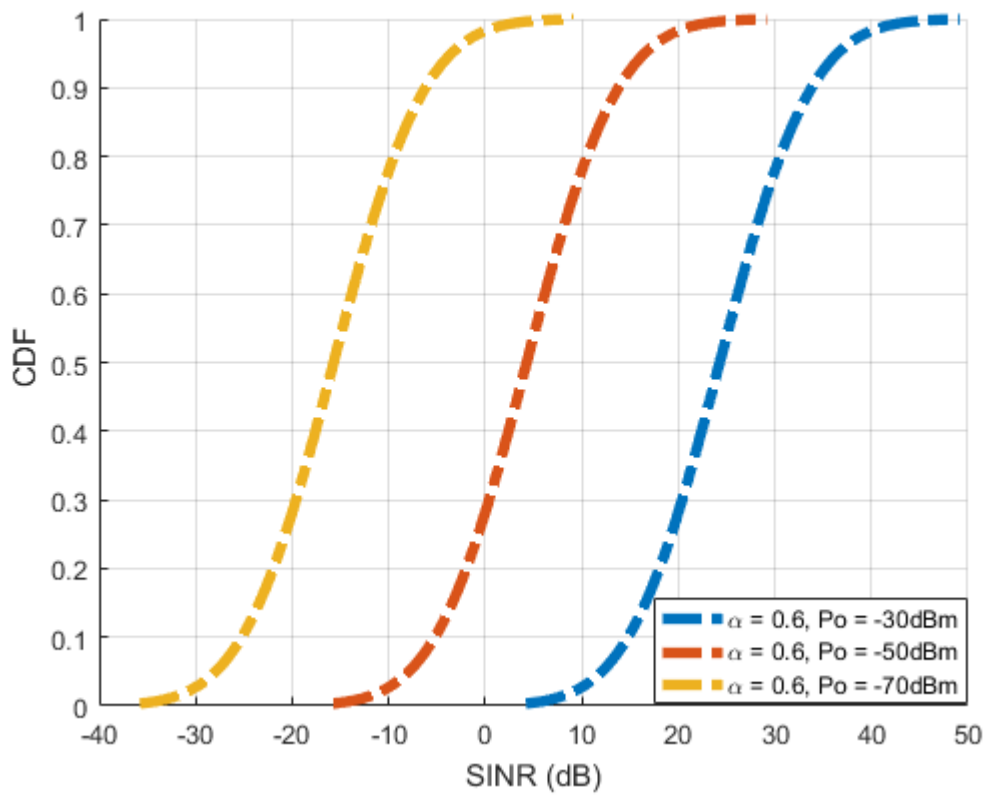


Figure 4.4: Impact on SINR per user when  $P_o$  is varied and  $\alpha = 0.6$

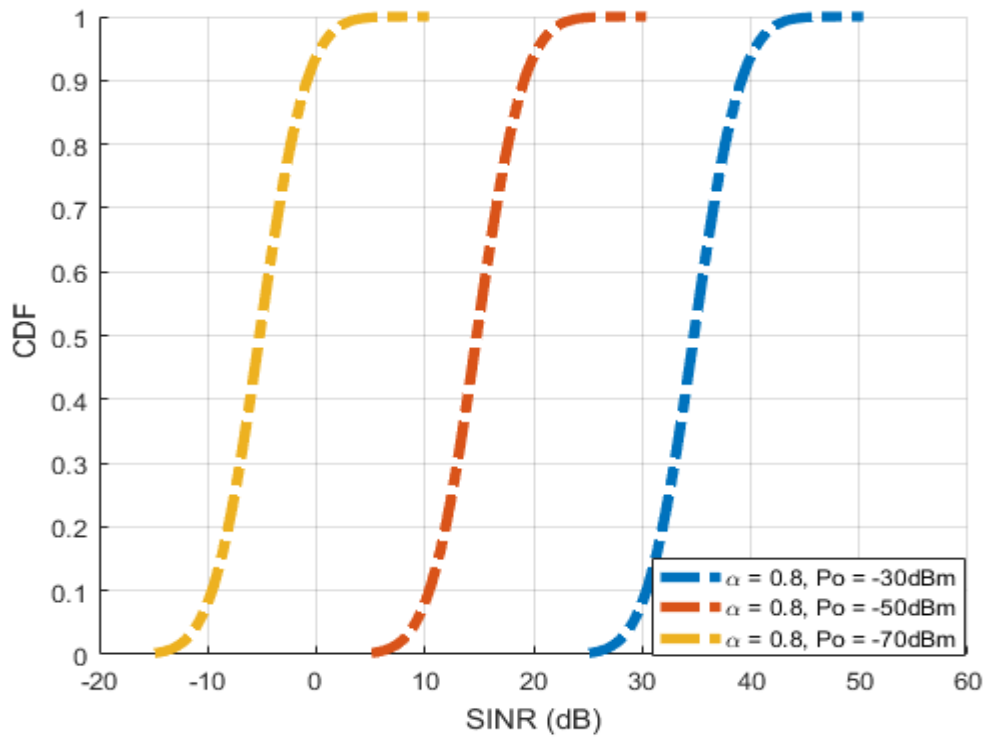


Figure 4.5: Impact on SINR per user when  $P_o$  is varied and  $\alpha = 0.8$

For instance, considering the plot of  $\alpha = 0.6, P_o = -30dBm$  in Figure 4.4 and  $\alpha = 0.8, P_o = -30dBm$  in Figure 4.5, this observation is confirmed with the subsequent plots following the same pattern, where Figure 4.4 has a wider SINR distribution spread than Figure 4.5. Although, lower values of  $\alpha$  gives wide SINR distribution, these lower values are associated with low SINR. Hence it can be deduced that Figure 4.5 has higher SINR compared with Figure 4.4. However, the increase in  $P_o$  in Figure 4.4 and Figure 4.5 increases the transmit power level of the users, consequently causing an increase in interference with a lower rise in SINR than expected [59]. These results are similar to [26],[27], where the authors focused on LTE power control mechanisms for uplink channels in a cellular network setting as discussed earlier in Chapter 2.

## 4.6 Conclusion

The performance of Fractional open loop power control scheme in D2D communication underlying cellular networks is analysed. The focus is to control the transmit power of D2D UEs to minimise the interference caused by D2D pairs when they share the same channel with cellular UEs. The performance evaluation of this power control method was carried out in MATLAB simulation environment while considering received signal power and path loss compensation factor as performance indicators. The mathematical expressions required in the formulation of the power control problem were presented in this chapter.

The impact of path loss compensation factor on transmit spectral density is studied. The simulation result portrayed that users at the edge of a cell encounter higher level of path loss than the users at the centre of a cell. Hence the conventional OLPC compensates for the path loss by allowing the D2D UEs to transmit at a higher power when compared with the fractional OLPC which compromises between the No power control method and the conventional open loop power control scheme. The effects of varying the initial power per channel,  $P_o$  and path loss compensation component,  $\alpha$  on SINR are evaluated. The simulation results showed that the expected performance of SINR is dependent on  $P_o$  and  $\alpha$ ; a reduction in  $\alpha$  results in a lower transmit power with reduced SINR and an increase in  $P_o$  leads to higher transmit power with a lower rise in the expected SINR. Hence it is necessary to finely adjust these parameters for improved performance of SINR.

## Chapter 5

# 5 Uplink Interference Management for Device-to-Device Communication Underlying Cellular Networks

## 5.1 Introduction

Device-to-Device communication provides several performance gains by allowing UEs to communicate directly without going through the base station. Despite these benefits, as discussed in Chapter 2, integrating D2D communication as an underlay to cellular networks introduces several challenges in areas such as radio resource allocation and interference management. Accordingly, these challenges need to be addressed to harness the full potentials of D2D communication. The cause of interference is mainly as a result of D2D UEs sharing the same uplink or downlink channels belonging to cellular UEs. As outlined in Section 1.6, D2D pairs are only permitted to reuse the uplink channels of cellular users in this work.

The QoS for cellular communication should not be degraded by the introduction of D2D communication as an underlay to the cellular network. If this happens, then the applicability and significance of D2D communication will not be established effectively. The performance of D2D communication becomes practically limited when the communicating D2D pairs have bad channel conditions or long distances. Hence there is the need for the introduction of relay UEs to assist in D2D communication in such conditions to help enhance performance. Consequently, the issue of interference associated with D2D communication underlying cellular network is tackled in several research works.

This chapter considers modelling the problem of channel allocation in a single cell using the two scenarios illustrated in Figure 5.1, namely D2D communication and relay-assisted D2D communication scenarios. A mode selection algorithm using Nearest Neighbour Search (NNS) is implemented to select the mode of communication for users. Then, a power minimisation problem is formulated to obtain a power allocation solution for D2D transmitters and relay UEs. It is presumed that at most, one channel belonging to a cellular user can be reused for D2D communication. Hence, a channel allocation scheme is implemented to minimise interference to cellular users while maximising the number of permitted D2D pairs for

communication. This is achieved by formulating an assignment problem for channel allocation and obtaining solution using an admission control process to permit D2D pairs with minimal interference while rejecting the D2D pairs that cause strong interference to the cellular users. A heuristic algorithm that uses a greedy approach is implemented to allocate channels for reuse by D2D pairs, and a comparative analysis of performance is made with the Kuhn-Munkres algorithm and a Random channel allocation method. The choice for the comparison of the heuristic method with the Kuhn-Munkres algorithm is because the latter approach solves the assignment problem by obtaining the optimal matching in a weighted bipartite graph to improve overall performance. In addition, the performances of the proposed algorithms in the two system model scenarios considered are analysed.

The remaining sections of this work are structured according to the following layout. Section 5.2 outlines a summary of the notations used in this chapter. Section 5.3 presents the system model description, problem formulation and the methodology used for the D2D communication and relay-assisted D2D communication scenarios. Section 5.4 provides the simulation parameters used for the implementation of the algorithms and discusses the simulation results obtained for the two system model scenarios. Section 5.5 concludes the chapter.

## 5.2 Notations

The notations used in this chapter are summarised in Table 5.1 as follows:

Table 5.1: Summary of Notations

Symbol	Description
$N_u$	Total number of users
$N$	Total number of transmitters
$M$	Total number of receivers
$R$	Set of relay UEs
$d_{d2d}^{th}$	D2D distance threshold
$d_r^{th}$	Distance threshold for relay UEs
$n_{d2d}$	D2D transmitter
$m_{d2d}$	D2D receiver
$N_{d2d}$	Total number of D2D transmitters
$M_{d2d}$	Total number of D2D receivers
$n_{cue}$	Cellular transmitter
$N_{cue}$	Total number of cellular transmitters
$P_{n_{cue}}$	Transmit power of a cellular user
$P_{n_{d2d}}$	Power of D2D transmitter
$P_r$	Transmit power of relay UE
$\gamma_{n_{cue},o}$	SINR of the receiver in cellular communication
$\gamma_{n_{d2d},m_{d2d}}$	SINR of the receiver in D2D communication
$\gamma_{n_{d2d},r}$	SINR for the D2D transmitter-relay UE link
$\gamma_{r,m_{d2d}}$	SINR for the relay UE-D2D receiver link
$\gamma_{n_{d2d},m_{d2d}}^{th}$	SINR threshold for D2D communication
$\delta^2$	Additive White Gaussian Noise at the receiver
$P_{n_{d2d}}^{min}$	Minimum power of D2D transmitter
$P_{n_{d2d}}^{max}$	Maximum power of D2D transmitter
$P_r^{min}$	Minimum power of relay UE
$P_r^{max}$	Maximum power of relay UE

### 5.3 System Model

In this chapter, two system model scenarios are considered. The first scenario comprises of cellular and D2D transmission modes, and the latter constituting cellular, D2D and relay-assisted D2D transmission modes in a single cell, made up of one eNB (denoted with  $o$ ) and randomly located users  $N_u$ ; which consists of  $N$  transmitters and  $M$  receivers.  $N = \{1, 2, 3, \dots, n\}$  denotes a set of transmitting UEs and  $M = \{1, 2, 3, \dots, m\}$  represents a set of receiving UEs. In the case of relay-assisted D2D communication,  $R = \{1, 2, 3, \dots, r\}$  is introduced to denote a set of relay UEs. A relay-assisted D2D transmission mode is assumed to be a two-hop communication, consisting of two D2D links, from a transmitter to relay (Dtx-R link), and from the relay to a receiver (R-Drx link). It is assumed that only one D2D link can share a channel with a cellular UE.

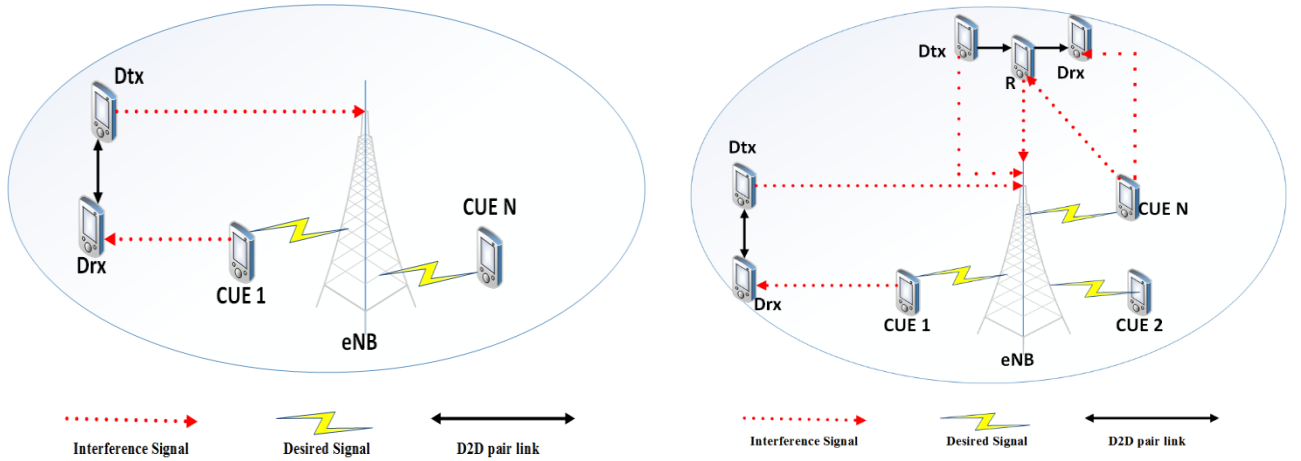


Figure 5.1: System Model for D2D communication - (a) Without relay (b) With relay

The channel is modelled by considering log-normal shadowing and Rayleigh fading model as the path loss model. The log-normal shadowing is used because it is the most common model to characterise attenuation emanating from objects in signal paths, and has been empirically asserted to accurately model the variation in received power in outdoor and indoor radio propagation environments [49]. The Rayleigh fading model is basically adopted because of its simplicity in typical cellular networks with a small number of reflectors [50]. Figure 5.1 (a) and (b) represent the system model for the D2D communication scenarios without and with relay assistance.

