RELAY ASSISTED DEVICE - TO - DEVICE COMMUNICATION WITH CHANNEL UNCERTAINTY

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This thesis is dedicated to God from whom every good and perfect gift comes, to my parents, Prof Udo Etuk Uyoata and late Mrs Ekaete Udo Uyoata whose sacrifices for me from a humble cradle to this unveiling epoch remain deeply appreciated. To their seeds of love, their example of hard work and their vision of excellence is this work also dedicated.

Declaration

I declare that the work in this thesis has been put together by myself. I confirm that this work is mine. Articles, books that were consulted in forming the concepts of this work are appropriately acknowledged. This work has not been submitted in part or as a whole to any other institution for examination for the award of any academic degree or diploma. This work is being submitted for a Doctoral degree in Electrical Engineering in the University of Cape Town.

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Abstract

The gains of direct communication between user equipment in a network may not be fully realised due to the separation between the user equipment and due to the fading that the channel between these user equipment experiences. In order to fully realise the gains that direct (device-to-device) communication promises, idle user equipment can be exploited to serve as relays to enforce device-to-device communication. The availability of potential relay user equipment creates a problem: a way to select the relay user equipment. Moreover, unlike infrastructure relays, user equipment are carried around by people and these users are self-interested. Thus the problem of relay selection goes beyond choosing which device to assist in relayed communication but catering for user self-interest. Another problem in wireless communication is the unavailability of perfect channel state information. This reality creates uncertainty in the channel and so in designing selection algorithms, channel uncertainty awareness needs to be a consideration. Therefore the work in this thesis considers the design of relay user equipment selection algorithms that are not only device centric but that are relay user equipment centric. Furthermore, the designed algorithms are channel uncertainty aware.

Firstly, a stable matching based relay user equipment selection algorithm is put forward for underlay device-to-device communication. A channel uncertainty aware approach is proposed to cater to imperfect channel state information at the devices. The algorithm is combined with a rate based mode selection algorithm. Next, to cater to the queue state at the relay user equipment, a cross-layer selection algorithm is proposed for a two-way decode and forward relay set up. The algorithm proposed employs deterministic uncertainty constraint in the interference channel, solving the selection algorithm in a heuristic fashion. Then a cluster head selection algorithm is proposed for device-to-device group communication constrained by channel uncertainty in the interference channel. The formulated rate maximization problem is solved for deterministic and probabilistic constraint scenarios, and the problem extended to a multiple-input single-out scenario for which robust beamforming was designed. Finally, relay utility and social distance based selection algorithms are proposed for full duplex decode and forward device-to-device communication set up. A worst-case approach is proposed for a full channel uncertainty scenario. The results from computer simulations indicate that the proposed algorithms offer spectral efficiency, fairness and energy efficiency gains. The results also showed clearly the deterioration in the performance of networks when perfect channel state information is assumed.

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List of Abbreviations

3GPP	Third Generation Partnership Project
5G	Fifth Generation
AF	Amplify and Forward
AWGN	Additive White Gaussian Noise
BS	Base Station
C-RAN	Cloud Radio Access Network
CAPEX	Capital Expenditure
CDF	Cumulative Density Function
CSI	Channel State Information
D2D	Device-to-Device
DF	Decode and Forward
DTN	Delay Tolerant Network
EE	Energy Efficiency
eNB	Evolved Node B
IoT	Internet of Things
KM	Kuhn Munkres
KPI	Key Performance Indices
LTE	Long Term Evolution
M2M	Machine-to-Machine

MAC	Multi Access Control
MANETS	Mobile and Ad-hoc Networks
MIMO	Massive Input Massive Output
MISO	Massive Input Single Output
mmW	Millimetre Wave
MU-MIMO	Multi User-Massive Input Massive Output
NFC	Near Far Communication
NOMA	Non-Orthogonal Multiple Access
NP	Non-deterministic Polynomial time
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open System Interconnect
PDF	Probability Density Function
PLNC	Physical Layer Network Coding
PPP	Poisson Point Process
ProSe	Proximity Service
QoS	Quality of Service
QSI	Queue State Information
RUE	Relay-enabled User Equipment
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDN	Semi Definite Programming
SDN	Software Defined Network
SD	Source Destination
SINR	Signal to Interference plus Noise Ratio
TDD	Time Division Duplex

UAV	Unmanned Aerial Vehicle
UE	User Equipment
WLAN	Wireless Local Area Network
ZF	Zero Forcing

Chapter 1

Introduction

1.1 Research Background

Wireless communication has evolved into a ubiquitous technology that sees application in personal, military and business scenarios. The proliferation of smart devices such as smartphones, wearable devices, tablets, phablets and laptops have contributed to the expansion of wireless communication. Furthermore, applications like smart metering, intelligent transport, wireless sensor networks, cloud computing, vehicular communication, machine to machine (M2M), device-to-device (D2D) communication and the internet of things (IoTs) are also driving the evolution of wireless communication [1]. There is also the overweening consumer demand for higher speed which has had its effect on the development or evolution of wireless communication technologies, an example is the online gaming industry where latency needs to be minimal. Additionally, autonomous vehicles and smart factories in the emerging Industry 4.0 will need connection to the network.

It is expected that the emerging so-called 5th generation (5G) of wireless networks will offer higher peak data rates, minimal latency and cater for a heterogeneous dense network [2], [3]. And so technologies have been put forward, developed and are currently being tested to meet the laid out requirements of the wireless networks of the foreseeable future with focus on 5G networks and also to address the limitations that present and previous generations of wireless technologies could not efficiently address. Such enabling technologies that could define the 5G wireless systems include massive multiple antenna deployment, a technology that promises higher throughput in fast fading environments [4], higher total energy efficiency [5], [6] and improved spectral efficiency [6]; cloud radio access network (C-RAN), a framework that separates baseband processing from radio access is envisaged to reduce latency [7] and improve energy efficiency [8]. Other features that could define future wireless networks are software-defined networking (SDN), a technology that will support the heterogeneous nature of cell deployments in the future [9] and enhance network management [10]; millimetre wave (mmW) communication that has been touted as a solution to the spectrum crunch and as a platform for the flourishing of massive MIMO deployment [11], [12]; and ultra-dense network, an overlap of cells of various sizes catering for a very dense collection of users and devices [13], [14].

Device-to-device (D2D) communication is also an enabling technology proposed as a candidate technology for future wireless communication. Although the viability of some of the aforementioned technologies may still be contested, it is indisputable that highly dense networks will be a key feature of the next phase of wireless networks and that implies many devices being in close proximity at most times. This close proximity makes the case for D2D communication where mobile devices can directly communicate with each other without routing their signals through the base station (BS)/eNodeB. D2D communication has been shown in the literature to offer increased overall network throughput, spectral efficiency through frequency reuse, extend cellular coverage and to reduce the traffic on the eNodeB. Envisaged applications include content sharing, device discovery, location-based applications, and emergency services. Furthermore, D2D communication is envisioned to be an enabler of IoTs. The third generation partnership project (3GPP) has made standardization efforts on D2D communication by introducing D2D communication for public safety communication in its Release 12 ProSe specifications [15].

To demonstrate the gains of deploying D2D communication in future wireless networks, various research efforts have been carried out on the subject matter. Most of these research works have taken on a system optimization approach.

D2D communication has been studied from the perspective of optimization where a utility function (which could be transmit power or resource unit) is optimized subject to stated constraints. In addressing optimization most authors have considered optimizing a single utility function or jointly optimizing more than a utility function. Such utility function could be data rate dependent, energy efficiency or transmit power dependent. For instance, transmit power optimization is studied in [16] and [17] where greedy optimization approaches in which D2D devices and traditional cellular devices seek to optimize their own utility at the expense of each other is presented. Joint optimization is studied in [18], [19]. While most of the optimization approaches have been heuristic sub-optimal algorithms considering that formulated optimization problems are NP-hard, game theory techniques have been proposed for D2D resource allocation [20]. Furthermore, game theoretic approaches in D2D communication research have been broadly cooperative or non-cooperative depending on whether the optimization of a distributed or centralised utility function is the target.

Apart from direct communication between devices, in situations where the channel does not allow direct traversing of signals, D2D communication can be achieved through relays. Such relays could be fixed (i.e. infrastructure based) or mobile user equipment. Employing relays to enforce D2D communication although promising bringss up some challenges. In scenarios where the relays are mobile user equipment, relay selection techniques and incentive schemes to motivate relaying become necessary. Therefore broadly, in relay-assisted D2D communication research, authors have either focused on relay selection, resource allocation or incentive designs for relay participation. Another issue of note in relay aided communication that uses mobile relays is channel uncertainty. A good number of works assume the availability of perfect channel state information and so the algorithms developed by such works are not channel uncertainty aware. There are works that have made efforts in factoring in the effect of imperfect channel state information in relay-assisted D2D communication. For instance, in [21], resource allocation algorithms proposed to be robust against uncertainties arising from imperfect knowledge of both the target link and the interference link are presented. The disparity between actual and nominal values was used in modelling the uncertainties. The relays considered are fixed infrastructure relays and so differs from the work in this thesis in that the relays modelled in this thesis are mobile devices. In [22] mobile relaying for overall coverage is considered although unlike the work in this thesis, channel uncertainty due to incomplete channel state information is not considered. Apart from that, the work in this thesis puts forward relay selection algorithms that are not only channel uncertainty aware but relay centric too. Hence this work attempts to fill the gap in relay-assisted D2D communication with a focus on channel uncertainty aware algorithms that are relay user equipment centric.

Moreover, in analysing mobile relay assisted D2D communication, most research works have assumed that the candidate relay is always willing to participate in aiding D2D communication hence optimizing the relay defined utility is ignored in the optimization problem. For the work in this thesis, we are proposing a slightly different look at relay assisted D2D communication. We consider an approach in which channel uncertainty from imperfect CSI is considered and relay defined utility is factored into the optimization problem formulation. To achieve this, deterministic uncertainty models are used in relay selection techniques proposed in chapters three, four and six.

In chapter five both probabilistic and deterministic uncertainty models are used. To achieve the relay centric target of relay selection, stable matching is employed in chapters three and four. In chapter six, the assignment algorithm is used for relay selection modelled as a bipartite graph. In modelling the selection as a bipartite graph, relay defined utility could be optimized in the process of relay selection by appropriately chosen weight functions.

1.2 Overview of D2D Communication

One of the defining technologies for future wireless communication networks is D2D communication. At the outset [23], D2D communication was put forward as a multi-hop technique for data forwarding between mobile devices. Currently, various use cases have been proposed for D2D communication with a highlight on D2D communication driving the rollout of massive machine type communication. Apart from researchers' interest in the possibility of D2D communication as seen in related literature, industry players have also shown interest in the technology. Qualcomm had made a prototype demonstration of the possibility of direct communication with their proprietary FlahLinQ [24] which is a peer-to-peer communication set up.

Presently 3GPP is working on standardization of D2D communication under its Proximity-based Services (ProSe) for public safety and commercial applications [25]. D2D communication enables user equipment to communicate directly or in clusters with limited supervision from the base station. In relay aided D2D communication, mobile relaying is introduced as mobile devices can help with message forwarding as against LTE-Advanced fixed relaying [26].

Direct communication between devices has been achieved using mesh networks, examples of which are WLAN and TETRA among others that mainly use the unlicensed frequency ranges. The downside of these technologies is their unplanned deployment which can create difficult interference scenarios. Architecture wise, D2D communication can be in-band or out-of-band depending on if it uses the same frequency band of the cellular network or not respectively. In-band D2D communication can be either overlay or underlay. Underlay D2D communication reuses the resources of cellular users and so improves resource utilization whereas, in overlay D2D communication, the D2D devices use orthogonal resources thereby limiting interference. For the work in this thesis, underlay D2D communication is considered.

There are ways in which a D2D communication link differs from a traditional cellular link. One of such ways is in the channel model being that the distance between

D2D users in a cell is small in comparison to the distance between most cellular users and a base station. Additionally, devices participating in D2D communication will averagely be at similar heights [27]. Moreover, in D2D communication, the participating entities are mobile, unlike a static infrastructure base station.

The application scenarios for D2D communication includes context-aware advertisement, gaming, content distribution among clustered devices and emergency communication (when the traditional infrastructure fails due to a disaster). The gains that can be derived from D2D communication includes improved network throughput [27], [28], [29]; cellular traffic offloading [29], [30] and improved use of available spectrum [31], [32] among others. Despite the gains that underlay D2D communication offers, there are challenges that face its successful deployment major among them being interference management.

Approaches to these challenges have included resource allocation, mode selection, power control, co-operative communication, multi-antenna beamforming, and relay selection. Relay selection becomes necessary when D2D communication is aided by a relay. Such a scenario can find application in video multicasting through a relay user equipment and drone mounted relay user equipment in emergency communications. The following subsection gives a brief overview of relay-assisted D2D communication highlighting a few literature on the work in the area.

1.3 Relay Assisted D2D Communication Overview

The gains of D2D communication may not be fully realised in scenarios where the D2D communication link experiences impairment. For such situations, nearby relay enabled mobile user devices can be employed to aid D2D communication. Such scenarios could arise when a disaster shuts down the communication infrastructure or when one member of a D2D pair is out of coverage. Research into relay assisted D2D communication is budding and some work has been done.

The achievable transmission rate of relay-assisted D2D communication is studied by Si Wen et al. [33] who consider the spatial density and transmit power of D2D users from an optimization standpoint. Their analysis shows that though relaying can offer power saving, having a large number of relays will diminish the gains that relaying affords. This conclusion can be inferred from the premise that a large number of relay hops defeats the proximity service idea and increases the delay in delivering target signals. When relays are involved in wireless communication, they can either cooperate with the source device in delivering the target signals to the destination or cooperation can be ignored.

Cooperative relaying schemes that are based on a superposition of signals are proposed in [34]. In one of the schemes, the designated relay user equipment broadcasts a combination of its signals and the signals of a cellular source UE. At the designated receiver, the D2D signal is decoded and at the BS, the cellular signal is also decoded from the superposed signals. The authors used numerical analysis to demonstrate the gains of their proposed schemes although the approach might have a complexity downside. The work in this thesis does not consider cooperative communication. At relays, relaying strategies could be decode and forward (DF) or amplify and forward (AF) though, with the power limitations of mobile devices, DF relaying is favoured in D2D mobile relaying.

DF relaying and transmit power optimization techniques are explored by Donghoon Lee et al.[35] to limit interference from cellular users towards D2D users. Such interference management techniques become necessary when D2D communication reuses the resources of cellular users. The authors considered a system model that allowed multi-hopping through more than one relay. Basically, the authors assumed that the direct link is sufficiently impaired to hinder direct communication between the source and destination. Results of statistical analysis and simulations showed that the probability of outage is reduced and the capacity of D2D communication was improved through relaying. The downside of the approach could be that since AF relaying is not employed at the relay, the signal power level could drop with more hops. Hence the work in this thesis does not consider multi-hopping.

Since relay aided D2D communication can either be deployed using fixed relays or mobile relays, in the literature optimal relay positioning has also been studied although for mobile relays, optimal position may not be enforceable when user equipment are used. Rather than optimal positioning, more insight can be obtained from deriving the optimal relay region. This becomes key for extending the coverage if a network operated cell to an out of coverage device.

In [22], mobile relaying for overall coverage extension is considered. A system level simulation is used in a Manhattan environment to demonstrate the viability of D2D communication as an alternative architecture to infrastructure-based relaying. Although the work studied D2D communication via mobile relays, unlike the work in this thesis, it assumed a perfect channel knowledge of both target and interfering channels.

Xiran Ma et al. [36] considered relay selection to reduce the transmit power of D2D users and so minimize interference. The authors' proposed non-centralised approach is benchmarked against the classical centralised relay selection approach. In the paper, the mobile relays measure the channels and agree on which relay should be used. The relays are assumed static and it is simulation-based without accompanying analytical formulation. Moreover, the QoS requirement of the D2D and cellular users were not considered. Also, the approach adopted by the authors ignored the self-interested nature of users of relay enabled user equipment.

In relay networks, finding the optimal relay position or region is an area of interest as it can provide insight into the energy efficient region of relay communication. In D2D communication, there is limited routing of signals through the base station and so energy saving is achieved. By using stochastic analysis, the energy saving zone (being the region where relaying is energy efficient) for relay-assisted D2D communication is described and a method of energy consumption comparison presented in [37]. The authors showed through stochastic geometry that the relay region is elliptically shaped and lies around the halfway point between the D2D pairs. A key assumption of the work is that channel uncertainty is not a consideration and the work did not propose a relay selection algorithm.

Chen Zhengwen et al. [38] considered joint resource sharing and relay selection when D2D communication underlays a cellular network. The authors showed through simulation the network capacity improvement that their proposed relay selection technique can afford. In enabling D2D underlay communication, the authors ensured that the uplink cellular resources were re-used in order to limit the interference to cellular users. Their proposed approach was not relay centric and assumed perfect knowledge of the channel at the relay and the source device.

Whereas the broadcast nature of wireless systems presents an advantage that cooperative communication exploits, it also exposes wireless communication to eavesdropping from potential interceptors. To tackle this problem and maintain the secrecy of D2D communication, Keeth Jayasinghe et al. [39] proposed robust beamforming precoders and decoders. The authors modelled channel uncertainty as Gaussian and used physical layer network coding at the relay. Unlike the work in this thesis, the authors considered a single fixed relay and so no relay selection technique was proposed. Moreover, whereas the channel gain between the D2D pair and the eavesdropper is considered to be uncertain, the channel between the D2D pair and the relay is considered perfect. Hence the authors considered only a partial uncertainty scenario.

Given the foregoing, there is a vibrant interest in relay-assisted D2D communication howbeit there are gaps that still need to be filled. Most research works in the literature have focused on scenarios where the relay is a fixed infrastructure (i.e. a low power base station). Not many research works have considered the use of relay enabled user equipment. Where research works have considered mobile relaying, most approached their analysis from the standpoint of the availability of perfect knowledge of the associated channels at the mobile relays and the D2D pair. This approach ignores the dynamic nature of wireless channels and also the uncertainty that variations in the channel can cause. Also, fixed relays may be mounted on vehicles so that the UEs within the vehicle could engage in D2D communication within the vehicles (for example a train or a drone in an emergency rescue scenario). Such mobility scenario can create channel estimation errors. Hence the need for channel uncertainty aware algorithms.

Moreover, selection techniques are mostly skewed towards optimizing the benefits that accrue to the D2D pairs or the entire network without considering the benefit of the relaying entity. This becomes even more necessary when the relays are mobile UEs whose users being rational are self-interested. Thus rehashing the need for not only D2D centric algorithms but relay UE centric algorithms too.

1.4 Research Motivation

As wireless communication keeps evolving, enabling technologies have emerged which are envisioned to play key roles in future wireless networks. D2D Communication is one of such technologies which seeks to exploit the proximity of mobile users to transmit directly between these users with limited supervision by the base station.

While there is a body of work focused on resource allocation, interference management and content distribution, the analysis in most research works have assumed scenarios in which perfect CSI is inherent. The availability of perfect CSI at the relay UE and D2D pairs may not be guaranteed due to the channel estimation errors. Since relay UEs may be in motion, the effect of channel variation can impact on the acquired CSI. Hence a need to craft channel uncertainty aware algorithms.

Moreover relayed communication can improve spectral utilization and this is desirable for network operators. A way to motivate more relay participation to enforce D2D communication is necessary. Therefore a relay centric approach that allows the optimization of relay defined utility functions is necessary without sacrificing the QoS of D2D pairs.

Furthermore, in the area of clustered D2D communication, there is a dearth of works in robust beamforming for multicast D2D communication. D2D group or multicast communication is promising because it allows for offloading cellular traffic. Thus a need to design robust beamforming algorithms. Moreso, where the relay has a single antenna, robust formulations of D2D clustering problems are necessary to provide insight into their resolvability and the performance of the resulting solutions.

1.5 Problem Statement

Realising the gains of D2D communication can be hampered when the link between a source and destination device is degraded by fading or separation. In which case exploiting the presence of idle devices between source and destination can help enforce D2D communication and so realise the gains of D2D communication. Having a pool of idle relay enabled UEs raises the problem of relay selection. How should the relays be selected? Since these devices are held by users that are rational and self-focused, taking cognisance of their preferences while not degrading the performance of D2D communication is necessary. Thus the problem of designing relay centric selection algorithms. Moreover, the unavailability of perfect CSI at the relay UEs and D2D pairs constitutes channel uncertainty. Hence the problem of designing channel uncertainty aware relay selection algorithms that are relay centric.

1.6 Research Question

This research will seek to answer the following research questions:

- Does a stable matching based relay selection algorithm offer an optimal solution to a relay assisted D2D communication rate maximization problem in a manner that is also relay centric?

- What gains does a cross-layer uncertainty aware relay selection algorithm offer over non cross-layer, non-relay centric approaches that are not channel uncertainty aware?

- Can a robust multicast rate maximization for D2D group communication problem be solved efficiently and does the solution result in improved data rate over non-clustered communication? What performance will a robust D2D multicast communication offer?

- What gains are obtainable from an uncertainty-aware joint power control and relay selection algorithm when compared to an approach in the literature? Does the relay-centric selection algorithms enable the participation of more relay user equipment?

1.7 Research Objectives

Specifically this research work will seek to meet the following objectives:

- To formulate an uncertainty-aware rate maximization problem for relay aided D2D communication and propose an optimal/ near optimal algorithm that selects relay UEs in a relay centric manner.
- To formulate a robust cross-layer relay selection optimization problem for underlay relay aided D2D communication and formulate an optimal/near optimal relay selection algorithm to solve the proposed cross-layer optimization problem based on stable matching.
- To formulate a robust rate maximization problem for group D2D communication under channel uncertainties and solve the formulated problem to demonstrate the performance of D2D group communication. To also propose a re-transmitter selection strategy for the D2D group. To propose robust beamforming for D2D group communication with multi-antennae group transmitters.
- To formulate a joint power allocation and relay selection problem for D2D underlay communication and propose step-wise power control and relay selection algorithm and demonstrate the performance of the proposed algorithm in comparison with available algorithms in the literature.

1.8 Research Methodology

For this research work, computer simulations were used to generate results for analysis. Computer codes were developed and tested. Optimization problems were formulated and solved using the convex optimization tool (CVX). Underlay D2D communication was considered. User equipment (UEs) or mobile devices were modelled as uniformly distributed points within circular cells. We considered isolated cell scenarios and except in chapter five where inter-cluster interference applies, in the other chapters, inter-cell interference was assumed non-existent.

The channel model adopted was distance dependent path loss model and the relaying strategy is decode and forward (DF). One way DF, two way DF and full duplex DF relaying strategies were considered separately in the work in this thesis. Channel state information was assumed to be imperfect and the uncertainty was modelled as additive to the channel gain. Cases of partial uncertainty where channel imperfection existed only in the interfering channel and full uncertainty where channel uncertainty existed in all channels were considered.

1.9 Research Scope

This research focused on relaying in underlay D2D communication with channel uncertainty. It proposed a cross-layer relay selection strategy, a joint power control and relay selection algorithm, a re-transmitter selection technique for group communication. It formulated and solved robust multicast D2D communication problems using simplifications to relax constraints.

Channel state information in the interfering channels are considered imperfect and so our analysis involves resulting uncertainty. Deterministic and probabilistic uncertainty approaches are employed. Where channel uncertainty is also present in the non-interfering channel (a case known as full channel uncertainty), the equations are re-formulated to factor the uncertainty into the interfering channel. For the robust multicast scenario, both full and partial uncertainty modes are studied.

The relaying strategy in use in this work is DF relaying and cooperative communication between devices and relays is not considered. One way DF and 2 way DF relaying have been considered in this work. Furthermore, this work does not consider network coding and so it is not within the scope of this thesis.

User discovery and pairing between devices are assumed already initiated and so the actual conveying of data between source and destination is the focus of this thesis. It is held in this work that the UEs have single antennas and where multiple antennas are used in the analysis, such are employed at the base station/eNodeB or at the relay UEs.

1.10 Thesis Novel Contribution

This thesis deviates in many ways from the works available in the literature. The system models used in this thesis build from concepts available in the literature, adapting them to suit the focus area of the research in this thesis. The novelty of this research work are listed below:

- A channel uncertainty aware relay centric relay selection algorithm is put forward in chapter three. By employing the stable matching algorithm, not only D2D pairs but relay UEs can specify their preferences for participating in relayed D2D communication.
- A cross-layer relay selection algorithm based on physical layer and MAC sublayer parameters is proposed in chapter four. This algorithm is not only channel uncertainty aware but caters for a relay defined utility function through the stable matching's feature of preference definition.
- In chapter five, D2D multicast communication is formulated as a robust rate maximization problem. Moreover, a k-means based cluster head selection approach is proposed for multicast communication. Furthermore, cumulative distribution function simplifications were proposed to simplify probabilistic constraints. As far as we know the formulation of a robust multicast D2D beamforming is unique to the work in this thesis.
- A joint power allocation and relay selection problem formulated for full duplex D2D communication is solved using linear programming and two algorithms: a relay utility based algorithm and a social distance based algorithm. The employing of the assignment algorithm for relay utility based and social distance based algorithms for D2D selection is unique to the work in this thesis.

The research publications that were undertaken during the course of the work in this thesis are:

1.10.1 Journal Publication

- U. Uyoata, J.Mwangama and M. Dlodlo, "Robust Multicast Beamforming for Device to Device Communication, IEEE Communication Letters, March, 2019. [Submitted]
- U. Uyoata and M. Dlodlo, "Cross Layer Relay selection in D2D communication" Springer Wireless Personal Communication, 2019. [Accepted]

1.10.2 Conference Proceedings

- U. Uyoata, M. Dlodlo and J. Mwangama "Robust Multicast Device to Device Communication" IEEE ANTS 2018, Indore, India.
- U. Uyoata and M. Dlodlo, "Joint power allocation and relay selection for relay assisted D2D communication with channel uncertainties," IEEE EUROCON 2017 -17th International Conference on Smart Technologies, Ohrid, Macedonia 2017, pp. 486-490
- U. Uyoata and M. Dlodlo, "Relay selection in D2D communication with channel uncertainties: A stable matching approach," 2017 Global Wireless Summit (GWS), Cape Town, South Africa 2017, pp. 262-265.
- U. Uyoata and M. Dlodlo, "Incentive/reward based relay selection for device to device communication," 2017 IEEE AFRICON, Cape Town, South Africa 2017, pp. 256-261.
- U. Uyoata, M. Dlodlo and J. Mwangama, "Relay Assisted Device-to-Device and Massive MIMO interplay" SATNAC 2018

1.10.3 Preprints

- U. Uyoata and M. Dlodlo, "Relay Assisted Device-to-Device Communication: Approaches and Issues." $http://arxiv.org/abs/1810.07799$

1.11 Thesis Organisation

The thesis is made up of seven chapters. In chapter one, an introduction is given and the basis for the work is laid out with highlight on a few literature on the subject matter of this thesis. Chapter two critically examines related literature to establish the state-of-the-art and point areas where our work endeavoured to fill. In chapter three, a stable matching based relay selection technique for D2D communication is proposed in the face of channel uncertainty. The proposed algorithm is compared with other algorithms and discussions are drawn.

Chapter four discusses the performance of a proposed cross-layer relay selection algorithm in comparison with other benchmark algorithms. It shows through energy efficiency, spectral efficiency and fairness parameters the performance of the proposed algorithm.

Stretching the discussion to clustered communication, chapter five focuses on transmitter selection and cluster formation for D2D communication. A robust formulation of a rate maximization problem of D2D multicast communication is formulated and solved. Furthermore, a multi-antenna transmitter scenario is presented and its formulated robust beamforming problem is also solved. The chapter addressed the effect of cluster size and channel uncertainty due to channel estimation errors.

In chapter six, a joint power allocation and relay selection algorithm is presented. Two relay selection algorithms are proposed and their performances presented. The conclusion of the work in this thesis is given in the seventh chapter and recommendations for further work are also presented in chapter seven. In appendix 1, the complexity of the cornerstone algorithms upon which our work is based is given. Appendix 2 gives a proof of convexity of the problem formulated in chapter 5 and in appendix 3 is a demonstration of D2D underlay massive MIMO enabled network.

Chapter 2

Relay Assisted D2D Communication: A Review

2.1 Introduction

A concise review of literature related to relay assisted D2D communication is given in this chapter to provide insight into the state of research in the subject area and to also underscore the gaps that the work in this thesis has endeavoured to fill. Firstly the architecture of D2D communication is laid out before the various aspects of relay-assisted D2D communication research are delved into.

Wireless communication has come a long way: from the putting forward theoretically the possibility of wireless propagation by James Clarke Maxwell through the experimentation by Marconi to the present era there has been an evolution of wireless networks from the mainly analogue first generation (1G) to the emerging data-centric high speed, very low latency 5th generation. Moreover, in evolving from 1G towards 5G wireless communication networks, the wireless communication networks are moving from network centric designs to device-centric approaches.

The envisaged ultra-dense and heterogeneous nature of future wireless networks have motivated proposals of possible technologies for future generation networks. Moreover, mobile data traffic is envisaged to form a larger part of the mobile communication service in 5G communication networks.

Some of the enabling technologies that have been proposed and are being investigated include machine type communication (MTC), massive multi-input-multi-output (MIMO), small cells, and D2D communication among others. The drive to test and deploy these technologies are hinged on the promise of the improved data rate, improved energy efficiency and significantly reduced latency which a 5G wireless communication network is expected to offer. D2D communication has the potential to facilitate the meeting of outlined key performance indicators (KPIs) of the 5G networks owing to the gains D2D offers as outlined in the literature.

D2D communication has been shown to offer improved spectral efficiency [29], extend cell coverage [15] and energy efficiency of cellular networks which are attractive reasons for mobile network operators (MNO) to consider the D2D technology.

A first step into D2D communication was an initiative by Qualcomm. It developed FlashLinQ [24]; a peer-to-peer communication scheduler that is based on time division duplex (TDD) orthogonal frequency division multiplexing. FlashLinQ allowed for peer discovery and distributed networking. From this initial foray into direct communication between devices, D2D communication has gone mainstream seeing standardization efforts by 3GPP to make it part of its releases.

Apart from low frequency push to talk (walkie talkie) device, the prospect of direct communication between devices clearly emerged in the third generation of wireless communication networks in which technologies like Bluetooth and WLAN became largely available. Although similar to MANETs architecturally, D2D communication in the underlay mode can avoid the uncontrolled interference that can arise from contention based approaches like WLAN. Furthermore, the losses that may arise from multi-hop based approaches like MANETs are reduced by D2D communication that can be achieved in at least two hops. D2D communication differs from MANETs in that although a central network entity may be passively involved in D2D operation, the central entity undertakes just some limited functions. Such functions include synchronisation, allocation of resources and communication session set up which are all control functions [27]. Architecturally D2D communication can be structured based on which entity in the network controls the link establishment. For network controlled link establishment, the D2D architecture can be:

1. Direct communication between a device within a network and another outside the network coverage or
2. Direct communication between two devices within a network.

When the link establishment is controlled by one of the devices, the D2D architecture can be:

1. Direct communication between devices or
2. Relaying between two devices within a network.

To realise the potentials of D2D communication, there are technologies that can be integrated into D2D communication or used together with D2D communication. Such technologies include cognitive radio, cooperative communication, millimetre wave technology and massive MIMO communication. A brief review of these technologies is given in the following.

2.1.1 Cognitive Radio

Cognitive radio (CR) is a technology that allows a device to vary the configuration of its parameters to suit its surrounding environments. Through cognitive radio networks, the available spectrum can be properly utilized by allowing secondary users to transmit in the unused available spectrum bands of primary users. A hybrid cognitive radio network with D2D communication has been put forward in the literature.

D2D communication can be modelled as a cognitive radio network in which the D2D devices act as secondary users that opportunistically share spectrum with the primary users. In [40], the deployment of D2D and cognitive radio network for disaster management in a mobile cloud set up is proposed and the problem of relay selection in this network is formulated as a mixed-integer non-linear problem. Moreover, cooperative communication between D2D nodes and CR nodes is proposed. D2D communication over CR network is considered in [41] where a cooperative MAC protocol is proposed. Combining CR and D2D communication although promising throws up interference scenarios especially in the underlay mode.

The work in this thesis does not consider the coexistence of CR and D2D communication.

2.1.2 Millimetre wave technology

The increasing demand for bandwidth draining applications puts a strain on the available scarce spectrum for wireless communication in the microwave frequency range. A solution to the limited bandwidth availability has been the promising millimetre wave (mmW) which allows the use of higher frequency for wireless communication. Implementing D2D communication in the mmW band holds promise because of the bandwidth available in these bands which could allow for overlay D2D communication. Moreover, since there are unlicensed bands in the mmW frequency range, D2D communication in these bands can be carried out without incurring interference to cellular users.

2.1.3 Massive MIMO communication

To meet the stringent KPIs of the future broadband networks, an earmarked enabler for 5G communication networks is the deployment of antennas at the BS such that the number of antennas at the BS far exceeds the number of UEs in the network. This technique which is referred to as Massive MIMO has been demonstrated to show increased spectral efficiency being that the BS can communicate at the same time to many UEs in the network. In [42], the coexistence of Massive MIMO and underlaid D2D communication is studied and an exclusion zone is proposed to limit the incidence of pilot contamination in massive MIMO communication. In [43], offloading cellular data to D2D communication is studied to demonstrate a trade-off between achievable capacity and the number of off-loadable users.

While combining D2D communication and massive MIMO communication is attractive, understanding the compromise (trade-offs) between energy efficiency and spectral efficiency in such a scenario is key to efficient designs. Moreover determining the volume of D2D users that can be permitted in a cell in which massive MIMO is deployed is important. This problem is explored by Serveh Shalmashi et al. [44] who showed that the performance of the average sum rate and energy efficiency are not the same under different D2D user and number of antennae density although perfect CSI is assumed by the work.

The work in this thesis considers a MISO D2D multicast scenario with full channel uncertainty.

2.1.4 Full Duplex Communication

Full duplex communication allows the concurrent transmission and reception of signals. Full duplex communication can be in-band in which transmission and reception occur on the same band or out-band where transmission and reception occur on separate bands. Tests have shown that the major drawback of full duplex communication which is self-interference can be overcome by cancellation techniques in the literature. Leveraging the potential energy efficiency of D2D communication and spectral efficiency that could be derived from full duplex communication, integrating full duplex communication into D2D communication has been proposed in the literature.

An overview of the potentials and challenges of combining in-band full duplex communication and D2D communication is provided by Li Wang et al. [45]. Two cooperative modes are proposed for full duplex D2D communication in [46] to allow resource sharing between D2D and cellular devices.

An investigation into full duplex D2D communication for a cellular network in [47] considered where a power control technique to limit interference to cellular users and interference from cellular to D2D users is handled by a proposed reduced interference area where D2D communication can occur. Similar investigation into the performance of full duplex communication [48] shows the gains of allowing full duplex radios to communicate using D2D communication.

The work in this thesis like the aforementioned works considers a full duplex scenario in chapter six but with a relay centric and channel uncertainty bend.

Although the 5th generation of communication networks has not been yet finalised, research in D2D communication is based on some protocols and architecture that were earlier introduced but will be given a broader description in the following subsections.

2.2 D2D Communication for Future Wireless Communication: Classifications and Architecture

D2D communication can be classified based on the frequency bands within which D2D communication operates. Thus D2D communication can be out-of-band or in-band D2D. Basically whereas in out-of-band D2D communication, communication occurs in frequency bands that are different from the bands used by cellular users, in in-band D2D communication, both cellular users and D2D users share the available band. Out of band D2D communication can employ unlicensed Wi-Fi frequency bands. In in-band D2D communication, the D2D UEs can either re-use the frequency resources of cellular UEs (an approach named underlay D2D communication) or use a dedicated frequency resource (also called overlay D2D communication).

2.2.1 Out-of-Band D2D Communication

Out-of-band refers to when D2D devices use frequency bands different from the licensed band set aside for cellular communication. The advantages of this approach include reduced co-channel interference, increased frequency re-use although since the band of interest is unlicensed, contention for access may need to be dealt with. Furthermore controlling interference between the D2D devices and other devices (like Wi-Fi) sharing the unlicensed spectrum can cause interference.

In [49], a channel sensing and resource allocation scheme is proposed for the coexistence of D2D and WLAN. It uses a sort of clustering approach in which a cluster head or group head (a D2D pair) contends for resources on behalf of a cluster in order to limit inter-group contention. In the proposed design, an intending D2D sender senses the available spectrum to determine if it is occupied by WLAN devices or not before it initiates communication directly to its intended D2D receiver. Where the channel is occupied, the D2D sender backs off. It transmits in a case where the channel is free during which neighbouring WLAN station remain silent.

In [50], a scheduling protocol for the coexistence of WiFi-Direct and LTE is discussed. The scheme proposed allows LTE D2D devices to form clusters based on the quality of the Wi-Fi connection. The scheme is shown to offer performance gains over round robin (RR) scheduling. Out-of-band D2D has been researched for content sharing as proposed in [51], [52]. The focus of the work in this thesis is on in-band D2D communication.

2.2.2 In-Band D2D Communication

In this case, D2D communication occurs in the same frequency band as cellular communication. In-band D2D can either be underlay, where the D2D UEs share the same resources or overlay where the spectrum allotted to the cellular UEs is orthogonal to that od the D2D UEs. In the former case, interference between the D2D UEs and the cellular USe needs to be managed although this approach is spectrally efficient. The overlay approach assigns orthogonal channels to D2D communication with respect to cellular communication and so interference between them is minimized. Overlay spectrum sharing in OFDMA based WiMAX is proposed in [32] showing the possibility of coexistence of D2D devices and cellular devices without breakage of cellular communication. This work does not compare the performance with an underlay approach. On the other hand, the work in [29] studies an underlay approach defining interference management schemes and session management protocols.

The work in this thesis focuses on underlay in-band D2D communication.

2.2.3 Architecture of LTE D2D Communication

There have been efforts to standardize D2D communication, main among them is the LTE Proximity Services (ProSe) developed by 3GPP. ProSe under which D2D communication falls has gone through standardization phases beginning in 2011 and is ongoing. These standardization efforts have sought to among other goals come up with specifications on the system architecture, use cases, security, privacy, protocols at the network layer, performance evaluation models and terminal provisioning at the physical layer. Based on 3GPP specifications [25], the four scenarios (so far) under which D2D communication can be employed are given as:

- Scenario A: outside network coverage,
- Scenario B: partial network coverage (relay),
- Scenario C: in network coverage (intra-cell) and
- Scenario D: in network coverage (inter-cell).

These scenarios are as depicted in Fig. 2.1.

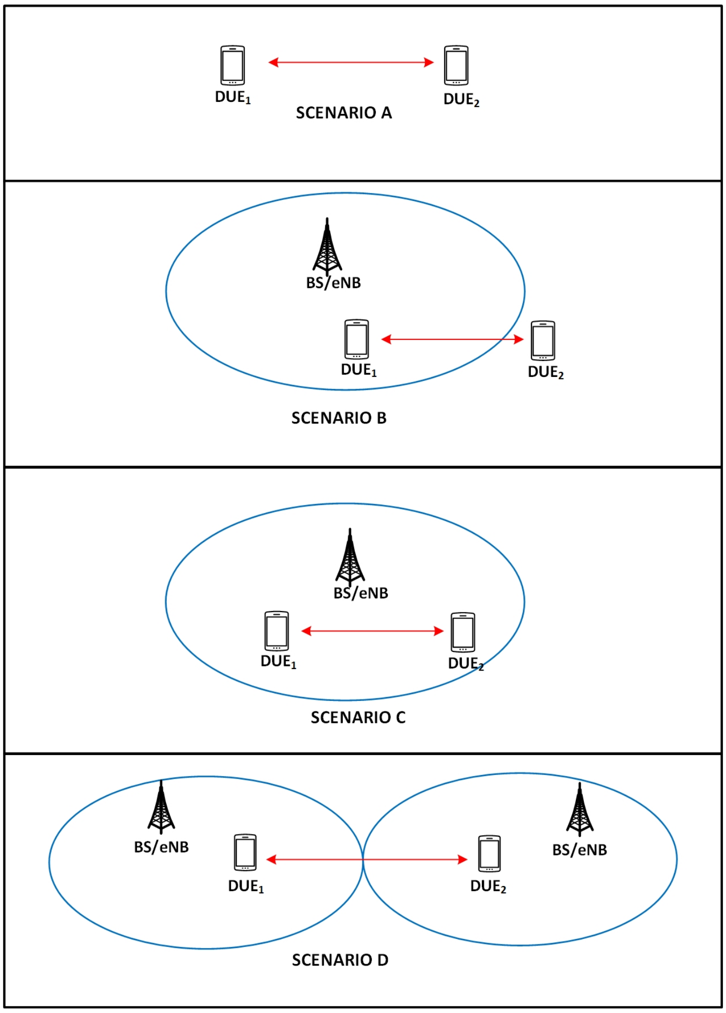

Figure 2.1: LTE D2D communication architecture

Scenarios A and B are reserved for public safety application whereas scenarios C and D apply to both public safety and commercial use cases. These scenarios are similar to the one described by Mohsen Nader Tehrani et al. in [53] wherein D2D communication is divided into four modes namely:

- Device Relaying with Operator Controlled Link Establishment (DR-OC),

- Direct D2D communication with Operator Controlled Link Establishment (DC-OC),
- Direct Relaying with Device Controlled Link Establishment (DR-DC) and
- Direct D2D communication with Device Controlled Link Establishment (DC-DC).

In DR-OC, the D2D devices transmit their signals through other devices to the BS with the BS (or eNodeB) managing and controlling the link set-up. This finds application in scenarios where a device is at a cell edge and can reach the serving BS through another device within coverage using direct communication.

The BS also controls the link set up in DC-OC although mobile devices do not need a relay(s) for retransmission. This architecture can be applied in sharing multimedia content between devices that are interested in the same content and so offload the network of the burden of serving individual devices.

In DR-DC, the terminal devices control and manage their link set-up but do not directly communicate; a situation which may offer cooperative diversity gain. Communication between the source device and destination device occur through relay(s). The communication can be cooperative where the existence of a direct link is assumed or non-cooperative where the direct link between the source and destination is non-existent.

DC-DC on the other hand, involves direct communication and device managed control; this communication scenario can apply where devices are in out-of-coverage scenarios. Basically, these D2D scenarios can either be:

- Network authorised D2D communication or
- Network independent D2D communication.

Network independent D2D communication, although similar to MANETs varies in various ways. MANETs lack a central control and the contentious manner in which resources are shared within MANETs by ad-hoc nodes makes QoS guarantees difficult. Furthermore, D2D communication employs single hops as against the multi-hop feature of MANETs. The aforementioned communication scenarios are possible under an architectural framework. Relay-assisted D2D communication which is the focus of this thesis becomes necessary when the direct link does not allow for direct communication due to the separation between devices or deep fading. For the work in this thesis, the DR-OC is applicable.

2.3 D2D Communication for Future Wireless Communication: Research Approaches

Research in D2D communication for future wireless communication is thriving and has shown the benefits that network providers and users of communication networks can derive. These benefits can improve the CAPEX for network providers and also improve user experience. To realise these benefits, there are design and implementation challenges to overcome.

The introduction of D2D communication in cellular networks wells up challenges prime among them is interference. Interference in underlay D2D communication can be in four forms depending on whether D2D communication reuses the uplink or the downlink resources of cellular users. When the uplink resources are used, the serving BS experiences interference whereas the neighbouring cellular users experience interference when downlink resources are used. UEs engaging in D2D communication also suffer interference from cellular communication. Within a D2D pair, the D2D destination or receiver does experience interference from cellular users in the downlink and from adjacent D2D communication in the uplink.

Introducing D2D communication into a cellular architecture in an underlay mode changes the architecture making it a multi-tier set-up and so creates scenarios. Whereas the interference towards the BS can be relaxed considering its inherent computational capacity, the interference towards the UEs (whether cellular or D2D) is consideration worthy being that if such interference is not mitigated, deterioration of the potential gains of adopting the D2D technology can be experienced. Interference in D2D communication underlaying cellular communication can be categorised based on the tier or category that the devices causing interference falls into.

When D2D and cellular communication coexist, a cellular tier and a D2D tier are created and so interference from this perspective can either be co-tier interference or cross-tier interference. This can also be categorised as D2D tier interference and cellular-D2D tier interference. D2D tier interference points to the interference that a D2D transmitter causes to nearby UEs that are not its target destination. This category of interference can occur when D2D communication re-uses the uplink or downlink resource whereas cellular tier interference refers to the interference experienced by cellular UEs and the BS. For these interference paradigms, research efforts to tackle or mitigate interference in D2D enabled cellular communication networks have been proposed. These approaches can be centralised in which a central entity (eNodeB/BS) coordinates the interference, distributed wherein D2D UEs handle interference mitigation or a hybrid of the two.

Theoretically, a straightforward approach to coordinate interference in D2D enabled cellular communication would be to allocate dedicated resources for each tier of communication. This viewpoint informs the overlaid mode of D2D communication although it has the disadvantage of inefficient spectrum utilization. Interference management algorithms have been mainly in the following categories:

- Power control,
- Mode selection and
- Resource allocation.

In the following subsections, snapshots of research works on these interference management techniques are given.

2.3.1 Power Control

Power control is a straightforward approach to limiting interference. Defining an allowable power level for D2D communication can ensure the coexistence of D2D communication and cellular communication with reduced interference. Power control allows the transmit power of D2D UEs to be statically or dynamically allotted in order to limit interference to neighbouring cellular and D2D UEs. Furthermore, power control algorithms can be implemented centrally or in a distributed fashion.

D2D communication also suffers from the so-called near-far problem since the D2D signal is weaker in comparison with the stronger cellular signals. An interference cancellation technique is proposed to tackle the near-far problem in [54] that allows the BS locate near-far interference prone cellular UEs through common control channel (CCC) and so informs D2D devices to reduce their transmit power. It assumes an autonomous D2D system, a CSMA/CA MAC protocol, considers uplink frequency re-use, and uses D2D SINR levels to determine near-far interference to cellular UEs.

The use of SINR as a parameter to determine a threshold for power control is explored in [55] where obtained SINR of the D2D devices are used to limit the interference caused to the BS (in the uplink) and the cellular users (in the downlink) by controlling the power used in D2D communication based on the distance of D2D devices from the BS. From the work, it is shown that for D2D users near the BS, sharing downlink resources offer better performance and for farther users, sharing uplink resources is better.

Power control is considered in [56] for uplink resource allocation using a centralised power control algorithm. While a centralised scheme exploits already available infrastructure, the signalling overhead makes it involved especially for a dense concentration of UEs in a cell.

2.3.2 Mode Selection

In deploying D2D communication within a cellular network, D2D UEs may not engage in D2D communication all the time except where the conditions favour D2D communication. Such conditions could be channel quality or the separation between the devices. Moreover switching to D2D communication should be such that the potential benefits are realised. The modes to select between could be cellular or direct communication; relayed or direct communication [57]; underlay or overlay; in-band or out-band communication. Interference can also be mitigated using appropriate mode selection techniques in which the operation modes of D2D UEs are selected for optimal communication performance.

While power control has been studied as a means of resource management, mode selection is also an area that has received attention. Mode selection is considered for undelay D2D communication system by Timo Koskela et al. in [58] where clustering is viewed as a D2D communication mode. System simulations were used to demonstrate the superiority of the mode selection schemes proposed therein. Mode selection hinges on a certain parameter or criteria which determines the particular mode to select, such parameters could be the distance in between the D2D devices [57], transmit power of the D2D devices [57], D2D and cellular link quality [59]. Choosing between modes is not the only approach to limit interference: allocating the finite time/frequency resource to devices in either D2D mode or cellular mode is also an approach.

2.4 Resource Allocation

Resource allocation, a corpus of techniques that aims to efficiently allot time/frequency resource blocks to UEs has been proposed by various authors as an interference control approach. Mostly formulated as optimization problems to optimize some metric, many algorithms have been studied for resource allocation designed for D2D communication. Example techniques explored hinge on concepts like frequency reuse [60], graph theory [61], matching theory, game theory [62] and time-frequency hopping [63].

The work in this thesis focuses on relay assisted D2D communication and a survey of the same is provided in the following section.

2.5 A Survey of Relay Aided D2D Communication

Hop gain, proximity gain, reuse gain and diversity gain which are potential wins of D2D communication has attracted the interest of industry and the academia. These potential gains of direct communication between devices may not be fully realised when the separation between the source and destination devices and the deterioration of the channel between the D2D pairs makes direct communication inefficient. In such scenarios, instead of switching to cellular communication; the presence of nearby idle UEs can be exploited for mobile relaying in order to enforce D2D communication. Such mobile relaying can be cooperative where the direct link between a source and destination device is assumed available or it could be non-cooperative where the direct link assumed non-existent. The work in this thesis does not consider cooperative communication. A diagram showing a basic setup for relay aided D2D communication is given in Fig. 2.2.

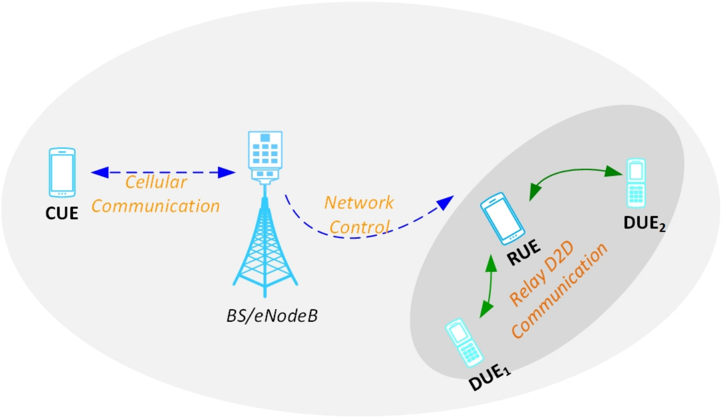

Figure 2.2: Underlaid relay assisted D2D communication set-up

Hence, despite that D2D communication is focused on user devices that are in close proximity, channel impairment and the separation between a D2D pair can deteriorate the performance of a D2D communication setup. In such cases, employing a relay enabled user equipment becomes necessary. Relay aided D2D communication is not just an area of research interest, it has also been considered by a standardization body namely the 3GPP. The 3GPP, apart from introducing direct communication between devices in the 12th release of its specifications, have also made provisions for relay aided coverage extension in release 13 of the its specifications [64]. There are some works in the literature on relay aided D2D communication.

These works can be broadly categorised into:

- Resource allocation,
- Performance Analysis and
- Relay Selection

2.5.1 Resource Allocation for Relay Assisted D2D Communication

The race to meet the key performance indices of future wireless communication networks has motivated research efforts into techniques for allocating frequency resources to devices in these networks. There have also been resource allocation algorithms put forward for relay-assisted D2D communication. Whereas there have been centralised allocation algorithms proposed in the literature, the seemingly ad-hoc nature of D2D communication has also inspired distributed techniques.

Resource allocation for relay-assisted D2D communication with fixed infrastructure relays is considered in [65]. The authors proposed a message exchange approach between the user equipment and the relay to achieve optimal resource allocation for D2D communication. The relay node modelled in the work is the LTE-A L3 relay. The authors modelled the resource allocation problem as a sum rate maximization problem for which a message passing approach was proposed. The authors did not consider relay selection and moreover assumed the availability of perfect CSI at the relays.

A centralised resource allocation technique is proposed for relay-assisted D2D communication in [66] using numerical optimization. The authors formulated the resource allocation problem as a mixed integer non-linear problem which was shown to be difficult to solve and so certain constraints were relaxed to make for a tractable solution. The authors did not consider the effect of channel uncertainty and showed a distance threshold for deriving target gains from D2D relaying for the considered scenario. Unlike our proposed work, relay selection was not considered. The nature of the wireless channel can cause errors in the estimation of the channels at receiving and transmitting nodes. Although assuming perfect channel can ease analysis, such analysis serve as benchmarks to others that consider imperfect channel conditions. Few authors have considered channel uncertainties in D2D communication analysis.

In [67], distributed resource allocation based on stable matching is proposed for a formulated resource allocation optimization problem. The authors considered the existence of channel uncertainty and for the channel uncertainty model, a bounded uncertainty set was employed. Although the work considered full channel uncertainty and used stable matching as in our work, static infrastructure relays and not mobile user equipment were modelled.

Monowar Hasan et al. [21] factored in channel uncertainties in their proposed distributed resource allocation algorithm for underlay D2D communication assisted by non-mobile relays that are part of the core network. Channel uncertainty is modelled as a bounded value that is added to the channel gain. Using the worst case uncertainty approach, resource allocation and power allocation is formulated as a robust optimization problem for which constraints are relaxed and the problem solved. Relay selection is not considered and the relays are not mobile relays but are rather stationary fixed low power BS. Junquan Deng et al. [68] presents SC-FDMA relaying in the uplink in a multi-cell, multi-user network and performed a joint resource allocation and relay selection. The relay selection algorithm is based on the position of the relay UEs and knowledge of the channels of consideration are assumed perfect.

2.5.2 Performance Analysis of Relay Assisted D2D Communication

Apart from research works in resource allocation for relay assisted D2D communication, there has also been some work on the theoretical analysis and capacity limits of relay assisted D2D communication.

Kiran Vanganuru et al. [22] considered a centralised relay selection approach for D2D communication and showed that the system capacity and network coverage can be enhanced using relay enabled user equipment. The analysis employed cooperative relaying protocol and assumed the availability of perfect CSI.

When a single relay is considered in wireless communication, at least one hop is envisaged. A high number of hops can guarantee connectivity for, say a cell edge UE although a threshold is reached where the hop gain declines. An Outage probability analysis and an ergodic capacity analysis were carried out in the work by Donghoon Lee et al. [35] for a multi-hop DF capable relay assisted D2D communication setup. The analysis assumes a single D2D pair and a single interfering cellular UE. While such simplicity offers insight, it is not representative of the dense nature of future wireless communication networks.

Akram Al-Hourani et al. [37] proposed an energy efficient relaying region for relay-assisted D2D communication using stochastic analysis. In the work, an elliptical region is proposed for energy efficient relaying in D2D communication. The authors also showed through simulations a distance threshold for beneficial relay assisted communication. Single and multi-relay scenarios were considered although relay selection was not considered and the relays modelled were not mobile relays.

In [69], closed form expressions for the ergodic rates and power allocation for a two time slotted two way relay assisted D2D communication are presented. Underlay D2D communication is considered with cross-tier interference. The ergodic rate was studied for a range of SNRs, and the separation between the BS and D2D UEs. This analysis assumed that the relay UEs are willing to surrender their resources to assist neighbouring D2D pairs in need of relaying service.

Yang Yang et al. [70] carried out a numerical analysis to determine the transmission capacity when cellular communication underlaid and overlaid with D2D communication is enhanced by the introduction of relays. Using Poisson point process (PPP) to model the simulation scenario, the transmission capacity for relay aided D2D communication was shown for a range of parameters like D2D user density and separation between D2D pairs. Perfect CSI is assumed and so channel uncertainty analysis is not considered in the work.

In [71], close form expressions for the transmission capacity of relay aided D2D communication underlaid in cellular communication is presented. Defining the position the relay UEs as a distribution, a distance based relay selection criteria is used to study the performance of relay aided communication. The transmission capacity of the set-up is is shown for a range of D2D user density and D2D pair distance. Since underlay communication is considered, interference from and to cellular users is considered although perfect CSI is assumed for both the relay path and the direct D2D link. Furthermore relay incentivization is not part of the analysis.

Guopeng Zhang et al. [72] considered a full duplex relay set up in which a relay UE can serve simultaneously as a relay for cellular communication and a D2D transmitter.The authors considered downlink communication assuming self-interference cancellation at the full duplex relay UEs. While the idea of serving as a relay for both cellular and D2D users is attractive, the battery power of the relay UE and an incentive mechanism to motivate relaying was not factored into the analysis. Moreover using the downlink channel for D2D communication creates severe interference towards the cellular UEs

José Mairton B. da Silva et al. [73] proposed a combined power control and mode selection algorithm for undelay relay assisted D2D communication. Unlike the work in this thesis, it assumed perfect channel knowledge at the UEs and did not consider relay selection.

Rachad Atat et al. [74] considered a no-noise but interference limited network. In the work, an underlay cooperative relaying strategy is studied in which the interference at the relay and the destination UE are assumed to be correlated due to the proximity of the devices. D2D spectral efficiency is the performance metric used.

Andrea Abrardo et al. [75] considered a case of coverage extension in which D2D communication is used to assist a cell edge user send and receive information from a BS. AF) and DF relaying protocols are used at the relay UEs. Moreover physical layer networking coding (PLNC) is employed at the relay UE to cater for situations in which the relay has its own data to transmit apart from the data of the cell edge user. Heuristic schemes for resource block allocation and mode selection are proposed although relay selection is not considered in the work and perfect CSI are assumed to be available at the relay UEs.

2.5.3 Relay Selection in Relay Aided D2D communication

In the previous subsections, research works focused on resource allocation and capacity bounds of relay-assisted D2D communication have been reviewed. Those research works either considered scenarios with a single infrastructure relay assisting D2D communication or multiple relay UEs being part of a multi-hop chain. Having appropriate relay selection algorithms to select relay UEs in the neighbourhood of D2D pairs is also a key focus of some works in the literature. Furthermore, although fixed relaying is attractive, the presence of idle UEs in a network makes a case for employing them as relays. In this subsection, highlights of some relay selection approaches in the literature are discussed. It is followed by focused discussions of specific relay selection areas.

In [36], a timer based relay UE selection algorithm that selects a relay based on the level of experienced interference is put forward. The relay UE experiencing the lowest interference is selected and allocated the least time to send to the destination UE the signals it received from the D2D source. The approach is a distributed relay selection technique. Having a single D2D pair in a network can offer insight into the performance of proposed algorithms but with the envisioned dense deployment of devices, more pairs can be engaged in D2D communication at a time.

Chen Zhengwen et al. [38] stretched further the work in [36] to formulate a relay – D2D destination link capacity maximization problem subject to cellular interference constraints and QoS constraints. For this problem, a joint resource allocation and relay selection approach was proposed. The authors assumed that the relay UEs are able to intelligently sense the channels and also assumed that the relay UEs had perfect knowledge of the associated channels.

Weinchen Xia et al. [76] put forward a relay selection technique for D2D communication that is location aware (i.e. either indoor or outdoor). Where D2D communication is carried out outdoors, the distance between the D2D devices is used as a clustering criterion whereas when the D2D pairs are within buildings, the acquired CSI is employed as a relay clustering criteria. The proposed algorithm clusters candidate relay UEs based on the stated criteria and selects relay UEs using a utility function that is channel efficiency dependent. The work uses AF relaying protocol and assumed perfect knowledge of the channel.

One of the hurdles of relay aided D2D communication has been a way to incentivise the potential relay UE to surrender its resources in assisting a neighbouring device. Most research efforts assume that the potential relay UE is always willing to surrender its resources to assist a neighbour, but users are rational and so would prefer to improve or optimize their own utility.

This issue is tacked in [77]. The work proposed a learning algorithm through which potential RUEs can determine the relay approach that maximizes their defined utility. The algorithm is relay UE centric and does not optimize the utility of the D2D pair. The algorithm employs token passing between D2D devices and employs an AF cooperative protocol at the relay UEs. The work assumes perfect channel knowledge of the considered channels at the UEs.

Yicha Chen et al. [78] proposed an auction mechanism for relay selection. In the algorithm, the D2D pairs in need of relay assistance place bids for relay UEs and relays UEs are allocated through the auction process. The authors modelled the relay selection problem as a bipartite graph and showed improved throughput through computer simulations. The complexity of the proposed algorithm is not demonstrated by the author.

Stable matching is a game theoretic approach with players and strategies. Its preference feature allows players to optimize individual utility. This utility can be related or different. There are some works in the literature that have exploited the power of stable matching. Stable matching provides a framework that can be exploited for resource allocation, relay assignment in D2D communication [79].

Matching theory is used for allocating resources to D2D pairs in [80]. The D2D pairs and the cellular devices whose resources the D2D pairs seek to reuse are modelled as sets to be matched. The authors introduced a concept of cheating is introduced in this work such that D2D devices can provide false preferences to improve their utility. Minimum weight stable matching is used to obtain optimal matching. In [79], the problem of relay allocation is formulated as a matching problem between D2D pairs and candidate fixed relays. A bipartite graph is used and the aim is to minimize the power consumption of D2D communication. Knowledge of the channels at the relay and D2D devices are assumed to be perfect and the relays are fixed low power infrastructure devices and not mobile UEs. Although like the work in this thesis, matching theory has been considered in the literature, our work is unique in applying matching theory to the relay selection problem with channel uncertainties factored into the analysis.

Zufan Zhang et al.[81] proposed a hybrid criterion for relay selection which does not only cater for the physical distance between the D2D pairs but for the social distance between the pairs. In the physical domain; the SINR between the D2D transmitters and potential relay UEs is used while in the social domain; a parameter to represent the social ties (which is based on the encounter duration) between the relay UEs and D2D transmitters are employed. Although the authors use social distance, it is inherently assumed that social distance is sufficient incentive to motivate relay communication. To study the performance of the proposed centralised relay selection algorithm in an underlay D2D communication framework, the relay selection success rate and link cost are shown for a range of reliability threshold values and D2D decoding threshold values. Although like the work in chapter 6 of this thesis, the work in [81] used social distance, our work deviates from theirs by first modelling the problem as a bipartite problem with the weights of the graph being social distant dependent.

Chen Zhengwen et al. [38] proposed a simple relay selection algorithm in underlay D2D communication based on the channel gain of the D2D relay channel. Perfect CSI is assumed and the users of relay devices are assumed to not need motivation to forward the signals of neighbouring D2D pairs. DF relay protocol is employed in the analysis.

Jen-Yi Pan et al. [82] formulated the problem of relay selection as an optimization problem which was divided into power control, relay selection and resource allocation sub-problems. The relays in the context of the analysis are not only D2D pair helpers but helpers of cell edge cellular users. The complexity of their proposed approach may raise concerns.

In Hashem Kalbkhani et al. [83], femto relays are used to re-transmit signals for D2D pairs. At the femto relay nodes, random linear network coding is implemented and the problem of power allocation for D2D communication and relay selection are formulated as optimization problems for which analytical solutions are proposed. The outage probability and transmission rate performance of the proposed algorithms are analysed for a range of D2D pair distances. Unlike the work we proposed in this thesis, mobile relay UEs are not used and the channel information is considered perfect.

Nikolaos Nomikos et al. [84] considered a Non-Orthogonal Multiple Access (NOMA) network in which they show a procedure for determining the optimal power coefficients for efficient relay aided D2D communication. Using time slotted communication in which a selected DF relay receives a signal from a source in the first time slot and transmits towards two intended destinations, the relay uses NOMA for transmission towards the destination. To provide the power difference that NOMA requires, a method is proposed to determine the power coefficient. To select the relay from a pool of candidate relay UEs, a delay aware algorithm that considers or factors in the number of packets at the buffer of the candidate relays is proposed. Outage probability, average delay and throughput are used as analysis parameters and full duplex communication is also assumed. Relay incentives are not considered and channel uncertainty are not also factored into the analysis. The approach of the authors ignores the rational nature of holders of UEs and the dynamic nature of wireless communication network that can cause channel estimation errors.

Green energy has been an area of research interest for future wireless communication considering that reduction in energy consumption is one of the targets of the much talked about 5th generation of wireless communication networks. Tao Han et al. [85] proposed green relays for assisting D2D communication that are renewable energy powered and not having a backhaul. The relay assignment is formulated as a mixed integer problem to maximize the minimum D2D data rate for which a heuristic centralised selection algorithm is proposed. The algorithm iteratively assigns a relay to a D2D pair having the least data rate. The work considered infrastructure relay UEs and so deviates from the work in this thesis.

Junquan Deng et al.[68] formulated a joint relay selection and resource allocation problem for underlay D2D communication as backhaul and D2D data rate maximization problem. The authors proposed an algorithm to allocate resources between D2D links and backhaul links. Furthermore, a joint relay selection and resource allocation algorithm based on the calculated path loss of a link is proposed. The authors consider a coverage extension scenario with the aid of mobile relays.

Having gone through some background literature on D2D relaying, focused discussion on specific relay aided D2D communication approaches are now considered.

2.5.4 Relay Selection with Incentives

Relay-assisted communication using mobile relay UEs requires that resources such as stored battery energy and available memory of the relay devices are shared with the devices requesting relay services. The self-focused nature of holders of mobile devices implies that some motivation needs to be designed to encourage holders of idle devices to allow their resources to be employed in data forwarding or multicasting. Incentive-based relay assisted D2D communication can be approached from an incentive aware D2D communication standpoint whereby an incentive parameter or utility function is weaved into the relay selection criteria without necessarily providing a payment mechanism. Furthermore, a market-based approach where the D2D UEs or the network pays for the relay service can also be used. In designing payments for relay service, the D2D pair can be charged or the destination charged for the relayed packets.

Tingwei Liu et al. [86] proposed a credit based incentive mechanism for multi-hop D2D communication in which relays and destination UE submit receipts that reflect the number and size of forwarded packets. The proposed approach although might discourage cheating, tends to have a complexity that increases with the number of hops.

Nicholas Mastronarde et al. [87] proposed a supervised learning algorithm for relay-assisted D2D communication in which mobile devices use token traded electronically to reward counterparts for reciprocal data forwarding. Using the Markov decision process for mode selection, a token based relaying scheme was proposed in which devices can only take part in a relay scheme if they possess tokens. Furthermore the choice of a relaying strategy based on a learning algorithm. The proposed approach may not be encouraging for emergency services since a UE not having a token and out of coverage of the BS may be excluded from being helped by a relay. Such a learning-based approach might not be applicable for distributed scenarios.

Mohamed M.E.A. Mahmoud et al. [88] proposed a charging policy in which the source and destination pairs requiring relay services are charged by the network to enforce fairness in multi-hop cellular communication. To ensure the security of the incentive process a hashing method is used at the packet level.

In [89], incentive-based relay selection using reverse auction is proposed for relay aided communication between a cellular user and the BS. The authors proposed monetary rewards from the BS to the mobile devices that act as relays to extend the coverage of the BS. The authors designed a relay utility function based on the achievable data rate of a relay to destination link and the BS utility as a function of the achievable relay-destination data rate and the power cost of transmission. The performance of the proposed reverse auction based incentivised relay selection algorithm is studied using the average utility of relay and BS for a range of SINR values and number of cellular users. The work used an isolated cell case scenario and also an underlaid D2D communication was considered. The relay node selection is assumed to be performed by the network. The authors assumed perfect channel knowledge at the relay UEs

Social distance between users of mobile devices can be a motivation to participate in relayed communication. In the literature, social aware relay assisted D2D communication are basically approached from two standpoints: social trust in which there is exists some relationship between the mobile devices requesting relaying services and the potential relays and the social reciprocity approach in which there is no social relationship between them and a reciprocal mechanism is used. Exploiting the trust between socially close holders of UEs and the tendency to return a retransmission action, Xu Cheng et al. [90] proposed a centralised/network assisted relay selection algorithm for underlay cooperative D2D communication. Similar to the work by Zufan Zhang [81], social trust and social reciprocity are formulated as graphs, and social reciprocity is presented as an alternative to relay assistance cases without strong social ties between the cooperating entities. The system throughput, social links and relay selection cycles are used as analysis parameters. The relay protocol used is DF relaying in a full duplex scenario although the proposed algorithm is not channel uncertainty aware.

Mengyuan Zhang et al. [91] used both the physical separation between mobile devices and social ties between the users of the mobile devices to formulate a relay selection problem based on the finite-horizon optimal stopping theory. The proposed approach although offers performance gains over random selection does not clearly define a reward mechanism for the relaying users. Xin Pan et al.[92] compared a hybrid social and physical distance based relay selection algorithm with non-hybrid options. A probing approach similar to [91] was used.