## 5.4 Problem Formulation and Methodology

It is portrayed in Figure 5.1(a) that, each  $(n, m)$  transmission can be realised either through a cellular transmission mode, where  $UE_n$  communicates with  $UE_m$  via the eNB ( $o$ ) or the D2D transmission mode, where  $UE_n$  communicates directly with  $UE_m$ . Accordingly, an additional transmission mode is introduced in Figure 5.1(b) where  $UE_n$  communicates with  $UE_m$  via  $UE_r$ . The positioning of the cellular, relay and D2D UEs in the cell is obtained by using the  $x$  and  $y$  coordinates of UEs from the eNB, assumed to be placed at the centre of the cell. Hence, the Euclidean distance between a transmitter and receiver,  $d_{n,m}$  is calculated using the expression in Equation (5.1).

$$d_{n,m} = \sqrt{X_{n,m}^2 + Y_{n,m}^2} \quad (5.1)$$

Where  $X_{n,m}$  and  $Y_{n,m}$  are the respective differences in the  $x$  and  $y$  coordinates of a transmitter and receiver or a relay UE. The distance matrix denoted as  $D_{n,m}$ , obtained from  $N$  transmitting UEs to  $M$  receiving UEs is expressed in Equation (5.2) as:

$$D_{n,m} = \begin{matrix} & m_1 & m_2 & m_3 & \dots & m_m \\ n_1 & d_{1,1} & d_{1,2} & d_{1,3} & \dots & d_{1,m} \\ n_2 & d_{2,1} & d_{2,2} & d_{2,3} & \dots & d_{2,m} \\ n_3 & d_{3,1} & d_{3,2} & d_{3,3} & \dots & d_{3,m} \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ n_n & d_{n,1} & d_{n,2} & d_{n,3} & \dots & d_{n,m} \end{matrix} \quad (5.2)$$

A mode selection algorithm that is dependent on distance is derived and summarised in Algorithm 5.1. The aim is to optimally match all UEs from set  $N$  to their nearest neighbour UEs in set  $M$  using the Nearest Neighbour Search algorithm and based on given thresholds, matched UEs are assigned a transmission mode. This algorithm also caters for relay UE selection for D2D transmission mode with relay assistance.

---

**Algorithm 5.1: Proposed Mode Selection Algorithm**

---

1. **Initialisation:** Setting  $N_u$ ,  $N$ ,  $M$  and  $R$  to 0, and obtaining their coordinates
  2. **Set** value to the distance threshold,  $d_{d2d}^{th}$ ,  $d_r^{th}$
  3. **for**  $n = 1: \text{length}(N)$
  4.     **for**  $m = 1: \text{length}(M)$
  5.         Construct distance matrix  $D_{n,m}$
  6.         **if**  $N(n)$  is nearest node of  $M(m)$
  7.             Calculate  $D_{n,m}$  using Equation 5.2
  8.         **end if**
  9.         Compute NNS algorithm to match the nearest  $UE_m$  to  $UE_n$
  10.         For all  $(n, m)$  transmissions, perform mode selection for transmission either in cellular or D2D mode.
  11.         **if**  $D(n, m) \leq d_{d2d}^{th}$
  12.             Assign D2D transmission mode
  13.         **else if**  $d_{d2d}^{th} \leq D(n, m) \leq d_r^{th}$
  14.             Assign relay-assisted D2D transmission mode
  15.         **else**
  16.             Assign cellular transmission mode
  17.         **end if**
  18.     **end for**
  19. **end for**
  20. Perform relay selection for relay-assisted D2D pairs
  21. **for**  $n_{d2d} = 1: \text{length}(N_{d2d})$
  22.     **for**  $r = 1: \text{length}(R)$
  23.         Repeat steps 5 to 10
  24.     **end for**
  25. **end for**
  26. **for**  $r = 1: \text{length}(R)$
  27.     **for**  $m_{d2d} = 1: \text{length}(M_{d2d})$
  28.         Repeat steps 5 to 10
  29.     **end for**
  30. **end for**
  31. **if**  $D(n_{d2d}, r) \leq d_{d2d}^{th}$  &  $(r, m_{d2d}) \leq d_{d2d}^{th}$
  32.     Assign relay UE **end if**
-

The Signal-to-Interference-Noise-Ratio parameter is used as an indicator for QoS to reduce the average interference from D2D pairs to cellular users. The cellular users are prioritised and regarded as primary users by ensuring that the QoS of the cellular users is guaranteed while increasing the number of permitted D2D pairs to reuse channels with cellular users. The received SINR for an  $(n, m)$  cellular and D2D communication are given in Equations (5.3) and (5.4) respectively, similar to [60].

$$\gamma_{n\_cue,o} = \frac{P_{n\_cue} d_{n\_cue,o}^{-\alpha} |H_{n\_cue,o}|^2}{P_{n\_d2d} d_{n\_d2d,o}^{-\alpha} |H_{n\_d2d,o}|^2 + \delta^2} \quad \forall n\_cue \in N\_cue \quad (5.3)$$

$$\gamma_{n\_d2d,m\_d2d} = \frac{P_{n\_d2d} d_{n\_d2d,m\_d2d}^{-\alpha} |H_{n\_d2d,m\_d2d}|^2}{P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 + \delta^2} \quad \forall n\_d2d \in N\_d2d, m\_d2d \in M\_d2d \quad (5.4)$$

The distance-dependent path loss between a D2D link is denoted as  $d_{n\_d2d,m\_d2d}^{-\alpha}$  and the path loss from the  $n^{th}$  cellular user to eNB is represented as  $d_{n\_cue,o}^{-\alpha}$ .  $|H_{n\_d2d,m\_d2d}|^2$  and  $|H_{n\_cue,o}|^2$  depicts the Rayleigh channel fading between a D2D pair and a cellular UE and eNB respectively.  $|H_{n\_d2d,o}|^2$  denotes the Rayleigh channel fading between a D2D transmitter and eNB.  $|H_{n\_cue,m\_d2d}|^2$  represents the Rayleigh channel fading between a cellular UE and a D2D receiver.  $\delta^2$  denotes the Additive White Gaussian Noise at the receiver. In the same way for relay-assisted D2D communication, the SINR at the source-relay and relay-destination links are represented with  $\gamma_{n\_d2d,r}$  and  $\gamma_{r,m\_d2d}$  respectively as given in [45], and can be similarly expressed as Equations (5.3) and (5.4). The sum interference introduced into cellular communication as a result of the reuse of the uplink cellular channels by D2D transmitters is expressed in Equation (5.5) as:

$$I_{n\_d2d,n\_cue} = P_{n\_d2d} d_{n\_d2d,o}^{-\alpha} |H_{n\_d2d,o}|^2 + P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 \quad (5.5)$$

The sum interference from the transmission by relay UEs is expressed in Equation (5.6) as:

$$I_{r,n\_cue} = P_{r,m\_d2d} d_{r,o}^{-\alpha} |H_{r,o}|^2 + P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 \quad (5.6)$$

Where  $|H_{r,o}|^2$  and  $d_{r,o}^{-\alpha}$  denote the Rayleigh channel fading and distance between a relay UE and eNB respectively.  $P_{r,m\_d2d}$  is the transmit power of the relay UE.

Power control is vital especially in scenarios where the reuse of the channels of cellular users by D2D and relay-assisted D2D pairs cause interference to the cellular UEs. A power control problem is formulated in Equations (5.7) – (5.9) to reduce the transmit power of D2D UEs,  $P_{n\_d2d}$  subjected to SINR constraints.

$$\min \sum_{n\_d2d \in N\_d2d} P_{n\_d2d} \quad (5.7)$$

Subject to

$$\gamma_{n\_d2d,m\_d2d} \geq \gamma_{n\_d2d,m\_d2d}^{th} \quad \forall n\_d2d \in N\_d2d, \quad \forall m\_d2d \in M\_d2d \quad (5.8)$$

$$P_{n\_d2d}^{min} \leq P_{n\_d2d} \leq P_{n\_d2d}^{max} \quad \forall n\_d2d \in N\_d2d \quad (5.9)$$

The SINR threshold of a D2D receiver is denoted with  $\gamma_{n\_d2d,m\_d2d}^{th}$ . The permissible minimum and maximum power of a D2D transmitter are represented with  $P_{n\_d2d}^{min}$  and  $P_{n\_d2d}^{max}$  respectively. The optimal transmit power of relay UEs are obtained by solving the formulated power control problem in Equations (5.10) – (5.13). The transmit power of a relay UE,  $P_r$  represents the total power of  $P_{n\_d2d,r}$  and  $P_{r,m\_d2d}$ .

$$\min \sum_{r \in R} P_r \quad (5.10)$$

Subject to

$$\gamma_{n\_d2d,r} \geq \gamma_{n\_d2d,r}^{th} \quad \forall n\_d2d \in N\_d2d, r \in R \quad (5.11)$$

$$\gamma_{r,m\_d2d} \geq \gamma_{r,m\_d2d}^{th} \quad \forall m\_d2d \in M\_d2d, r \in R \quad (5.12)$$

$$P_r^{min} \leq P_r \leq P_r^{max} \quad \forall r \in R \quad (5.13)$$

The formulated power control problem in Equations (5.7) – (5.13) is convex because it consists of linear objective functions subjected to linear constraints. The feasible solutions of the transmit power values for D2D transmitters and relay UEs are obtained using the CVX optimisation tool. The CVX tool is a MATLAB based modelling platform for convex optimisation. The applications of convex optimisation span through areas such as communications and networks, data analysis and modelling, statistics and finance [61]. The proposed power control scheme is summarised in Algorithm 5.2.

---

**Algorithm 5.2: Proposed Power Control Algorithm**


---

1. **Begin:**  $\forall n_{d2d} \in N_{d2d}$
  2. **Initialise**  $P_{n_{cue}}, P_{n_{d2d}}^{min}, P_{n_{d2d}}^{max}$
  3.  $min \sum_{n_{d2d}} P_{n_{d2d}}$
  4. Constraints:  $\gamma_{n_{d2d},m_{d2d}} \geq \gamma_{n_{d2d},m_{d2d}}^{th}$
  5.  $P_{n_{d2d}}^{min} \leq P_{n_{d2d}} \leq P_{n_{d2d}}^{max}$
  6. Calculate optimal  $P_{n_{d2d}}$  if the condition of feasibility in the constraints are satisfied
  7. **end Begin**
  8. **Begin:**  $\forall r \in R$
  9.  $min \sum_r P_r$
  10. Constraints:  $\gamma_{n_{d2d},r} \geq \gamma_{n_{d2d},r}^{th}$
  11.  $\gamma_{r,m_{d2d}} \geq \gamma_{r,m_{d2d}}^{th}$
  12.  $P_r^{min} \leq P_r \leq P_r^{max}$
  13. Calculate optimal  $P_r$  if the condition of feasibility in the constraints are satisfied
  14. **end Begin**
- 

In order to guarantee priority, cellular or D2D transmission (relay-assisted or not) is not permitted if the interference generated by the users is higher than the predefined threshold. The admission control indices,  $\alpha_{n_{d2d},n_{cue}}$  and  $x_{r,n_{cue}}$ , are binary indicators.  $\alpha_{n_{d2d},n_{cue}}$  determines if a D2D pair is admitted to reuse the uplink channel of a cellular user as shown in Equation (5.17).  $x_{r,n_{cue}}$  indicates if a relay-assisted D2D pair is admitted to share the uplink channel of a cellular user as shown in Equation (5.18). The sum interference caused by D2D or relay-assisted D2D pairs when reusing the uplink channel of cellular users is expressed in Equation (5.14) as:

$$I_{n_{d2d},r,n_{cue}} = (\alpha_{n_{d2d},n_{cue}} I_{n_{d2d},n_{cue}} + x_{r,n_{cue}} I_{r,n_{cue}}) \quad (5.14)$$

An interference minimisation problem is formulated to reduce the total interference introduced into cellular communication by D2D communication in Equation (5.15) as:

$$min \sum_{\substack{n_{d2d} \in N_{d2d}, \\ n_{cue} \in N_{cue}, r \in R}} (\alpha_{n_{d2d},n_{cue}} I_{n_{d2d},n_{cue}} + x_{r,n_{cue}} I_{r,n_{cue}}) \quad (5.15)$$

The interference minimisation problem in Equation (5.15) can also be simplified in Equation (5.16) as given in [37].

$$\min \sum_{\substack{n_{d2d} \in N_{d2d}, \\ n_{cue} \in N_{cue}, r \in R}} I_{n_{d2d}, r, n_{cue}} \quad (5.16)$$

Subject to

$$\alpha_{n_{d2d}, n_{cue}} \in \{0,1\} \quad \forall n_{d2d} \in N_{d2d}, n_{cue} \in N_{cue} \quad (5.17)$$

$$x_{r, n_{cue}} \in \{0,1\} \quad \forall r \in R, n_{cue} \in N_{cue} \quad (5.18)$$

$$\sum_{n_{d2d} \in N_{d2d}} \alpha_{n_{d2d}, n_{cue}} \leq 1 \quad \forall n_{cue} \in N_{cue} \quad (5.19)$$

$$\sum_{r \in R} x_{r, n_{cue}} \leq 1 \quad \forall n_{cue} \in N_{cue} \quad (5.20)$$

$$\sum_{n_{cue} \in N_{cue}} \alpha_{n_{d2d}, n_{cue}} \leq 1 \quad \forall n_{d2d} \in N_{d2d} \quad (5.21)$$

$$\sum_{n_{cue} \in N_{cue}} x_{r, n_{cue}} \leq 1 \quad \forall r \in R \quad (5.22)$$

$$\alpha_{n_{d2d}, n_{cue}} + x_{r, n_{cue}} = 1 \quad \forall n_{d2d} \in N_{d2d}, \quad \forall r \in R \quad (5.23)$$

Equation (5.19) and Equation (5.21) guarantee that a maximum of one D2D transmitter can reuse a cellular channel and only one cellular channel can be reused by a D2D transmitter respectively. Similarly, Equation (5.20) and Equation (5.22) indicate that a maximum of one relay UE can share a cellular channel and only one cellular channel can be reused by a relay UE respectively. The constraint in Equation (5.23) ensures that only one cellular channel can be assigned for reuse in every transmission. The Equations (5.17) – (5.23) are 0-1 integer programming problems and with  $I_{n_{d2d}, r, n_{cue}}$  known, it is solved as an assignment problem using KM algorithm. However, not all admitted D2D pairs (relay-assisted or not) are permitted to reuse cellular channels. In the channel assignment algorithm, a D2D or relay-assisted D2D pair requesting to communicate consists of a source ( $s$ ) and target ( $t$ ). The target sends channel state information of the source to the eNB. The eNB then calculates the interference that could

be generated from each transmission to a cellular user. The proposed channel reuse algorithms are then applied in the channel assignment and the performances are analysed. The proposed channel reuse scheme is summarised in Algorithm 5.3 as follows:

---

**Algorithm 5.3: Proposed Channel Reusing Selection Algorithm**

---

1. **Initialisation:** Setting  $N_{d2d}$  and  $N_{cue}$ ,  $R$  to values.  
 $-140\text{dBm} \leq I_o \leq -90\text{dBm}$
  2. Generate interference matrix,  $[I_{n_{d2d},r,n_{cue}}]$
  3. **if**  $I_{n_{d2d},r,n_{cue}} \leq I_o$
  4. Compute KM algorithm for optimal channel assignment:
  5.  $O_{n_{d2d},r,n_{cue}} = \text{HUNGARIAN}(I_{n_{d2d},r,n_{cue}})$  where  $O_{n_{d2d},r,n_{cue}}$  is a Boolean matrix that depicts if  $n_{d2d}$  or  $R$  has been assigned to  $n_{cue}$
  6. Compute Heuristic algorithm:
  7. Sort  $[I_{n_{d2d},r,n_{cue}}]$
  8. Assign channels by first prioritising D2D pairs with less interference
  9. Compute random algorithm for channel assignment
  10. **else**
  11. Set  $[I_{n_{d2d},r,n_{cue}}] = inf$
  12. **end if**
- 

The KM algorithm deals with a non-negative square matrix where the index of the matrix represents the weight of the associated row and column. The rows and columns of the matrix denote D2D or relay-assisted D2D pairs ( $N_{d2d}|R$ ) and cellular UEs ( $N_{cue}$ ), respectively. In the case where  $(N_{d2d}|R) \gg N_{cue}$ , then  $(N_{d2d}|R) - N_{cue}$  dummy cellular UEs are introduced to obtain a square matrix and vice versa. The weight of the square matrix in this regard represents the possible interference from D2D or relay-assisted D2D pairs to cellular UEs, as expressed in Equation (5.16). In the KM algorithm, cellular channels are optimally assigned for reuse by D2D or relay-assisted D2D pairs with minimum interference. This optimality is achieved by manipulating the weights of a bipartite graph to calculate the minimum matched weights. Then, augmenting paths are searched until there exist any, and the perfect match with the minimum weight is computed. The assigned interference threshold,  $I_o$ , set between  $-140\text{dBm} \leq I_o \leq -90\text{dBm}$  and Equations (5.17) - (5.23) are applied in the

KM algorithm to return a boolean matrix constituting the assignments between D2D or relay-assisted D2D pairs and cellular UEs that introduce the minimum interference to cellular UEs.

In the proposed heuristic scheme, D2D or relay-assisted D2D pairs with good channel conditions and lower tendency of causing interference to cellular UEs are firstly given priority to select a cellular channel for reuse with minimal interference. Hence, step 2 of Algorithm 5.3 obtains the possible interference from D2D or relay-assisted D2D pairs to cellular UEs. Step 7 sorts the interference values in matrix  $[I_{n,d2d,r,n\_cue}]$  and then, the assigned interference threshold constraint and Equations (5.17) - (5.23) are applied to assign a cellular channel for reuse by D2D or relay-assisted D2D pairs with a minimised overall interference. Consequently, the Random channel allocation method is implemented by randomly assigning channels belonging to cellular UEs for reuse by D2D or relay-assisted D2D pairs.

## 5.5 Simulation Parameters, Results and Discussions

The simulation parameters are shown in Table 5.2.

Table 5.2: Simulation Parameters

Parameter	Value
Cell radius	300m
Channel bandwidth	10MHz
Additive White Gaussian Noise	-174dBm/Hz
Path loss model for D2D or relay-assisted D2D link	$148 + 40.6\log_{10}(d[\text{km}])$
Path loss model for cellular link	$128.1 + 37.6\log_{10}(d[\text{km}])$
Distance limitation for D2D link	30m
Maximum transmit power of D2D UE	21dBm
Maximum transmit power of cellular UE	24dBm
Distance limitation for relay-assisted D2D link	30 – 60m
SINR threshold	0dB
Minimum transmit power of D2D and relay-assisted D2D pair	0dBm
Number of Monte Carlo Simulation runs	500

The performances of the proposed channel allocation methods are analysed in both scenarios of the system model. The performance measures in this simulation are the number of D2D pairs permitted to reuse cellular channels and average interference caused when the uplink channels of cellular UEs are reused. Since the proposed optimal algorithm aims to minimise the sum interference introduced when reusing uplink cellular channels, and the heuristic algorithm firstly allocates reusing channels to D2D and relay-assisted D2D pairs with minimal interference, the proposed schemes to some extent are able to downsize the total interference caused to cellular users.

### 5.5.1 Scenario 1 (Without Relay)

This section discusses the performances of the proposed methods in the scenario of Figure 5.1(a), where the system model consists of only cellular and D2D transmission modes. Figure 5.2 illustrates the impact of varying the interference threshold on the performance of the proposed algorithms with regards to average interference from D2D pairs.

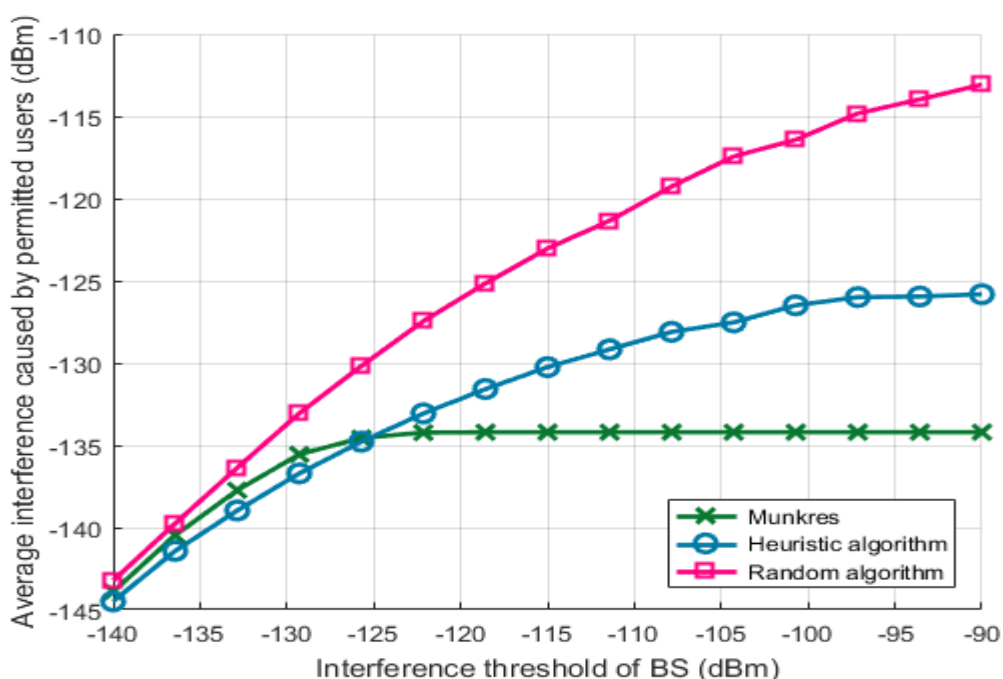


Figure 5.2: Performance comparison of the proposed algorithms in relation to average interference as interference threshold varies

The figure portrays that the average interference increases with a rise in the interference threshold from the eNB, since the increment in the interference threshold allows higher number

of D2D pairs to reuse cellular channels, therefore increasing the average interference in the system. Comparing the proposed channel reuse selection algorithms, it is observed that when there are few users in the network, the heuristic algorithm provides lower average interference than the KM algorithm. However, as the users within the network increase by raising the interference threshold from  $-140\text{dBm}$  to  $-125\text{dBm}$ , KM algorithm outperforms the Heuristic algorithm by assigning channels such that a lower total average interference is obtained. The two channel reuse selection methods, KM and heuristic algorithms performed significantly better than the random allocation method.

Figure 5.3 demonstrates the effect of the interference threshold on the number of D2D pairs that are permitted to share a channel with cellular UEs. A rise in the interference threshold results in more D2D pairs reusing cellular channels. Although the two proposed channel reusing selection methods, KM and heuristic algorithms have the same maximum average number of permitted D2D pairs of approximately 12.8 at interference threshold of  $-97\text{dBm}$ , with the random allocation method performing slightly worse, there are still some differences in performances in instances where there is a small number of users in the network. This is portrayed at  $-133\text{dBm}$  where the Kuhn-Munkres algorithm performed significantly better, followed by the heuristic algorithm and lastly by the random channel allocation method.

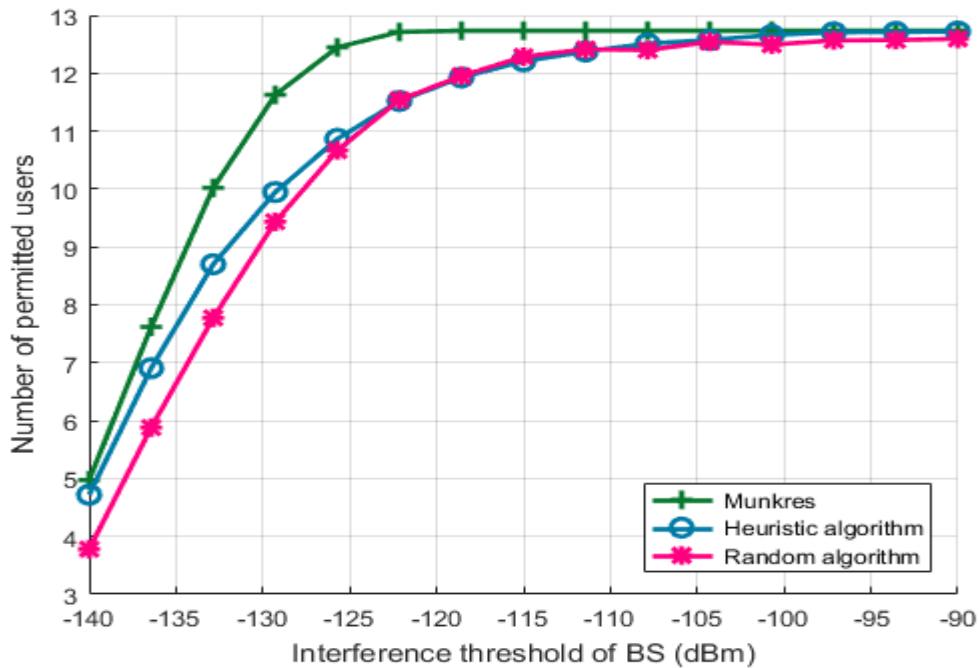


Figure 5.3: Performance comparison of the proposed algorithms in relation to the permitted number of D2D users as interference threshold varies

In Figure 5.4, the impact of SINR threshold on the average interference from the permitted number of D2D pairs is analysed. It is observed that a rise in the SINR threshold results in an increase in the average interference introduced by permitted D2D pairs. Although increasing the SINR threshold allows a fewer number of D2D pairs to reuse a cellular channel, as shown in Figure 5.5, it does not necessarily lead to a reduction in the total interference in the system. This is because a rise in the SINR threshold has a directly proportional increase in the transmit power of the permitted D2D pairs, hence the average interference caused by these permitted D2D pairs becomes greater. It is, therefore, necessary to set an SINR threshold that caters for the tradeoff in obtaining more D2D connections with less interference. The KM algorithm shows the highest performance improvement, followed by the heuristic algorithm and then the random allocation algorithm with the lowest improvement in performance.