M. N. Islam et al. [93] put forward a method for resource allocation based on bandwidth exchange enabled incentivised forwarding. The resource allocation problem is solved side by side a relay selection problem. The resource allocation is formulated as a utility (a data rate dependent parameter) maximization problem subject to rate and allocated bandwidth constraints. The relay selection problem is reduced to a maximum weighted matching problem. Bandwidth exchange although promising can be a restrictive payment mechanism.

Peng Li et al. [94] proposed a market model based incentive mechanisms to motivate participation in D2D communication. The approach is specifically Stackelberg game based and auction-based incentive mechanisms were proposed with focus on maximum profit and truthfulness although relay selection was not considered.

2.5.5 Multi-hop Relay Aided D2D Communication

Using field tests, Hiroki Nishiyama et al. [95] demonstrated a distributed UE relaying for public safety communication. The authors considered an emergency scenario where the infrastructure fails. Using a combination of MANET and DTN protocols, a demonstration of multi-hop relay through several UEs on a site and through an unmanned aircraft system to a remote site was demonstrated.

Donghoon Lee et al.[35] presented a multi-hop relay scenario in which more than one relay UE aids in the re-transmission of signals between a D2D pair. The authors derive the CDF and PDF of SINR of the relay hops which are employed in outage probability and ergodic capacity analysis for the considered cooperative D2D underlay communication and further proposed a power optimization technique for multi-hop D2D communication.

2.5.6 Relay Assisted D2D Communication and Security

Ensuring that the data for relaying is safe from malicious eavesdroppers that may pose as genuine potential relays, and maintaining the integrity of relayed information is an active discussion in D2D communication research. Maintaining the privacy of D2D UEs is also necessary to avoid identity theft. Two broad areas where security is a concern in D2D communication are in device pairing and in the user data integrity [96].

There has been some foray into the data integrity area of D2D communication security and proposed methods have either fallen into encrypting the transmitted data or employing the channel conditions to implement physical layer security.

Keeth Jayasinghe et al. [39] considered an underlay D2D communication scenario where there existed eavesdropper UEs that could compromise secure communication. The effect of channel estimation errors are considered in the work and the resulting uncertainty is modelled using Gaussian Markov uncertainty model. Fixed relays are considered with AF protocol employed at the relay node. Beamforming is proposed by the authors as a secure approach to steer away needed relayed information from eavesdroppers.

In Emad Abd-Elrahman et al. [97], a key management mechanism for D2D group communication to address the discovery phase of D2D communication and actual data communication is proposed. The mechanism uses identity-based encryption. The proposed method was compared to other similar algorithms in complexity and overhead although relay selection was not the focus of the work.

In Emmanouil Panaousis et al. [98], proposed a secure route selection algorithm where the best relay route is selected based on its probability to detect an intrusion by a malicious user. In selecting a more secure route for message delivery, the authors also considered the energy expenditure of the relays and the QoS(specifically the end-to-end delay) of the routes in consideration although the complexity of the proposed algorithm was not discussed.

Hang Zhang et al. [99] formulated the problem of improving the system secrecy capacity of D2D underlaid communication as a bipartite graph matching problem for which the Khun Munkres algorithm was proposed. They showed through simulation that interference from D2D communication can be exploited to improve the system secrecy capacity of the network.

Wei Xi et al. [100] proposed a secret key generation technique dubbed “KEEP” derived from the variations in the CSI of sub-carriers. The proposed KEEP algorithm used a validation - recombination algorithm to overcome the challenge of the correlation between the CSI measurements of sub-carriers.

Although secure D2D communication through mobile relays is necessary, accounting for the finite nature of relay UE resources is also key. Hence the proposal of cross-layer approaches.

2.5.7 Cross Layer Relay-Assisted D2D Communication

Ruofei Ma et al. [101] proposed a cross-layer relay selection approach for underlay D2D communication. Using a physical layer parameter which is defined as a function of spectral efficiency with the remaining battery time of a potential relay and the queueing delay at the MAC sub-layer, a cross-layer parameter was defined as a criterion for mobile relay selection. The proposed cross-layer approach was compared with non-cross layer approaches for end-to-end delays and success probability performances. Relaying willingness is assumed and the channels are considered devoid of channel estimation errors.

In [102], the authors consider using CSI and queue state information of potential relay UEs as criteria for relay selection. The hybrid approach is compared with a relay selection based on maximum CSI or QSI.

Abdulrahman Alabbasi et al. [103] proposed an energy efficiency metric (modified energy per good-bit) for D2D–cellular spectrum sharing scenario. The authors formulate a power minimization problem which they demonstrate as pseudo complex. The formulated problem is solved through variable decomposition and transformation. Transmit power is the physical layer parameter while the frame length is a parameter for the data link layer.

Wei Wang et al. [104] employ physical layer throughput and MAC layer queue length information in formulating resource control for underlay D2D communication. The authors consider dynamic resource control that is portrayed as a Markov decision process for which water filling power control algorithms are proposed. The algorithm builds on an interfering filtering MAC sub-layer protocol. The discussed algorithm in the literature under this section are generally channel uncertainty.

2.5.8 Relay Assisted D2D Communication Scenarios

The gains which D2D communication offers have been demonstrated through performance analysis and the scenarios which these gains can be obtained. The research works in the literature that have been reviewed so far fall into broad application use cases. Such use cases are cell range extension, public safety communication and group communication. D2D communication can be deployed when mobile devices are in such proximity that allows for direct communication or when the traditional infrastructure fails. Infrastructure failure can occur due to natural disasters. Moreover in scenarios where popular content files are cached in UEs in a cluster and are distributed to other members of the cluster.

Popular video content distribution using relay assisted D2D group communication is studied by Hao Xu et. al. [105] using an interference limited setup. For the work, relay selection is based on the distance between D2D pairs. The authors did not consider a robust formulation and did not factor in the effect of the mobility of the clusters into their analysis. Moreover, unlike our work, the authors did not formulate a probabilistically and deterministically constrained multicast communication problem.

A key use case for D2D communication is public safety communication. Although Terrestrial Trunked Radio (TETRA) is an already existing public safety communication system, its limited speed means there is a need for better options to meet emerging public safety situations.

D2D communication for public safety application is the focus of the work by G. Fodor et al. [106]. In the work, the authors put forward an architecture for deploying a D2D communication based public safety response network. Using clustered communication, the proposed architecture elects a cluster head to service out of coverage UEs. The position of cluster head changes if the previously elected cluster head is out of coverage. Although a viable architecture, the approach is largely centralised and increased signal overhead may result due to the need for synchronisation.

In [95], an actual deployment of multi-hop relaying by smartphones for disaster response is reported. In the work, the authors proposed the use of the distribution of mobile devices in the disaster area as a criterion to switch between the mobile ad-hoc network (MANET) and disruption-tolerant network (DTN) routing protocols. In the work, a mobile messaging app was also used to relay messages between mobile phones and UAV relaying was used to access a distant disaster area.

The broadcast nature of the wireless channel offers an opportunity which cooperative relaying exploits although it presents a security risk of eavesdroppers listening in or intercepting to modify a transmitted message. Such potential risks have motivated encryption algorithms at the upper layers.

In [39], robust beamforming is proposed as a technique to counter attempts by eavesdroppers to intercept information between a D2D pair. In the work, physical layer network coding is employed at the relay UE and channel estimation error is assumed to exist between the eavesdropper and the D2D pair whereas there is perfect knowledge of the D2D channel. The authors did not consider probabilistically constrained problems.

In this subsection, the use cases of relay-assisted D2D communication have been reviewed to include group communication, public safety and coverage extension.

The work in this thesis considers scenarios where the direct path between source and destination devices is not available and so mobile relaying is required. This scenario is modelled in chapters three and four. Also considered in this work is the multimedia content distribution case that is modelled as D2D multicast distribution in chapter five. In modelling these scenarios, the work in this thesis considers channel uncertainties.

2.5.9 Relay Assisted D2D Communication with Channel Uncertainty

As the work in this thesis includes the effect of channel uncertainty that can arise from channel estimation errors, a review of related literature in this area of D2D communication research is needful. To limit repeated mention of some literature, only key literature in this aspect of D2D communication research are reviewed.

Channel uncertainty arises in wireless communication when information about a channel measurement is imperfect. Such imperfections can come from errors in channel estimation or outdated channel information among others. Considering uncertainty in wireless channel whether such uncertainty is viewed from the channel or hardware impairment can provide a more realistic insight into the performance of proposed algorithms resulting from uncertainty aware robust problem formulations.

A few works in the literature have considered D2D communication relaying with channel uncertainty.

Yi Qin et al. [107] considered a coverage extension scenario in which the channels between mobile relays and neighbouring D2D receiver are uncertain due to channel estimation error. The authors formulate a total transmit power minimization problem for a system model with MIMO enabled BS subject to interference and QoS constraint. In modelling channel uncertainty, the authors use the additive approach that allows the estimation error to be added to the channel estimate. To solve the formulated robust minimization problem, the authors propose a joint beamforming design for the BS and D2D relays although relay selection is not considered. Moreover, unlike the work in this thesis, stable matching is not employed and so relay preferences are ignored.

Mengqi Li et al. [108] studied the joint resource allocation and power minimization problem in underlay D2D communication network. The joint problem is formulated as a rate maximisation problem subject to transmit power and cellular QoS constraints. To cater for channel uncertainty, the author introduces bounded error values into the channel between D2D and cellular channel. To represent the uncertainty set in a way that allows easier handling of the optimization problem, an ellipsoid is used to convey the uncertainty set. The formulated problem is solved analytically using the Lagrange dual composition method and compared to other algorithms for sum rate performance. The authors do not consider relays selection either.

In [109], relay assisted D2D communication in which the relay UE is a full duplex infrastructure relay is considered. The relay is modelled to undertake scheduling and allocation of resource for D2D communication. Assuming imperfect CSI in the backhaul channel between the relay and BS, the channel uncertainty is modelled as a finite set added to the channel estimate. The optimization problem was formulated as a sum rate maximization problem for which a student project matching algorithm was proposed. Unlike the work in this, the authors did not consider relay selection as part of the problem formulation. Furthermore, transmission rates were used in defining the preference lists for the matching game unlike the work in this thesis that used relay utility functions.

Towing a different path, Daquan Feng et al. [110] considered a resource allocation problem for underlay D2D communication. The problem is formulated as a sum rate maximization problem with QoS, power and assignment constraints. Probabilistic and partial feedback resource allocation strategies to combat the presence of inaccuracies in obtained CSI at the BS. These algorithms are shown for their performance for a range of outage thresholds values and channel models.

In [111], centralised and distributed power control strategies for underlay D2D communication with channel estimation errors are proposed. The problem of power control is formulated as an SINR maximization problem subject to power and QoS constraints. The authors show that channel uncertainty degrades system performance. The authors did not consider a relay centric approach as the work in our thesis.

Yin Qin et al. [107] proposed a joint BS and relay beamforming for relay-assisted D2D communication. The beamforming problem was formulated as a sum minimization problem subject to probabilistic and SINR constraint. Using the S-lemma simplification and semi-definite relaxation the authors formulated a robust optimization. The performance analysis in the paper provided some insights in D2D communication with channel uncertainty although unlike our work the authors did not focus on multicast communication. Furthermore, the authors assumed single antenna relay UEs; although with future communication systems, multi-antenna drones systems are possible.

Shimin Gong et al. [112] considered relay beamforming in D2D communication and energy harvesting through multiple relay UEs. The authors employed monotonic optimization and semidefinite relaxation to convert the formulated problem into a solvable format. The formulated problem is a maximization problem which is a trend in most literature, unlike our formulated work which considers a power minimization approach specifically in chapter 5 of this thesis.

Muhammad R.A.Khandaker et al. [113] considered a MISO downlink system model for simultaneous wireless information and power transfer (SWIPT). The authors formulated the optimization problem as a max-min problem subject to SINR and energy harvesting constraints. To make the robust version of the problem tractable and easily solvable, the authors applied the S–lemma and semi-definite relaxation. The work in this thesis does not consider SWIPT.

A core algorithm that is employed to solve the formulated problems in the work in this thesis is stable matching. Stable matching is an algorithm developed by D. Gale and L. S. Shapely [114] to solve the problem of assigning elements of a set to elements of another set in a manner that achieves stability. Stable matching originally developed to solve the stable marriage problem, has been expanded to solve other matching problems. In D2D communication, stable matching has been used in the literature to solve the problem of allocating resources to D2D communication and for D2D pair allocation. For the work in this thesis, one-to-one stable matching is used and unlike the reviewed work, the work in this thesis considers the use of stable matching to solve relay selection for D2D communication when the channel of interest and the interfering channel are uncertain. The existence of channel uncertainties makes the analysis non-trivial. Hence unlike the stable matching approaches for relay selection put forward in the literature, our offering is channel uncertainty aware.

Considering the foregoing, there is a paucity of research works in the area of relay-assisted D2D communication when imperfect channel conditions are experienced hence the need for uncertainty aware algorithms. Furthermore, where there are research works on cross-layer relay selection mechanisms, channel uncertainty analysis are not involved. In the literature, research endeavours in D2D multicast communication are few and to the best of our knowledge, work on robust D2D multicast communication for single and multi-antenna relay scenarios hence our foray into the area. Moreover, channel uncertainty aware cross-layer relay selection algorithms have not been considered in the literature. It can also be inferred that channel uncertainty aware algorithms that are relay centric have not been studied.

Thus the work in this thesis focuses on relay assisted D2D communication with channel uncertainty. We focus on column wise and ellipsoid channel uncertainty set in chapters 3 and 4 using stable matching as our technique in relay selection, a combination which is unique to our work. Furthermore, we formulate D2D multicast communication with channel uncertainty as an optimization problem which to the best of our knowledge has not been addressed. This multicast communication problem is the focus of chapter 5 for which we employ probabilistic and deterministic uncertainty models. This thesis also looked at joint power control and relay selection in D2D communication with channel uncertainty proposing social distance based and relay defined utility based relay selection algorithms. These proposed utility based techniques give the relay UE control in choosing which D2D pairs to assist.

In chapter three of this thesis, a stable matching based algorithm is put forward as a selection technique for device-to-device communication. Using the preference feature of stable matching, the relay user equipment rank the source to destination pairs according to a relay defined parameter and so do the source-destination pairs. This algorithm is coupled with a data rate based mode selection algorithm. The performance of the proposed algorithm showed promise nearing that of a greedy selection algorithm used as a benchmark. Moreover being channel uncertainty aware, the stable matching algorithm provided a more realistic insight. Additionally, the proposed algorithm showed far better spectral efficiency performance in comparison to a random selection algorithm and for low transmit power regimes (0-12 dBm) bested the greedy selection algorithm.

Relay user equipment are buffer enabled devices and in creating selection algorithms, a cross-layer approach that caters for the buffer of the relay user equipment is necessary. Hence in chapter four of this thesis, a cross-layer relay selection algorithm was put forward. Using a defined utility function that caters for both the data rate at the physical layer and the buffer state at the medium access control sub-layer, a utility maximization problem was formulated. The simulation results showed that the proposed algorithm offered spectral efficiency and energy efficiency gains over the best source-relay and best relay-destination selection algorithms. The proposed algorithm also showed higher fairness than the other compared algorithms using a modified fairness index. Again the proposed algorithm is channel uncertainty aware.

Clustering similarly interested user equipment into groups can help offload multimedia data from the network buy enabling relay assisted device-to-device communication. This is the focus of chapter five where the problem of clustering in device-to-device communication is formulated first as a rate maximization problem subject to deterministic and probabilistic constraints. Using the classic k-means algorithm, a group transmitter selection technique was proposed and the formulated problem solved after various simplifications. Through simulations, it was demonstrated that the proposed clustering approach resulted in improved data rate. It was seen that an increase in the number of clusters from 2 to 3 afforded a near 29 % increase in transmission data rate. It was also shown that increasing cluster dimension arbitrarily has adverse effects on the data rate performance of device-to-device multicast communication. The problem was further stretched to cover a multiple-input single-out scenario and robust beamforming was designed. For the multi-input single output case, it was shown through computer simulations that a probabilistic constrained problem approximates its deterministic counterpart when simplified using the cumulative distribution function.

In furtherance to the relay user equipment centric approach that the work in this thesis adopts, a joint power control and relay selection algorithms are put forward in the sixth chapter. The algorithms are social distance based relay selection algorithm and a relay utility selection algorithm. The power control problem was formulated as a linear programming problem whereas the selection problem was modelled as a bipartite graph. It was shown through simulations that the uncertainty aware social distance algorithm offered reduced total transmit power for small values of estimation errors while the relay utility based algorithm motivated more relay participation in comparison with an algorithm in the literature. The social distance-based algorithm afforded 10% total transmit power saving.

2.6 Conclusion

In this chapter, a review of related literature has been done and the areas the work in this thesis endeavours to address have been pointed out. In reviewing related literature, the modes, research approaches, architecture and use cases or application scenarios of D2D communication have been discussed. Furthermore, relay assisted D2D communication approaches in the literature have also been reviewed and their limitations pointed out. Our proposed algorithms for relay user equipment selection and their performances are laid out in chapters 3 to 6.

Chapter 3

Relay Assisted D2D Communication: A Stable Matching Approach

3.1 Introduction

D2D communication can be improved by exploiting the presence of idle UEs in the neighbourhood of the D2D pairs. Taking advantage of the presence of idle UEs holds the promise of ensuring the gains of D2D communication is achieved. D2D communication has been considered for future wireless communication system for application in an emergency or the so-called public safety communication. Emergency communication requires link reliability and in a case where direct communication is not beneficial, relayed communication can be used to ensure that the emergency services are available for UEs cut off from network coverage by a disaster. Therefore emergency service is a use case for the work in this chapter.

In this chapter, a relay selection strategy to choose a suitable mobile device to assist D2D communication is proposed. The term mobile relays and relay UEs or RUEs are used interchangeably in this chapter as in other parts of this thesis. The key assumptions in this chapter are:

- For a D2D pair, the D2D transmitter has information to send to the D2D receiver.
- The D2D pairs have discovered one another already. that is the discovery process has been undertaken.

Different from works reviewed in the literature, we employed one-to-one matching and considered the possibility of channel uncertainty due to estimation errors in both the target links and the interference link. The problem of relay selection is formulated as a data rate maximization problem. To ensure a tractable solution, the problem is modelled as a matching game between a relay UE set and a D2D pair set. The preference feature of stable matching allows the members of both sets to define their preferred member of the opposite set. The selection algorithm is combined with a rate based mode selection algorithm. With mode selection, D2D pairs can either engage in relay-assisted communication or unassisted D2D communication. The proposed algorithm although not optimal being that its performance falls below that of a greedy selection algorithm in high transmit power regimes, it provides spectral efficiency gains in the low transmit power ranges. The results from the proposed algorithm are compared with a greedy selection algorithm and a random selection algorithm. Hence in this chapter, our contribution includes proposing a combined mode selection and relay selection algorithm that is channel uncertainty aware. Furthermore, through the use of stable matching, RUEs can define their preferences making the proposed approach RUE centric too. This makes our work different form the work in the literature.

3.2 System Model

A circular cell is considered having a BS at the centre and uniformly distributed UEs in its coverage area. The cell is isolated and so the interference of concern is intra-cell interference and not inter-cell interference. Let the sets of cellular users be given by $C = \{c_1, c_2, ..., c_n\}$; the set of D2D pairs be given by $D = \{\ d_1, d_2, ..d_d\}$ and the set of potential relay UEs be given by $R = \{r_1, r_2, .., r_r\}$. Within a D2D pair is a D2D transmitter (DUE$_1$) and a D2D receiver (DUE$_2$) as shown in Fig. 3.1. The UEs participating in D2D communication are considered to have data to send to one another. For each source UE to send data to its destination, we hold that the direct path between the source and the destination is not available. Such a case can arise when the fading between D2D pairs degrades the direct link.

The channel fading used for the work in this chapter is the Rayleigh fading modelled between the UEs. The channel is modelled as a distance dependent path loss model such that for a distance d_{ab} between nodes a and b, the channel coefficient is given by $g_{ab} = h_{ab} d_{ab}^{-\frac{\alpha}{2}}$ where h_{ab} represents the fading between device a and b and α is the path loss exponent.

For the work in this chapter, relayed communication is performed in two phases: in the first phase, DUE$_1$ sends its information to an appropriately selected relay UE

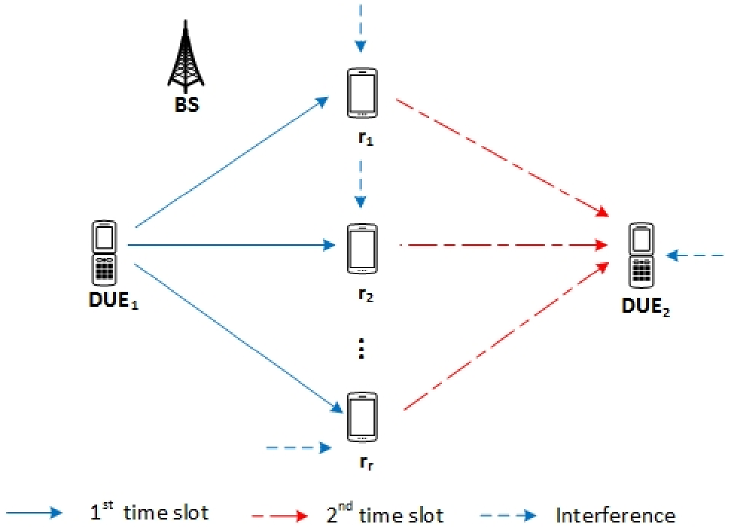

Figure 3.1: A D2D relay set up

(RUE). At the appropriately selected RUE, the signal is decoded, re-encoded and forwarded to DUE$_2$ in the second phase.

Hence for DUE$_1$ having signal s to send to the DUE$_2$ in the first time slot, the signal received by an appropriately selected RUE from DUE$_1$ is given by:

$$y_r = \sqrt{P_s} s g_{sr} + i_r + n_r, \tag{3.1}$$

where P_s is the transmit power of DUE$_1$, g_{sr} is the channel coefficient of the link between the DUE$_1$ and the selected RUE r. i_r is the sum interference that the RUE experiences from nearby transmissions while n_r is the additive white Gaussian noise (AWGN) at the selected RUE and has a distribution of $\mathcal{CN}(0, \sigma_r)$ whereas g_{sr} is modelled as random variable distributed as $\mathcal{CN}(0, \mid g_{sr} \mid^2)$. s is the signal received at the RUE from DUE$_1$.

Similarly, in the second phase, the RUE broadcasts the signal y_r that it received from the DUE$_1$ in the first phase. Thus the signal received at the DUE$_2$ is given by y_d.

$$y_d = \sqrt{P_r} y_r g_{rd} + i_d + n_d \tag{3.2}$$

In equations (3.2), the terms i_d is the interference that the DUE$_2$ experiences whereas n_d is the AWGN at the DUE$_2$ and n_d is distributed as $\mathcal{CN}(0, \sigma_d)$. The achievable end-to-end data rate can be expressed as:,

$$R_r = B\frac{1}{2}\log_2 min((1 + \frac{P_s \mid g_{sr} \mid^2}{\mid i_r \mid^2 + \sigma_r}), (1 + \frac{P_r \mid g_{rd} \mid^2}{\mid i_d \mid^2 + \sigma_d})), \tag{3.3}$$

where in equation (3.3), the 0.5 is indicative that relay assisted communication takes twice the time slot of direct communication. B is the channel bandwidth. Since underlay D2D communication is the consideration for this work, cellular communication is considered to also occur and so experience interference while also contributing interference to D2D communication. The SINR for a n_{th} cellular user transmitting in the uplink towards the BS can be expressed as:

$$SINR_k = \frac{P_c \mid g_{cb} \mid^2}{\mid i_c \mid^2 + \sigma_c}, \tag{3.4}$$

where P_c is the transmit power of a given cellular UE c to the BS, g_{cb} is the channel coefficient of the channel between cellular user c and the BS. i_c is the interference experienced by the BS. Furthermore, σ_c is the AWGN at the BS. Similarly if D2D communication does not involve a relay, the data rate can be rendered as :

$$R_d = \log_2(1 + \frac{P_s \mid g_{sd} \mid^2}{\mid i_d \mid^2 + \sigma_d}), \tag{3.5}$$

where P_s is the transmit power of the source UE.

Although the system model does not differ from the approaches in the literature, our propoposed channel uncertainty aware approach to realy selection is unique to this work.

3.3 Problem Formulation

The problem that this chapter sets forth to solve is the problem of appropriately selecting a relay UE to enforce D2D communication. The selected RUE is part of a pool of mobile relays that are in the vicinity of the D2D pairs.

The problem is formulated as an optimization problem that maximizes a stated objective function. The objective function used is the data rate of relay aided communication.

Thus the optimization is formulated as in equation (3.6).

$$\max_{x_{mr}} \sum_{d\in D}\sum_{r\in R} x_{mr}(R_r) \tag{3.6a}$$

subject to:

$$C_1 : \sum_{d\in D} x_{mr} \leq 1 \forall d_m \in D \tag{3.6b}$$

$$C_2 : \sum_{r\in R} x_{mr} \leq 1 \forall r_r \in R \tag{3.6c}$$

$$C_3 : R_d \geq R_{d_{th}}, \forall d_m \in D \tag{3.6d}$$

$$C_4 : x_{mr} = \{0, 1\}, \forall d_m \in D, \forall r_r \in R \tag{3.6e}$$

The optimization problem has constraints C_1, C_2, C_3 and C_4. The constraints C_1 places a limit on the number of relay devices that can assist a D2D pair to forward messages. It ensures that only one relay can act as a helper device for a D2D pair that have signals to transmit and require relay assistance. C_1 indicates that multi-hopping is not permitted. In a similar manner, constraint C_2 limits the number of D2D pairs that can be assisted by a single relay to 1. Constraint C_3 ensures that relayed communication at least meets the rate requirement of direct D2D communication. Hence a rate threshold $R_{d_{th}}$ is defined that needs be met. The idea is to ensure that relay assisted communication at least measures up to direct communication. x_{mr} is a decision/indicator variable that has a value of 1 or 0. The expression for R_r is given in equation (3.3).

To capture the concept of uncertainty, the optimization problem is reformulated to cater to channel uncertainty that arises from channel estimation errors. Channel estimation errors are modelled to exist in the acquired CSI available to the D2D pairs and relay UEs. To capture channel uncertainty, the channel estimation errors were introduced into the channel gain estimates. Following the channel uncertainty approaches in the literature that assume that the interfering channel is imperfect, the SINR equations are reformulated.

Let the SINR expressions in equations (3.2) - (3.4) be reformulated such that for a D2D pair made of UEs j and k, that suffer interference from a device or an aggregate of devices denoted as i, the SINR can be expressed as:

$$SINR_{jk} = \frac{P_j}{P_i \frac{|g_{ik}|^2}{|g_{jk}|^2} + \frac{\sigma_k}{|g_{jk}|^2}} \tag{3.7}$$

Let $g_k = \frac{|g_{ik}|^2}{|g_{jk}|^2}$ and $N_k = \frac{\sigma_k}{|g_{jk}|^2}$. Equation 3.7 can then be expressed as:

$$SINR_{jk} = \frac{P_k}{P_i g_k + N_k} \tag{3.8}$$

Channel uncertainty models can be probabilistic or deterministic. Deterministic uncertainty models can also be column wise or ellipsoidal. For the work in this chapter, the column-wise uncertainty set ($\mathfrak{R}_\mathfrak{c}$) is used. Considering the column-wise uncertainty set, the channel uncertainty term can be introduced into the ratio of the estimates of g_k such that:

$$g_k = \widehat{g}_k + \varepsilon_k : |\varepsilon_k| \leq \delta_k \forall d \in D \tag{3.9}$$

In equations (3.9), ε_k is the channel estimation error introduced through imperfect channel estimation and $\delta_k > 0$. Applying equations (3.9) to the SINR expressions in equations (3.3) and (3.6), we formulate the robust optimization problem as:

$$\max_{x_{mr}} \sum_{d \in D} \sum_{r \in R} x_{mk}(R_r) \tag{3.10a}$$

subject to:

$$C_1 : \sum_{d \in D} x_{mr} \leq 1 \forall d_m \in D \tag{3.10b}$$

$$C_2 : \sum_{r \in R} x_{mr} \leq 1 \forall r_r \in R \tag{3.10c}$$

$$C_3 : R_d \geq R_{d_{th}}, g_{sr} \in \mathfrak{R}_\mathfrak{c}, g_{rd} \in \mathfrak{R}_\mathfrak{c}, g_i \in \mathfrak{R}_\mathfrak{c}, \forall d_m \in D, \forall r_r \in R \tag{3.10d}$$

$$C_4 : x_{mr} = \{0, 1\}, \forall d_m \in D, \forall r_r \in R \tag{3.10e}$$

In equation (3.10), constraint C_3 indicates that the channel gains g_{sr}, g_{rd} and g_i lie within a bounded set , $\mathfrak{R}_\mathfrak{c}$.

3.4 Proposed Algorithm

The nature of the problem in equation (3.10) makes solving it difficult due to the non-convex nature of the problem. Since equation (3.3) is part of the objective function, solving the problem with a convex solver is not workable except relaxations are introduced. Therefore stable matching is proposed as an alternative approach to solving the relay selection problem. Stable matching affords the modelling of a selection problem as a match between members of one set to members of another set.

Intrinsically, stable matching or the so-called deferred acceptance algorithm allows members of disparate sets to be matched to one another in such a manner that stability is achieved. In stable matching, the matching is based on a list of preferences in which members of the opposite set are ranked according to their desirability.

The constraints C_1 and C_2 in equation (3.10) are met by one-to-one matching because, in one-to-one matching, a member of one set can only be matched to one member of the opposite set. Hence a stable matching based relay selection meets the first two constraints C_1 and C_2 but that will be so if one set is a set of potential relay UEs and the opposite set is a set of D2D pairs. This agrees with our earlier assumption that user pairing is implied. Mathematically, matching (Ψ) is a function from the set $D \cup R$ into the set of $D \cup R$ such that [114]:

1. For each D2D pair, $\mid \Psi(d) \mid = 1$
2. $\Psi(d) \in R \cup \oslash$.
3. For each relay UE, $\mid \Psi(r) \mid = 1$
4. $\Psi(r) \in D \cup \oslash$.
5. $d \in \Psi(r)$ if and only if $\Psi(r) = d$

These intrinsic properties of one-to-one matching allows the constraints C_1 and C_2 to be met.

The relay selection problem is therefore a matching problem defined by a tuple $(R, D, \succ_R, \succ_D)$, where $\succ_R$ are the preferences of elements of the relay set and $\succ_D$ are the preferences of the elements of the D2D pairs set.

To partly meet the QoS constraint C_3, a mode selection algorithm is used to select between D2D and relayed communication by comparing R_r and R_d.

For the work in this chapter, the preference list of D2D pairs is populated using the source-relay data rate. In designing the preference list of the D2D pairs, using the data rate of the source-relay UE link is not out of place since the D2D transmitter can estimate the link quality although imperfectly. Although the source-relay UE link may be a bottle neck for DF cooperative communication, the work in this chapter does not consider cooperative communication.

Moreover, for the objective function, the basis for populating the preference list of the potential relay UEs satisfies the objective function of equation (3.10) being that the criterion for preference listing is the term, R_r. This implies that each potential

RUE ranks the D2D pairs according to the data rate of relay aided D2D communication. In so doing our proposed algorithm is also RUE centric. It is unique to the work in this thesis that a channel uncertainty aware relay selection algorithm that is also RUE centric is proposed. Unlike other stable matching approaches that use the same criterion for popualting both preference lists, the critera for populating the preference lists for the work in this thesis are different and not completely dependent.

As an example, if for 3 D2D pairs; d_1, d_2 and d_3 the source-RUE data rates are given by $0.1, 034$, and 0.54 bps/Hz respectively. If there are 5 potential RUEs, r_1, r_2, r_3, r_4 and r_5, it implies that at the end of a matching process, three RUEs will be selected and two will not be selected. Let the data rate of D2D communication when a relay is used to aid the communication of each of the D2D pairs be given by the entries in Table 3.1.

Table 3.1: Rate (R_r) Table for Relay UEs

	R_{r_1}	R_{r_2}	R_{r_3}	R_{r_4}	R_{r_5}
d_1	0.23	1.43	0.89	1.24	1.85
d_2	1.43	0.56	0.91	0.62	0.12
d_3	1.64	0.85	1.26	0.76	0.43

From Table 3.1, the relay r_1 will rank the D2D pairs thus $d_3 > d_2 > d_1$. Similarly the D2D pair, d_1 will rank the relay UEs thus $r_5 > r_2 > r_4 > r_3 > r_1$. Other relay UEs and D2D pairs also rank members of the opposite set accordingly. These preferences are used to match D2D pairs to RUEs. The matching algorithm achieves stability when each member has either been matched to a member of the opposite set or it is not. In our case, when there are more RUEs than D2D pairs, some RUEs will be unassigned after the algorithm converges and vice versa. This implies that the sizes of the D2D pair set and the RUE set do not need to be the same. The algorithm terminates when either all the D2D pairs have been assigned RUEs or all the potential RUEs are assigned to D2D pairs.

This approach of defining preferences can also be employed as an incentive design mechanism where for the potential RUEs, their preferences can be incentive metrics to motivate relay D2D communication. This is useful considering the self-focused nature of holders of mobile devices.

For the work in this chapter, a mode selection algorithm is combined with the above explained relay selection algorithm to allow the assisting of only D2D pairs for which relayed communication is beneficial. To do so, the achievable data rate of direct

D2D communication is compared to the achievable data rate of relayed communication. For a D2D pair, if using a particular relay UE to assist the communication of the D2D pair results in less data rate than allowing direct communication, the RUE is eliminated from the pool of RUEs. The proposed algorithmm does not need the D2D pairs set to be of the same size as RUE set. It works for same set size and for set sizes that are not the same. The proposed algorithm is shown in Algorithm 1.

The performance of the proposed algorithm is compared with other algorithms. Specifically, a random selection algorithm and a greedy selection algorithm are the algorithms used to compare with the proposed. For the random selection algorithm, a relay UE is selected without a specific metric whereas, in the greedy relay selection algorithm, the relay UEs that offer the highest data rate are selected. The greedy algorithm provides an upper bound on the data rate performance. The greedy algorithm used as a benchmark for comparing the proposed algorithm choses the relay UE for which the data rate is maximum, i.e. given a set of D2D pairs, D and potential RUE set, R if for a D2D pair d_m that requires relay assistance, the achievable data rate from using an RUE, r_r is greater than the achievable data rate from using the other RUEs in the set R, then the algorithm choses r_r to act as the relay for d_m. This procedure is repeated until either there are no more RUEs in the set or there are no more D2D pairs to assist. In so doing the algorithm assigns the maximum rate achiving RUE to each D2D pair and so it is used to provide an upper bound.

The parameters used for simulation are listed in Table 3.2.

Table 3.2: System parameters

Parameter	Value
Channel bandwidth (B)	20 MHz
Maximum number of D2D pairs	10
Noise power (σ)	-174 dBm/Hz
Minimum D2D inter-distance	20 m
Maximum D2D inter-distance	100 m
Number of relay UEs	1 - 10
Number of D2D pairs	1 - 10
Path loss exponent (α)	4
D2D Maximum transmit power	23 dBm
Channel estimation error range (ϵ)	0.1 - 1
Channel model	Distance dependent
Cell radius	500m
UE distribution	Uniform distribution
Maximum number of iterations	1000000

Algorithm 1 Stable matching based relay selection

```
Input parameter:
$P_r, P_s$ : transmit power values,
$g_{rd}$ : relay-destination channel coefficient
$g_{sd}$ : source-destination channel coefficient
$g_{sr}$ : source-relay channel coefficient
$d_{sr}, d_{sd}, d_{rd}$ : UE distances
$\sigma_c, \sigma_d, \sigma_r$ : noise power values
$\sigma_c = \sigma_d = \sigma_r = \sigma$
$N_d$ : number of D2D pairs
$N_r$ : number of relay UEs
$\alpha$ : path loss exponent
$\varepsilon_k$ : channel estimation error
$u = zeros(Nr, Nd)$ place holder
For i = 1 : $N_d$
    Compute $R_d(i) = \log_2(1 + \frac{P_s|g_{sd}|^2}{|i_d|^2+\sigma_2})$
    For j = 1 : $N_r$
        Compute $R_{sr}(i,j) = \log_2(1 + \frac{P_s|g_{sr}|^2}{|i_r|^2+\sigma_r})$
        Compute $R_{rd}(i,j) = \log_2(1 + \frac{P_r|g_{rd}|^2}{|i_d|^2+\sigma_d}))$
        Compute $R_r = \frac{1}{2}min(R_{sr}, R_{r,d})$
        Replace channel gains in $R_r$ and $R_d$ with uncertainty aware terms as in equation (3.9)
        Mode Selection
        If $R_r(i,j) < R_d(j)$
            $ru(i,j) = 1$
        End
        If $u(:,j) == 0$
            $du(j) = 1$
        End
        $nR_r = ru. * R_r$
        $nR_d = du. * R_d$
        Relay Selection
        Compute the preferences $(\succ_D, \succ_R)$
        $\succ_D = R_{s,r}$ , $\succ_R = nR_r$
    End
End
Matching = $SM(\succ_D, \succ_R)$ // where SM is the stable matching algorithm
output Relay selection decision
```

3.5 Performance Discussion

This section discusses the simulation results obtained from testing the relay selection algorithm proposed in the work in this chapter. The performance metric used for discussion is the D2D spectral efficiency and this is a ratio of the calculated D2D data rate to the channel bandwidth. The performance of the D2D spectral efficiency is plotted against parameters such as D2D transmit power, channel estimation error, number of relay UEs and number of D2D pairs. The proposed relay selection algorithm (Proposed RS Algorithm) is compared to a greedy relay selection algorithm (GRS) and a random relay selection (RRS) algorithm.

In Fig. 3.2, the impact of channel uncertainty is studied for the considered algorithms. The figure shows the performance of the proposed algorithm and the two benchmark algorithms. To provide some more insight, the performances of uncertainty aware variant of the benchmark algorithms are also shown. These uncertainty aware algorithms are Uncertainty aware GRS (i.e. Uncertainty aware greedy relay selection) algorithm and Uncertainty aware RRS (i.e. Uncertainty aware random relay selection) algorithm. These uncertainty aware benchmark algorithms like the proposed algorithm factor in the effect of channel uncertainty arising from estimation errors. For this figure, the number of relay UEs is fixed at 5, the number of D2D pairs is maintained at 10 and the transmit power of source and relay UEs is also fixed at 23 dBm. It can be inferred from the figure that our proposed uncertainty aware algorithm responds to errors in the channel estimation thereby giving a more realistic insight into the performance of the D2D selection algorithms. The pattern of the plot shows that as the channel estimation error is increased from 0.1 to 1, there is degradation in the spectral efficiency of the proposed algorithm whereas, for the non-uncertainty aware benchmark algorithms, the performance is indifferent. Considering that channel uncertainty can arise in wireless communication deployment, the GRS and RRS algorithms do not offer a realistic insight into the performance of the D2D setup. It can also be observed that although for larger channel estimation error values (0.5-1) the GRS algorithm provides higher spectral efficiency performance, our proposed algorithm shows better performance below $\varepsilon = 0.5$. Moreover, for the sake of comparison, the performances of the uncertainty aware counterparts of the benchmark algorithms were also plotted. The performance gap between the uncertainty aware GRS algorithm and our proposed RS algorithm is 0.05 bps/Hz at $\varepsilon = 0.1$ narrowing as ε approaches 1. This goes to show that designing uncertainty aware algorithms provide better design insight into wireless communication systems performance. The indifference of the GRS and RRS algorithms is because these algorithms assume availability of perfect channel state information. Furthermore, the proposed RS algorithm fared better than the RRS algorithm for the uncertainty aware and non-uncertainty aware cases. This is because, although the RRS algorithm is simpler, its selection criteria is non-structured. The complexity of stable matching algorithm is provided in Appendix A1.

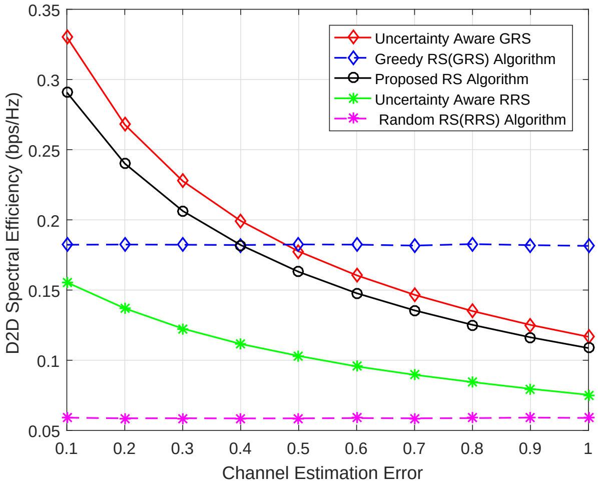

Figure 3.2: D2D spectral efficiency(bps/Hz) vs. Channel estimation error (ε)

In Fig. 3.3, D2D spectral efficiency is plotted against a number of relay UEs. The pattern of the curves shows that having more relay UEs available for selection improves the spectral efficiency of D2D communication. This is not counter-intuitive being that with more participation in relay aided communication, the available bandwidth resource is more utilized. Note that the number of D2D pairs is maintained at 10 and the transmit power of relay UEs and source UEs is fixed at 23 dBm. From the figure, it can also be inferred that although our proposed algorithm trails the greedy algorithm that seeks the best channels, it offers gains over randomly selecting available relay UEs. The gap in performance between the GRS algorithm and our proposed algorithm is roughly 0.07 bps/Hz at 5 relay UEs and widens to 0.1 bps/Hz at 10 relay UEs.

Fig. 3.4 shows the performance of D2D communication as the number of D2D pairs is varied from 1 to 10 for a fixed number of relay UEs in this case 5. From the figure, the fixed number of relay UEs has an effect on the performance of the studied algorithms. This is so because, beyond the point where the number of relays is equal

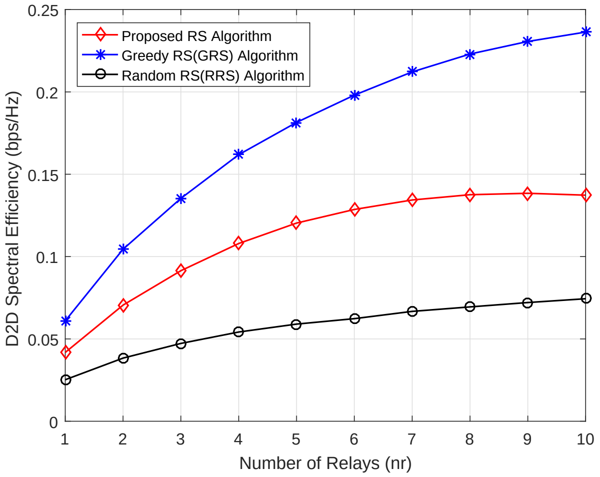

Figure 3.3: D2D spectral efficiency(bps/Hz) vs. Number of relay UEs (nr)

to the number of D2D pairs, the trajectory of the plots are no more linear because there are no more new relay entries into the relay UE sets. The performance of the GRS algorithm and the proposed algorithm is also affected by the maximum distance between the source UE and potential relay UEs and the maximum distance between the potential UEs and the destination UE. For the simulations resulting in Fig. 3.4, there are two maximum distances considered viz. 50 m and 100 m. This increase in maximum distance results in a slight increase in spectral efficiency for both the GRS and the proposed RS algorithm.

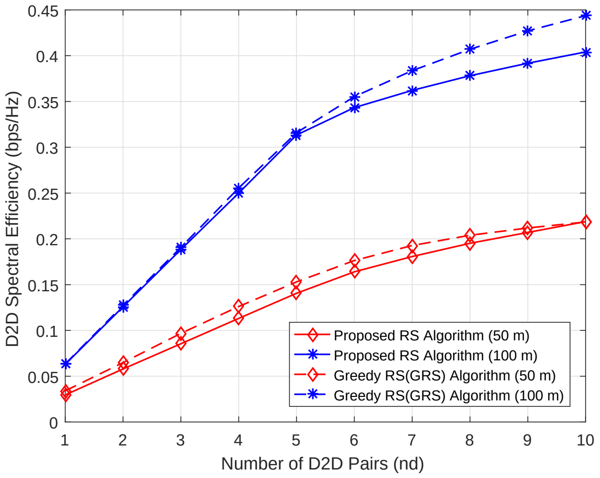

Figure 3.4: D2D spectral efficiency(bps/Hz) vs. Number of D2D pairs (nd)

For the discussed results so far, the transmit power of the source UEs and the relay UEs have been fixed at 23 dBm. In Fig. 3.5, the D2D spectral efficiency is plotted against the D2D transmit power. D2D transmit power here refers to the transmit power of the source UE and the relay UE. For this figure, the number of D2D pairs in the cell is 10 and the number of relay UEs available for selection is fixed at 5. The channel estimation error in the interfering channel is fixed at 0.1. For the range of transmit power considered (0-12 dBm), the proposed algorithm offers higher D2D spectral efficiency over the GRS algorithm and the RRS algorithm to the tune of 33 % and 79 % at a transmit power of 12 dBm respectively. For the simulation resulting in Fig. 3.5, the proposed algorithm is channel uncertainty aware whereas the other two benchmark algorithms are non-channel uncertainty aware. Furthermore, the preference feature of stable matching allows the relay UEs to control their choice of D2D pairs to assist.

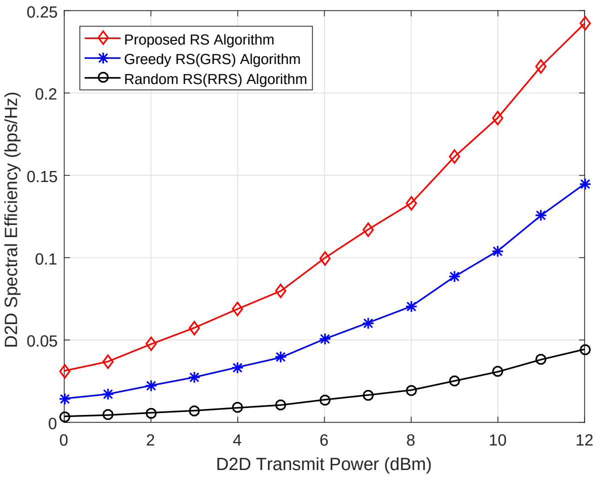

Figure 3.5: D2D spectral efficiency (bps/Hz) vs. D2D transmit power (dBm)

To provide insight into the performance of the proposed algorithm, the effect of preference list selection criteria is shown in Fig. 3.6. The proposed algorithm uses the data rate of relay aided communication to define the preference list of the relay UEs whereas, for the D2D pairs, the preference list is defined by the source-relay UE data rate. It can be seen from the figure that the proposed algorithm (Proposed RS Algorithm A) which is based on these preference list definition offers improved spectral efficiency over its B variant. Unlike the algorithm that the work in this chapter puts forward, the compared variant (proposed RS Algorithm B) bases the relay UE's preference list on the distance between the source UEs and the relay UEs. This goes to show the impact of appropriate choice or preference list selection criteria for stable matching based algorithms.

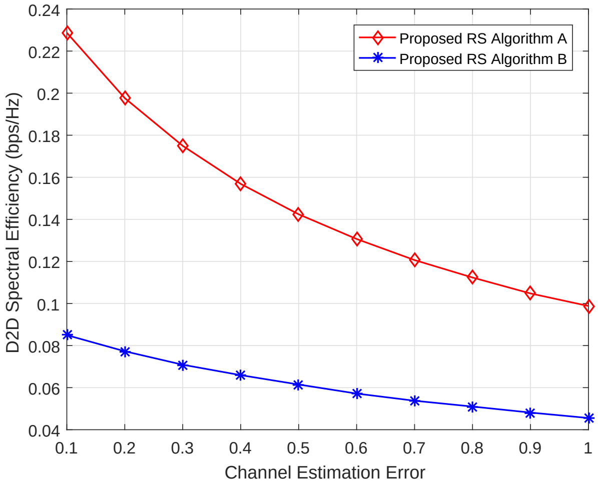

Figure 3.6: D2D spectral efficiency (bps/Hz) vs. Channel estimation error (ε)

The reason for the trailing performance of proposed RS Algorithm B can be explained by the fact that since the objective function is the data rate for the relay link, choice of preference parameters needs to contribute to the objective function. Moreover ranking the D2D pairs based on distance can derail performance as wider distance can deteriorate the rate performance.

In Fig. 3.7, the convergence of the proposed algorithm is presented. The number of iterations is varied from 10 to 100000, the transmit power of source UE and relay UE is 23 mW, there are 5 relay UEs available for selection and there are 10 D2D pairs. Moreover, the channel estimation error is maintained at 0.4. From the figure, the resulting D2D spectral efficiency values increase between 10 to 1000 iterations and converge to approximately 0.182 beyond 1000 iterations. For the simulations resulting in the plots shown in Figs. 3.2 - 3.7, the number of iterations is kept constant at 100000. As expressed in Appendix A.1, the complexity of the stable matching algorithm increases as the square of the number of D2D pairs which brings up the issue of scalability of the proposed method. For the proposed algorithm, although the preference lists are created in the UEs, the matching is performed by the BS which has the computational resources to handle large D2D connections.

3.6 Conclusion

In conclusion, the work presented in this chapter has proposed a relay selection algorithm based on stable matching where preferences are defined by members of the relay UE set and D2D pair set. The proposed algorithm has been compared to a

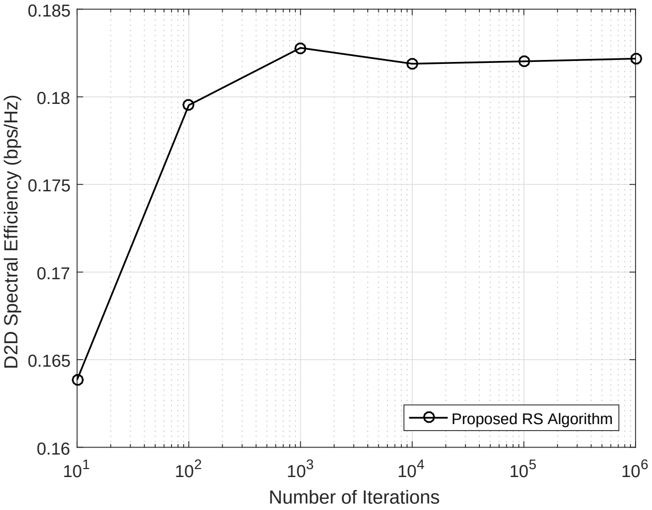

Figure 3.7: D2D spectral efficiency (bps/Hz) vs. Number of iterations

greedy selection algorithm that provided an upper bound and a random selection algorithm. Unlike the benchmark algorithms, the proposed algorithm is channel uncertainty aware. Although the proposed algorithm trailed behind the greedy selection algorithm for a fixed high transmit power value (23 dBm), for a lower range of transmit power values (0-12 dBm), it showed spectral efficiency improvement over the greedy selection algorithm. Furthermore, intuitively the greedy selection algorithm has a weakness of repetitive selection of a particular relay whereas for the proposed algorithm, such weakness does not come up being that the relay UEs are ranked according to preferences.

The proposed algorithm was combined with a mode selection algorithm that ensured that only D2D pairs for which relayed communication was beneficial were assisted, unlike the benchmark algorithms. From the results discussed, the effect of channel uncertainty due to estimation errors is demonstrated and the effect of distance, the number of relay UEs and D2D pairs in the network was also presented. The convergence of the proposed algorithm was also shown. The proposed relay selection algorithm is not only centred on improving D2D communication but it is also RUE centric because it affords the relay UEs a ranking of the D2D pairs.

Considering the available buffer space of relay UEs is also key in relay selection. The next chapter focuses on a cross-layer approach to relay UE selection for D2D communication.

Chapter 4

Cross Layer Relay Selection in D2D Communication with Channel Uncertainty

4.1 Introduction

The previous chapter considered relay selection for D2D communication and the performance of the algorithm proposed in that chapter was discussed. Several performance metrics were used to show the gains of the proposed algorithm in comparison to other traditional algorithms in the literature.

In this chapter, the problem of relay selection is extended to capture the layered nature of the protocol stack of the OSI model. The OSI model is shown in Fig. 4.1. Available relay selection algorithms mostly focus on the use of parameters from the physical layer of the OSI model as a metric for relay selection. Where cross layer selection algorithms are proposed in the literature, the algorithms are not channel uncertainty aware. Although the single layer approach to relay UE selection can provide helpful insight into the performance of formulated algorithms, it may fall short in giving a holistic performance evaluation of selection algorithms. As stated in the literature, a cross layer approach to relay selection provides a multi-layered view of the performance of algorithms designed to optimize a wireless communication system. In relay UE selection, employing a cross-layer approach to relay selection becomes even more necessary being that, although a link can report good link quality for relaying through measured channel state information (CSI), the relay buffer state reported through the queue state information (QSI) may not allow the involvement of a relay UE. Apart from the link quality and the buffer state, the battery state of the relay UE may not allow sufficient relay duration to forward received data.

There are cross layer selection algorithms in the literature, but to the best of our knowledge, employing stable matching as an approach for cross layer relay selection in D2D communication in the face of channel uncertainty is unique to the work in this thesis.

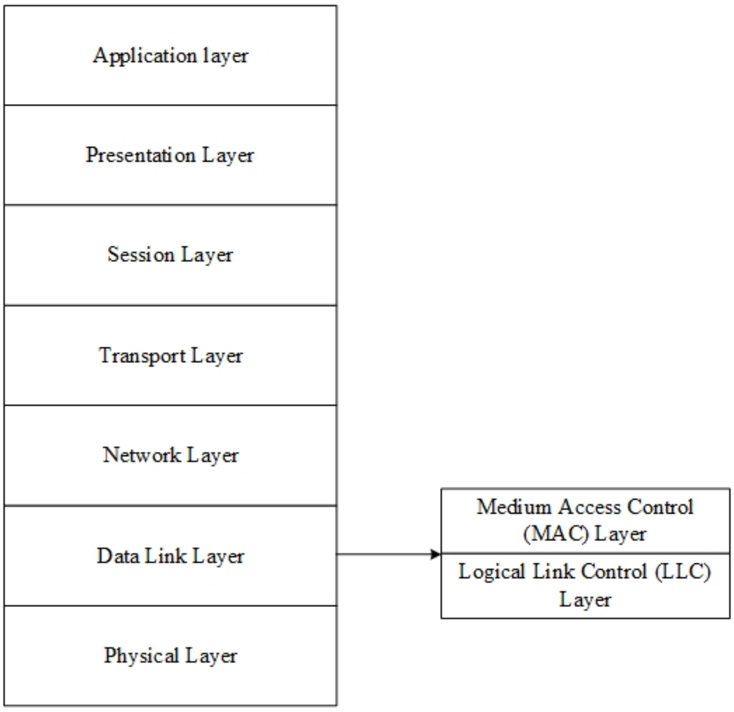

Figure 4.1: The OSI model

Hence, this chapter proposes a cross-layer selection approach for relay-assisted D2D communication. In so doing, the relay selection criteria not only captures the quality of the relay link but also captures upper layer parameters which in the case of this chapter is the queue state information. The QSI used for the work in this chapter is defined as a function of the buffer state of the relay UEs. Our approach to cross-layer relay selection involves defining a selection parameter that is a function of both the CSI and QSI.

The problem of cross-layer relay selection is formulated as a utility maximization problem subject to data rate constraint. And unlike the cross-layer D2D relay selection algorithms reviewed in chapter two of this thesis, our formulation is not only channel uncertainty aware but also employs stable matching to solve the formulated cross-layer relay selection problem. Using computer simulations, the performance of the proposed algorithm is shown in comparison to other algorithms and the results discussed.

Consider a cellular network with direct communication allowed between D2D enabled devices which make up a set $D = \{d_1, d_2, d_3, ..., d_m\}$. Let the set of relay enabled devices that can serve as helper nodes to help forward signals of neighbouring D2D pairs that need relay services be given by $R = \{r_1, r_2, r_3, ..., r_k\}$ as in Fig. 4.2.

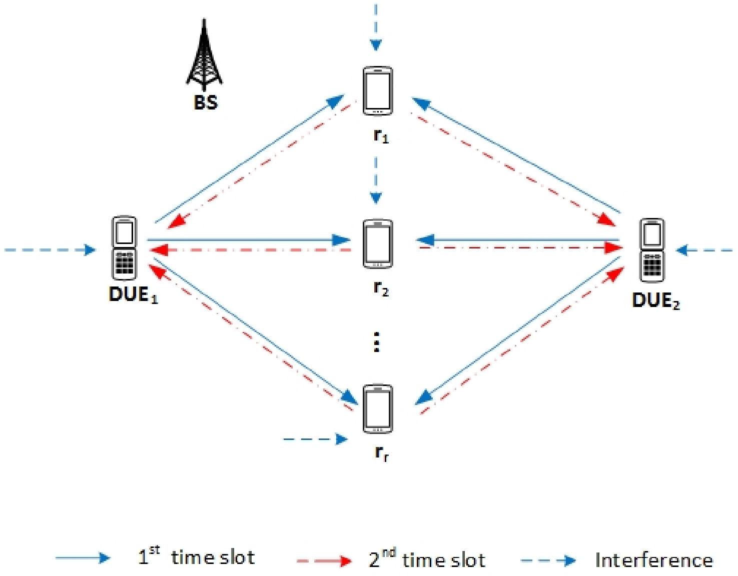

Figure 4.2: A 2 way D2D relay set up

For the relay enabled UEs, two way relaying using the DF technique is implemented such that a D2D pair (DUE$_1$ and DUE$_2$) can both send data to a selected relay simultaneously. The use of two way relaying makes the work in this chapter different from the work in chapter three of this thesis. The D2D pair (DUE$_1$ and DUE$_2$) can also receive from the selected relay UE a combination of the signals they had sent. From these combined signals, they can extract their signal of interest. This two-way communication is accomplished in two time slots. That is in the first time slot, a selected relay UE receives signals from DUE$_1$ and DUE$_2$. In the second time slot, the relay UE broadcast a combination of the signals. This communication set up assumes that both DUE$_1$ and DUE$_2$ have data or signals to send to one another. Let the devices (whether D2D pairs or relay enabled UEs) be uniformly distributed within a cell. It is assumed that the BS has the capabilities to co-ordinate inter-cell interference. Moreover being that uplink communication is considered, interference arising from D2D communication is directed towards the BS and not cellular UEs.

Selecting a relay UE to assist a neighbour D2D pair forward packets should consider more than the link quality. Although operators of mobile networks desire to provide an acceptable quality of service, deploying relay assisted D2D communication in which relay UEs are selected without considering their limited buffer size may lead to dropped packets.

The main contributions of the work in this chapter include:

- Formulating the relay selection problem as a utility maximization problem. In so doing the relay selection is presented in a mathematical format for which an algorithm can be provisioned to solve the formulated problem,
- Formulating a cross-layer parameter for relay selection. The proposed cross-layer parameter combines feeds from the physical layer (the data rate) and the MAC layer which is a data link sub-layer. This approach ensures that the relay selection process is not only D2D pair focused but also relay UE centric,
- Proposing a cross-layer channel uncertainty aware stable matching based relay selection algorithm. Unlike most cross-layer designs in the literature, we consider imperfect channel information and so incorporate channel estimation errors into the formulated problem and
- Demonstrating through simulations the performance of the proposed algorithm over traditional best source-relay and best relay-destination selection algorithms. Our proposed cross-layer relay selection algorithm meets the constraints of the formulated selection problem and allows for relay and D2D pair defined preferences. To the best of our knowledge, this approach of using stable matching for D2D cross-layer relay selection is unique to our work.

To provide a background to the formulation of the utility function, the physical layer and MAC layer parameters are discussed.

4.2 Physical Layer: End-to-End Data Rate

The task of improving a communication system can be achieved by optimizing a physical layer parameter such as the spectral efficiency, probability of outage, energy efficiency among other such parameters. The parameter of interest at the physical layer for the work in this chapter is the end-to-end data rate of the source-relay-destination link. To avoid ambiguity in expressions, DUE_1 is used to denote the D2D transmitter whereas DUE_2 denotes the D2D receiver. The terms, receiver and transmitter may not be appropriate since both devices transmit to and receive from the selected relay UE in the two way DF relaying setup that is considered in the work in this chapter.

For relay assisted D2D communication using 2 way DF relaying, let the information that DUE$_1$ intends to send to DUE$_2$ be given by s_1 and the information DUE$_2$ intends to send be given by s_2. Let the channel between DUE$_1$ and the selected RUE, r be given by h_1 and the channel between DUE$_2$ and the RUE, r be given by h_2. Then in the first time slot, RUE r receives y_r. y_r is given by:

$$y_r = \sqrt{P_1} s_1 h_1 + \sqrt{P_2} s_2 h_2 + i_r + n_r, \tag{4.1}$$

where P_1 is the transmit power of DUE$_1$, P_2 is the transmit power of DUE$_2$, the Additive White Gaussian Noise (AWGN) at the relay is denoted by n_r modelled as $\mathcal{CN} \sim (0, N_r)$, i_r is the sum interference experienced by the selected RUE. In the second time slot, the D2D pair receive a filtered version of y_r having been filtered through h_1 and h_2 respectively. The channel is modelled as a distant dependent path loss model such that $h_i = \beta d_{ij}^{-\frac{\alpha}{2}}$ for a separation $d_{i,j}$ between UEs i and j with path loss exponent of α. β captures the small scale fading of the channel. The channels between each pair of devices are considered equal and reciprocal.

The received signal y_r is broadcast by RUE, r to both DUE$_1$ and DUE$_2$ in the second time slot. Thus in the second time slot, the signal sensed at the D2D pair, DUE$_1$ and DUE$_2$ can be expressed as:

$$y_1 = \sqrt{P_r} y_r h_1 + i_1 + n_1 \tag{4.2}$$

and

$$y_2 = \sqrt{P_r} y_r h_2 + i_2 + n_2, \tag{4.3}$$

where P_r is the relay transmit power while n_1 and n_2 are the AWGN at DUE$_1$ and DUE$_2$ respectively modelled as $\mathcal{CN} \sim (0, N_1)$ and $\mathcal{CN} \sim (0, N_2)$ respectively. i_1 and i_2 are respectively the interference that DUE$_1$ and DUE$_2$ respectively experience. The two way DF relay communication can be decomposed into two one-way relay aided communication flows thus:

- DUE$_1$ - RUE - DUE$_2$ and
- DUE$_2$ - RUE - DUE$_1$.

Denote the end-to-end data rate associated with each flow as R_1 and R_2 respectively where,

$$R_1 = 0.5 \times min(\log_2(1 + \frac{P_2|h_2|^2}{|i_r|^2+N_r}), \log_2(1 + \frac{P_r|h_1|^2}{|i_1|^2+N_1})) \tag{4.4}$$

and

$$R_2 = 0.5 \times min(\log_2(1 + \frac{P_1|h_1|^2}{|i_r|^2+N_r}), \log_2(1 + \frac{P_r|h_2|^2}{|i_2|^2+N_2})) \quad (4.5)$$

Having $\frac{1}{2}$ in equations (4.4) and (4.5) shows a halving of the data rate due to the introduction of relays. This points to the fact that whereas direct communication will use a single time slot, a relayed communication uses twice the number of slots. The data rate of the two way DF D2D communication rate for unit bandwidth can be expressed as [115],

$$R_r = min(R_1 + R_2, R_m), \quad (4.6)$$

In equation (4.6),

$$R_m = 0.5 \times \log_2(1 + \frac{P_1|h_1|^2}{i_r + N_1} + \frac{P_2|h_2|^2}{i_r + N_2}) \quad (4.7)$$

For unassisted D2D communication where D2D pairs communicate directly, the data rate measured at DUE$_2$ can be expressed as,

$$R_{12} = \log_2(1 + \frac{P_1|h_{12}|^2}{i_2 + N_2}) \quad (4.8)$$

.

Hence at the physical layer, we define a data rate based selection parameter U which is the difference between the data rate for relayed communication and that for direct un-relayed communication between DUE$_1$ and DUE$_2$, i.e. $U = \text{diff}(R_r, R_{12})$. This can be viewed as the gain from relaying. The relaying gain is beneficial to the D2D pair since DUE$_1$ and DUE$_2$ want to obtain reasonable improvement in the communication experienced from relay assistance. Although this relaying gain can be used as a parameter for a relay reward or incentive scheme, it does not consider the state of the relay buffers. Therefore, in the work in this chapter, the defined relaying gain is optimized in combination with a MAC sub-layer parameter.

4.3 The Data Link Layer: The Queuing State Information

Apart from the physical layer, there are other layers in the OSI (open system interconnect) model. One of such layers is the data link layer within which is the MAC sub-layer. For each idle relay capable UE that is a candidate for relay selection, there is a non-elastic buffer. The buffer size is independent of the channel state and so although an idle UE may seem to be a good candidate for relay aided communication based on reported or measured link quality, the buffer state of the idle UE may not allow the storing and forwarding of target D2D communication information. Therefore the need to design relay UE selection parameters to cater to the buffer states of relay UEs.

To cater to the buffer state of potential relay UEs, a MAC sub-layer parameter namely QSI is defined. In the work in this chapter of the thesis, the QSI is defined as q_r. Denote an indicator parameter, c such that:

$$q_r = \frac{1}{c}, c = \begin{cases} 1, & \text{if } \frac{Q_r}{B_r} < 1 \\ \infty, & \text{if } \frac{Q_r}{B_r} > 1, \end{cases} \tag{4.9}$$

where the size of the buffer of the relay enabled UE is denoted by B_r and the size of the queue of packets at the relay UE buffer is denoted by Q_r. Q_r is a uniformly distributed value betwen 100 and 500. q_r is a binary indicator that signifies the state of the queue of a candidate RUE's buffer. q_r indicates whether the buffer is full or not full. Therefore the cross-layer parameter for optimization is expressed as:

$$U \times q_r, \tag{4.10}$$

where $U = \text{diff}(R_r, R_{12})$. The goal of the work in this chapter is to select RUEs in a manner that optimizes the defined cross-layer parameter. The choice of this metric as a cross layer metric for relay selection in D2D communication is informed by the fact that it captures both the performance metric at the physical layer and the performance metric at the MAC sublayer. In using the product of the U and q_r, having a report of optimal data rate for a give RUE path is not sufficient for selecting a relay UE, rather the value of q_r which is indicative of the state of the buffer is factored into the choice of a candidate RUE.

4.4 Problem Formulation

The relay selection is then formulated as an optimization problem to maximize the cross-layer function $U \times q_r$. In so doing, parameters from the physical layer and the data link layer are factored into the relay selection problem. Improved data rate is important to D2D communication and the state of buffers is also important to relay

UEs. Hence the optimization problem can be rendered as:

$$\max_{x_{mk}} \sum_{d\in D}\sum_{r\in R} x_{mk}(U \times q_r) \tag{4.11a}$$

subject to:

$$C_1 : \sum_{d\in D} x_{mk} \leq 1 \forall d_m \in D \tag{4.11b}$$

$$C_2 : \sum_{r\in R} x_{mk} \leq 1 \forall r_k \in R \tag{4.11c}$$

$$C_3 : R_d \geq R_{th} \forall d_m \in D \tag{4.11d}$$

$$C_4 : x_{mk} = \{0,1\}, \forall d_m \in D, \ \forall r_k \in R \tag{4.11e}$$

The constraints C_1 ensures that only one relay UE can assist the communication of a D2D pair. This means that multi-hoping is not permitted. Moreover, C_2 ensures that a relay UE can only assist a D2D pair. i.e. not more than the data of a D2D pair can be carried by a relay per time. Constraint C_3 is a QoS constraint that ensures that the data rate of D2D communication is met. The work in this chapter goes an extra mile to define a cross-layer parameter for optimization. Keeping to one of the anchors of the work in this thesis, the effect of channel uncertainty arising from the presence of channel estimation errors is also considered. C_4 shows an indicator variable $x_{mk} = \{0, 1\}$.