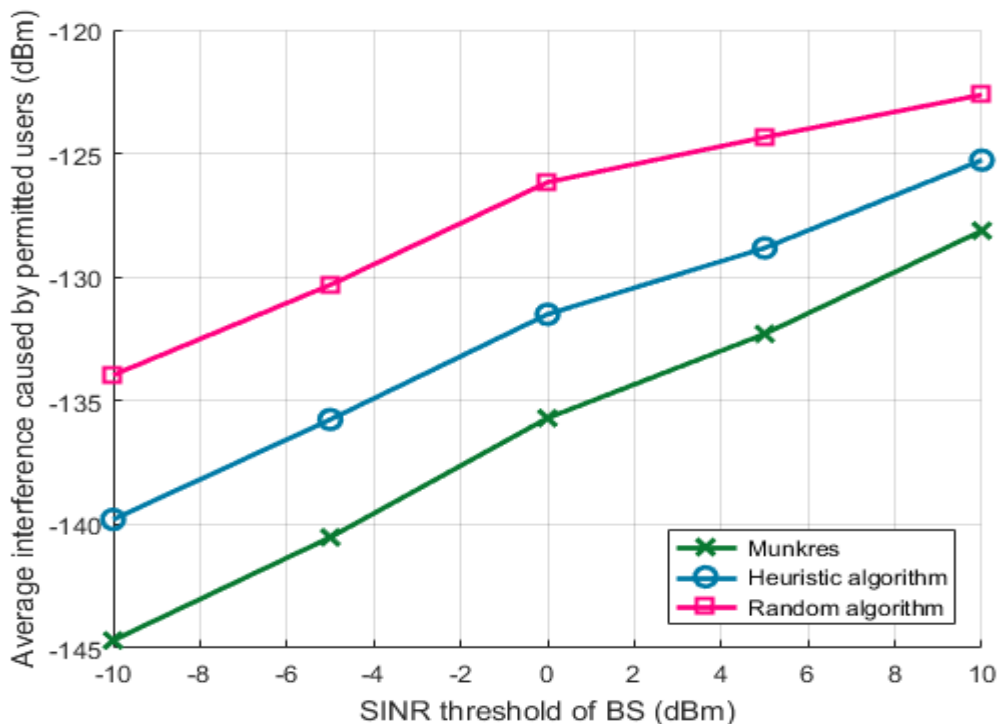


Figure 5.4: Performance of the proposed algorithms in relation to the average interference caused by permitted D2D pairs as the SINR threshold varies

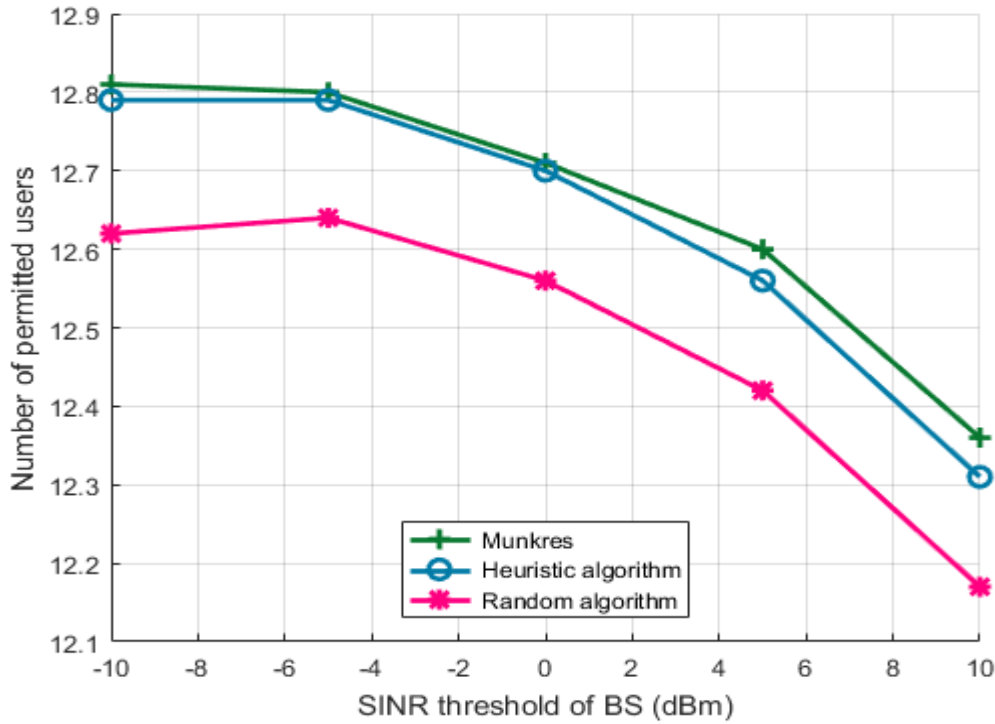


Figure 5.5: Performance of the proposed algorithms in relation to the number of permitted D2D pairs as the SINR threshold varies

### 5.5.2 Scenario 2 (With Relay)

The performances of the proposed algorithms in the system model scenario of Figure 5.1(b), consisting of cellular, D2D and relay-assisted D2D transmission modes are analysed in this section. In Figure 5.6, the effect of the proposed algorithms on the overall average interference introduced by the permitted users sharing cellular channels is evaluated as the interference threshold is varied. The increase in the interference threshold results in a proportional increase in the average interference from permitted D2D pairs (relay-assisted or not). Similar to Figure 5.2, the heuristic method achieved higher performance than the KM algorithm with a few users. But as the number of users in the cellular network increase with an increasing interference threshold from  $-140\text{dBm}$  to  $-133\text{dBm}$ , the KM algorithm outperformed the heuristic algorithm. Also, both algorithms performed better than the random channel allocation algorithm.

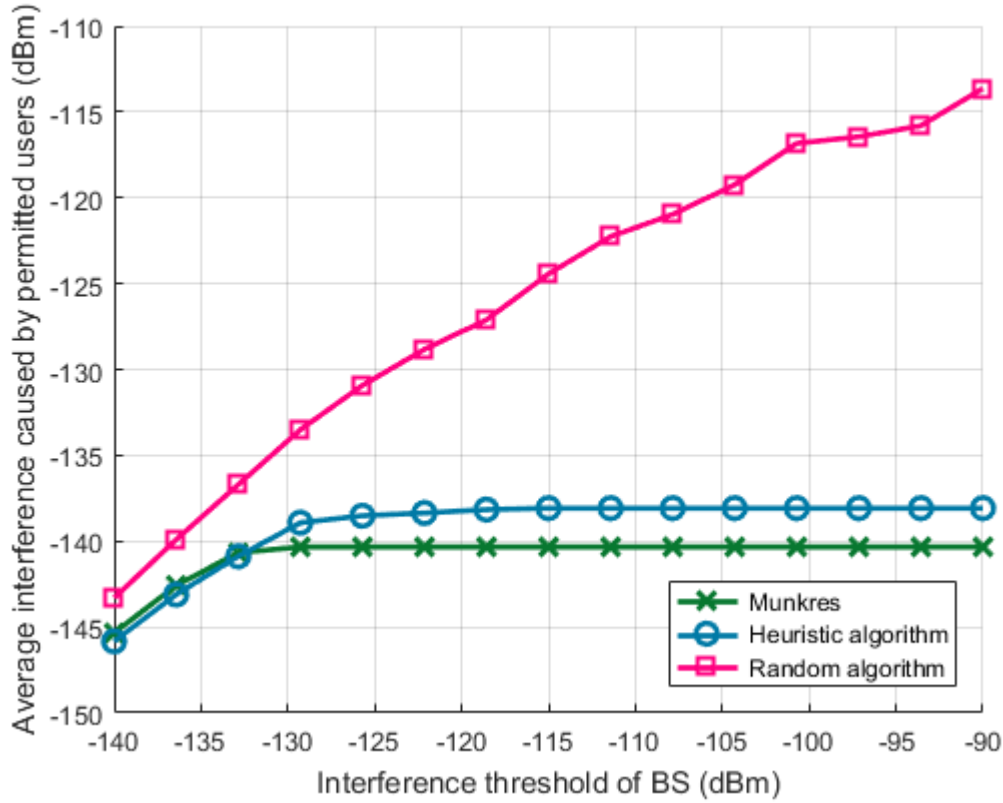


Figure 5.6: Interference threshold Versus Average interference caused by permitted users

Figure 5.7 illustrates the performance comparison of the proposed algorithms on the number of permitted D2D and relay-assisted D2D pairs as the interference threshold is contrasted. The number of users permitted to share channels with cellular users increases as the interference threshold is maximised. The performances of the presented algorithms differ when the interference threshold is lower than  $-122dBm$ . For instance, at an interference threshold of  $-140dBm$ , the average number of permitted users is 7.5, 7.0 and 5.6 for the KM, heuristic and random channel allocation algorithms respectively. This clearly indicates that the proposed heuristic algorithm performed closely to the KM algorithm, with both methods outperforming the random channel allocation algorithm. Also, above  $-115dBm$  the proposed channel reuse selection algorithms approach stability with the same average number of permitted D2D and relay-assisted D2D pairs.

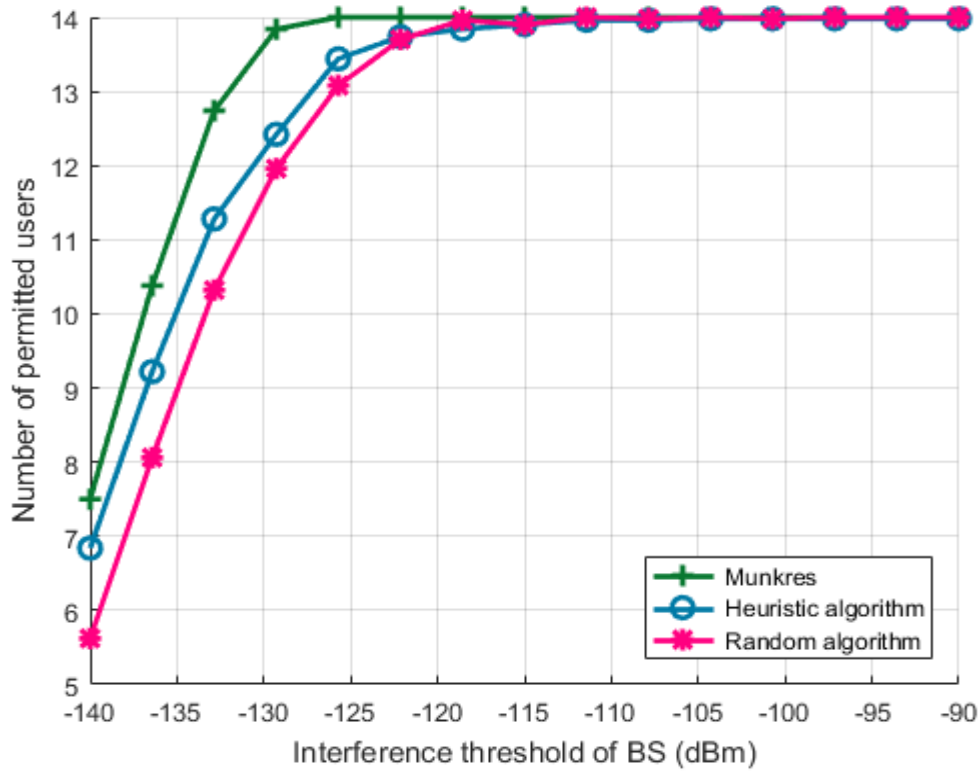


Figure 5.7: Interference threshold Versus Number of permitted users

The impact of the SINR threshold on the average interference from permitted D2D and relay-assisted D2D pairs when sharing cellular channels is investigated in Figure 5.8. Similar to Figure 5.4, the rise in the SINR consequently leads to an increase in the average interference from the permitted users due to high power transmissions. On the contrary, the number of permitted D2D pairs (with or without relay assistance) decreases as the SINR threshold increases, as shown in Figure 5.9. The heuristic algorithm in both figures has a close performance improvement to the KM algorithm and both schemes performed better than the random channel allocation algorithm.

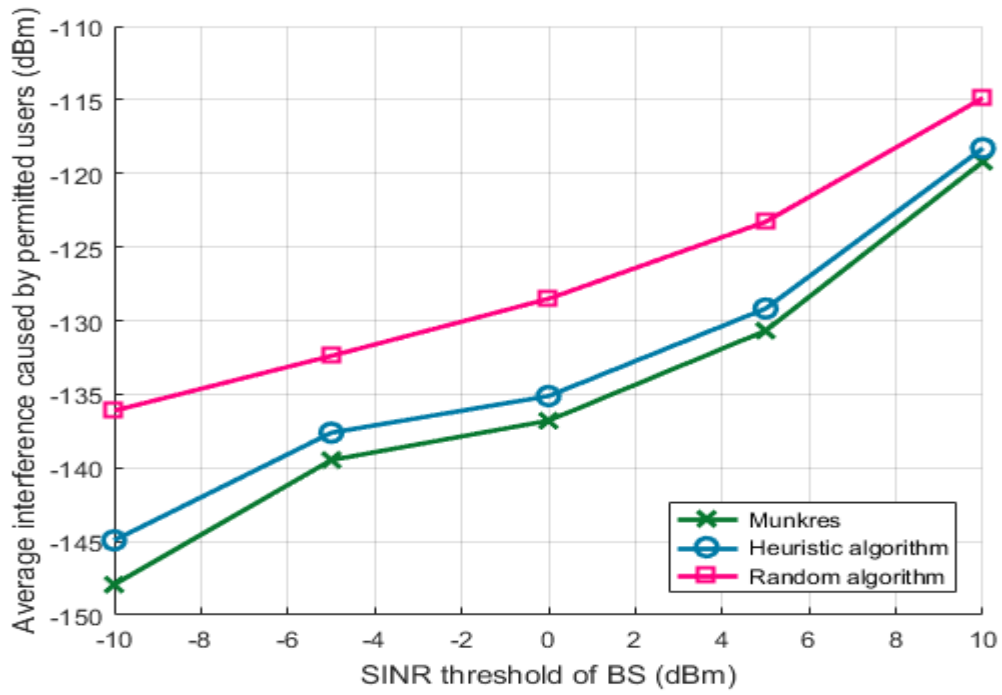


Figure 5.8: SINR threshold Versus Average interference caused by permitted users

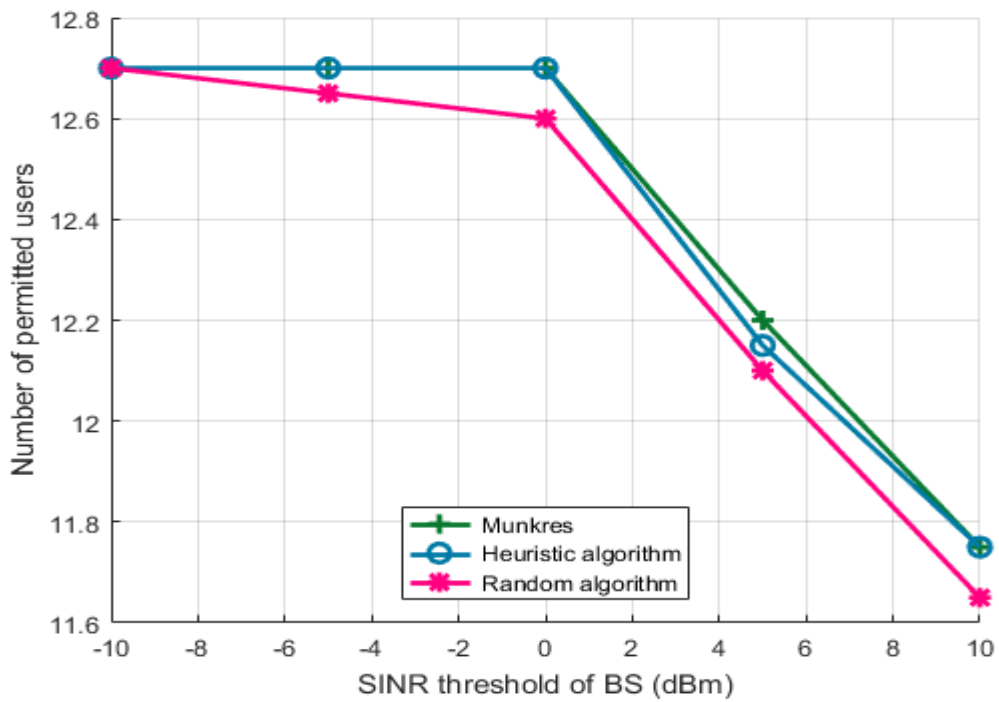


Figure 5.9: SINR threshold Versus Average number of permitted users

The performance of the proposed relay selection algorithm is compared with a random relay selection method with regards to the proposed heuristic and random channel allocation methods. An instance of only relay-assisted D2D pairs is considered and the selection methods are applied to choose a relay for the D2D pairs. The impact of the selection methods on the average interference from relay-assisted D2D pairs is evaluated by varying the SINR threshold of the BS for the proposed heuristic and random channel allocation methods. The simulation results indicated that the presented relay selection method outperformed the random relay selection method with reduced average interference in the proposed heuristic channel allocation method. However, the proposed relay selection method had a close performance to the random relay selection method in the random channel allocation algorithm.