4.4.1 Channel Uncertainties

Channel uncertainty sources include channel estimation errors, channel state information sourcing delay, feedback quantization errors [116] and channel ageing. The additive error model adopted by similar works [107] in which a bounded channel estimation error is added to the channel estimate is the approach followed in this thesis. As in chapter three, a deterministic uncertainty model is adopted for the analysis in this chapter. In deterministic models, the error being modelled is assumed to lie within a bounded region which could be a line segment or an ellipse. To apply or introduce channel estimation errors into the analysis, the SINR terms in equations (4.4), (4.5) and (4.8) are reformulated. Thus for a channel a_{jk} between UEs j and k, with j transmitting at a power level P_j and UE k experiencing an interference given by $P_i|a_{ik}|^2$ and with a noise power of N_0, the SINR at UE_k is given by:

$$SINR_{jk} = \frac{P_j}{P_i\frac{|a_{ik}|^2}{|a_{jk}|^2} + \frac{N_0}{|a_{jk}|^2}} \tag{4.12}$$

$$SINR_{jk} = \frac{P_j}{P_i a_k + N_k} \tag{4.13}$$

To keep notations lean, the ratio $\frac{|a_{ik}|^2}{|a_{jk}|^2}$ is expressed simply as a_k and similarly the ratio $\frac{N_0}{|a_{jk}|^2}$ is given by N_k in equation (4.13). The channel estimation errors can then be introduced into the channel gains such that the SINR with normalised or scaled channel gains having channel estimation errors introduced can be expressed as:

$$SINR_{jk} = \frac{P_j}{P_i \overline{a}_k + N_k}, \tag{4.14}$$

where for column wise uncertainty set as in [117],

$$\overline{a}_k = a_k + \xi_k : |\xi_k| \leq \delta_k \forall d \in D \tag{4.15}$$

In equation (4.15), $\overline{a}_k$ is the noisy channel estimate, ε_k is the channel estimation error introduced through imperfect channel estimation. a_k is the perfect channel estimate and is bounded by δ_k. $\delta_k > 0$. This approach of using the column wise uncertainty set is also employed in [117]. Adapting and applying equations (4.14 - 4.15) to the optimization problem in equation (4.11), we formulate the uncertainty aware optimization problem as:

$$\max_{x_{mk}} \sum_{d \in D} \sum_{r \in R} x_{mk} (U \times q_r) \tag{4.16a}$$

subject to:

$$C_1 : \sum_{d \in D} x_{mk} \leq 1 \forall d_m \in D \tag{4.16b}$$

$$C_2 : \sum_{r \in R} x_{mk} \leq 1 \forall r_k \in R \tag{4.16c}$$

$$C_3 : R_d \geq R_{d_{th}}, a_{ij} \in \overline{a}_{ij}, a_{jr} \in \overline{a}_{jr}, \forall d_m \in D, \tag{4.16d}$$

$$C_4 : x_{mk} = \{0, 1\}, \forall d_m \in D, \forall r_k \in K \tag{4.16e}$$

4.4.2 Relay Selection

To solve the formulated problem in equation (4.16), we propose a cross-layer relay selection algorithm that is based on one-to-one stable matching. The choice of an alternative approach to solving the formulated problem is due to its non-convex nature.

Algorithm 2 Cross - layer relay selection

```
Input parameter:
$B_r$ : relay buffer size
$Q_r$ : relay queue size
$\eta$ amplifier efficiency
$P_1, P_2, P_r$ : transmit power values,
$h_1$ : DUE$_1$ - relay UE channel coefficient
$h_2$ : DUE$_2$ - relay UE channel coefficient
$h_{12}$ : DUE$_1$ - DUE$_1$ channel coefficient
$d_{1r}, d_{21}, d_{12}$ : UE distances
$n_d$ : number of D2D pairs
$n_r$ : number of relay UEs
$\alpha$ : path loss exponent
for i = 1 : $N_d$ do
    Compute $R_d(i) = \log_2(1 + \frac{P_1|h_{12}|^2}{i_2+N_2})$
    for j = 1 : $N_r$ do
        Compute $R_1(i,j) = \log_2(1 + \frac{P_2|h_2|^2}{|i_r|^2+N_r}), \log_2(1 + \frac{P_r|h_1|^2}{|i_1|^2+N_1})$
        Compute $R_2(i,j) = \log_2(1 + \frac{P_1|h_1|^2}{|i_r|^2+N_r}), \log_2(1 + \frac{P_r|h_2|^2}{|i_2|^2+N_2})$
        Compute $R_r, U = diff(R_r(i,:)), (R_d(i))^T)$ where $(.)^T$ is the transpose operation. Reformulate $R_r$, $U$ based on equation (4.15)
    end for
end for
if $\frac{Q_r}{C_r} < 1$ then
    $q_r = 1$
else
    if $\frac{Q_r}{C_r} > 1$ then
        $q_r = 0$
    end if
end if
for i = 1 : $N_d$ do
    for j = 1 : $N_r$ do
        $\succ_R = U(i,j) * q_r(1,j)$ // preference of relay UEs
        $\succ_D = R_{1,r}(i,j) * q_r(1,j)$ // preference of D2D UEs
    end for
end for
$\succ_R$ ($\succ_R$== 0) = [ ] eliminate relays with full buffers
$\succ_D$ ($\succ_D$== 0) = [ ] eliminate relays with full buffers
$[mM, uM] = SM(\succ_D, \succ_D)$ // where SM is one-to-one stable matching algorithm
D2D data rate for assisted communication $=sum(R_r(nM,:))$
output Relay selection decision
```

Stable matching allows the modelling of the problem as a matching market. Let the cross-layer relay selection problem be designed as a matching market denoted by the tuple $(D, R, \succ_D, \succ_R)$ where $\succ_D$ and $\succ_R$ are the preference lists that elements of the D2D set D hold over elements of the relay set, R and vice versa. Each D2D pair defines a list in which members of the relay set are ranked according to their desirability. Similarly, the relay UEs rank members of the D2D pair set according to their desirability.

For the work in this chapter, the criteria for ranking relay pairs is the data rate of DUE_1 - relay UE link, R_{1r} whereas the relay gain function U is used by the relay UEs to rank members of the D2D pair set. The use of U can be seen as an incentive measure since it points to the relaying gain. Our choice of one-to-one stable matching is because the nature of one-to-one stable matching satisfies the first two constraints. That is in one-to-one stable matching, one member of a set can be matched to only a member of an opposite set. This characteristic of the one-to-one stable matching fits with constraints C_1 and C_2. Moreover, by defining the preference list as a function of the data rate, the third constraint is equally satisfied. The proposed cross-layer algorithm is dubbed: "Cross layer". A detailed flow of the selection algorithm is given in Algorithm 2. In the proposed cross-layer algorithm, the equation (4.9) holds. That is if a potential relay UE has an available buffer space of whatever size, the relay UE remains part of the potential relay UE set. A relay UE is only excluded from the relay UE list if its buffer is full. The problem of cross layer relay selection can be modelled as a Markov chain and this approach has been studied by R. Ma et al. [101]. For the work in this chapter, we approach cross layer relay selection differently by modelling the problem as a matching market which is unique to the work in this thesis. Not using the Markov chain approach, the accompanying concepts of the distribution of the arrival process is avoided.

4.5 Analysis of Results

In this chapter, an uncertainty-aware cross-layer relay selection algorithm for relay aided D2D communication is proposed. Parameters in the physical and data link layers are employed in the cross-layer relay selection technique. In this section, the performance of the proposed algorithm is analysed and the results are discussed. The parameters employed for simulation are laid out in Table 4.1.

The four algorithms considered are the proposed cross-layer algorithm, a best source-relay algorithm, a best relay-destination algorithm and a random selection algorithm. The best source-relay link selection algorithm chooses the RUE for which the DUE_1-RUE link offers the highest data rate. Similarly, the best relay-destination

Table 4.1: System Parameters

Parameter	Value
Amplifier efficiency	0.3
Circuit power	0.1
Buffer size	500
Queue length	100 - 500
Channel bandwidth	20 MHz
Maximum number of D2D Pairs	10
Noise power (σ)	-174 dBm/Hz
Minimum D2D inter-distance	50 m
Maximum D2D inter-distance	100 m
Number of relays	2 - 5
Path loss exponent (α)	4
D2D maximum transmit power	23 dBm
Channel estimation error range (ξ)	0.02 - 0.2
Channel model	Distance dependent
Cell radius	500m
UE distribution	Uniform distribution
Maximum number of iterations	100000
Number of interfering sources	10

link selection algorithm selects the RUE for which the RUE-DUE$_2$ data rate is the highest. The random selection algorithm on the hand selects an RUE in a non-defined manner.

The first result is shown as numbers in Table 4.2. Using a modified Jian fairness index [118], the fairness of the proposed cross-layer relay selection algorithm, its non-cross layer alternatives are presented in Table 4.2. If for x resources allocated to n processes in a way that a resource x_i is allocated to the i^{th} process, then the index of fairness as defined by Jain et. al. [118] can be rendered as:

$$f(x) = \frac{\sum\limits_{i=1}^{n} x_i}{\sum\limits_{i=1}^{n} x_i^2}, \tag{4.17}$$

where x is the ratio of an allocation to the optimal allocation. Analysing the fairness index of the algorithms using equation (4.17), the resulting index will be equal for all the algorithms if x is the number of RUEs. And so this motivated the use of spectral efficiency as x in equation (4.17) for the Jain's index calculation.

From the entries in Table 4.2, the Cross layer algorithm offers higher fairness in comparison to the rest of the algorithms whereas random relay selection algorithm has

Table 4.2: Jian's Fairness Index

Cross layer	Best S-R	Best R-D	Random selection
0.9281	0.9181	0.9117	0.9021

the least fairness value. The performance of the proposed Cross layer algorithm can be attributed to stable matching which is its underlying algorithm. It is characteristic of stable matching to allow for preference definition from members of sets that make up a matching market and that explains the higher fairness value. The best source-relay algorithm has a higher fairness index value than the best relay-destination algorithm whereas the random selection algorithm has the least fairness index.

For Fig. 4.3, the transmission time is plotted against the D2D transmit power. Transmission time is formulated as an inverse of the data rate ($\frac{1}{R_r}$) where R_r is the data rate of the relay path for unit bandwidth.

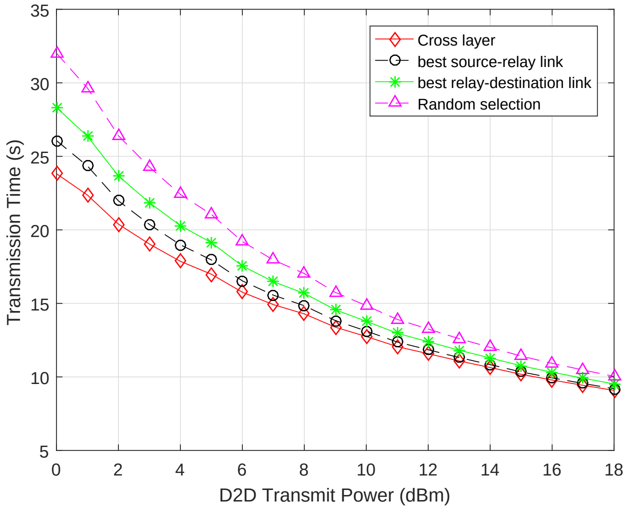

Figure 4.3: Transmission time(s) vs D2D transmit power (dBm)

The proposed algorithm offers the least transmission time in comparison with the other algorithms and shows that the proposed algorithm has the potential to provide less delay. As the D2D transmit power is increased, the transmission time performance gap narrows between the proposed Cross layer algorithm and the compared algorithms. The superior performance of the proposed Cross layer algorithm in the low D2D transmit power region is promisisng as this can contribute to better energy efficiency in implementation. The random selection algorithm not having a clear selection structure showed the worst performance among the studied algorithms whereas the best source-relay algorithm bested the best relay-destination selection algorithm.

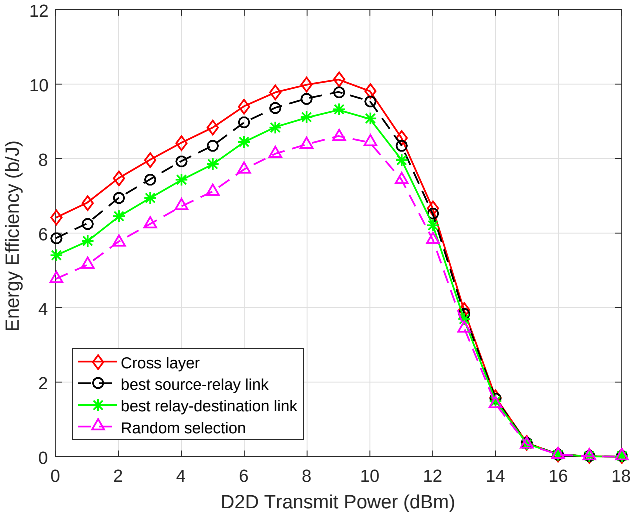

Figure 4.4: Energy efficiency(b/J) vs. D2D transmit power (dBm)

The energy efficiency plots of the Cross-layer selection algorithm in relation to the other discussed algorithms are shown in Fig. 4.4. The energy efficiency (EE) is obtained using the formula:

$$EE = \frac{R_r}{P_T}(b/J), \tag{4.18}$$

where as in [119], the total power P_T is obtained from adding together the transmit power(P_{tr}) and the devices' circuit power (P_c). Therefore P_T can be expressed as:

$$P_T = \frac{1}{\eta}P_{tr} + P_c, \tag{4.19}$$

where η denotes the amplifier efficiency of the UEs. Note total power combines the transmit power of the D2D pair and selected RUE, i.e.

$$P_{tr} = 2n_d P_i + n_r P_r \tag{4.20}$$

$$P_{cir} = 2n_d P_{cir_i} + n_r P_{cir_r}, \tag{4.21}$$

where $i = 1, 2$, n_d refers to the number of D2D pairs and n_r denotes the number of RUEs.

For these plotted curves, the D2D transmit power is varied from 0 dBm to 18 dBm. The trajectory of the plotted curves shows a rise in energy efficiency from

D2D transmit power of 0 dBm. The rise in the curves reaches an apex at 9 dBm beyond which the curves taper off to its minimum at 18 dBm. The apex gives an insight into the threshold beyond which D2D communication is not energy efficient for the considered simulation parameters and the considered algorithms. Note that there are 10 D2D pairs and 5 RUEs for the simulation resulting in Fig. 4.4. The pattern of the plots do not deviate from patterns of energy efficiency plots in the literature. The proposed algorithm offers higher energy efficiency over other compared algorithms although it is channel uncertainty aware. The compared algorthms only approach the proposed algorithm when the transmit power of D2D communication is in the high regimes. And so implementing the proposed algorithm has the potential to provide energy saving. This gain in energy can make for the complexity of the proposed algorithm which increases as the squatre of the number of D2D pairs. And being that the matching occurs at the base station, the complexity is handled by the computational power of the base station.

For the work in this chapter, potential relay UEs are randomly positioned between D2D pairs. To reap the benefits of relay networks, the position of the relay between source and destination devices is also key. Thus in Fig. 4.5, the spectral efficiency of D2D communication is plotted for a source-relay distance.

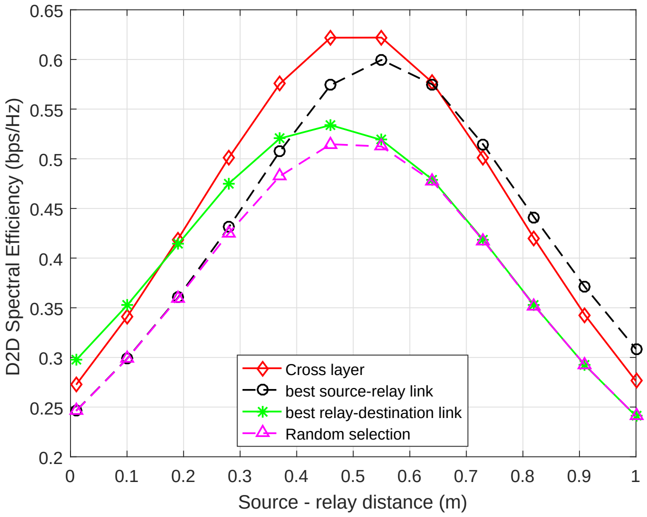

Figure 4.5: D2D spectral efficiency (bps/Hz) vs. Source - relay distance (m)

From the curves in Fig. 4.5, the optimal relay position is in the region halfway between the D2D pair. Whereas the proposed Cross layer algorithm shows that positioning a relay UE exactly halfway between the D2D pairs is optimal as in the literature [58]; the best source-relay and best relay-destination algorithms show that for these algorithms the optimal relay position deviates from the halfway position and are either nearer the destination (DUE_2) or the source UEs (DUE_1) respectively. The proposed Cross layer algorithm on the average offers improved spectral efficiency for the range of relay UE position but falls slightly below the best source-relay link algorithm when the relay UE is positioned nearer the destination. The performance of the best source-relay and best relay-destination algorithms stems from the fact that these selection algorithms are based on the performance of either side of the two phases of (DUE_1-to-RUE and RUE-to-DUE_2) communication hence the one-sided biases in the optimal positioning. Again our uncertainty aware algorithm shows improved performance.

Fig. 4.6 shows the plot of D2D spectral efficiency against source–relay distance for a range of channel estimation errors. For this figure, the Cross layer algorithm is considered. The channel estimation error used for the figure are $\xi = 0.02$, 0.06 and 0.2. The transmit power of D2D communication is pegged at 23 dBm. The figure shows that as the considered channel estimation error is increased, there is an accompanying drop in spectral efficiency. The drop in performance is about 20 % for an increase of estimation error from 0.02 to 0.06 and about 40 % drop for an increase in estimation error from 0.06 to 0.2. This is indicative of the effect of channel uncertainty on the performance of D2D communication and so makes the case for channel aware relay selection algorithms. Moreover, since even for a fixed channel estimation error of $\xi = 0.1$ in the previous figures, our algorithm shows better EE, transmission time and fairness over the other non-cross layer algorithms, the proposed algorithm can be seen to offer an edge.

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The number of relay UEs available for relaying can affect the performance of relay networks. This is demonstrated in Fig. 4.7 in which the plots of D2D spectral efficiency versus the number of relays is presented. The number of RUEs is varied from 2 to 5. The pattern of the graphs shows an increase in spectral efficiency as the number of available relays is increased. This performance is not counter-intuitive as with more relays, there is increased opportunity for participation in relay aided D2D communication and hence improved spectrum utilization. For Fig. 4.7, the number of D2D pairs is fixed at 10 and the channel estimation error is kept at 0.1 and the maximum D2D separation is 100 m.

In Fig. 4.8, the D2D spectral efficiency versus the D2D transmit power performance of four algorithms are plotted. For the plots in Fig. 4.8, the number of D2D pairs in the cell is 10 and the number of relay UEs is 5. In Fig. 4.8, there is a general

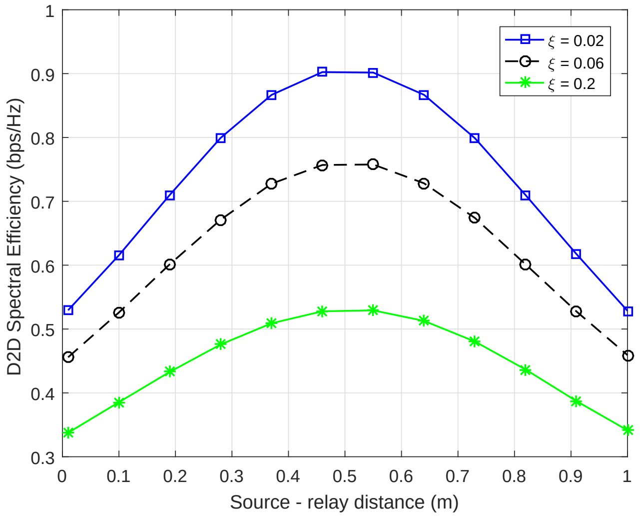

Figure 4.6: D2D spectral efficiency (bps/Hz) vs. Source - relay distance (m)

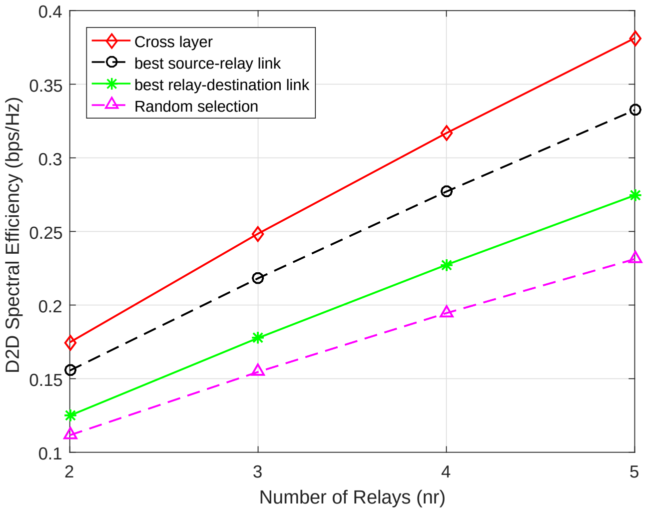

Figure 4.7: D2D spectral efficiency (bps/Hz) vs. number of relays

rise in the curves as the D2D transmit power is increased from 0 dBm to 18 dBm indicating increasing spectral efficiency as the transmit power of D2D communication is increased. The plots show that the random selection algorithm offers the least spectral efficiency falling behind the Cross layer algorithm, the best source-relay algorithm and the best relay-destination algorithm. Between the best source-relay and the best relay-destination algorithms, the former provides higher spectral efficiency for increasing transmit power as in [117] giving up to 4% improvement in performance. Furthermore, the proposed Cross layer algorithms outperform the other three algo-

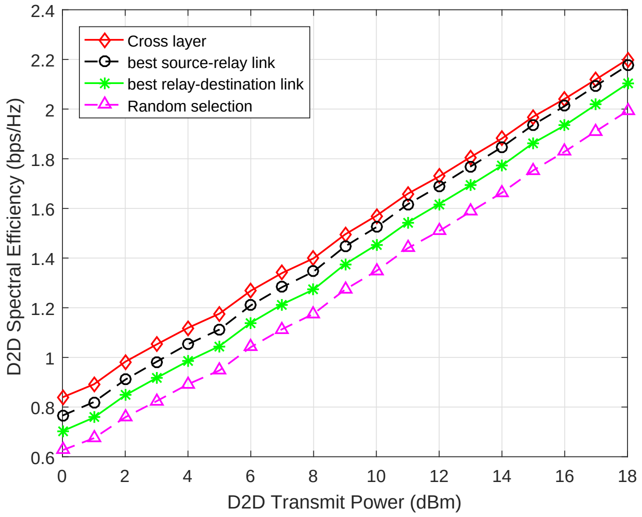

Figure 4.8: D2D spectral efficiency vs. D2D transmit power(dBm)

rithms offering nearly 9% increase in spectral efficiency over the random selection algorithm at 16 dBm. For this plot, the channel estimation error is fixed at 0.1 and the number of interfering cellular UEs are fixed at 10.

In this chapter as in chapter three, relay selection algorithms are proposed for D2D communication. These algorithms are based on the stable matching algorithm. It is shown in the literature that the computational complexity of stable matching algorithm is $\mathcal{O}(|n_d|^2)$ [114]. The algorithm is still scalable since the matching is performed at the BS and the UEs only need to submit their preferences to the BS.

4.6 Conclusion

In this chapter, a cross-layer relay selection algorithm for D2D communication was proposed and its performance was studied. Using two way relaying and half duplex mode at the relay UE, the performance of the proposed technique was analysed.

Performance metrics that were employed included transmission time, spectral efficiency, energy efficiency and fairness. To provide a realistic insight into the performance of the proposed algorithm, channel uncertainty was weaved into the reformulated interference channel expression. Ignoring the buffer of a potential relay UE assumes that the buffer is always empty, hence the cross-layer approach.

The results presented showed that the proposed Cross layer algorithm offers a fairness advantage to relay selection apart from spectral efficiency and energy efficiency gains.

The proposed algorithm showed improvements despite being uncertainty aware in comparison to other algorithms that were not uncertainty aware. The work in this chapter has proposed a cross-layer technique and showed through computer simulations the performance of this technique. The cross-layer nature of proposed algorithms makes relay selection not only D2D centric but also relay UE centric. This caters for the rational nature of users of relay UEs. For the work in chapters three and four, we have kept a fixed transmit power. That is, power allocation has not been part of the work in these chapters. In chapters five and six, we relaxed that approach to allow for power allocation. In chapter six, the UEs are allocated transmit power through linear programming whereas robust beamforming is used in chapter five.

A promising use case of relay-assisted D2D communication is group communication. Group communication has the potential to offload reasonable traffic from the network being that a group transmitter can send requested data to a cluster of UEs instead of the group of UEs depending on the BS for such data. In the next chapter, D2D multicast communication is considered in which D2D UEs are clustered for group communication.

Chapter 5

Robust D2D Multicast Clustering

5.1 Introduction

In chapters three and four, point to point communication through RUEs were considered. In this chapter of the thesis, a case of multicast communication is considered in which the RUE that is selected as a cluster head or group transmitter transmits to members of a group. D2D communication has the potential to not only enable direct communication but to also enable group communication. Such group communication can relieve the network by offloading some network traffic to D2D communication. A use case for applying group communication is content distribution. Consider that a number of UEs requests popular content from the network. If that requested content is available in one or more of the UEs that are within the range of other members of the group, the BS can direct the UEs that have copies of the requested content to send through D2D multicast communication to other members of the group. Such content could be a short music video or a replay of a highlight in a sporting event.

This use case brings up the challenges of:

- creating clusters,
- selecting cluster heads/ transmitter(s),
- selecting the transmission rate for group transmission.

In this chapter, the problem of cluster formation and cluster head or relay/transmitter selection are considered. The work in this chapter models the D2D multicast communication problem as a rate optimization problem. It proposes a simple machine learning based approach for clustering UEs into groups. Considering an inter-cluster interference limited setup, the interference channel is modelled as imperfect; an approach that is unique to the work in this chapter. Performance analysis shows the dependence of the performance of D2D multicast communication on channel uncertainty. Furthermore, the dependence of the performance of D2D multicast communication on the dimensions of D2D clusters is also demonstrated. Additionally, a case in which the cluster head is equipped with more than one antenna is also considered. For this case, the D2D multicast communication problem is formulated as a beamforming problem.

Thus the contribution made in this chapter includes the following:

- Formulating D2D multicast communication as a rate maximization problem subject to power and interference constraints.
- Formulating a robust equivalent of the rate maximization problem with deterministic and probabilistic interference constraints. Channel uncertainty arising from imperfect channel estimation is considered in the inter-group interfering channel. The formulated robust problem is shown to be convex and with an appropriate solver, the formulated problem is solved.
- Showing through simulations the gains of D2D multicast communication
- Formulating convex robust beamforming for D2D communication as a power minimization problem with full channel uncertainty. Channel uncertainty is considered in the target and interfering channel.
- Showing through simulations that the performance of a probabilistically constrained beamforming problem approximates the non-probabilistically constrained problem for the considered parameters.

5.2 D2D Clustering

Consider an isolated cell having a serving BS and UEs distributed uniformly within the coverage area of the BS. Among the cellular users, there is/are (a) group(s) of users that have placed a request to the BS for a particular content. Such content could be a replay of the highlight of a game or a short comedy video. The BS transmits towards the group through multicast communication. Since the channels between the BS and each UE experience different fading, some of the UEs in the group may not receive correctly the content from the network. Let the set of UEs that receive correctly the content from the BS be denoted as $A = \{a_1, a_2, a_3, ...a_n\}$ and let the UEs that receive incorrectly the sent content be denoted by set $S = \{s_1, s_2, s_3, ...s_m\}$.

To satisfy the request of elements of set S, the BS can either re-transmit the content or could exploit the presence of elements of the A set. Without loss of generality, the separation between elements of the A set and elements of the S set can be assumed to be relatively smaller than the separation between the BS and S set elements. Therefore if the BS chooses to exploit the presence of the UEs that received the content from it correctly, the network is likely to gain assuming that these UEs are not constrained by their residual battery energy. For the work in this chapter of the thesis, exploiting the availability of such potential relay UEs is the focus.

In considering multicast D2D communication, this work differs from most work in the literature in that the interference channel between clusters is modelled as uncertain. In multicast communication, cluster or group heads may acquire knowledge of the channels between them and cluster members but perfect knowledge of the interfering channels may be difficult to acquire. Hence in the work in this chapter, the interference channel is modelled as uncertain. The uncertainty in the interference channel is modelled as deterministic and probabilistic. The system set-up for the work in this chapter is shown in Fig. 5.1. By considering uncertainty in the inter-cluster interference channel, our system model is unique.

Given the aforementioned, the associated equations are derived. Consider that for the discussed system model, the BS clusters UEs in its coverage area into k groups $\{k_1, k_2, ..k_K\}$. The signal-to-interference plus noise (SINR) for group D2D communication experienced at a receiver w in the k_{th} group can be rendered as:

$$\gamma_{k,w} = \frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha_d}}{P_{c,w} g_{c,w} d_{c,w}^{-\alpha_c} + \sum_{k' \neq k} P_{k',w} g_{k',w} d_{k',w}^{-\alpha_d} + \sigma_w} \qquad \forall k \in K, \forall w \in W. \tag{5.1}$$

In equation (5.1), the transmit powers are given by $P_{k,w}$, $P_{c,w}$ and $P_{k',w}$ where the transmit power of the k_{th} group transmitter/cluster head is given by $P_{k,w}$, the transmit power of the cellular UE sharing a channel with a D2D UE w is denoted as $P_{c,w}$ implying cellular interference to w. $P_{k',w}$ is the transmit power of the D2D transmitter in group k' that causes interference to the D2D receiver w in group k. The channel gains are given by $g_{k,w}$, $g_{c,w}$ and $g_{k',w}$ where $g_{k,w}$ denotes the link gain from D2D transmitter in group k to the D2D receiver w, $g_{c,w}$ is the channel gain of the link between an interfering cellular UE and the D2D UE w. Furthermore the link gain of the link between the D2D transmitter in group k' and the D2D receiver w in group k is denoted $g_{k',w}$. $d_{k,w}$ is the distance between the k_{th} group's transmitter

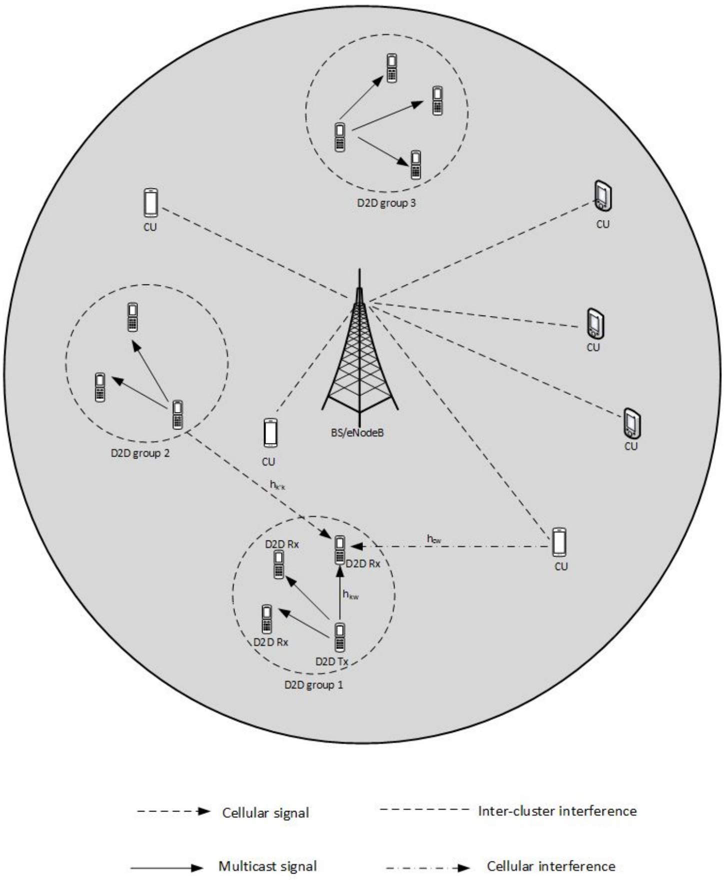

Figure 5.1: D2D group communication set up

and the w_{th} receiver, $d_{c,w}$ is the distance between an interfering cellular transmitter and the w_{th} receiver whereas $d_{k',w}$ is the distance between the transmitter of a nearby group. Meanwhile α_c is the path loss exponent for the cellular link whereas α_d is the path loss exponent for the D2D link. Using the approach of separating the distance and the channel gain is to allow us demonstrate the effect of distance on the set-up's performance. In equation (5.1), σ_w denotes the noise power of the additive AWGN at the D2D receiver w.

Since in multicast communication, the transmission rate depends on the UE experiencing the worst channel condition the transmission data rate (bps/Hz) of the k_{th} D2D group can be expressed as:

$$r_k = \log_2(1 + min_{w \in W_k}(\gamma_{k,w})), \tag{5.2}$$

Hence for the k_{th} group, if there are M members, the aggregate D2D transmission rate for the k_{th} group is given by,

$$R_k = Mr_k, \tag{5.3}$$

5.3 Channel Uncertainty Model

In this section of this chapter's work, perfect knowledge of the channel between D2D UEs within a group/cluster and the group transmitter is assumed. The uncertainty which is studied is in the interference channel between D2D transmitter of the k_{th} group and any neighbouring group. This implies that the D2D transmitter of a given group k does not have perfect knowledge of the inter-cluster interfering channel.

To model the uncertainty in the interfering channel we adopt a deterministic representation as in [120] and [121] such that for a channel between the D2D re-transmitter in group k and the receivers in group $k^{'}$, the channel is modelled as the sum of the channel estimate $\widehat{h}_{k,k'}$ and the estimation error, $\triangle h_{k,k'}$ (i.e. $h_{k,k'} = \widehat{h}_{k,k'} + \triangle h_{k,k'}$). Hence the channel gain, ($g = |h|^2$) when channel uncertainty from estimation errors is considered can be expressed as:

$$g_{k,k'} = (\widehat{h}_{k,k'} + \triangle h_{k,k'})(\widehat{h}_{k,k'} + \triangle h_{k,k'})^* \tag{5.4}$$

$$g_{k,k'} = \widehat{h}_{k,k'}\widehat{h}^*_{k,k'} + 2\Re(\widehat{h}_{k,k'} \triangle h^*_{k,k'}) + \triangle h_{k,k'} \triangle h^*_{k,k'} \tag{5.5}$$

In equation (5.5), denote $\widehat{h}_{k,k'}\widehat{h}^*_{k,k'}$ as the channel gain estimate, $\widehat{h}_{k,k'} \triangle h^*_{k,k'} + \triangle h_{k,k'} \triangle h^*_{k,k'}$ as the estimation uncertainty. $\Re(\cdot)$ points to the real part of $(\cdot)$. Considering the maximum absolute uncertainty, the channel gain set then becomes [122]:

$$g_{k,k'} \in L = \{\widehat{g}_{k,k'} + u\delta_{max_{k,w,k'}} || u |\leq 1\}, \tag{5.6}$$

where L is a line segment on the middle of which lies the channel estimate, $\widehat{g}_{k,k'}$ and $\delta_{max_{k,w,k'}} = 2\Re|(\widehat{h}_{k,k'} \triangle h^*_{k,k'})| + \triangle h_{k,k'} \triangle h^*_{k,k'}$. L is the uncertainty region for $g_{k,k'}$.

During the transmission of a signal say $x_{k,w}$ to a D2D destination, w, a member of a nearby D2D group $k^{'}$ with separation $d_{k,k'}$ from the transmitter of group k experiences interference. This interference term can be expressed as:

$$y_{k,k'} = \sqrt{P_{k,w} d_{k,k'}^{-\alpha_d/2}} h_{k,k'} x_{k,w}, \tag{5.7}$$

5.4 Problem Formulation

The focus of the work in this chapter is to optimize D2D multicast communication in the light of power constraints, interference constraints and factored in channel uncertainties. Hence the problem formulation is rendered as:

$$\max_{P_{k,w}} \sum_{k=1}^{K} R_k \tag{5.8a}$$

subject to:

$$C_1 : P_{k,w} \leq P_{max}, \forall k \in K \tag{5.8b}$$

$$C_2 : d_{k,k'}^{-\alpha_d} g_{k,w,k'} P_{k,w} \leq I_{th}, \forall k \in K \tag{5.8c}$$

$$C_3 : P_{k,w} \geq 0, \forall k \in K \tag{5.8d}$$

In equation (5.8), constraints C_1 and C_3 are transmit power constraints that restrict the transmit power of the cluster head within allowable limits. C_3 limits the interference caused by the k_{th} group head. The robust equivalent of equation (5.8) using worst-case optimization can be rendered as:

$$\max_{P_{k,w}} \sum_{k=1}^{K} R_k \tag{5.9a}$$

subject to:

$$C_1 : P_{k,w} \leq P_{max}, \forall k \in K \tag{5.9b}$$

$$C_2 : P_{k,w} \leq \frac{I_{th}}{d_{k,k'}^{-\alpha_d}(\widehat{g}_{k,w,k'} + |\delta_{max_{k,w,k'}}|)}, \forall k \in K, \forall g_{k,w,k'} \in L, \tag{5.9c}$$

$$C_3 : P_{k,w} \geq 0, \forall k \in K \tag{5.9d}$$

The constraint C_2 for a unit distance can be re-expressed as $P_{k,w}\widehat{g}_{k,w,k'} + \triangle(P)$ where $\triangle(P)$ is given by $P_{k,w}(g_{k,w,k'} - \widehat{g}_{k,w,k'})$ and $\triangle(P)$ is called the protection function for the constraint C_2. The protection function approach is an alternative approach to the uncertainty region approach and is adopted by other researchers [123].

An alternative approach to formulating the optimization problem is to craft it as a transmit power minimization problem in a way that the objective function in equation (5.8) is integrated into the constraints thus:

$$\min_{P_{k,w}} \sum_{k=1}^{K} P_{k,w} \tag{5.10a}$$

subject to:

$$C_1 : R_k \geq R_{th}, \forall k \in K \tag{5.10b}$$

$$C_2 : P_{k,w} \leq P_{max}, \forall k \in K \tag{5.10c}$$

$$C_3 : d_{k,k'}^{-\alpha_d} g_{k,w,k'} P_{k,w} \leq I_{th}, \forall k \in K \tag{5.10d}$$

$$C_4 : P_{k,w} \geq 0, \forall k \in K \tag{5.10e}$$

As an extension to the uncertainty models of chapters 3 and 4, this chapter considers the probabilistic approach whereby constraint C_2 is replaced with a probabilistic constraint. If the probability of meeting the constraint is kept within some threshold ξ, then:

$$Pr(d_{k,k'}^{-\alpha} g_{k,w,k'} P_{k,w} \leq I_{th}) \geq \xi \; \forall k \in K, \tag{5.11}$$

The expression in equation (5.11) shows a non-deterministic control of the inter-cluster interference within a known level [124]. The inequality within brackets in equation (5.11) can come across as the cumulative distribution function (cdf) of an exponential function taken at I_{th}. In this case the channel gain, $g_{k,w,k'}$ has an exponential distribution given that for the work in this thesis, channel fading is a random variable. And so equation (5.11) becomes:

$$1 - e^{-\frac{I_{th}\lambda}{d_{k,k'}^{-\alpha} P_{k,w}}} \geq \xi, \tag{5.12}$$

where in equation (5.12) the parameter of the channel gain term $g_{k,w,k'}$ is given by λ. After some basic manipulation,

$$P_{k,w} \leq \frac{I_{th}\lambda d_{k,k'}^{\alpha}}{-[\ln(1-\xi)]} \tag{5.13}$$

Hence the optimization problem formulated with a probabilistic constraint is given by:

$$
\begin{aligned}
&\max\nolimits_{P_{k,w}} \sum_{k=1}^{K} R_k && (5.14a)\\
&\text{subject to:} && \\
&C_1 : P_{k,w} \leq P_{max}, \forall k \in K && (5.14b)\\
&C_2 : P_{k,w} \leq \frac{I_{th}\lambda d^{\alpha}_{k,k'}}{-[\ln(1-\xi)]}, \forall k \in K, && (5.14c)\\
&C_3 : P_{k,w} \geq 0, \forall k \in K && (5.14d)
\end{aligned}
$$

The formulated problem in equation (5.14) is convex and its convexity is proven in Appendix 2. Therefore it can be solved in a tractable fashion using available solvers like the one put forward in [125]. Formulating D2D clustering as in (5.14) is unique to the work in this thesis.

5.4.1 Group Formation

Having formulated the optimization problem that was constructed as a rate maximization problem with transmit power and inter-cluster interference constraint, the group formulation/ clustering algorithm is discussed. Also, the proposed cluster head selection technique is also explained. Grouping UEs in clusters requires a parameter common to the UEs. For the work in this chapter, grouping the UEs in clusters is performed centrally by the BS and it is based on the distance of UEs from one another.

The BS employs the k-means clustering algorithm to group UEs for multicast communication. The choice of k-means is due to the lower complexity of the algorithm. In k-means clustering, points are grouped based on their distances from a calculated centroid. The choice of using the distance as a metric for clustering UEs can be argued form the stance that for popular video content, for example, there is a likelihood of UEs being in close proximity like in a stadium where viewers may want to view a replay.

It also selects the UE that serves as the cluster head or the transmitter for each of the created groups. In selecting the group transmitter, the BS uses proximity to the centroid of the created cluster. This centrality of the selected transmitter affords needed cluster coverage. Although k-means clustering is an established approach, selecting the group transmitter based on proximity to the centre of a cluster of D2D users is unique to the work in this thesis, to the best of our knowledge. The algorithm for the cluster formation and transmitter selection is given in Algorithm 3.

Algorithm 3 Clustering and group transmitter selection

```
Input $d_x, d_y, k$ (D2D UEs positions)
for $\forall d \in D$ do
    $[ix, cx] = kmeans(d_x, d_y, k)$
    $k_k = [d_x(ix), d_y(ix)]$ : D2D groups
    $d_k = \sqrt{k_k^2 - cx_k^2}$ : distance of UEs from group centroids
    $tx_k = min(d_k)$ : assign group transmitter
end for
output D2D groups and group transmitters
```

.

Table 5.1: Simulation Parameters

Noise Power	-174dBm
Max. D2D groups	3
Transmit power of cellular devices	23 dBm
Radius of clusters	20 - 60 m
D2D transmit power	-5 - 25 dBm
Path loss exponent(α_c)	2
Cell radius	500 m
Path loss exponent(α_d)	3
UE distribution	Uniform
Interference threshold probability	0.1 - 0.9

5.5 Results Analysis

Since the formulated problems (5.10) and (5.14) are non-concave, they can be solved using a convex solver like cvx [125]. The results from the solution are discussed in this section of the chapter. In Table (5.1), some of the parameters used for simulation are given and in Figures 5.2 - 5.6 the results are shown.

In Fig. 5.2, the D2D group transmission rate is plotted for a range of channel uncertainty values. The channel values is varied from $(10^{-5} - 10^{0})$. Cases of three clusters are considered i.e. $k = 1, 2, 3$. The pattern of the plots shows that between $(10^{-5} - 10^{-3})$ of added channel uncertainty values, the transmission rate stays steady remaining constant. This goes to show that for negligible or unconsidered uncertainty in a network, there is no perturbation in the obtained data rate.

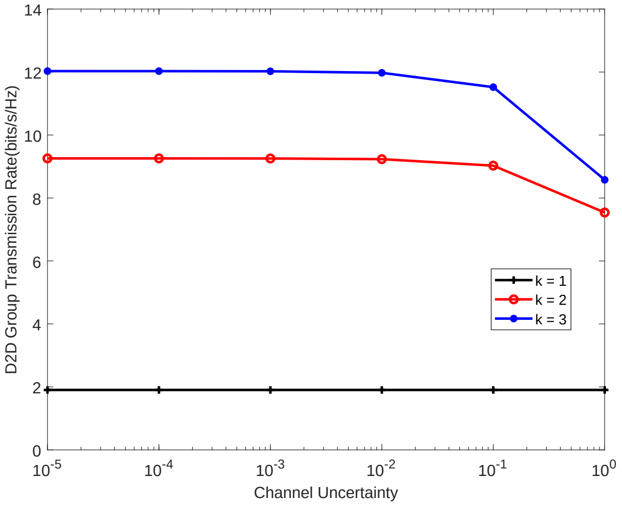

Figure 5.2: D2D data rate versus Channel uncertainty

Between the $(10^{-3} - 10^{0})$, there is degradation in the transmission rate obtainable from D2D group communication for $k = 2$ and $k = 3$. Unlike the cases of $k = 2$ and $k = 3$, for the single cluster case $(k = 1)$, the data rate remains constant. Since for a single cluster multicast communication case, the inter-cluster interference channel (where channel uncertainty is factored in for the work in this chapter) is non-existent, the data rate stays constant.

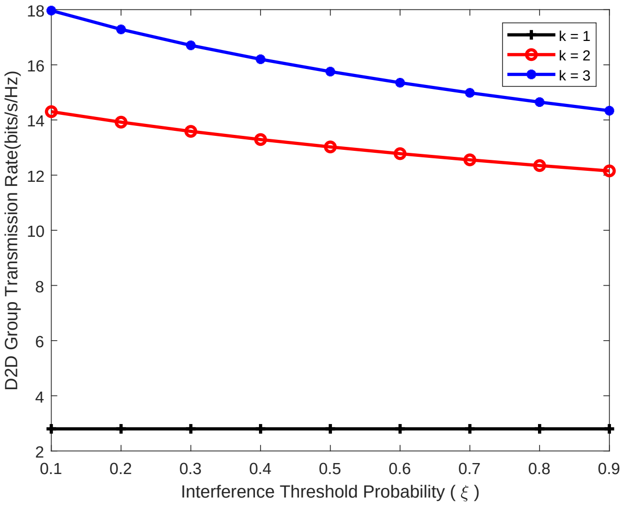

Figure 5.3: D2D data rate versus Interference threshold probability (ξ)

Figure 5.2 also shows that there is an increase in group transmission rate as the number of multicast clusters is increased from 1 to 3. Specifically when the number of clusters is increased from 2 to 3, there is a 29 % increase in the D2D group transmission rate. This shows the gain of enabling group communication.

The performance of group transmission rate for a range of interference threshold probability values (ξ) is shown in Figure 5.3. Again having more clusters in a cell offers increased D2D transmission rate. Increasing the interference probability threshold has adverse effect on obtainable data rate in D2D group communication given the descent in the $k = 2$ and $k = 3$ plots as the value of ξ is varied from 0.1 to 0.9. As in Figure 5.2, the single cluster case is non-responsive to variations in the values of ξ and so for the remaining figures, the $k = 1$ case is dropped. The plots in Figure 5.3 indicates that the higher the probability of breaking the interference constraint, the less the data rate that is obtainable. This can give insight for practical implementation of D2D group communication, by providing a guide on choice of interference thresholds.

Figure 5.4 considers what happens when I_{th} is varied from -5 to 10 dBm and demonstrates that increasing the inter-cluster interference threshold improves the data rate performance of both 2-cluster and 3-cluster cases. For this figure as in the previous two, the diameter of the clusters is maintained at 50 m. The channel uncertainty is fixed at 0.01. The improvement of data rate as the interference threshold increases although advantageous masks the deteriorating effect of uncontrolled interference. But in combination with the interference threshold probability, a meeting point can be reached where levels of inter-cluster interference are tolerable with meaningful data rate improvement.

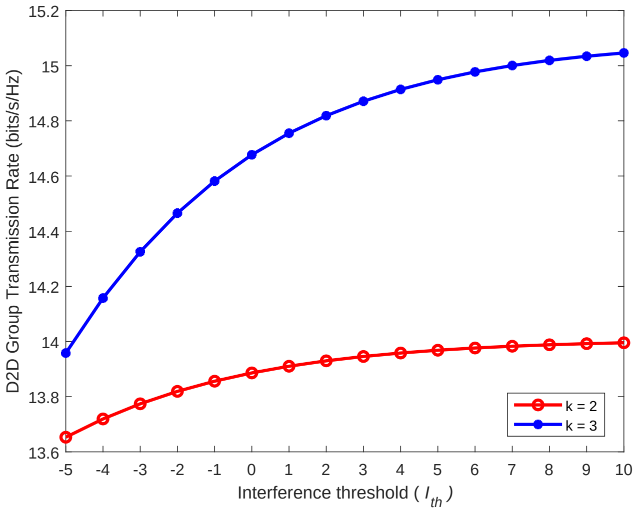

Figure 5.4: D2D data rate versus interference threshold

Although the gain of clustering has been shown so far in the plots of Figures

5.2 - 5.4, the effect of the size of clusters is also worth considering. The diameter of each cluster delineates the boundaries within which devices are distributed. In figure 5.5, D2D group transmission rate is plotted against the D2D group diameter. The diameter is varied from 20 m to 60 m for constant interference threshold (0 dB) and estimation error (0.01). The plots show that although having more clusters is beneficial, there is a drop in performance as the size of the clusters is increased beyond 30 m. This implies that arbitrarily increasing the size of clusters can have an adverse effect on the achievable data rate of group communication as in [126]. For further work, the trade-off between cluster size, number of groups can can be exploited further to include other performance metrics such as energy efficiency or outage probability.

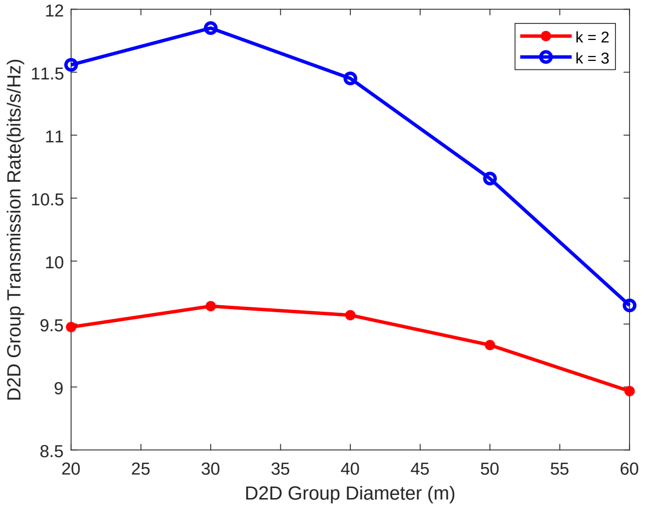

Figure 5.5: D2D data rate versus D2D group diameter

The effect of increasing the maximum D2D transmit power is shown in Figure 5.6. Expectedly allowing devices to transmit at higher power increased the data rate of group communication. This is seen for both the $k = 2$ and $k = 3$ cases. Also the three cluster case results in higher group transmission rate than the two cluster case. Being that future wireless communication systems are required to be energy efficient, trade-offs between achievable data rate of group transmission and the interference to neighbouring groups from increased transmit power needs be established.

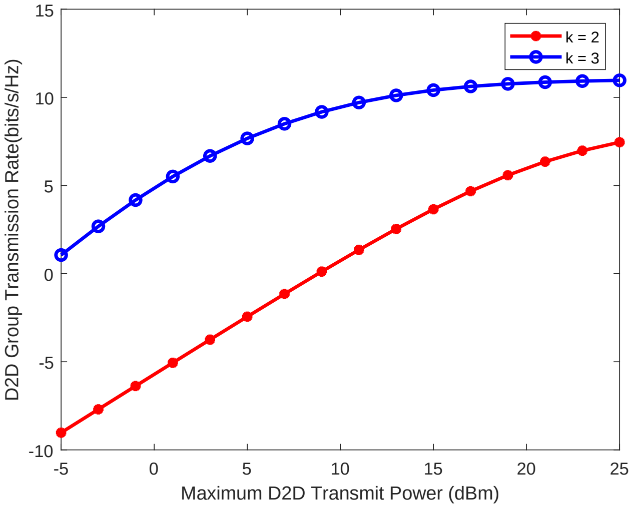

Figure 5.6: D2D data rate versus maximum transmit power

5.6 D2D Multicast Beamforming

In this section, we extend the work to consider a case where the D2D group transmitters or group heads have more than one antenna ($N_{tx} > 1$) whereas the D2D group members have just one receive antennas ($N_{rx} = 1$). For this case, the set-up becomes a MISO multicast scenario. A practical use case is where the relay or group transmitter is a drone mounted transceiver or a vehicle mounted transceiver deployed to a disaster area to broadcast discovery messages. The set up is as shown in Fig. 5.7. The problem can be formulated as a MISO beamforming problem subject to rate threshold, power and interference constraints.

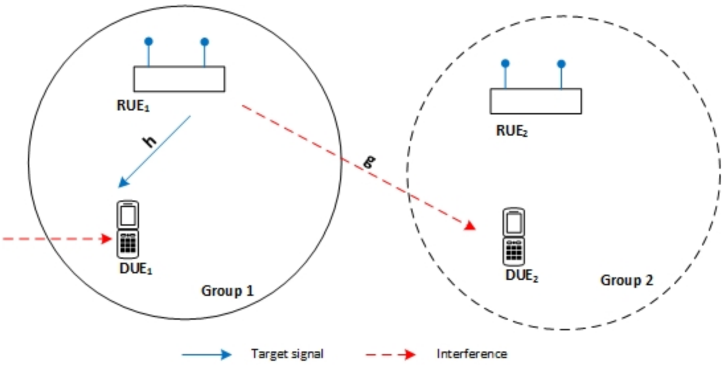

Figure 5.7: MISO system set-up

It can also be formulated as a rate maximization problem for group communication. Denote the received signal at the w_{th} receiver in the k_{th} group as:

$$y_k = h_k^H x + n_k, \tag{5.15}$$

where h_k^H is the complex channel vector between the group transmitter and a representative receiver in the k_{th} group, n_k is the additive white Gaussian noise that is circularly symmetric complex Gaussian variable with distribution $n_k \sim \mathcal{CN}(0, \sigma_k^2)$. To lessen notation ambiguity, single lettered subscripts are adopted in this section. Note that in equation (5.15),

$$x = fs, \tag{5.16}$$

where f is the beamforming vector that the group transmitter applies to the transmitted symbol, s. Therefore the SNR at the w_{th} receiver in the k_{th} group can be expressed as:

$$SNR = \frac{|h^H f|^2}{\sigma_k^2}, \tag{5.17}$$

where $(^H)$ is the Hermitian transpose. If inter-cluster interference experienced by the groups is considered, the SINR can then be expressed as:

$$SINR = \frac{|h^H f|^2}{P_i + \sigma_k^2}, \tag{5.18}$$

where P_i is the interference experienced by a member of the k_{th} group. For a 2 cluster case as shown in Fig. 5.7, the interference caused by the k_{th} group transmitter (in this case RUE$_1$) to a UE (DUE$_2$) in a nearby group can be rendered as:

$$|g^H f|^2, \tag{5.19}$$

where g is the interfering channel between RUE$_1$ transmitter and DUE$_2$.

5.7 D2D Multicast Beamforming without Channel Uncertainty

To provide a background, a MISO D2D multicast communication is considered without channel estimation errors. That is it is assumed that the D2D group transmitter has perfect knowledge of the inter-cluster interference channel. The transmit beamforming optimization problem can be formulated as:

$$\min_{f} \left(|h^H f|^2\right) \tag{5.20a}$$

subject to:

$$C_1 : \frac{|h^H f|^2}{P_i + \sigma_k^2} \geq \gamma_{th}, \forall k \in K \tag{5.20b}$$

$$C_2 : |g^H f|^2 \leq I_{th}, \forall l \in L \tag{5.20c}$$

$$C_3 : \|f\|^2 \leq P_T, \forall k \in K, \tag{5.20d}$$

where γ_{th} is the target SINR of the k_{th} group receiver and I_{th} is the inter-cluster interference threshold of a receiver in a neighbouring group. P_T is the maximum allowable transmit power. If semi-definite relaxation is applied to the non-robust beamforming problem in equation (5.20), it becomes convex and available solvers like CVX [125] can be employed to solve it efficiently. In practical applications, the availability of perfect CSI may not be guaranteed hence the analysis of robust multicast beamforming for D2D communication.

5.8 Robust D2D Multicast Beamforming

In practical deployment of D2D multicast communication, a cluster head or group transmitter may not have perfect knowledge of the inter-cluster interfering channel. This is so because the wireless channel is not static with respect to time. To capture such reality, channel estimation errors can be introduced into the interfering channel in additive format. In this section, the work in section 5.1 is extended to consider the case where not only the channel between a D2D group head and a receiver in a neighbouring group is uncertain but also the channel between the receiver in a considered group and the transmitter in the same group is also uncertain.

Hence taking into consideration the presence of channel estimation errors, the considered channels in the setup in Fig. (5.7) can be framed as:

$$h = \widehat{h} + \delta_h, \tag{5.21}$$

$$g = \widehat{h} + \delta_g, \tag{5.22}$$

where δ_h and δ_g are channel estimation errors for the channel estimates $\widehat{h}$ and $\widehat{g}$ respectively. This can be viewed as the measured channel being in the region of the estimated channel. Therefore the robust D2D multicast beamforming problem can be framed as:

$$\min_{f} \min_{\|\delta_h\|\leq\xi} |(\hat{h}+\delta_h)^H f|^2 \tag{5.23a}$$

subject to:

$$C_1 : \min_{\|\delta_h\|\leq\xi} \frac{|(\hat{h}+\delta_h)^H f|^2}{P_i+\sigma_k^2} \geq \gamma_{th}, \forall\|\delta_h\|\leq \xi \tag{5.23b}$$

$$C_2 : \max_{\|\delta_g\|\leq\xi} |(\hat{g}+\delta_g)^H f|^2\leq I_{th}, \forall\|\delta_g\|\leq \xi \tag{5.23c}$$

$$C_3 : \|f\|^2\leq P_T, \tag{5.23d}$$

where ξ is the boundary of the region of uncertainty. The formulated optimization problem in equation (5.23) unlike its non-robust counterpart in equation (5.20)[after semi-definite relaxation] is not convex and so requires some relaxation to allow tractable solution. The problem in equation(5.23) has a structure not far from the problem (14) in [127] and so can be implied to be not tractable due to its quadratic constrained nature. To solve the problem in a tractable fashion, it is first re-formulated using the approach outlined in [127] as a convex semi-definite programming problem.

The constraint (C_1) and the objective function both contain a similar expression $(\hat{h}+\delta_h)^H f$, therefore the result from simplifying one of them can be used for the other.

From the triangle inequality, it is known that for any two vectors a and b,

$$|a+b|\leq \|a\|+\|b\| \tag{5.24}$$

and implies that $|a+b|\geq \|a\|-\|b\|$. Applying the same concept to the function $(\hat{h}+\delta_h)^H f$ gives;

$$|(\hat{h}+\delta_h)^H f|\geq |\hat{h}^H f|-|\delta_h^H f| \tag{5.25}$$

According to the Cauchy–Schwarz inequality, for two arbitrary vectors a and b,

$$|\langle a,b\rangle|\leq \|a\|\|b\| \tag{5.26}$$

Going by that same reasoning and given that $\|\delta_h\|\leq \xi$, then $|\delta_h^H f|\leq \xi\|f\|$. Hence equation (5.25) becomes:

$$|(\hat{h}+\delta_h)^H f|\geq |\hat{h}^H f|-\xi\|f\| \tag{5.27}$$

Since the formulated problem in equation (5.23) is a minimization problem, a lower limit to the transmit power constraint can be introduced without losing the structure of the problem. In this case, we introduce a lower limit to the transmit power, i.e. $\|f\|^2 \geq P_{min}$ where P_{min} is the lower limit of the allowable transmit power. This is practical so that the optimal transmit power is in a region that allows for reliable transmission. Being that the optimal solution of the problem in equation (5.23) is in the region of the lower limit of the allowable transmit power (P_{min}), and for a global minimum, the optimal transmit power can be equated to P_{min}, (i.e. $\|f\|^2 = P_{min}$) therefore:

$$|(\hat{h} + \delta_h)^H f| \geq |\hat{h}^H f| - \xi\sqrt{P_{min}} \tag{5.28}$$

For small values of the channel uncertainty, the inequality can give way to equality [127]. Hence the objective function can be refashioned as:

$$\min_{\|\delta_h\| \leq \xi} |(\hat{h} + \delta_h)^H f|^2 = ||\hat{h}^H f| - \xi\sqrt{P_{min}}|^2. \tag{5.29}$$

Similarly for constraints C_1 and C_2, a reformulation will result in:

$$|\hat{h}^H f| - \xi\sqrt{P_{min}} \geq \sqrt{\gamma_{th}(P_i + \sigma_k^2)} \tag{5.30}$$

and

$$|\hat{g}^H f| - \xi\sqrt{P_{min}} \leq \sqrt{I_{th}} \tag{5.31}$$

respectively. Thus by replacing constraints C_1 and C_2 with the expressions in equations (5.30 and 5.31) respectively, the robust beamforming optimization problem can be presented as:

$$\min_{f} |\hat{h}^H f|^2 \tag{5.32a}$$

subject to:

$$C_1 : |\hat{h}^H f|^2 \geq (\sqrt{\gamma_{th}(P_i + \sigma_k^2)} + \xi\sqrt{P_{min}})^2 \tag{5.32b}$$

$$C_2 : |\hat{g}^H f|^2 \leq (\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2 \tag{5.32c}$$

$$C_3 : P_{min} \leq \|f\|^2 \leq P_T, \tag{5.32d}$$

Moreover, the semi-definite relaxation approach can be used to modify the problem in equation (5.32) to give:

$$\min_{F \succeq 0} Tr(\hat{H}F) \tag{5.33a}$$

subject to:

$$C_1 : Tr(\hat{H}F) \geq (\sqrt{\gamma_{th}(P_i + \sigma_k^2)} + \xi\sqrt{P_{min}})^2 \tag{5.33b}$$

$$C_2 : Tr(\hat{G}F) \leq (\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2 \tag{5.33c}$$

$$C_3 : P_{min} \leq Tr(F) \leq P_T, \tag{5.33d}$$

$$C_4 : Rank(F) = 1 \tag{5.33e}$$

The presence of the rank constraint (C_4) is indicative that the problem is non convex and to enforce convexity, constraint C_4 is eliminated. In equation (5.33), $\hat{H} = \hat{h}^H\hat{h}$ and $\hat{G} = \hat{g}^H\hat{g}$. In so doing a robust beamforming optimization problem subject to power, interference and SINR constraints has been formulated.

5.9 Analysis of results

The results of solving the problem formulated in equation (5.33) are discussed in this section. The performance metrics used is the total transmit power for a range of variables that includes maximum allowable transmit power, minimum allowable transmit power, interference threshold and target SINR. To keep the system model simple we have considered two clusters in this analysis although the approach can be generalised to include more clusters than two. Simulation parameters are given in Table 5.2.

Table 5.2: Simulation Parameters

Noise Power	-174dBm
Maximum D2D groups	2
D2D transmit power	-5 - 18 dBm
Target SINR(γ_{th})	0 - 25 dBm
UE distribution	Uniform
Interference threshold	8 - 14 dBm

In Fig. 5.8, the multicast transmit power is plotted for a range of target SINR (γ_{th}) of cluster one. γ_{th} is varied from 0 - 25 dBm. The maximum transmit power (P_{max}) is maintained at 23 dBm and the minimum transmit power is also maintained at 0 dBm. The variance of the AWGN at the receiver is fixed at -174 dBm. Moreover the number of antennas at the transmitter (N_{tx}) = 6. From the plots in Fig. 5.8, it can be seen that as γ_{th} is increased, the transmit power of the cluster head increases. That is the cluster head increases its transmit power to meet the SINR target. This pattern is not different from the pattern in the result discussion in [127] and [113]. Furthermore, the effect of imperfect CSI is seen in that as the error from imperfect CSI increases, the transmitter increases its transmit power to meet the target γ_{th}.

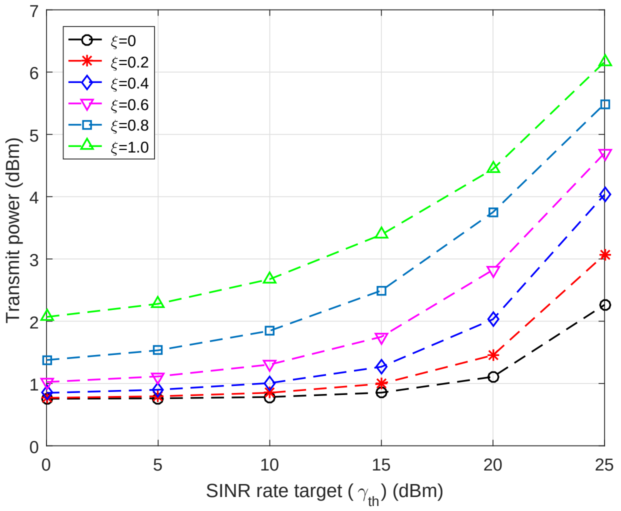

Figure 5.8: Transmit power (dBm) vs. target SINR (γ_{th})

In Fig. 5.9, the performance of the transmit power is investigated for a range of interference threshold values, I_{th} (dBm). For this figure, the number of transmitter antennas $(N_{tx}) = 6$, target SINR $(\gamma_{th}) = 0$ dBm and as in Fig. 5.8, $P_{min} = 0$ dBm and $P_{max} = 23$ dBm. The figure shows that the transmit power increases with increasing set interference threshold for the interference threshold range considered.

Plots of the transmit power of a group head against the maximum allowable transmit power are shown in Fig. 5.10. This applies directly to one half of the constraint C_4 in the formulated problem in equation (5.33). The pattern of the curve points to increasing transmit power as the transmit power limit is raised. This increase is more noticeable between 16 dBm and 18 dBm. For this figure, the $\gamma_{th} = 0$ and the lower limit of allowable transmit power (P_{min}) is 0 dBm. Again the pattern of the curves indicates that when the interference threshold is increased, the cluster head increases its transmit power.