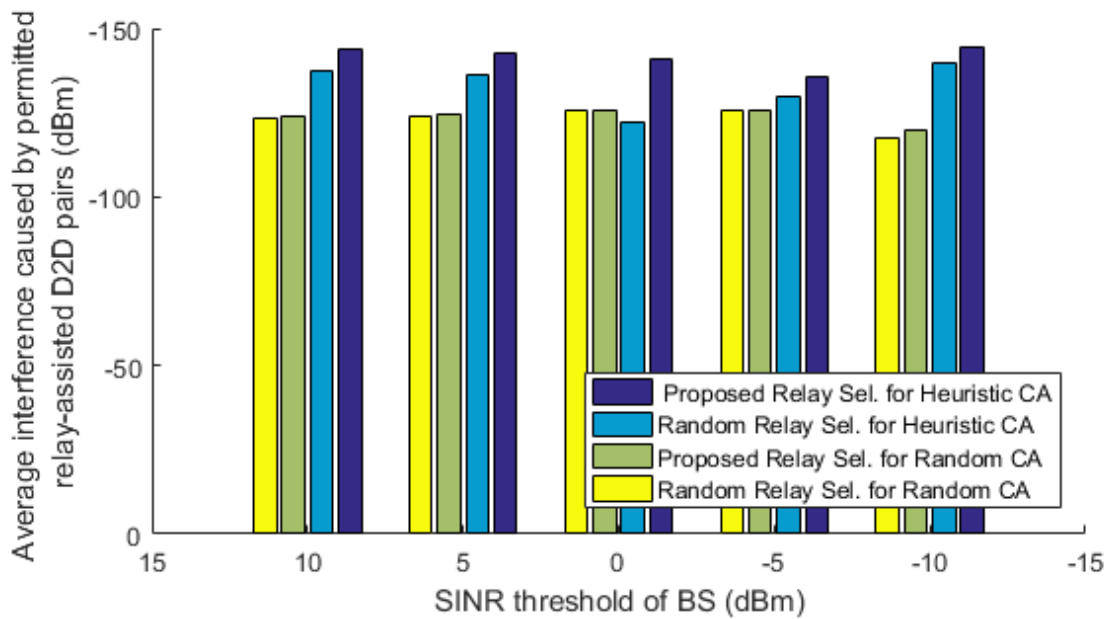


Figure 5.10: Performance comparison of the proposed relay selection algorithm

The two system model scenarios are also evaluated in this work. In terms of the relationship between the interference threshold and the average interference introduced by the permitted users, the relay-assisted D2D communication system model scenario outperformed the D2D communication system model scenario as portrayed by Figure 5.2 and Figure 5.6. The performances of Figure 5.3 and Figure 5.7 in the two system model scenarios that discuss the impact of the interference threshold and the average number of permitted users are considered. In Figure 5.3, at an interference threshold of  $-140\text{dBm}$ , the KM, heuristic and random channel

allocation schemes provided an average number of 5.0, 4.8 and 3.8 users respectively to share cellular channels.

Whereas in Figure 5.7, at an interference threshold of  $-140dBm$ , the KM, heuristic and random channel allocation schemes provided an average number of 7.5, 7.0 and 5.6 users respectively to share cellular channels. This indicates that the system model with relay assistance performs better than the system model without relay assistance. From the two system model scenarios of Figures 5.4 and 5.8, we analyse the effect of SINR threshold on average interference to cellular users. The performances of the proposed channel reuse algorithms in the system model scenario without relay assistance introduced higher interference to cellular users when compared with the system model scenario with relay assistance.

## 5.6 Conclusion

In this chapter, two system model scenarios where D2D communication underlay a cellular network with and without the assistance of relay UEs were considered. Firstly, a mode selection algorithm is proposed to determine the user transmission modes. Then, a power control problem is formulated, and its feasible solutions are obtained using CVX optimisation solver tool to allocate optimal power to D2D transmitters. A channel reuse selection scheme is proposed to help guarantee the QoS of cellular users, while optimally increasing the number of permitted D2D pairs and relay-assisted D2D pairs that reuse the uplink channels of cellular users. The Kuhn-Munkres, heuristic and random channel allocation algorithms are proposed for the channel reusing selection for the two system model scenarios.

The performances of the proposed algorithms are evaluated using MATLAB. The simulation outcome showed that the proposed heuristic algorithm obtained a near optimal performance to the KM algorithm, with both algorithms outperforming the random channel allocation method. In addition, the performances of the proposed algorithms in the two system model scenarios are analysed. The simulation results illustrated that the system model scenario with relay-assisted D2D communication portrayed a significant improvement in performance when compared to the system model scenario of D2D communication without relay assistance.

## Chapter 6

# 6 Interference Minimisation for Uplink Channel Reuse in Device-to-Device Communication Underlying Cellular Networks – A Stable Matching Approach

### 6.1 Introduction

The emerging applications, proliferating data traffic and mobile devices demands are a few of the principal determinants for improving the capacity of the cellular network. The limitation on the availability of spectral resources poses a difficulty for network operators to support these ever-increasing requirements associated with the next generation networks. Device-to-Device communication is associated with several advantages but faces the problem of interference as discussed in the earlier chapters.

The matching theory has recently emerged as an effective method in wireless communication. Hence, this research considers the issue of interference emanating from underlying cellular networks by D2D users and applies matching theory in resource allocation to investigate performance improvement. Accordingly, several authors have carried out extensive research on interference in D2D communication.

This chapter carries out an in-depth study of matching theory and its application in resource allocation. A single cellular network with D2D and relay-assisted D2D users coexisting and reusing the uplink radio channels of cellular UEs are considered. The Nearest Neighbour Search algorithm coupled with transmission constraints is used to implement mode selection to determine either cellular, D2D or relay-assisted D2D transmission modes for the users within a cell. The exact Nearest Neighbour Search using a naïve approach to provide the closest neighbouring node is considered because it is an optimising proximity search algorithm. Moreover, D2D communication provides proximity-based communication, hence this search method is utilised in transmission mode selection, similar to Table 5.1. A channel allocation problem is formulated, and solutions of the matching problem are obtained using the Gale – Shapley algorithm to guarantee fairness in the assignment of cellular channels to D2D pairs. The performance of the GS method is examined through a comparison analysis with a proposed optimal approach.

The remaining sections of this chapter are structured as follows: Section 6.2 summarises the concept of matching theory. Section 6.3 highlights the key notations used in this chapter. Section 6.4 presents the system model considered to analyse the problem of interference caused by D2D pairs from reusing uplink cellular channels. Section 6.5 outlines the formulated problem and methodology considered for the implementation of this scheme. Section 6.6 presents the simulation parameters and discusses the results obtained from the simulation. Section 6.7 provides the conclusion of this chapter.

## **6.2 Concept of Matching Theory**

The matching theory is a tool in economics used to study the formation of mutually beneficial relationships among different players. Recently, the matching theory has gained attention in wireless communication. In the case of wireless communication, a resource management problem can be represented as a matching problem between resources and users. The ultimate purpose of matching theory in resource management is to optimally match resources and users based on different preferences. The notion of preferences denotes an individual view that a user has of a resource and vice versa based on local information. A user (or resource) builds a ranking of the resources (or users) using a preference list. A preference list of a player is defined as an ordered list based on the acceptable preferences over the other set of players.

Stability is a basic requirement in a matching model, and it refers to the nonexistence of a blocking pair in a matching. A blocking pair occurs when a user player and resource player ( $up, rp$ ) prefer to be matched, other than to their current partners. The Gale-Shapley algorithm can be used to obtain a stable matching, and it is adopted in this work.

### 6.2.1 Matching Theory Classifications

The matching problems can be classified as follows [62]:

- One-to-one matching: A player of a set can be matched to at most one player, from the opposite set. Examples include stable marriage problem and stable roommate problem. One-to-one matching can be a bipartite matching with two-sided preferences, or bipartite matching with one-sided preference or non-bipartite matching.
- Many-to-one matching: A player of a set can be matched to more than one player from the opposite set. An example includes university admission problem. Many-to-one matching can be a bipartite matching with two-sided preferences or bipartite matching with one-sided preference or non-bipartite matching.
- Many-to-many matching: Players from both matching sets can be matched to more than one player. Examples include creating a partnership in P2P networks and assigning workers to firms problem. Many-to-many matching can be a bipartite matching with two-sided preferences or bipartite matching with one-sided preference or non-bipartite matching.

A bipartite matching with two-sided preferences involves dividing the players into two disjoint sets where each player of a set ranks the players of the other set in order of preferences. A bipartite matching with one-sided preference also involves dividing the players into two disjoint sets, but only one set of players ranks the players of the other set. In a non-bipartite matching, all the players form a single set, and each player ranks other players based on the order of preferences. In this work, we considered One-to-one matching and modelled the channel allocation problem similar to that of the stable marriage problem.

### 6.3 Notations

A few notations used in this chapter are summarised in Table 6.1 as follows:

Table 6.1: Summary of Notations

Symbol	Description
$N_u$	Total number of randomly distributed active users in a single cell
$N$	Total number of transmitters
$M$	Total number of receivers
$R$	Total number of relay UEs
$n_{d2d}$	D2D transmitter
$m_{d2d}$	D2D receiver
$N_{d2d}$	Total number of D2D transmitters
$M_{d2d}$	Total number of D2D receivers
$n_{cue}$	Transmitting cellular UE
$N_{cue}$	Total number of transmitting cellular UEs
$P_{n_{d2d}}$	D2D transmit power in the uplink channel
$H_{n_{d2d},m_{d2d}}$	Fading coefficients of a D2D pair
$H_{n_{cue},m_{d2d}}$	Fading coefficients of a cellular UE
$P_{n_{d2d}}^{max}$	Maximum D2D transmit power in the uplink channel
$\delta^2$	Additive White Gaussian Noise at the receiver
$PL_{n_{cue}}$	Preference list of cellular UEs
$PL_{n_{d2d}}$	Preference list of D2D pairs (with or without relay assistance)
$(I_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}$	Preference list of cellular UE (interference from D2D transmitter and relay UE)
$(G_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}$	Preference list of D2D transmitter and relay UE (cellular channel gain)

### 6.4 System Model

A single cell comprising of one eNB and  $N_u$  randomly distributed active users is considered.  $N_u$  denotes the total number of users in the single cellular network and  $o$  represents the eNB.

$N_u$  is made up of  $N$  transmitters and  $M$  receivers, where  $N = \{1, 2, 3, \dots, n\}$  denotes a set of transmitting UEs and  $M = \{1, 2, 3, \dots, m\}$  represents a set of receiving UEs.  $R = \{1, 2, 3, \dots, r\}$  denotes a set of relay nodes (idle cellular UEs) which are not in transmission and are willing to provide relay service. The interference among users in the same channel is eliminated in this research because they are presumed to orthogonally access spectrum [63]. A relay-assisted D2D transmission mode is assumed to consist of two D2D links. In addition to the assumptions made in this study, at most one cellular channel can be reused by a D2D link (relay-assisted or not). A transmission from a transmitter to a receiver is denoted as  $(n, m)$ , where  $n \in N$  and  $m \in M$ . Figure 6.1 represents the system model for D2D communication (relay-assisted or not) co-existing with cellular communication.

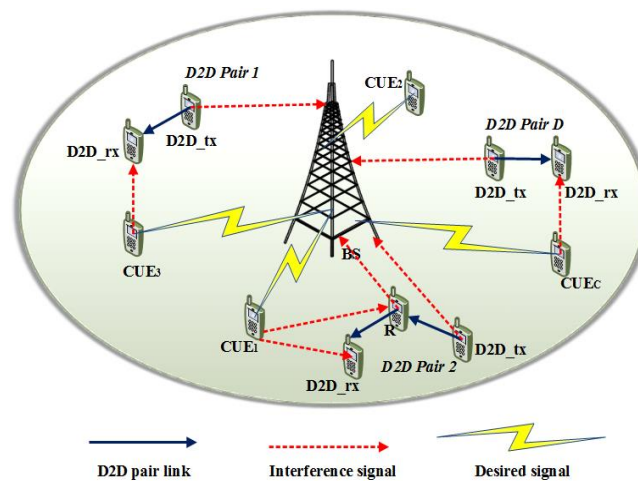


Figure 6.1: System Model for D2D communication underlying cellular network

## 6.5 Problem Formulation and Methodology

Each  $(n, m)$  transmission in Figure 6.1 is achieved by employing the following modes [45]:

1. Cellular transmission mode:  $UE_n$  communicate with  $UE_m$  via the eNB ( $o$ ).
2. D2D transmission mode:  $UE_n$  communicates directly with  $UE_m$ .
3. Relay-assisted D2D transmission mode:  $UE_n$  communicates with  $UE_m$  via  $UE_r$ , an idle cellular UE acting as a relay.