Similar to the plots in Fig. 5.10, Fig. 5.11 shows the performance of the transmit power for a range of P_{min} values and is related to the constraint C_3 in equation (5.33). The general trajectory of the plots is that of an increase in transmit power and for lower (P_{min}) values, the transmit power is similarly low. As in Figs. 5.8 - Fig. 5.11,

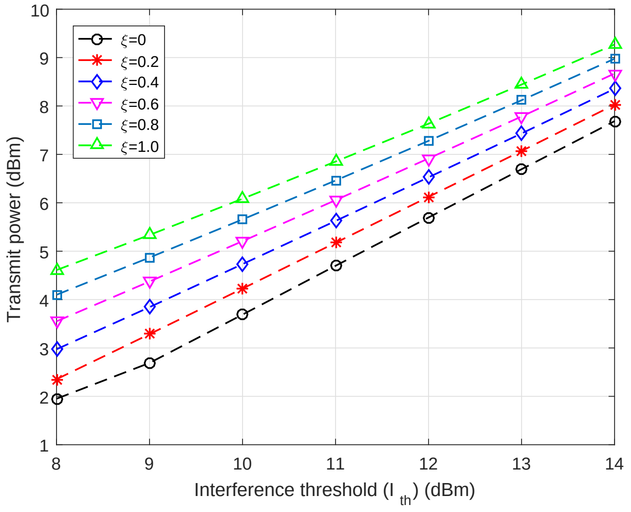

Figure 5.9: Transmit power (dB) vs. interference threshold (γ_{th})

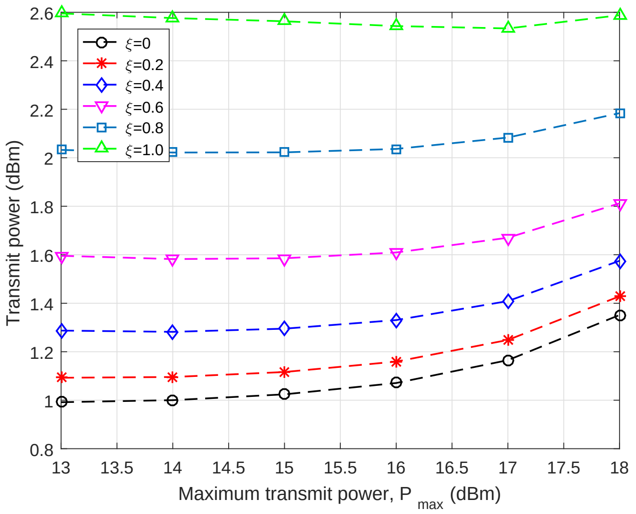

Figure 5.10: Transmit power vs maximum transmit power (P_{max})

the effect of errors due to imperfect CSI is demonstrated. Higher values of CSI errors (ξ) in the channel results in higher transmit power to curb the effect of such errors. This can provide insight on the design of adaptable transmit power transmission for D2D communication that adjusts to channel uncertainty levels to maintain desired transmission rate.

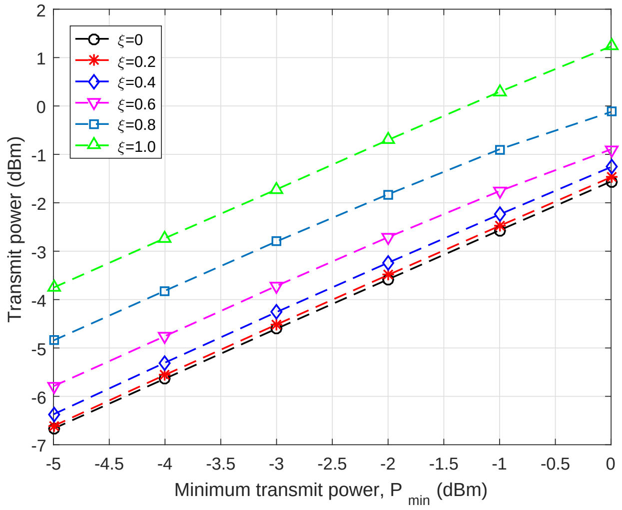

Figure 5.11: Transmit power vs minimum transmit power (P_{max})

5.10 Formulated Robust Problem with Probabilistic Constraint

In this subsection, a case of probabilistic constraint is considered in which the constraint C_2 in equation (5.33) is replaced by a probability term. The constraint C_2 ensures that the interference caused by a transmitter to a nearby multicast group is not higher than a protection function (I_{th}). This protection function can be replaced by a probability threshold η such that in equation (5.33), constraint C_3 becomes:

$$Pr\left(|\hat{g}^H f|^2 \geq (\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2\right) \leq \eta \tag{5.34}$$

Since the channel in wireless communication is often modelled as a normally distributed random variable, its variance can be considered to be exponentially distributed. Hence $|\hat{g}^H|^2$ can be inferred to be an exponential function. Equation (5.34) can be re-expressed such that the inequality ($\geq$) on the left hand side (LHS) of equation (5.34) is replaced with a $\leq$ thus:

$$1 - Pr\left(|\hat{g}^H|^2 \leq \frac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2}{|f|^2}\right) \leq \eta \tag{5.35}$$

The term $Pr\left(|\hat{g}^H|^2 \leq \frac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2}{|f|^2}\right)$ can be viewed as the cumulative distribution function of $|\hat{g}^H|^2$. If the mean of an exponentially distributed, x function is given by $1/\lambda$ where λ is the parameter of the exponentially distributed function, then the

CDF of x is given by 1− $\exp^{-t\lambda}$. Applying the same reasoning to equation (5.35), it becomes:

$$1 - \exp^{-\beta\lambda} \leq \eta, \tag{5.36}$$

where β is $\dfrac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2}{|f|^2}$. Hence equation (5.36) reduces to:

$$\exp^{-\beta\lambda} \leq \eta. \tag{5.37}$$

Applying the approximation that for $\beta\lambda \ll 1$, $\exp^{-\beta\lambda} = 1 - \beta\lambda$. Substituting the expression for β into equation (5.37) will result in:

$$1 - \frac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2\lambda}{|f|^2} \leq \eta \tag{5.38}$$

Where the mean $1/\lambda \approx |\hat{g}^H|^2$, then the constraint becomes,

$$|\hat{g}^H f|^2 \geq -\frac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2}{\eta - 1} \tag{5.39}$$

The robust beamforming problem with a probabilistic constraint can then be expressed as:

$$\min_{F\succeq 0} Tr(\hat{H}F) \tag{5.40a}$$

subject to:

$$C_1 : Tr(\hat{H}F) \geq (\sqrt{\gamma_{th}(P_i + \sigma_k^2)} + \xi\sqrt{P_{min}})^2 \tag{5.40b}$$

$$C_2 : Tr(\hat{G}F) \geq -\frac{(\sqrt{I_{th}} + \xi\sqrt{P_{min}})^2}{\eta - 1} \tag{5.40c}$$

$$C_3 : P_{min} \leq Tr(F) \leq P_T, \tag{5.40d}$$

In Fig. 5.12, the transmit power is plotted against target SINR. The optimization problem with probabilistic constraint is compared to the deterministic constrained problem. For the plots in this figure, the $P_{min} = 0$ dBm , the target interference (I_{th}) = - 0.5 dBm and $\eta = 0.01$. The pattern of the plots shows increasing transmit power as the target SINR increases. Moreover, the probabilistic constrained problem is a good approximation of the deterministic approach since for the range of target SINR studied (0 - 25 dBm), the performance of both approaches are indistinguishable as the figure reveals.

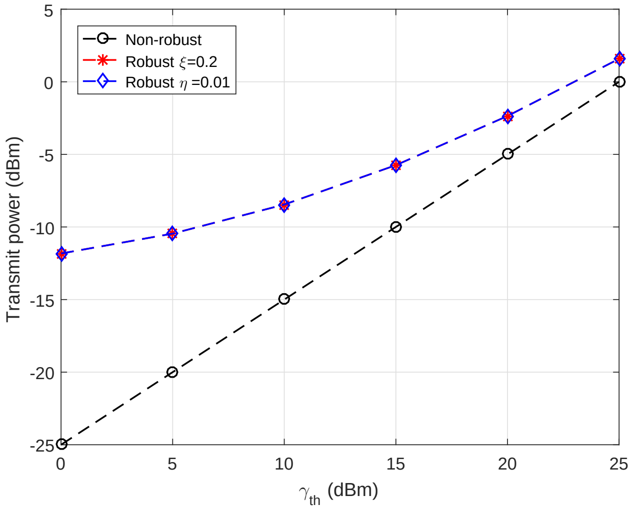

Figure 5.12: Transmit power vs target SINR (γ_{th})

5.11 Conclusion

In this chapter, D2D multicast communication has been studied and the results analysed. A clustering algorithm namely the k-means clustering algorithm was used to segment the D2D UEs into groups. Deterministic and probabilistic channel uncertainty models were used for inter-cluster interference. The robust D2D group communication problem was formulated and the performance analysed through simulation. Channel uncertainty consideration gives a more realistic performance measure for D2D multicast communication than otherwise. The effect of the interference threshold and D2D dimension was also demonstrated. Through discussed results, the dependence of data rate on channel uncertainty was shown using deterministic and probabilistic channel uncertainty models.

The results show that increasing data rate can be obtained through having more D2D groups although increasing the D2D dimensions arbitrarily in an unrestrained manner deteriorates the data rate of D2D group communication.

Furthermore, the D2D multicast problem was extended to consider the case of having more than one antenna at the group transmitter. The problem transitions into a beamforming problem for which optimization problems were formulated. A non-robust problem was formulated and a robust beamforming alternative was derived using the triangle inequality and the Cauchy-Schwarz inequality. Moreover, to enforce convexity, semi-definite relaxation was used and the problem made solvable.

The results show that an increase in threshold parameters such as target SINR, target interference, allowable transmit power limits (both upper and lower) affects the resulting transmit power of the multicast transmitter. D2D communication can underlay a massive MIMO cellular network, and insight into such case is given in Appendix 3.

In chapters three and four, relay selection algorithms were proposed for relay aided D2D communication. The transmit power of the UEs were fixed for both D2D UEs and RUEs. In the next chapter, instead of allowing fixed transmit power, a case of allocating the transmit power to UEs is considered. This becomes necessary to limit interference to nearby UEs. Hence in the next chapter, a joint power allocation and relay selection problem is considered. Furthermore, in furtherance to the RUE centric nature of the work in this thesis, the next chapter proposes a social distance based and a relay utility based relay UE selection algorithms.

Chapter 6

Joint Power Control and Relay Selection in D2D Communication with Channel Uncertainty

6.1 Introduction

In this chapter, the joint problem of power control and relay selection is studied. The problem is formulated and approaches are proposed. The results of using the proposed approaches are also discussed. Since underlay D2D communication re-uses the resources of the cellular tier of the network, it is suitable to have power control techniques to limit the transmit power of D2D transmitters and relay UEs (RUEs) from exceeding the allowable power range. In so doing interference towards the cellular communication tier can be reduced.

The work in this chapter proposes a social distance based relay selection algorithm and a relay utility based selection algorithm. Being that relay aided D2D communication using mobile relays involves a device user allowing scarce resources to be used to assist the communication of neighbouring devices, a way to motivate the participation of relay UE holders is necessary. Exploiting social distance between source UEs and potential RUEs can motivate the participation of RUEs in D2D communication. This is so since users of devices are self-interested and would more likely assist those with whom they share some social connection.

Similarly, where relay selection maximizes a RUE defined utility function (U_r), device users can be motivated to serve as relays. The utility function used for this work is a function of relay UEs transmit power (P_r) and so directly depends on the power expenditure of a RUE.

For the work in this chapter, DF relaying is used at the selected relay UE and full duplex communication is considered. The joint problem is formulated as a sum power minimization problem that is segmented into two subproblems: power control and relay selection.

The power control sub-problem is fashioned as a total power minimization problem subject to given SINR and power constraints. To solve the optimization problem, a convex solver, CVX [125] is used to obtain the optimal values of the transmit power of the D2D transmitter (P_t) and the transmit power for the selected RUE (P_r).

For the relay selection sub-problem, a bipartite graph is used to model this problem. Modelling the problem as a bipartite graph reduces it to a one-to-one matching between RUEs and D2D pairs.

To solve the modelled problem, a social distance based (SDB) and relay utility-based (RUB) algorithms are proposed and their performances evaluated. The uniqueness of the work put forward in this chapter is employing the social distance between the RUEs and D2D transmitters (and a relay defined utility) as the weights of the edges of the bipartite graph. Furthermore, our formulation considers the effect of channel uncertainty arising from channel estimation errors. Therefore in this chapter, the contribution includes:

- Formulating an uncertainty-aware relay selection optimization problem for full duplex D2D communication. This caters to the variations in the wireless channel. We use the partial uncertainty model in which the channel estimation errors only exist in the interfering channels. This varies from a similar work in [128] that considered a full channel uncertainty approach.

- Modelling the formulated problem as a bipartite graph. In so doing the modelled problem is simplified to allow the application of an assignment or matching algorithm.

- Proposing SDB and RUB selection algorithms based on the assignment algorithm. Although social distance and relay utility approaches have been proposed in the literature, employing Kuhn Munkres algorithm [129] for a social distance and relay utility based selection algorithm to the best of our knowledge is unique to our work.

- Demonstrating through simulations a near 10% reduction in total transmit power in comparison to [79].

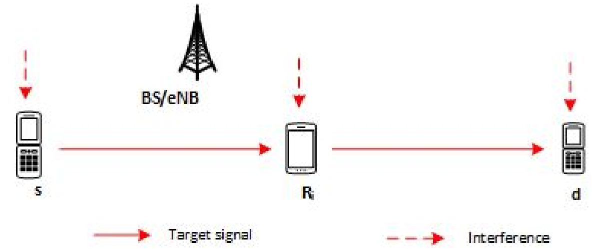

Figure 6.1: Relay Assisted D2D Communication

6.2 Problem Formation

An isolated cell scenario having a base station (BS) at the centre of the cell is considered. For the work in this chapter, there is a set of cellular users $C = \{c_1, c_2, c_3, ..., c_i\}$, a set of D2D pairs $D = \{d_1, d_2, d_3, ..., d_j\}$ and a set of idle UEs $R = \{r_1, r_2, r_3, ..., r_k\}$ that are candidates for relay selection. The UEs are uniformly distributed within the cell. Each RUE is assumed to be enabled to carry out full duplex relaying. Full duplex enabled UEs is a thriving research concept for future wireless communication and so the possibility exists. The gains of full duplex communication over half duplex communication have been highlighted in the literature to include improved speed of transmission and when combined with other enabling technologies such as mmWave and D2D communication, further gains can be achieved. For the work in this chapter, full duplex D2D communication is considered. User and relay scheduling are not part of the focus of this chapter.

The channels between devices in the cell are modelled using the distance-dependent path loss model and incorporates both the large scale and small scale fading components.

A D2D UE is assumed to have the capability to discover its pair through peer discovery and the BS has knowledge of the channels between devices in the cell. Each UE is equipped with a single antenna and the relay UEs are full duplex DF relay UEs. The system set up is shown in Fig. 6.1.

Considering a two-time slot full duplex communication, the signal to interference plus noise ratio (SINR) at a selected RUE is given by:

$$\gamma_{sr} = \frac{P_{sr} g_{sr}}{I_r + N_1}, \tag{6.1}$$

where the P_{sd} is the transmit power of the D2D source, g_{sr} is the channel gain of the the source-relay channel with $g_{sr} = | h_{sr} d_{sr}^{-\alpha/2} |^2$. h_{sr} is a random variable that captures the small scale fading of the channel, the channel being a Rayleigh fading channel. d_{sr} is the distance between the source UE and selected relay UE whereas α is the path loss exponent. Since full duplex DF relaying is considered, $I_r = P_{rd}g_{LI}$ indicates the self-interference that a relay UE experiences and N_1 is the variance of the AWGN measured at the relay. The AWGN is modelled as circularly complex Gaussian random variable ($n \backsim \mathcal{CN}(0, N_1)$). Similar notation interpretation is used for subsequent equations. The D2D receiver receives the signal that the relay UE forwards and the SINR at the D2D receiver can be rendered as:

$$\gamma_{rd} = \frac{P_{rd}g_{rd}}{I_d + N_2}, \tag{6.2}$$

where g_{rd} is the channel gain of the relay-destination link, P_{rd} is the transmit power of the relay UE towards the destination UE and N_2 is the AWGN variance at the destination UE. $I_d = P_{sr}g_{sd}$ is the interference that the destination experiences from the D2D transmitter. From equations (6.1) and (6.2), the SINR of the relay link can be expressed as:

$$\gamma_{s,r,d} = min(\frac{P_{sr}g_{sr}}{I_r + N_1}, \frac{P_{rd}g_{rd}}{I_d + N_2}), \tag{6.3}$$

and consequently the data rate of the relay aided communication or the mutual information of the full duplex two hop DF relay path is given by: [130],

$$R_r = Blog_2(1 + \gamma_{s,r,d}), \tag{6.4}$$

where B is the bandwidth of the communication system. In order to ensure that relay assisted D2D communication is achieved and contributes interference that does not limit cellular communication, the problem of relay selection is formulated as a power minimisation problem thus:

$$\underset{P_{sr}, P_{rd}}{\text{minimize}} \ (P_{sr} + P_{rd}) \tag{6.5a}$$

$$\text{subject to}$$

$$C1 : R_r \geq R_{th}, \forall d \in D, \ \forall r \in R \tag{6.5b}$$

$$C2 : 0 \leq P_{sr} \leq P_d^m, \ \forall d \in D, \ \forall r \in R \tag{6.5c}$$

$$C3 : 0 \leq P_{rd} \leq P_r^m, \ \forall r \in R, \ \forall d \in D \tag{6.5d}$$

The constraint C_1 in equation (6.5) is a QoS constraint that ensures that the data rate of relay aided communication does not fall below the allowed threshold (R_{th}) which is associated with the threshold SINR (γ_{th}). The second constraint C_2

is a power constraint for the D2D transmitter while C_3 limits the transmit power of selected relay UE. To ease the solving of the problem in equation (6.5), the constraint in C_1 can be further expressed as:

$$C1 : \frac{P_{sr}g_{sr}}{N_1 + P_{rd}g_{SI}} \geq \gamma_{th} \tag{6.6a}$$

$$C2 : \frac{P_{sr}h_{sr}}{N_2 + P_{sr}g_{sd}} \geq \gamma_{th} \tag{6.6b}$$

The ratio in the LHS of C_1 and C_2 can be further simplified to:

$$C1 : P_{sr}g_{sr} - \gamma_{th}P_{rd}g_{SI} \geq \gamma_{th}N_1, \forall d \in D, \forall r \in R \tag{6.7a}$$

$$C2 : P_{rd}g_{rd} - \gamma_{th}P_{sr}g_{sd} \geq \gamma_{th}N_2, \forall d \in D, \forall r \in R \tag{6.7b}$$

The simplification in equation (6.6) is not counter-intuitive being that in equation (6.3), the $\gamma_{s,r,d}$ could be either γ_{sr} or γ_{rd}. The problem formulation rendered in equations (6.5 - 6.6) applies when consideration of uncertainties in the communication channels are not made. Such channel uncertainties could arise from channel estimation errors as is the case in the work in this chapter or from quantization errors. For this work, the effect of channel uncertainty is factored into our analysis.

When channel uncertainty is considered in the communication channels, the rendering of equations (6.5 - 6.7) changes. For the work in this chapter, channel estimation error is modelled as an additive parameter to the channel estimate value; i.e. if the channel coefficient of the channel between node i and j is given by y and the channel estimate is given by $\hat{y}$, then the channel coefficient with added channel estimation error can be denoted by $y = \hat{y} + e$ where e as the channel estimation error. Therefore the channel gain for that channel can be denoted as:

$$|y|^2 = (\hat{y} + e)(\hat{y} + e)^*, \tag{6.8}$$

$$|y|^2 = \hat{y}\hat{y} + \hat{y}e^* + \hat{y}^* + ee^*, \tag{6.9}$$

$$|y|^2 = \hat{a} + \xi. \tag{6.10}$$

In equation (6.10), the term $\hat{a} = \hat{y}\hat{y}^*$ stands for the channel gain whereas $\xi = y\hat{e}^* + \hat{y}^*e + ee^*$ captures the channel uncertainty. Note that the channel estimation error is within a bounded region, i.e.

$$|y|^2 = \hat{y} + u\xi \mid -1 \leq u \leq 1 \tag{6.11}$$

It can be implied that $|y|^2$ is part of a line segment, $\mathcal{L}$, i.e. $g \in \mathcal{L}$. As in [117], maximum channel estimation error scenario (such could arise from a moving relay UE) is considered and that is captured using the worst case scenario approach, hence channel gain becomes:

$$|y|^2 = \hat{y} + u\xi_{max} \mid -1 \leq u \leq 1 \tag{6.12}$$

Therefore the earlier formulated optimization problem is reformulated as a robust optimisation problem as it captures the channel uncertainty arising from channel estimation errors thus:

$$\underset{P_{sr},P_{rd}}{\text{minimize}} \; (P_{sr} + P_{rd}) \tag{6.13a}$$

$$\text{subject to}$$

$$C1 : P_{sr}g_{sr} - \gamma_{th}P_{rd}g_{SI} \geq \gamma_{th}N_1, \forall d \in D, \; \forall r \in R \tag{6.13b}$$

$$C2 : P_{rd}g_{rd} - \gamma_{th}P_{sr}g_{sd} \geq \gamma_{th}N_2, \forall d \in D, \; \forall r \in R, \; \forall g_{sd} \in \mathcal{L}_{sd} \tag{6.13c}$$

$$C3 : 0 \leq P_{sr} \leq P_s^m, \; \forall d \in D, \; \forall r \in R \tag{6.13d}$$

$$C4 : 0 \leq P_{rd} \leq P_r^m, \; \forall r \in R, \; \forall d \in D \tag{6.13e}$$

To make for the threshold data rate, the infinum function is employed to constraint C_2:

$$inf\{P_{rd}g_{rd} - \gamma_{th}P_{sr}g_{sd}\} \tag{6.14}$$

$$\Rightarrow inf\{P_{rd}g_{rd}\} - inf\{\gamma_{th}P_{sr}g_{sd}\} \tag{6.15}$$

$$\Rightarrow P_{rd}g_{rd} - \gamma_{th}P_{sr}inf\{\hat{g}_{sd} + u\xi_{max_{sd}} | -1 \leq u \geq 1\} \tag{6.16}$$

$$\Rightarrow P_{rd}g_{rd} - \gamma_{th}P_{sr}(\hat{g}_{sd} - \xi_{max_{sd}}) \tag{6.17}$$

Replacing the left hand side of C_2 with equation (6.12) and re-writing equation (6.17) gives:

$$\underset{P_{sr},P_{rd}}{\text{minimize}} \; (P_{sr} + P_{rd}) \tag{6.18a}$$

$$\text{subject to}$$

$$C1 : P_{sr}g_{sr} - \gamma_{th}P_{rd}g_{SI} \geq \gamma_{th}N_1 \tag{6.18b}$$

$$C2 : P_{rd}g_{rd} - \gamma_{th}P_{sr}(\hat{g}_{sd} - \xi_{max_{sd}}) \geq \gamma_{th}N_2 \;, \forall g_{sd} \in \mathcal{L}_{sd} \tag{6.18c}$$

$$C3 : 0 \leq P_{sr} \leq P_s^{max}, \forall d \in D, \forall r \in R \tag{6.18d}$$

$$C4 : 0 \leq P_{rd} \leq P_r^{max}, \forall r \in R, \forall d \in D \tag{6.18e}$$

The problem in equation (6.18) is a power minimization problem subject to power and QoS constraints. Solving the optimization problem does not necessarily solve the relay selection problem for relay aided D2D communication. It rather results in the optimal power levels for the D2D transmitter and the candidate relay UEs (i.e. P_{sr}^{*} and P_{rd}^{*} respectively). The problem in equation (6.18) is solvable and available solvers like [125] can be employed to optimally solve the optimization problem. The obtained optimal transmit power values are then employed for actual relay selection.

The relay selection problem is modelled as a bipartite graph that connects candidate relay UEs and D2D pairs. This representation can allow for the use of a matching algorithm as a selection technique. Our modelling of relay aided D2D communication as a bipartite graph is given in the next section.

6.3 Relay Aided D2D Communication as Bipartite Graphs

Bipartite graphs allow the representation of problems using two disparate or disjoint sets. These sets or vertices are composed of similar elements. The elements of one set are connected to elements of the opposite set by edges. These edges that connect elements of both sets are defined by their weights. For the work in this chapter, the disjoint sets are the set of candidate relay UEs $R = \{r_1, r_2, r_3, ..., r_k\}$ and the set of D2D pairs $D = \{d_1, d_2, d_3, ..., d_j\}$ as shown in Fig. 6.2.

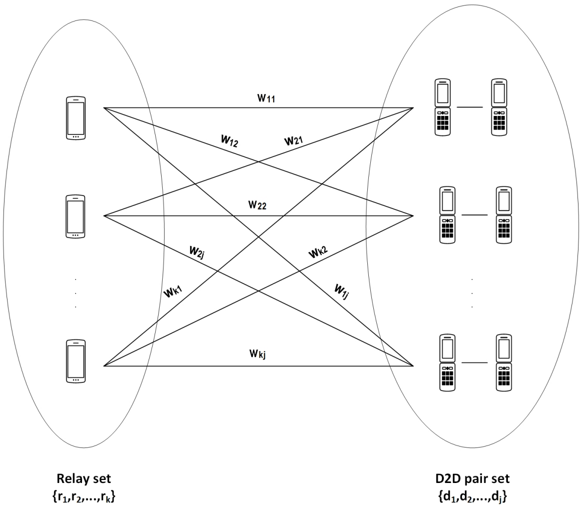

Figure 6.2: A relay aided D2D communication bipartite graph

Modelling the relay assisted D2D communication a bipartite graph reduces the relay selection problem to a matching problem. In this case a one-to-one matching between members of the relay set and members of the D2D pair set. A feature of bipartite graphs is the edges that connect the vertices and these edges are defined by their weights. Weights can be defined based on the relationship between the elements of the opposite sets that the edges connect. For the work in this chapter, there are two definitions of the weights of the edges of the modelled bipartite graph in Fig. 6.2. Firstly the weights of the edges are defined by the scaled transmit power of the potential relay UEs ($s_{kj}P_r$) where $s_{kj} = \{0, 1\}$ is the social distance between the k_{th} relay UE and the j_{th} source UE. This distance is a randomly generated variable between 0 and 1. By so doing, the relationship between the potential relay UEs and the source UE is exploited for relay selection. This approach makes the relay selection not just D2D pair centric but also potential relay UE centric.

Secondly, the weights of the edges are also represented by a relay UE defined utility function (U_r). Having a relay UE defined utility function ensures that the relay is factored into the relay selection process. This approach caters to the self-focused nature of users of mobile devices who need an incentive to motivate their participation in relaying for other users.

Hence the proposed relay selection algorithms for the work in this chapter can be viewed as relay centric selection algorithms.

In this chapter the algorithms that are considered are:

- Social distance based relay selection (SDB RS (KM)) and
- Relay utility based relays selection (RUB RS (KM))

6.4 Social Distance Based Relay Selection (SDB RS (KM))

The SDB RS (KM) algorithm uses the social distance between RUEs and the source UEs as the weight of the edges in the aforementioned bipartite graph and these weights serve as the metric for selecting a suitable relay to assist D2D communication. This approach is based on the assumption that users of devices are more motivated to surrender their resources to assist other UEs that they have some level of social tie to. Hence if the weight of the edge connecting a D2D pair and a RUE is less than the weight of another edge, the latter is more likely to be selected than the former RUE. The SDB RS(KM) primarily uses the capabilities of Kuhn Munkres (KM) [129] assignment algorithm to appropriately match relay UE to D2D pair. Since the assignment algorithm seeks for the least cost assignment while our work seeks to select relay UEs in a way that a higher benefit is offered to the relay whether by social distance or relay utility; the KM algorithm is applied to the inverse of the function $(s_{kj}P_r.)$. A detailed description of the SDB RS (KM) algorithm is given in Algorithm 4 where it is clearly laid out. .

Algorithm 4 Social distance based relay selection (SDB RS (KM))

```
Input parameters:
$P^r_{max}, P^s_{max}$ : maximum transmit power values,
$h_{SI}$ : relay self interference
$h_{rd}$ : relay-destination channel coefficient
$h_{sd}$ : source-destination channel coefficient
$h_{sr}$ : source-relay channel coefficient
$s_{kj}$ : social distance matrix
$d_{sr}, d_{sd}, d_{rd}$ : UE distances
$J$ : number of D2D pairs
$K$ : number of RUEs
Power control
for $j = 1, 2, 3, ..., J$ do
    for $k = 1, 2, 3, .., K$ do
        solve: minimize $(P_{sr} + P_{rd})$ s.t. $C1 : C4$
        $P^*_{sr}(j,k)$, $P^*_{rd}(j,k) = \min\ (P_{sr} + P_{rd})$
        output $P^*_{sr}$, $P^*_{rd}$
        Determine $s_{kj} * P^*_{rd}$
        output $s_{kj} * P^*_{rd}$
    end for
end for
 Relay selection
$[a_i\ c] = \mathrm{KM}(inverse(s_{kj} * P^*_{rd}))$
where KM is the Kuhn Munkres assignment algorithm,
$a_i$ is the assignment vector and $c$ is the assignment cost.
$ua$ = (find $a_i = 0$) // find unassigned D2D pairs.
$P^*_{sr}(ua, :) = [\ ]$ // eliminate unassigned D2D pairs
$a_i(a_i = 0) = [\ ]$ // eliminate 0 terms in assignment vector
Let $P^T_{sr} = 0$ // $P^T_{sr}$ is the total source relay power
Let $P^T_{rd} = 0$ // $P^T_{rd}$ is the total relay destination power
for  $n = 1$ to length $(a_i)$ do
    $P^T_{sr} = P^T_{sr} + P^*_{sr}(n, a_i(n))$
    $P^T_{rd} = P^T_{rd} + P^*_{rd}(n, a_i(n))$
end for
$P_T = P^T_{sr} + P^T_{rd}$
output $P_T$ // total transmit power
```

6.5 Relay Utility Based Relay Selection (RUB RS (KM))

The other relay selection algorithm here proposed is the relay utility based relay selection (RUB RS (KM)) algorithm. The RUB RS (KM) algorithm is based on a relay defined utility function. In this algorithm, the relay participates in relay aided D2D communication in a manner that optimizes its utility. Mathematically, the relay defined utility (U_r) is defined as:

$$U_r = (q - c) \times P_r \tag{6.19}$$

where c is the cost of unit power that the RUE incurs for assisting in forwarding information between a D2D pair, q is the unit power price that each relay imposes on a D2D pair when that relay offers to assist in D2D communication and P_r is the transmit power of the relay UE. Hence for the RUB RS(KM) algorithm, the relay UEs seek to participate in relay aided D2D communication to improve their utility. As an optimization problem, this can be expressed as:

$$\underset{q \geq 0}{\text{maximize}} \; (U_r) \tag{6.20}$$

The optimal utility value from solving the optimization problem in equation (6.20) can be fed into the KM algorithm for suitable relay-D2D pair matching. Note that as in SDB RS (KM), the inverse values of the weights due to the nature of the KM algorithm. The detailed flow of the RUB RS (KM) is given in Algorithm 5.

.

Some of the parameters used for computer simulations that resulted in the plots discussed in this chapter are given in Table 6.1.

Table 6.1: Simulation parameters

Parameter	Value
P_s^m	23 dBm
P_r^m	23 dBm
Noise power (N_1, N_2)	-176 dBm/Hz
Maximum distance between nodes	500 m
Bandwidth (B)	1 MHz
Minimum data rate requirement	2 Mbps/Hz
D2D path loss exponent (α)	4
Shadowing standard deviation	12 dB
D2D path loss model	148 + 40 log10 (d [km]) [58]

Algorithm 5 Relay utility based relay selection (RUB RS(KM))

```
**Input parameters**:
$P^r_{max}, P^s_{max}$ : maximum transmit power values,
$h_{SI}$ : relay self interference
$h_{rd}$ : relay-destination channel coefficient
$h_{sd}$ : source-destination channel coefficient
$h_{sr}$ : source-relay channel coefficient
$s_{kj}$ : social distance matrix
$d_{sr}, d_{sd}, d_{rd}$ : UE distances
$J$ : number of D2D pairs
$K$ : number of relay UEs
**Power control**
**for** $j = 1, 2, 3, ..., J$ **do**
    **for** $k = 1, 2, 3, .., K$ **do**
        solve: minimize $(P_{sr} + P_{rd})$ s.t. $C1 : C4$
        $P^*_{sr}(j, k)$, $P^*_{rd}(j, k) = \min\ (P_{sr} + P_{rd})$
        **output** $P^*_{sr}$, $P^*_{rd}$

        solve: maximize $\{(q - c) \times P^*_{rd}(j, k)\}$ s.t. $(q > 0)$
        **output** $q$, $U_r$
    **end for**
**end for**
 **Relay selection**
$[a_i\ c] = \mathrm{KM}(inverse(U_r))$
where KM is the Kuhn Munkres assignment algorithm,
$a_i$ is the assignment vector and $c$ is the assignment cost.
$ua =$ (find $a_i = 0$) // find unassigned D2D pairs.
$P^*_{sr}(ua, :) = [\ ]$ // eliminate unassigned D2D pairs
$a_i(a_i = 0) = [\ ]$ // eliminate 0 terms in assignment vector

Let $P^T_{sr} = 0$ // $P^T_{sr}$ is the total source relay power
Let $P^T_{rd} = 0$ // $P^T_{rd}$ is the total relay destination power
**for** $n = 1$ to length $(a_i)$ **do**
    $P^T_{sr} = P^T_{sr} + P^*_{sr}(n, a_i(n))$
    $P^T_{rd} = P^T_{rd} + P^*_{rd}(n, a_i(n))$
**end for**
$P_T = P^T_{sr} + P^T_{rd}$
**output** $P_T$ // total transmit power
```

6.6 Results Discussion

The discussions of results from simulations are presented in this section. The results for the SDB RS (KM) algorithm is first presented. To provide a background, the performances of the SDB RS (KM) algorithm with perfect channel conditions for a range of relay UEs and loop interference values are considered. Then for a range of D2D pairs, the SDB RS (KM) algorithm with imperfect channel conditions is studied. For all these cases, the benchmark algorithm (SPB RS) considers perfect channel conditions.

In Fig. 6.3, the total transmit power (that is the sum of the source transmit power and relay transmit power) versus the number of relay UEs is plotted. Our proposed algorithm is compared to the algorithm put forward in [79]. The proposed algorithm is a social distance based relay selection algorithm (SDB RS(KM)). For the simulation resulting in Fig. 6.3, the number of D2D pairs is fixed at 10, the data rate threshold for D2D communication is maintained at 2 Mbps/Hz and the self-interference at the RUE is fixed at -70 dB.