A distance matrix from all UEs in set  $M$  to all UEs in set  $N$  is obtained using NNS algorithm and based on distant dependent constraints, a transmission mode selection algorithm is formulated to optimally choose a suitable nearest UE from the set  $M$  to match a UE in set  $N$ .

When D2D pairs share the same channels with cellular UEs, the received signal at D2D receiver,  $y_{m\_d2d}$  is given in Equation (6.1), similar to [64] as:

$$y_{m\_d2d} = H_{n\_d2d,m\_d2d} \sqrt{P_{n\_d2d} d_{n\_d2d,m\_d2d}^{-\alpha}} x_{n\_d2d} + H_{n\_cue,m\_d2d} \sqrt{P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha}} x_{n\_cue} + \delta^2 \quad (6.1)$$

Where  $x_{n\_d2d}$  and  $x_{n\_cue}$  represent the transmitted uplink D2D and cellular signals respectively.  $P_{n\_d2d}$  and  $P_{n\_cue}$  denote the transmit power of D2D and cellular UEs respectively.  $\delta^2$  denotes the Additive White Gaussian Noise at the receiver. The received SINR for the cellular and D2D communication is expressed in Equations (6.2) and (6.3) respectively as used in [60]:

$$\gamma_{n\_cue,o} = \frac{P_{n\_cue} d_{n\_cue,o}^{-\alpha} |H_{n\_cue,o}|^2}{P_{n\_d2d} d_{n\_d2d,o}^{-\alpha} |H_{n\_d2d,o}|^2 + \delta^2} \quad \forall n\_cue \in N\_cue \quad (6.2)$$

$$\gamma_{n\_d2d,m\_d2d} = \frac{P_{n\_d2d} d_{n\_d2d,m\_d2d}^{-\alpha} |H_{n\_d2d,m\_d2d}|^2}{P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 + \delta^2} \quad \forall n\_d2d \in N\_d2d, m\_d2d \in M\_d2d \quad (6.3)$$

The SINR at the Source-Relay and Relay-Receiver links are denoted with  $\gamma_{n\_d2d,r}$  and  $\gamma_{r,m\_d2d}$  respectively as given in [45], and can be expressed in the same way as Equation (6.3).  $|H_{n\_d2d,o}|^2$  represents the Rayleigh channel fading between D2D pairs and eNB.  $|H_{n\_cue,o}|^2$  is the Rayleigh channel fading between cellular UEs and eNB. The sum interference introduced into cellular communication as a result of the reuse of the uplink cellular channels by D2D transmitters is expressed in Equation (6.4) as:

$$I_{n\_d2d,n\_cue} = P_{n\_d2d} d_{n\_d2d,o}^{-\alpha} |H_{n\_d2d,o}|^2 + P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 \quad (6.4)$$

In the case of transmission by relay UEs, the sum interference introduced into cellular communication as a result of the reuse of the uplink cellular channels can be expressed in Equation (6.5) as:

$$I_{r,n\_cue} = P_{r,m\_d2d} d_{r,o}^{-\alpha} |H_{r,o}|^2 + P_{n\_cue} d_{n\_cue,m\_d2d}^{-\alpha} |H_{n\_cue,m\_d2d}|^2 \quad (6.5)$$

$|H_{r,o}|^2$  and  $d_{r,o}^{-\alpha}$  represent the Rayleigh channel fading and the distance between a relay UE and eNB respectively.  $P_{r,m\_d2d}$  is the transmit power of the relay UE. The total system sum rate,  $R_{sum}$  contribution when a D2D pair (relay-assisted or not) shares the same channel with a cellular user is given in Equation (6.6) using Shannon's capacity formula as:

$$R_{sum} = B \log_2(1 + \gamma_{n\_cue,o}) + B \log_2(1 + \gamma_{n\_d2d,m\_d2d}) + B \min(\log_2(1 + \gamma_{n\_d2d,r}) + \log_2(1 + \gamma_{r,m\_d2d})) \quad (6.6)$$

Where  $B$  denotes the bandwidth of a cellular channel. A power control problem is formulated in Equations (6.7) - (6.12) to minimise the transmit power of D2D and relay UEs subjected to SINR constraints, and the feasible solution is derived from an optimisation solver.

$$\min \sum_{\substack{n\_d2d \in N\_d2d, r \in R, \\ m\_d2d \in M\_d2d}} \{P_{n\_d2d}, (P_{n\_d2d,r} + P_{r,m\_d2d})\} \quad (6.7)$$

Subject to

$$\gamma_{n\_d2d,m\_d2d} \geq \gamma_{n\_d2d,m\_d2d}^{th} \quad \forall n\_d2d \in N\_d2d, \quad \forall m\_d2d \in M\_d2d \quad (6.8)$$

$$P_{n\_d2d}^{min} \leq P_{n\_d2d} \leq P_{n\_d2d}^{max} \quad \forall n\_d2d \in N\_d2d \quad (6.9)$$

$$\gamma_{n\_d2d,r} \geq \gamma_{n\_d2d,r}^{th} \quad \forall n\_d2d \in N\_d2d, r \in R \quad (6.10)$$

$$\gamma_{r,m\_d2d} \geq \gamma_{r,m\_d2d}^{th} \quad \forall m\_d2d \in M\_d2d, r \in R \quad (6.11)$$

$$P_r^{min} \leq P_r \leq P_r^{max} \quad \forall r \in R \quad (6.12)$$

Where  $P_{n\_d2d}$ ,  $P_{n\_d2d,r}$  and  $P_{r,m\_d2d}$  denote D2D transmit power, source-relay and relay-receiver transmit power respectively.  $\gamma_{n\_d2d,m\_d2d}$ ,  $\gamma_{n\_d2d,r}$  and  $\gamma_{r,m\_d2d}$  represent SINR at D2D receiver, source-relay and relay-receiver respectively. It is necessary to consider how D2D or relay-assisted D2D pairs reuse the channel of a cellular UE in order to minimise interference.

The sum interference from D2D or relay-assisted D2D pairs is expressed in Equation (6.13) as an objective function that seeks to minimise the total interference when assigning channels for reuse.

$$\min \sum_{\substack{n_{d2d} \in N_{d2d}, \\ n_{cue} \in N_{cue}, r \in R}} (\alpha_{n_{d2d}, n_{cue}} I_{n_{d2d}, n_{cue}} + x_{r, n_{cue}} I_{r, n_{cue}}) \quad (6.13)$$

Equation (6.13) is further expressed as:

$$\min \sum_{\substack{n_{d2d} \in N_{d2d}, \\ n_{cue} \in N_{cue}, r \in R}} I_{n_{d2d}, r, n_{cue}} \quad (6.14)$$

Subject to

$$\alpha_{n_{d2d}, n_{cue}} \in \{0, 1\} \quad \forall n_{d2d} \in N_{d2d}, n_{cue} \in N_{cue} \quad (6.15)$$

$$x_{r, n_{cue}} \in \{0, 1\} \quad \forall r \in R, n_{cue} \in N_{cue} \quad (6.16)$$

$$\sum_{n_{d2d} \in N_{d2d}} \alpha_{n_{d2d}, n_{cue}} \leq 1 \quad \forall n_{cue} \in N_{cue} \quad (6.17)$$

$$\sum_{r \in R} x_{r, n_{cue}} \leq 1 \quad \forall n_{cue} \in N_{cue} \quad (6.18)$$

$$\sum_{n_{cue} \in N_{cue}} \alpha_{n_{d2d}, n_{cue}} \leq 1 \quad \forall n_{d2d} \in N_{d2d} \quad (6.19)$$

$$\sum_{n_{cue} \in N_{cue}} x_{r, n_{cue}} \leq 1 \quad \forall r \in R \quad (6.20)$$

$$\sum_{\substack{n_{d2d} \in N_{d2d}, \\ r \in R}} (\alpha_{n_{d2d}, n_{cue}} + x_{r, n_{cue}}) = 1 \quad \forall n_{cue} \in N_{cue} \quad (6.21)$$

The admission control indices,  $\alpha_{n_{d2d}, n_{cue}}$  and  $x_{r, n_{cue}}$  for D2D transmitters and relay UEs respectively, are used to determine if a channel has been assigned for reuse; and expressed in Equation (6.15) and Equation (6.16), similar to [37]. Equation (6.17) and Equation (6.19) ensure that a maximum of one D2D transmitter can reuse a cellular channel and vice versa respectively. Likewise, Equation (6.18) and Equation (6.20) indicate that a maximum of one relay UE can share a cellular channel and only one cellular channel can be reused by a relay UE respectively. Equation (6.21) ensures that only one cellular channel can be assigned for

reuse in every transmission. Also, Equations (6.13) – (6.21) form an assignment problem that is solved using GS and KM algorithms.

In the proposed optimal scheme, the transmitting and receiving D2D or relay-assisted D2D pairs request to communicate with each other. The D2D receiver sends channel state information to the eNB, which then calculates interference,  $I_{n\_d2d,r,n\_cue}$  from the D2D or relay-assisted D2D transmission to cellular transmissions. The KM algorithm is then used for the channel assignment in Algorithm 6.1. As earlier discussed in the previous chapter, the KM algorithm solves the assignment problem using a bipartite graph to find the possible minimum interference introduced when D2D or relay-assisted D2D pairs share channels belonging to cellular UEs.  $G(X, E)$  represents the bipartite graph where  $X$  and  $E$  denote the vertex and edge sets respectively as shown in Figure 6.2.

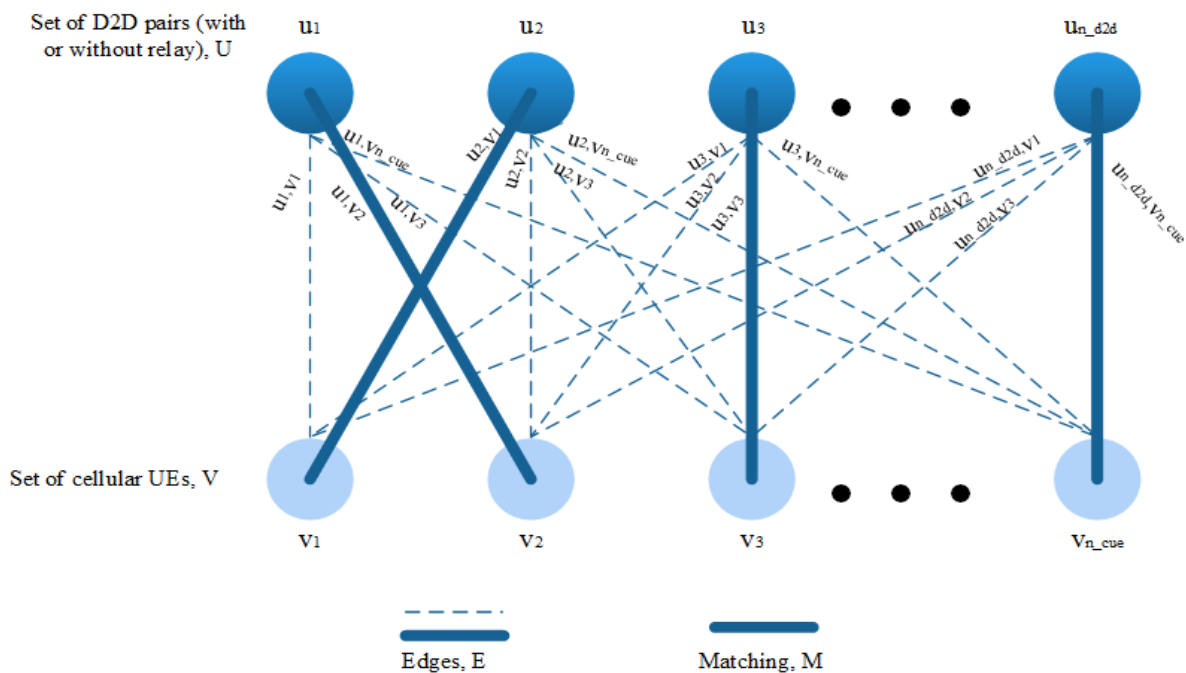


Figure 6.2: A bipartite graph with one-to-one matching

The graph  $G$ , is bipartite when  $X$  can be divided into two disjoint subsets,  $U$  and  $V$ , and each edge in  $E$  has an endpoint in  $U$  and the other endpoint in  $V$ . The vertex,  $U$  represents D2D and relay-assisted D2D pairs whereas  $V$  denotes cellular UEs. The weight of the edge,  $w(u, v)$  represents the interference,  $I_{n\_d2d,r,n\_cue}$  that is introduced due to the reuse of cellular channels by D2D or relay-assisted D2D pairs, where  $u \in U$  and  $v \in V$ . The KM algorithm searches for the augmenting paths until there exist any and computes the perfect matching set  $M$  with the

minimum weight, where  $M \subseteq E$  is a matching from  $U$  to  $V$  such that no two edges in  $M$  have the same vertex. The sum rate of the matched D2D pairs (either relay-assisted or not) are then obtained. The KM algorithm is adapted from [65],[66] and summarised in Algorithm 6.1 with a computational complexity of  $O(N^3)$ .

The stable matching approach focuses on matching two sets of players based on their individual preferences. With regards to the two finite and disjoint sets of players,  $C = \{1, 2, \dots, n_{cue}, \dots, N_{cue}\}$  and  $D \in (T \cup S)$ , where  $T = \{1, 2, \dots, n_{d2d}, \dots, N_{d2d}\}$  and  $S = \{1, 2, \dots, r, \dots, R\}$ .  $C$  denotes the set of cellular UEs and  $D$  represents the set of D2D transmitters and relay UEs. Each player  $n_{cue} \in C$  ranks the players of the opposite set of players  $D$ , using the preference relation  $\succ_{n_{cue}}$ , where a player  $n_{cue}$  can be matched to at most one player of the opposite set  $D$ . Each player of a set constructs preference lists on the opposite set of players. The preferences of cellular UEs over D2D pairs (either relay-assisted or not) are defined based on the incurred interference from the reuse of cellular channels by D2D pairs (either relay-assisted or not). Also, the preferences of D2D pairs (either relay-assisted or not) over cellular UEs are constructed depending on the channel gains of the cellular UEs to D2D pairs (either relay-assisted or not),  $G_{n_{d2d},r,n_{cue}}$  and preferable cellular channels are assigned to D2D pairs (either relay-assisted or not).

A stable matching is obtained if there exists no matched pair constituting a cellular UE and D2D pair (either relay-assisted or not) that both prefer each other over their current partners. The GS algorithm, also known as the Deferred acceptance algorithm, is applied to match the D2D pairs with cellular channels to achieve a stable matching. The GS algorithm is summarised in Algorithm 6.2 with a computational complexity of  $O(N^2)$ . Figure 6.3 represents the flow chart of the stable matching algorithm used in this research work, similar to [67]. In the matching game, each man and each woman permute the opposite player set according to his or her preference. Likewise, D2D pairs (either relay-assisted or not) and cellular UEs can be regarded as men and women, respectively.

**Preference List ( $PL_{n_{cue}}$ ) 1.** Cellular UEs prefer D2D pairs (either relay-assisted or not) where  $PL_{n_{cue}} = \{(I_{n_{d2d},r,n_{cue}})_1 < (I_{n_{d2d},r,n_{cue}})_2 \dots < (I_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}\}$

**Preference List ( $PL_{n_{d2d}}$ ) 2.** D2D pairs (either relay-assisted or not) prefer cellular UEs where  $PL_{n_{d2d},r} = \{(G_{n_{d2d},r,n_{cue}})_1 > (G_{n_{d2d},r,n_{cue}})_2 \dots > (G_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}\}$

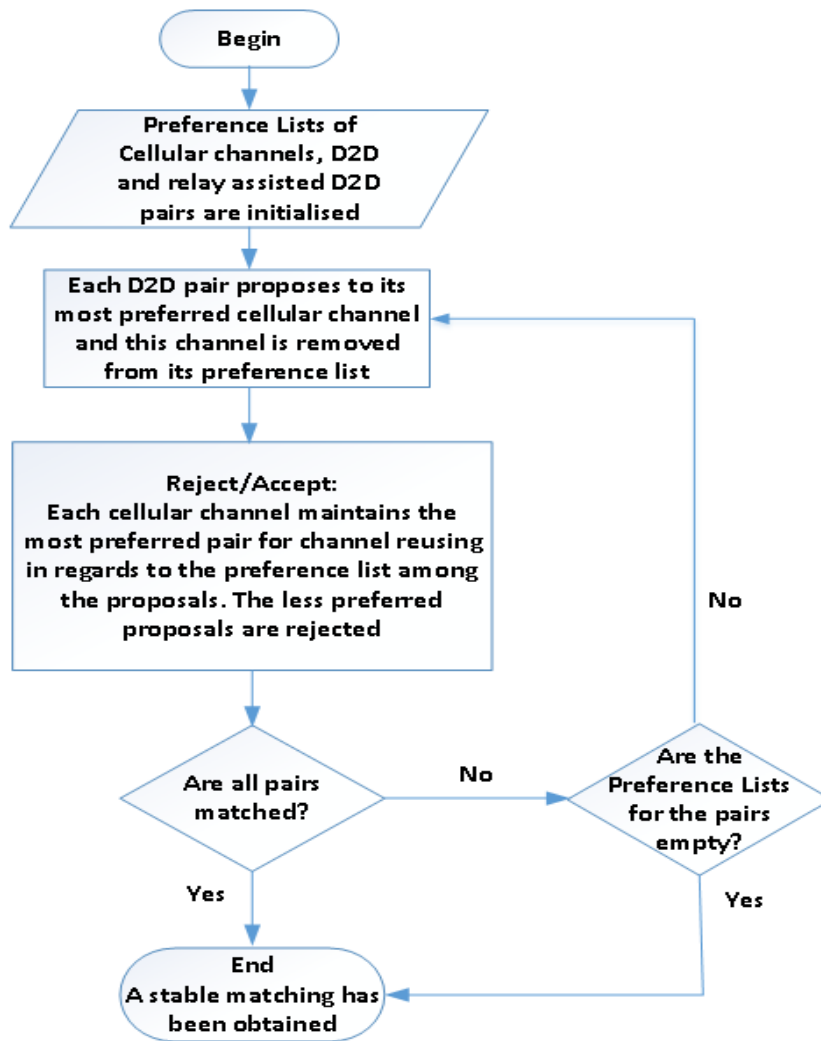


Figure 6.3: Flow chart of stable matching algorithm

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**Algorithm 6.1: KM Algorithm**

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1. Generate interference matrix,  $I_{n\_d2d,r,n\_cue}$
  2. **if**  $I_{n\_d2d,r,n\_cue} \leq I_o$
  3. Performing KM algorithm for channel allocation: Let  $U$  and  $V$  represent  $(N\_d2d \& R)$  and  $N\_cue$  respectively,  $w(u, v) = I_{n\_d2d,r,n\_cue}$
  4. **Step 1. Initialisation:** Find a matching  $M$  in subgraph  $G_l$  and generate initial labelling as follows:
    5.  $l(u) = \min\{w(u, v)\} \quad \forall u \in U$
    6.  $l(v) = 0 \quad \forall v \in V$
  7. **Step 2. if**  $M$  is a perfect matching, then stop and return  $M$  as the minimum weight matching
  8. **else** let  $x$  be a free vertex where  $x \in X$
  9. Set  $S = \{x\}$  and  $T = \emptyset$
  10. **end if**
  11. **Step 3. if**  $N_{G_l}(S) \neq T$ , go to **Step 4**
  12. **else** calculate  $\alpha_l = \max_{\substack{u \in S \\ v \in T}} l(u) + l(v) + w(u, v)$
  13. 
$$\hat{l}(x) = \begin{cases} l(x) - \alpha_l & \forall x \in S \\ l(x) + \alpha_l & \forall x \in T \\ l(x) & \text{otherwise} \end{cases}$$
  14. Replace  $l$  with  $l'$  and  $G$  with  $G'$
  15. **end if**
  16. **Step 4.** Select a vertex  $v \in N_{G_l}(S) - T$
  17. **if**  $v$  is matched to a vertex  $z$ , then add  $(z, v)$  to the alternating tree
  18. Set  $S = S \cup \{z\}$ ,  $T = T \cup \{v\}$  and go to **Step 3**
  19. **else** let  $P$ , an  $(x, v)$  augmenting path replace  $M$  with  $M = M \Delta E(P)$ , go to **Step 2**
  20. **end if**
  21. **Calculate**  $R_{sum}$  for all permitted D2D pairs
  22. **else**
  23. Set  $I_{n\_d2d,r,n\_cue} = \inf$
  24. **end if**
-

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**Algorithm 6.2: GS Algorithm**

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1. Performing Deferred Acceptance algorithm for channel allocation:
  2. **Initialisation:** Setting  $N_{d2d}$ ,  $R$  and  $N_{cue}$  to values.
  3. **Construct** preference list:  $PL_{n_{cue}} = \{(I_{n_{d2d},r,n_{cue}})_1 < (I_{n_{d2d},r,n_{cue}})_2 \dots < (I_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}\}$   
 $PL_{n_{d2d}} = \{(G_{n_{d2d},r,n_{cue}})_1 > (G_{n_{d2d},r,n_{cue}})_2 \dots > (G_{n_{d2d},r,n_{cue}})_{N_{d2d},R,N_{cue}}\}$
  4. **Construct** unmatched D2D pairs (relay-assisted or not) list; where  $T = \{1, 2, \dots, n_{d2d}, \dots, N_{d2d}\}$  and  $S = \{1, 2, \dots, r, \dots, R\}$ ,  $D \in (T \cup S)$  Cellular UEs;  $C = \{1, 2, \dots, n_{cue}, \dots, N_{cue}\}$
  5. **while** ( $D \neq \emptyset$ ) **do**
  6.     **for**  $n_{d2d} \in D$
  7.          $n_{d2d}$  proposes to cellular UE,  $n_{cue}$  that ranks the highest on the preference list
  8.     **end for**
  9.     **for**  $n_{cue} \in C$
  10.         **if**  $n_{d2d} \succ_{n_{cue}} n_{d2d}'$ ;  $n_{cue}$  receives a proposal from  $n_{d2d}$  and  $n_{d2d}$  is more preferred than the current hold  $n_{d2d}'$
  11.              $n_{cue}$  holds  $n_{d2d}$  and rejects  $n_{d2d}'$
  12.              $n_{d2d}$  is removed from the preference list
  13.         **else**
  14.              $n_{cue}$  rejects  $n_{d2d}$  and gets matched to  $n_{d2d}'$  if there are no better preferences
  15.              $n_{d2d}'$  is removed from the preference list
  16.         **end if**
  17.     **end for**
  18.     **Calculate**  $R_{sum}$  for all permitted D2D pairs
  19. **end while**
-

## 6.6 Simulation Parameters and Results Discussion

The presented methods considered for this work are evaluated and the simulation parameters are shown in Table 6.2. The key performance measurement indicators of interest are the permitted number of D2D users, total system sum rate and the average interference from D2D users (relay-assisted or not) when reusing an uplink cellular channel.

Table 6.2: Simulation Parameters

Parameter	Value
Cell radius	300m
Channel bandwidth	10MHz
Additive White Gaussian Noise	-174dBm/Hz
Path loss model for D2D or relay-assisted D2D link	$148 + 40.6\log_{10}(d[\text{km}])$
Path loss model for cellular link	$128.1 + 37.6\log_{10}(d[\text{km}])$
Distance limitation for D2D link	30m
Maximum transmit power of D2D UE	21dBm
Maximum transmit power of cellular UE	24dBm
Distance limitation for relay-assisted D2D link	30 – 60m
SINR threshold	0dB
Minimum transmit power of D2D and relay-assisted D2D pair	0dBm
Number of Monte Carlo Simulation runs	300

The relationship between varying interference thresholds and the number of permitted D2D users is portrayed in Figure 6.4. It is observed that an increase in the interference threshold results in a higher number of permitted D2D pairs (relay-assisted or not). The performance of the KM algorithm over the GS algorithm is less significant since both algorithms assign channels to all D2D pairs within an interference threshold. The GS algorithm achieved a slightly lower performance than the KM algorithm because of the consideration of preferences for channel assignment.

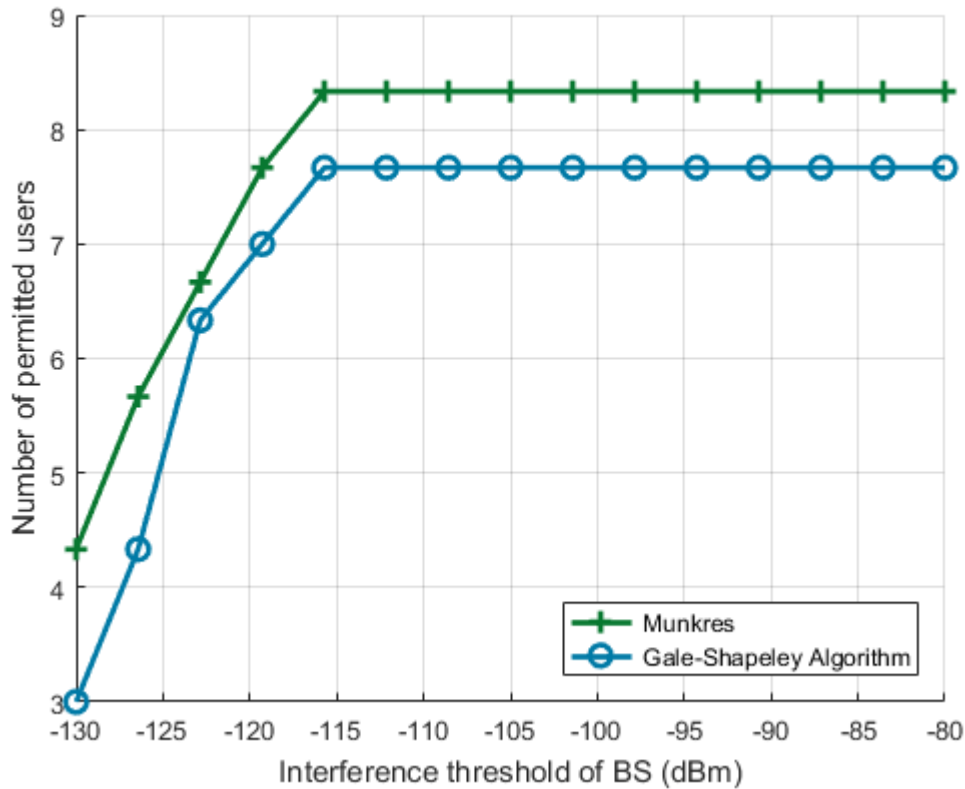


Figure 6.4: Performance comparison of proposed algorithms in relation to the permitted number of D2D users

In Figure 6.5, the effect of contrasting interference threshold of the eNB on the average interference from permitted D2D users in the presented methods is examined. From this figure, there is a rise in the average interference as the interference threshold of eNB increases. This is because a higher interference threshold increases the total permitted D2D users and consequently raises the sum interference from these users. The Kuhn-Munkres approach performed better than the Gale-Shapley method because it is observed in the simulation that the players proposing received the best match whereas those receiving proposals got the not best match thereby affecting the interference.

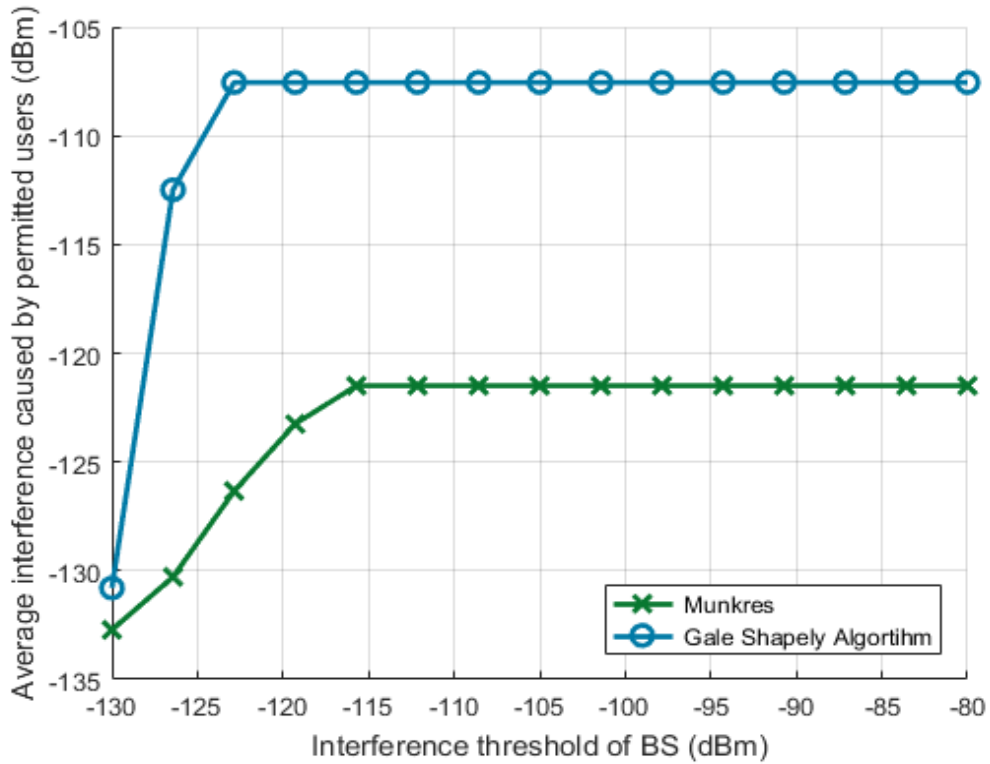


Figure 6.5: Performance comparison of the proposed algorithms in relation to the average interference caused by permitted D2D users

The performances of the KM and GS algorithms are analysed based on different number of permitted D2D pairs (with or without relay assistance) in Figure 6.6. The simulation results portrayed that the increase in the number of permitted D2D pairs increase the system sum rate, since D2D pairs communicate over short communicating distances leading to lower power transmissions and higher sum rates. This is illustrated in Figure 6.6, where the increase in the number of permitted D2D pairs from 3 to 39 consequently resulted in an increase in the system sum rate from 41.8 – 48.1 (*Mbps*) and 45.7 – 49.5 (*Mbps*) in the GS and KM algorithms. Hence, it is concluded that the KM algorithm performed better than the GS algorithm.

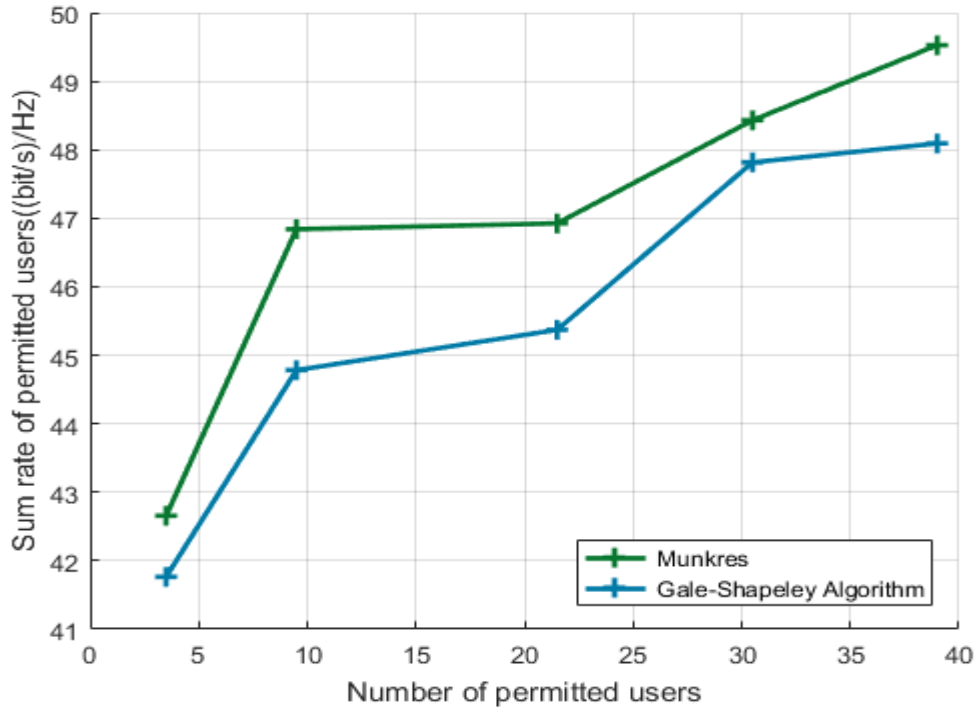


Figure 6.6: The system sum rate with varying number of permitted D2D pairs

## 6.7 Conclusion

This section concludes Chapter 6. In this study, a D2D and relay-assisted D2D communication coexisting and reusing cellular channels is considered. The Gale-Shapley algorithm is adopted to assign cellular channels to D2D pairs with fairness to obtain a stable system. A performance comparison analysis of the GS algorithm and Kuhn-Munkres algorithm is conducted. The outcome of the simulation portrays that the KM algorithm outperformed the GS algorithm. Although the GS algorithm does not perform optimally as the KM algorithm, it has a lower computational complexity of  $O(N^2)$  when compared with the KM algorithm with  $O(N^3)$ . GS algorithm also takes into consideration the preferences of users to obtain a stable network. While the Gale-Shapley algorithm does not provide an optimal solution with a stable matching, a minimax algorithm with an optimal performance can be considered. Minimax algorithm searches game trees with a time response of  $O(b^m)$  and may not always be stable [68]. Where  $b$  is the number of legal moves at each point and  $m$  is the maximum depth of the tree. Also, given that the computational burden could be outsourced to the high-speed servers in the Evolved Packet Core (EPC) network segment for processing within seconds, it is also important to determine the performances of the algorithms with regards to time response since it is a distinguishing factor in cases of D2D UEs densely underlaying the cellular network.

## Chapter 7

### 7 Conclusion and Future Work

#### 7.1 Conclusion

The increase in data traffic demands on the current 4G network and beyond is mainly driven by factors such as emerging bandwidth consuming applications and introduction of smart devices with enhanced service capabilities, consequently posing a challenge to network operators to overcome the shortage in spectrum and limited capacity. The next generation 5G network is envisioned to provide enhanced mobile broadband and connectivity to billions of heterogeneous devices with varying requirements and hence, there is the need for a drastic change in the network architecture to support these requirements. There are many proposed techniques that have emerged as key enabling technologies for the next generation networks, with D2D communication as one of the promising paradigms. The integration of D2D communication into the next generation networks provides benefits such as increased traffic offloading, improved communication availability and reliability, high throughput, reduced latency and lower power consumption.

The study addressed some useful research questions required to tackle the problem of interference in D2D communication underlying cellular networks. This dissertation aims to find out how cellular channels can be efficiently assigned to D2D pairs for reuse as an underlay to cellular networks with minimal interference while determining the influence of mode selection and power control approaches on the level of interference introduced by D2D pairs. The research work further continues to find out how the performance of D2D communication can be maintained with contributing factors such as bad channel quality or increased distance and determines how relay UEs can be selected from other optional relay UEs to assist in D2D communication with minimal interference.

The dissertation presented two network model scenarios for performance analysis, with the first network model comprising of D2D pairs and cellular UEs while the latter network model consists of D2D pairs, cellular UEs and relay-assisted D2D pairs. Using the first network model, a comparative analysis of the selected indicators, received signal power and path loss compensation factor, is carried out to examine the performance of the Open Loop Power Control scheme in D2D communication underlying a cellular network. Also, given the fact

that the OLPC scheme is mostly associated with low signal overheads, it thereby provides simple implementation and low operation costs. The analysis of the open loop components is necessary for efficient radio resource management from the perspective of network operators.

It was discovered in the results that the cell-edge users experience higher level of path loss than the users at the centre of the cell. The conventional OLPC scheme compensates for the path loss by allowing D2D UEs to transmit at a higher power when compared with the fractional OLPC that allows power transmission that compensates for a fraction of the path loss. The impact of fractional open loop power control parameters on the SINR encountered by D2D receivers is further investigated. The results obtained suggested that there is a tradeoff in SINR performance between the path loss compensation component and transmit power level, such that a rise in transmit power level results in an increase in interference with a rise in SINR whereas a decrease in the path loss compensation components leads to lower interference with reduced SINR. Consequently, it is important to adjust these parameters to improve the performance of SINR.

The research work further examines the two presented network models with regards to minimising interference. A mode selection algorithm using Nearest Neighbour Search approach with a distance criterion is implemented to select the transmission modes for users. Then, a power control optimisation problem is formulated and transmit power solutions are assigned to D2D transmitters and relay UEs. A heuristic algorithm that uses a greedy approach is implemented to allocate cellular channels for reuse by D2D pairs, and a comparative analysis of performance is carried out with the Kuhn-Munkres algorithm and a Random channel allocation method.

The results showed that the proposed heuristic method had a close performance to the KM algorithm, and both algorithms outperformed the Random channel allocation method with regards to minimising interference while guaranteeing a maximised number of permitted D2D pairs to reuse cellular channels. In the case of the relay-assisted D2D pairs, a relay selection algorithm is applied and performance in terms of minimising interference is compared with a random relay selection approach. Also, the performances of the proposed algorithms in the two network model scenarios are examined. The outcome of this analysis suggested that the second network model consisting of D2D pairs, cellular UEs and relay-assisted D2D pairs portrayed a significant increase in performance than the network model consisting of only D2D pairs and cellular UEs.

Due to this outcome, the study further examines the second network model by taking into consideration the preferences of the cellular UEs and D2D or relay-assisted D2D pairs in the allocation of cellular channels for reuse. Hence a matching problem for channel allocation is formulated, and the Gale-Shapley algorithm is implemented to obtain a stable matching. Then, a comparison in performance is made with the KM algorithm. The results showed that the KM algorithm outperformed the Gale-Shapley algorithm with regards to the total sum rate and the interference caused by the permitted D2D or relay-assisted D2D pairs reusing cellular channels, with a higher computational complexity.

The results obtained in this study concludes that the proposed algorithms have a beneficial impact on improving the performance of a D2D communication underlaying cellular network. In addition, based on the findings in this dissertation, the introduction of relay-assisted D2D communication can improve the quality of a network while utilising the available spectral resources without additional infrastructure deployment costs.

The dissertation content is structured into seven chapters. Chapter 1 presents the introduction of the dissertation, where the concept and evolution of cellular networks are discussed without disregarding the progress of direct communication in the generations of cellular networks. The envisioned requirements and use cases for the 5G network are summarised and the need for considering D2D communication as one of the approaches to support the 5G network requirements is highlighted. Also, the objectives that seek to address the identified research problem statement are outlined, and the research questions to tackle the defined problem statement are presented. The chapter further outlines the scope and limitation of the research work and finalises with the dissertation organisation that covers the structuring of the remaining chapters.

In Chapter 2, an extensive overview of D2D communication is provided. The applications of D2D communication, including traffic offloading, coverage extension, local data services and emergency services are outlined. The classification of D2D communication based on the involvement of base stations and spectrum usage is indicated. The chapter finally discusses the existing literature on the interference mitigation approaches for D2D communication underlaying cellular networks.

Chapter 3 discusses the analytical system model for the identified research problem. In the research work, two scenarios are taken into account. Firstly, a system model scenario consisting

of cellular and D2D transmission modes is considered and then lastly, a relay-assisted D2D transmission mode is introduced to coexist with the already existing cellular and D2D transmission modes. The work aims to reduce intra-cell and co-channel interference resulting from the reuse of uplink cellular channels by D2D pairs. The assumptions considered in the implementation of the two system model scenarios are outlined. The fading components selected for the channel model and the types of channel gains considered in the system model are highlighted. Finally, the chapter is concluded by presenting the performance metrics considered for the evaluation of the proposed methods for the mitigation of interference in D2D communication underlying cellular networks.

Chapter 4 presents the performance evaluation of the fractional power control in uplink D2D communication. The performance of the power control method is analysed with regards to the received signal power and path loss compensation factors. The effect of path loss on transmit power spectral density is studied while varying the path loss compensation factor with constant initial power. It is observed that the transmit power spectral density increases with an increase in path loss. Also, the effect of fractional open loop power control parameters, path loss compensation component and initial power on SINR is investigated.

In Chapter 5, a channel allocation problem is modelled in a single cell using two system model scenarios. A proposed mode selection algorithm is implemented to determine the transmission modes of the users, and a power allocation method is proposed to minimise the power of D2D transmitters and relay UEs. An assignment problem for channel allocation is further formulated to minimise interference caused by D2D transmitters and relay UEs when sharing the same channel with cellular users. The performances of the proposed algorithms are compared using performance indicators such as average interference and the number of permitted users. The proposed heuristic algorithm has a close performance to the KM algorithm, while both algorithms outperformed the random channel allocation method. In addition, the performances of the proposed algorithm in the two system model scenarios are evaluated. The simulation results indicated that the system model with relay-assisted D2D communication performed better than the system model without relay-assisted D2D communication.

Chapter 6 provides an overview of matching theory and its application in resource allocation. A system model consisting of D2D pairs (with and without relay assistance) and cellular UEs is considered. The Gale-Shapley algorithm is presented to solve the formulated channel

allocation problem. The performances of the GS approach are then compared with the Kuhn-Munkres method and the outcome of the simulation showed that the former performed slightly lower than the latter.

Chapter 7 concludes the dissertation and future research works are proposed.

## **7.2 Recommendations for Further Study**

This dissertation focuses on intra-cell and co-channel interference management in D2D communication underlying cellular communication. It applies mode selection, power control, channel allocation and relay selection methods to minimise the interference introduced when uplink cellular channels are simultaneously reused by D2D pairs. The propositions in this dissertation in the area of D2D communication have the potential for wide explorations such as the application of D2D communication in Internet of Things (IoTs) and the use of cognitive radio networks in D2D communication which enables the D2D users to make autonomous decisions and adjust their transmit power, operating frequency, and spectrum access policy opportunistically [69]. The scope of this research work did not consider the mobility scenario of users and the reuse of downlink cellular channels. Following the same approach in this dissertation, interference minimisation in D2D communication underlying cellular networks can be performed for reuse of downlink channels. Also, an efficient relay selection approach for a user mobility scenario of a full duplex relay-assisted D2D communication can be considered for the extension of this work.

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