From the plots, it can be seen that when there are more available RUEs assisting D2D pairs (with the number of D2D pairs $\geq$ number of relays), there is increased total transmit power hence the trend in Fig. 6.3. The proposed SDB RS(KM) algorithm offers considerable power saving over the SPB RS(KM) algorithm; the gap in performance increasing as the number of RUEs increases. The performance gain is up to 33 % in power savings at number of relays = 10. Unlike our proposed algorithm, the SPB RS(KM) algorithm uses the source power of the D2D pair as the weight of the edges of the bipartite graph.

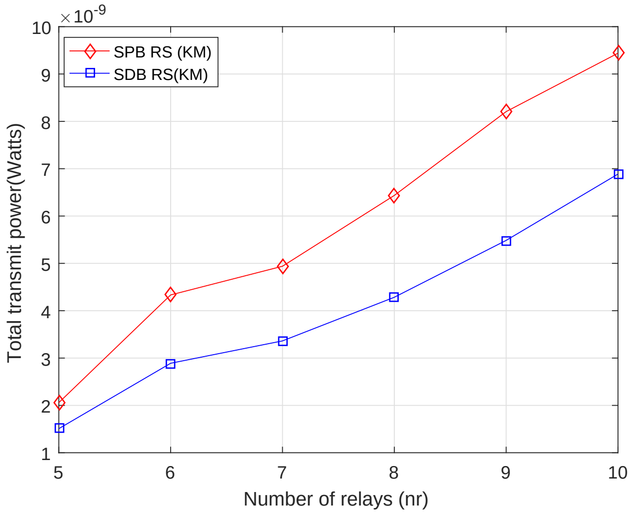

Figure 6.3: Total transmit power vs. number of relay (nr)

Since the work in this chapter considers full-duplex relaying, the effect of the loop interference or self-interference at the relay UEs is worth studying. Fig. 6.4

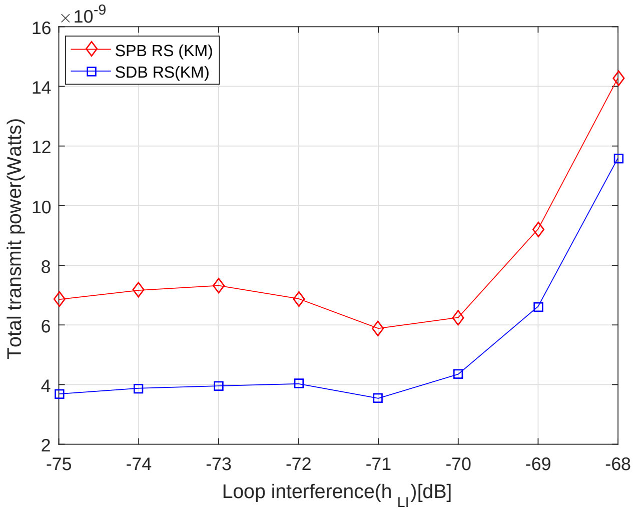

Figure 6.4: Total transmit power vs. self- interference (h˙LI)

shows the performance of the studied algorithms for a range of loop interference values with a fixed number of relay UEs at 5 and D2D pairs at 10. Loop interference at the relay UEs can deteriorate performance since the power expenditure for relay aided D2D communication increases as the loop interference at RUEs increases. This is observed for both SDB RS (KM) and SPB RS (KM) algorithms although the proposed algorithm also offered power savings.

To offer more insight into the performance of the proposed algorithms, the total transmit power is plotted against the number of D2D pairs (nd) in Fig. 6.5. The number of D2D pairs for the simulations resulting in this figure is increased from 1 to 12 whereas the number of RUEs is fixed at 5. For this figure, we consider two cases of the SDB RS (KM) algorithm namely the case where the channel uncertainty, $\xi =$ 0 and where the channel uncertainty is $\xi = 0.08$. The trend of the result indicates an increase in total transmit power as more D2D pairs are considered in the simulation. It is seen from Fig. 6.5 that the SDB RS(KM) results in lower total transmit power when compared to SPB RS (KM) algorithm, thereby offering a power saving of up to 10 % when there are 9 D2D pairs and up to 30 % total power saving for 12 D2D pairs. The observed total transmit power saving increases as the number of D2D pairs increases. The pattern of increasing total transmit power with increase in D2D pairs is indicative of more devices transmitting and so contributing to the total transmit power. Moreover, for a high number of participating D2D pairs, the channel uncertainty aware proposed algorithm (SDB RS (KM)+ U) also resulted in less total transmit power in comparison with the benchmark algorithm. This goes to show that for low values of channel uncertainty error, our proposed algorithm offers some power saving when more D2D devices participate in D2D communication.

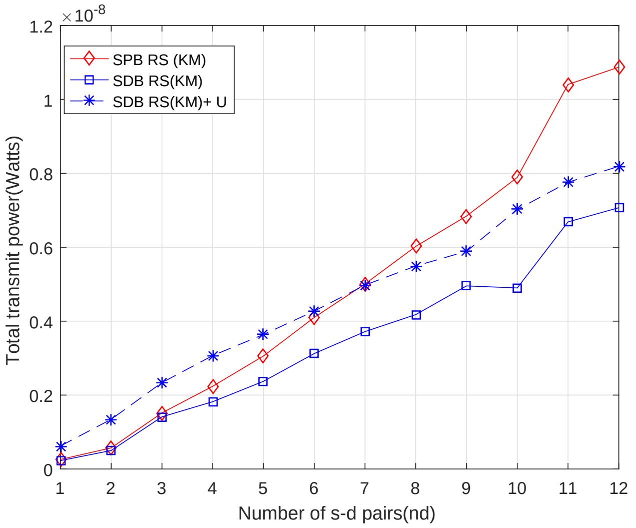

Figure 6.5: Total transmit power (Watts) vs. number of D2D pairs(nd)

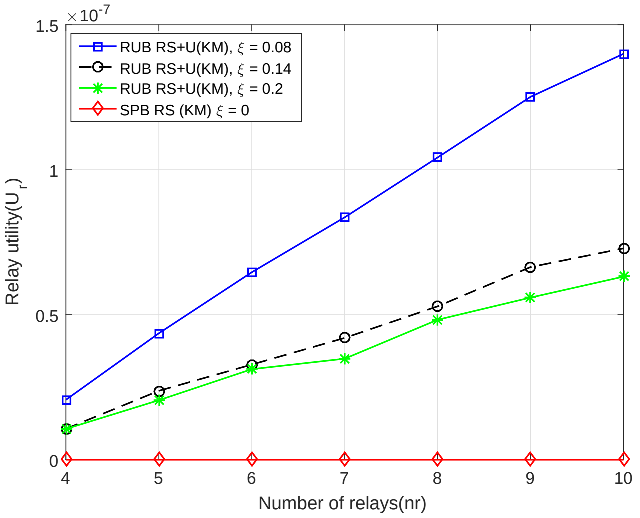

Figure 6.6: Relay utility (U_r) vs number of relays (nr)

In Fig. 6.6, the relay utility (U_r) is plotted against the number of RUEs (nr). The proposed RUB RS (KM) algorithm is compared to SPB RS(KM). For the proposed RUB RS (KM) algorithm, there is an increase in relay utility as the number of RUEs increases from 4 to 10 unlike for the SPB RS(KM) algorithm for which the utility stays constant despite an increase in the number of RUEs. Increased utility as the number of available RUEs increases points to a willingness to participate in relay aided D2D communication due to resulting improvement in relay utility. Hence the proposed RUB RS (KM) algorithm motivates relay aided communication participation. Moreover, it is aware of the power expenditure of the potential relay UEs and provides relays with a reward measure through the defined utility.

Furthermore, for selected channel estimation error values ($\xi = 0.08$, 0.14 and 0.2), the proposed RUB RS(KM) algorithm offered improved relay utility although the improvement drops as the channel estimation error is increased from 0.08 to 0.2 indicating the effect of channel perturbations on the relay utility performance. Despite the drop in performance, the channel uncertainty aware RUB RS(KM) algorithm is more responsive to relay utility in comparison to the SPB RS(KM) algorithm.

Similarly Fig. 6.7 shows the relay utility performance for a range of source-destination pairs. The effect of channel estimation errors is also observed in the figure. Our proposed algorithm shows improved relay utility as there are more potential D2D pairs to assist, unlike the compared algorithm. The compared algorithm shows an indifferent performance remaining constant despite variation in D2D pair size. Moreover, although the proposed algorithm is uncertainty aware, that is it factors in channel estimation errors, it results in improved utility for the relay with more D2D pairs.

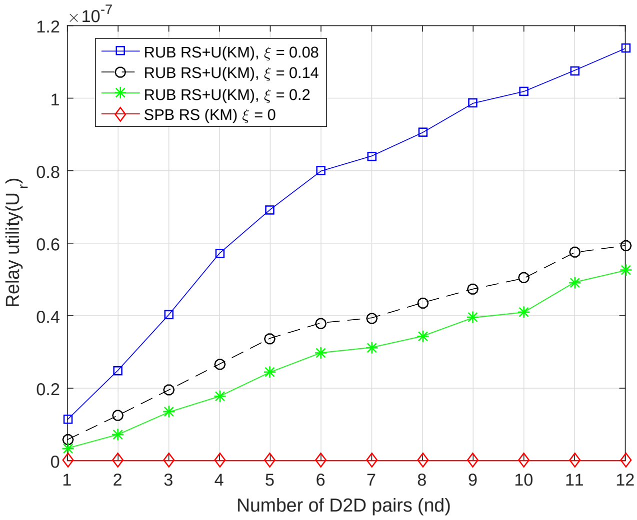

Figure 6.7: Relay utility (U_r) vs number of D2D pairs (nd)

Social distance based and relay utility aware algorithms are proposed in this chapter. The algorithms are based on the Khun Munkres assignment algorithm. And the computational complexity of the assignment algorithm is given by $\mathcal{O}(|n_d|^3)$ [129] where

n_d is the number of D2D pairs. Being that the matching is performed in the base station which has the computational resources, the complexity can be handled.

6.7 Conclusion

In this chapter, the performances of two proposed algorithms have been studied for joint power control and relay selection in D2D communication. The power control section of the problem was solved as an optimization problem whereas, for the relay selection part of the problem, social distance based relay selection and relay utility based selection algorithms are proposed. The two algorithms are uncertainty aware in that perfect knowledge of the channel between the source and destination pair is not available either at the source nor the destination. For the social distance based selection algorithm, the social distance was uniformly distributed between 0 and 1 whereas, for the relay utility based algorithm, a utility function was defined. Both proposed methods exploited the power of the assignment algorithm to achieve relay selection.

The social distance-based algorithm showed promise offering reduced total transmit power in comparison to a benchmark algorithm for a range of relay and D2D pair sizes. The relay utility based algorithm provided improved utility with respect to relay size and D2D pair size. Unlike the benchmark algorithm, our uncertainty aware algorithms still performed better than the benchmark algorithm for the relay utility based algorithm and for the social distance based algorithm with low values of channel uncertainty.

This chapter considered full duplex relaying and this can be extended to hybrid full duplex relaying in which the relay decides to use full duplex or half duplex mode based on a selected metric.

Summarily, in the work in this thesis, a case of one way DF relaying was considered in chapter three and in chapter four, a cross-layer selection technique was proposed for a two way DF relaying scenario. In chapter five, the focus shifted to rate improvement and robust beamforming for D2D multicast communication. Finally, in this chapter, a full duplex DF relaying scenario was presented and relay UE centric algorithms were proposed. The gains of the proposed algorithms in the various scenarios were also presented. A detailed conclusion is given the next chapter.

Chapter 7

Conclusion and Recommendation for Future Research Work

7.1 Conclusion

In this thesis, relay assisted device-to-device communication (D2D) has been studied and designed algorithms put forward. Relay selection for data forwarding between pairs of devices was considered in chapters three and four whereas in chapter five, D2D group communication was considered with a D2D transmitter selection algorithm proposed. Channel uncertainty arising from imperfect channel estimation was considered in this thesis. The relaying protocol deployed at the relay was decode and forward relaying. In chapter three, one-way decode and forward relaying was used. In chapter four, two way decode and forward relaying was used, whereas, in chapter six, full duplex decode and forward relaying was employed. Problem formulations put forward in this thesis included rate maximization, utility maximization, transmit power minimization and beamforming problems. These problems were formulated as optimization problems with perfect channel estimation and their channel uncertainty aware counterparts were also formulated. Robust multicast problems were also formulated for non-beamforming and beamforming scenarios. Uplink communication was considered in this thesis. In this thesis, relay selection algorithms proposed have included cross-layer selection algorithm, relay utility based relay selection algorithm and a social distance-based algorithms. Details of the chapter summaries are as follows:

In chapter three, a physical layer (specifically data rate) based relay selection algorithm was proposed and formulated as an optimization problem that was solved heuristically using the proposed stable matching based algorithm. Our proposed algorithm outperformed a random selection algorithm and offered comparable performance to a greedy selection algorithm especially for low transmit power regimes.

In chapter four, a cross-layer relay selection algorithm for D2D communication is proposed. The proposed algorithm defines a cross-layer term that is a function of the data rate of relayed communication and the buffer state of the potential relay devices. The relay selection was formulated to maximize the defined cross-layer term subject to given constraints. To solve the problem, a cross-layer relay selection algorithm was proposed and the performance demonstrated through computer simulations. The results of the proposed algorithm showed appreciable gains in data rate, energy efficiency and transmission time. The proposed cross-layer selection algorithm was shown to offer significant gains over the compared algorithms namely random selection, best source-relay link selection and best relay-destination link selection.

In chapter five, robust multicast communication was considered. The scenario painted involved the base station grouping D2D users into clusters and selecting a group transmitter for each group to act as a multicast transmitter. The problem of D2D multicast communication was formulated as a rate maximization problem constrained by SINR, transmit power and interference protection values. Both non-robust and robust counterpart of the problem were formulated and the convexity of the robust problem was demonstrated. To group the D2D users, K-means clustering was used and the proximity to the centre of the cluster was used to select a group head. The solution of the formulated optimization problem showed the gains of clustering in D2D communication. It also showed that our proposed robust formulation which was channel uncertainty aware compared to the non–clustered, non-robust version showed significant rate gains. In formulating the optimization problem, both non-probabilistic and probabilistic constraint approaches were used and the results from using these constraints were presented.

Furthermore, in chapter five, a case of multi-antenna equipped cluster heads was also considered which presented a MISO situation. For this MISO set up, a robust beamforming problem for D2D multicast communication was formulated. In this MISO case, a full channel uncertainty scenario was considered. Using triangle inequality, Cauchy-Schwarz inequality and SDP simplification, a convex robust beamforming problem was arrived at. The results from solving the formulated optimization problem were presented. It was shown through computer simulations that the probabilistic constrained problem when simplified approximated the non-probabilistic constrained problem for the range of parameters studied.

Chapter six saw the proposal of two relay selection algorithms. To cater to the self-interested nature of users of mobile devices, a social distance and relay utility based relay selection algorithms were put forward. Relay aided D2D communication was fashioned as a joint problem of power control and relay selection. The power control problem was simplified to a linear programming problem whereas relay selection was undertaken by the two proposed algorithms. The results showed that the social distance-based algorithm offered reduced transmit power in comparison to the benchmark algorithm for low channel estimation errors. On the other hand, the relay utility based algorithm showed that with increased relay utility, motivation to relay (indicated by an increase in the number of relay UEs) was increased.

Stable matching has been central to the formulation of proposed selection algorithms. In chapters three and four, stable matching was the core of the proposed selection algorithm. The assignment algorithm was the core of the proposed algorithms in chapter six. A comparison of the performance of both approaches is given in Appendix 1 and their complexity is also stated.

7.2 Recommendation for Future Research Work

D2D communication research has progressed consistently leading to the putting forward of architectures, protocols and algorithms. In the work in this thesis, algorithms have been proposed and their performances have also been analysed. There are areas where the work presented in this thesis can be further researched.

7.2.1 Unmanned Aerial Vehicle (UAV) Assisted D2D Communication

In this thesis, relay assisted D2D communication was studied and algorithms proposed for relay selection. The work of relay-assisted D2D communication can be extended to study the performance of UAV assisted D2D communication. A use case for UAV assisted D2D communication is emergency communication for device users that are not able to access the network due to a disaster. UAV mounted transceivers can be deployed for search and rescue operations in such scenarios. Since UAVs are mobile at speeds higher than mobile phones, to propose efficient algorithms for their deployment, channel models for UAV based relaying needs be developed. Furthermore, the impact of channel uncertainty due to channel ageing will need to be analysed. In chapter six of this thesis, selection algorithms that are relay centric were proposed. Extending the work in chapter six to providing incentives for UAV relay participation is an area that can be further researched. Such is applicable where network operators can seek to exploit the availability of privately owned UAVs for quick/temporary network deployment. Moreover, appropriate association techniques for multiple UAVs in a network needs to be explored.

7.2.2 Blockchain Based Relay Incentive for D2D Communication

Incentive designs in D2D communication research mostly base the incentive mechanism on auctioneering which can suffer from cheating by device users. Blockchain techniques can be exploited to provide incentive and payment models for relayed communication in a manner that is transparent to the network and the devices. Providing lean algorithms based on blockchain principles is an area that requires further prodding. Although there have been few forays into crypto-currency based relay incentives, the use of blockchain based algorithms for incentives can provide insights into the suitability of the technology. Blockchain techniques can be used for discovery sessions where D2D pairs can identify potential relay UEs in a manner transparent to the network using the concept of the shared ledger.

7.2.3 Relay Assisted Energy Harvesting in D2D Communication

For the work in this thesis, data communication has been considered and for further work, it would be insightful to consider relay aided energy harvesting. Also, concurrent information and energy transfer via relays using concepts in D2D communication has not really been delved into. More so employing energy transfer as a reward for relay services is promising since the information forwarding service by a relay is reciprocated by energy transfer for a served D2D pair. Such two-way transfer is an area that can be further researched.

7.2.4 Machine Learning Clustering for D2D Communication

Chapter five of the work in this thesis solved robust clustering problems. It employed a classic approach, the K-Mean to achieve clustering of devices into groups. That concept can be stretched further to include other emerging machine learning techniques that make a decision on device clustering based on acquired data of user behaviour. Furthermore, artificial intelligence based clustering and selection algorithms is an area worth extending the work in chapter five to cover. Furthermore, a stochastic game and reinforcement learning are further areas to explore in cluster formation and cluster head selection.

7.2.5 Uncertainty Paradigms

The work in this thesis has considered channel uncertainty due to imperfect channel state information. Both deterministic and probabilistic constrained problems were studied. Worst case uncertainty model was considered for the deterministic case and for the probabilistic models, known probability sets were used. The work in this thesis can be extended to consider the cases of other deterministic models such as ellipsoidal and D-norm models.

Appendix A

Optimality of Proposed Algorithm

Our proposed algorithm in chapter six is compared with the Kuhn Munkres (or Hungarian) algorithm which finds the optimal assignment of a given cost matrix. In creating the cost matrix, the difference between the relay path and the direct D2D path ($R_r - R_d$) was used. Spectral efficiency being the performance metric was shown for a variation of D2D transmit power and the number of relays. As was explained in chapter 3, the proposed stable matching (deferred acceptance [DA]) algorithm attempts to solve a formulated optimization problem albeit not optimally. The optimality or otherwise of the stable matching based relay selection proposed in this thesis is demonstrated here in comparison with the Hungarian algorithm which is an optimal assignment algorithm. Fig. A.1 shows the plot of the system data rate against D2D transmit power. Using D2D communication offers higher system spectral utilization as shown by the system data rate whether mode selection between cellular and D2D communication is used or more involved algorithms like the DA and the Kuhn Munkres (KM) based selection algorithms are used. The performance of the KM-based selection algorithm over the stable matching based algorithm shows higher optimality although the KM algorithm does not offer players (relay UEs and D2D) a preference listing opportunity and so ignores the rationality of players. Moreover, stable matching is shown in the literature to achieve stability. Further insight into how the stable matching based algorithm stands in comparison with the optimal KM algorithm is given in Fig A.2 where the maximum separation between source-destination pairs is varied from 5 m to 100 m. The number of relay UEs is also increased from 5 to 10. Having more relay UEs available to assist D2D communication improves D2D data rate since the D2D pairs can participate in relay aided communication resulting in increased resource utilization. The availability of idle UEs that can serve s relay UEs increases participation in relay aided D2D communication. From the plot, the difference between the optimal algorithm and the proposed algorithm narrows as the

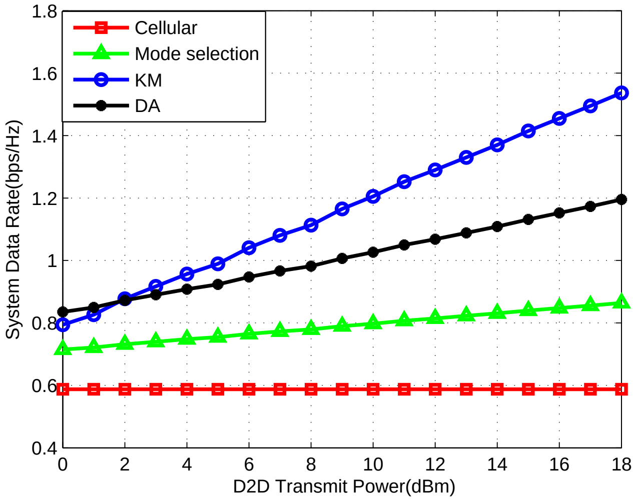

Figure A.1: D2D Spectral Efficiency (bps/Hz) vs. D2D transmit power

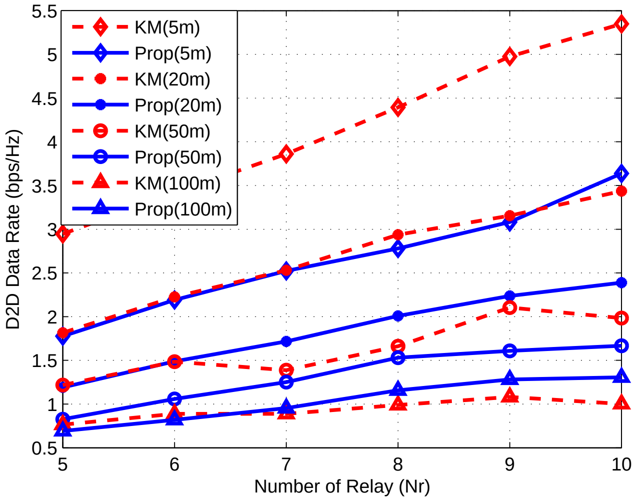

Figure A.2: D2D Spectral Efficiency (bps/Hz) vs. Number of relays separation increases towards 100 m. It can be implied that although not optimal, the proposed algorithm approaches the optimal algorithm for wider separation between D2D pairs.

A.1 Complexity of Employed Algorithms

In chapters three and four, relay selection algorithms are proposed for D2D communication. These algorithms are based on the stable matching algorithm. It is shown in the literature that the computational complexity of stable matching algorithm is $\mathcal{O}(|n_d|^2)$ [114]. Social distance based and relay utility aware algorithms are proposed in chapter 6. The algorithms are based on the Khun Munkres assignment algorithms. And the computational complexity of the assignment algorithm is given by $\mathcal{O}(|n_d|^3)$ [129]. In both cases, n_d is the number of D2D pairs.

Appendix B

Proof of Convexity of Formulated Problem

In this research work, optimization problems have been formulated and solutions to them have been proposed. For some of the optimization problems (as in chapters 3 and 4), the difficulty does not allow a tractable solution using available optimization tools. The formulation in chapter 5 is a convex problem which is solvable. In this section, the convexity of the formulated problem is proved. The rate maximization problem for D2D group communication subject to power and interference constraints was formulated as:

$$\max_{P_{k,w}} \sum_{k=1}^{K}(R_k) \tag{B.1a}$$

subject to:

$$C_1 : P_{k,w} \leq P_{max}, \forall k \in K \tag{B.1b}$$

$$C_2 : P_{k,w} \leq \frac{I_{th}}{d_{k,k'}^{-\alpha}(\widehat{g}_{k,w,k'} + |\delta_{max_{k,w,k'}}|)}, \forall k \in K, \tag{B.1c}$$

$$C_3 : P_{k,w} \geq 0, \forall k \in K \tag{B.1d}$$

where C_1 and C_3 are essentially transmit power constraint while C_2 is an interference threshold constraint. The SINR that the w_{th} receiver in the k_{th} group experiences be given by:

$$\gamma_{k,w} = \frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}{P_{c,w} g_{c,w} d_{c,w}^{-\alpha} + \sum_{k' \neq k} P_{k',w} g_{k',w} d_{k',w} + \sigma_w} \quad \forall k \in K, \forall w \in W, \tag{B.2}$$

Let the denominator in equation B.2 be given by I_k for simplicity of expression such that;

$$I_k = P_{c,w} g_{c,w} d_{c,w}^{-\alpha} + \sum_{k' \neq k} P_{k',w} g_{k',w} d_{k',w}^{-\alpha} + \sigma_w, \tag{B.3}$$

Then the equation B.2 becomes,

$$\gamma_{k,w} = \frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}{I_k} \forall k \in K, \forall w \in W, \tag{B.4}$$

The associated data rate expression can then be written as:

$$r_k = \log_2(1 + min_{w \in W_k}(\gamma_{k,w})), \tag{B.5}$$

Let $min_{w \in W_k}(\gamma_{k,w})$ be given by $\gamma_{k,w}$, that is:

$$\gamma_{k,w} = \frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}{I_k} \tag{B.6}$$

such that the rate term R in the objective function becomes,

$$R_k = M \log_2 \left(\frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}{I_k} \right), \tag{B.7}$$

The optimization problem an then be expressed as:

$$\max_{P_{min}} \sum_{k=1}^{K} (M \log_2 \left(1 + \frac{P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}{I_k} \right)) \tag{B.8a}$$

subject to:

$$C_1 : 0 \leq P_{k,w} \leq P_{max}, \forall k \in K \tag{B.8b}$$

$$C_2 : P_{k,w} h_{k'} \leq I_{th}, \forall k \in K, \tag{B.8c}$$

where $h_{k'} = d_{k,k'}^{-\alpha}(\widehat{g}_{k,w,k'} + |\delta_{max_{k,w,k'}}|)$ According to the Lagrange multiplier approach, the summation of the derivatives (with respect to the transmit power $(P_{k,w})$) of the objective function and the constraints is equated to 0. That is:

$$\bigtriangledown \left(\sum_{k=1}^{K} (R_k) \right) - \lambda \bigtriangledown \left(P_{k,w} - P_{max} \right) - \upsilon \bigtriangledown \left(P_{k,w} h_{k'} - I_{th} \right) = 0, \tag{B.9}$$

where $\bigtriangledown$ is the derivative symbol w.r.t $P_{k,w}$, λ and υ are non-negative Lagrange multipliers that relate to C_1 and C_2. Assuming $\log_2 \cong$ the natural log (ln), then the derivative of the objective function is given by $\frac{g_{k,w} d_{k,w}^{-\alpha}}{I_{th} + P_{k,w} g_{k,w} d_{k,w}^{-\alpha}}$. The derivative of the objective function is a decreasing function in $P_{k,w}$. Substituting this derivative expression into equation B.9 gives:

$$\frac{g_{k,w}d_{k,w}^{-\alpha}}{I_{th}+P_{k,w}g_{k,w}d_{k,w}^{-\alpha}}-\lambda-h_{k}^{'}v=0 \tag{B.10}$$

$$P_{k,w}=\left[\frac{1}{\lambda+h_{k}^{'}v}-\frac{I_{th}}{g_{min}d_{min}^{-\alpha}}\right] \tag{B.11}$$

The optimal solution in B.11 should satisfy the KKT conditions

$$\lambda\Bigg(P_{k,w}-P_{max}\Bigg)=0, and \tag{B.12}$$

$$v\Bigg(P_{k,w}h_{k'}-I_{th}\Bigg)=0 \tag{B.13}$$

Appendix C

Performance of Relay Assisted D2D Communication with Massive MIMO

As a follow up to the MISO work in chapter 5, in this appendix a demonstration of the gains of the co-existence of massive MIMO at the base station and relayed D2D communication is provided. Metrics for performance analysis are basically spectral efficiency and energy efficiency.

Considering a multi-antenna equipped base station (with N_t antennas) serving single antenna equipped M mobile devices ($N_t \geq M$) among which are D2D devices. Some of these mobile devices being relay enabled can perform relaying functions. This creates a MU-MIMO situation.

Using a distance dependent path loss model, the channel model between two devices (a,b) that are apart by a separation d_{ab} is given by $hd_{ab}^{-\alpha}$. Denote h as the channel between the devices and α is the path loss exponent.

Since uplink communication is used, the BS experiences interference from non-cellular communication that re-uses uplink cellular communication. SINR at the BS is given by:

$$SINR_{BS} = \frac{P_{kc} g_{kc}}{I_{dc} + I_{cc} + \sigma^2}, \tag{C.1}$$

In equation (C.1), P_{kc} is uplink transmit power of the k_{th} cellular device. D2D communication creates interference since it re-uses the cellular resources. The aggregate interference from such D2D sources and cellular sources causing interference to the k_{th} cellular device is given by I_{dc} and I_{cc} respectively. $g_{kc} = |h|^2 d_{ab}^{-\alpha}$ is the channel gain of the link between the BS and the k_{th} cellular user whereas σ is the nose power.

Let the SINR for D2D communication without relay assistance be given by:

$$SINR_{SD} = \frac{P_{sd}g_{sd}}{I_{cd} + \sigma^2}, \tag{C.2}$$

In equation (C.2), denote the D2D transmit power as P_{sd}, g_{sd} as the D2D channel gain, I_{cd} as cellular communication interference.

For relayed D2D communication, the SINR can be expressed as:

$$SINR_R = 0.5min(\frac{P_{sr}g_{sr}}{I_{cr} + \sigma^2}, \frac{P_{rd}g_{rd}}{I_{cd} + \sigma^2}), \tag{C.3}$$

where g_{sr} and g_{rd} are respectively the channel gains of Source - relay and relay - destination links. Similarly the transmit power of the source and relay are respectively P_{sr} and P_{rd}. I_{cr} and I_{cd} are respective interference terms.

Given the SINR of a link, the spectral efficiency (SE) can be expressed as:

$$SE = Blog_2(1 + SINR), \tag{C.4}$$

and for a a given SINR of a link, the corresponding energy efficiency of a communication link is given by:

$$EE = \frac{SE}{P_T} \tag{C.5}$$

where P_T is the total transmit power $P_T = P_c + P_t$ (that is the sum of transmit, P_t and circuit power, P_c).

Being a MU-MIMO scenario, a MIMO receiver technique has to be deployed at the BS. A simple receiver technique namely zero forcing (ZF) receiver is deployed at the BS. Using a product of the inverse of a channel matrix and the received signal, ZF achieves the recovery of the transmitted signal.

C.1 Mode Selection

Here a simple mode selection between direct D2D mode and relayed D2D communication mode that is based on the data rate of the channel is used. The mode selection algorithm is given in Algorithm 6 and simulation parameters are listed in Table C.2.

C.2 Performance Evaluation

In Fig. C.1 shows the effect of the number of BS antennas on the area spectral efficiency (ratio of the spectral efficiency per square area of the cell) for 15 dBm and 23

Algorithm 6 Mode Selection Algorithm

```
Input set of users, $C$
Obtain $R_C$, $R_d$, $R_r$, $D$,
For i = 1:$N_d$
If $R_r$ ¡ $R_d$
Compute $SINR_d$
Else
Compute $SINR_r$
Compute ASE, EE
```

Table C.1: Simulation Parameters

Parameter	**Value**
Bandwidth	20MHz
Radius of cell (r)	500m
P_{max}	15,23dBm
P_c	15,23dBm
Power Amplifier Efficiency (P_A)	0.5
Circuit power	0.1
Noise Power(σ^2)	-176dBm/Hz
No. of Cellular Users	250
No. of D2D pairs	50
No. of Relays	20
No. of BS antennas	10-100
Path loss exponent (α)	3.5,4
Channel dependent constant (β)	1

dBm transmit power values. It can be inferred that relayed aided D2D communication offers improved area spectral efficiency over direct D2D communication. And that not enabling D2D communication reduces spectral efficiency - this is logical since D2D communication allows spectrum re-utilization. The plot in Fig. C.1 shows cellular communication, D2D communication and relay aided D2D communication. Two transmit powers are considered (15 dBm and 23 dBm). It can also be inferred that with more antennas at the BS, the ASE also improves for all approaches.

Fig. C.2 the EE is plotted against the number of antennas (10 - 100). It can be implied from the figure that the EE of relay aided communication performance is better that that of D2D communication and cellular communication considered alone. Furthermore although spectral efficiency enjoys an improvement with increased transmit power in C.1, the EE experiences a drop in performance in C.2. The separation (varied from 20 to 400 m) between D2D pairs is demonstrated in Fig. C.3 and Fig. C.4. It can be inferred from Fig. C.3, that when considered alone, the SE performance

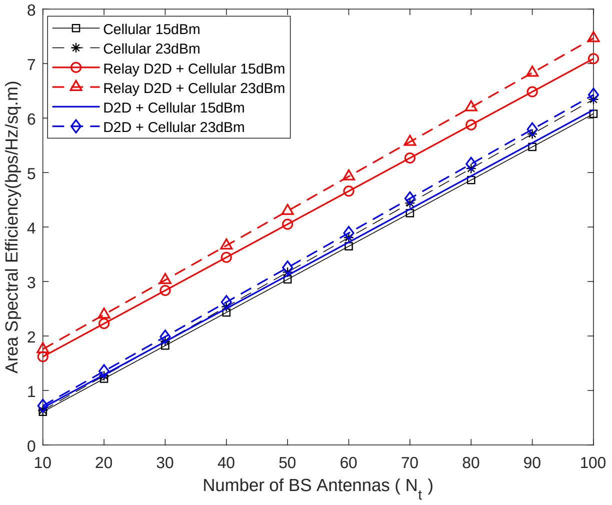

Figure C.1: Effect of number of antennas on ASE for $P_t = 15dBm, 23dBm$

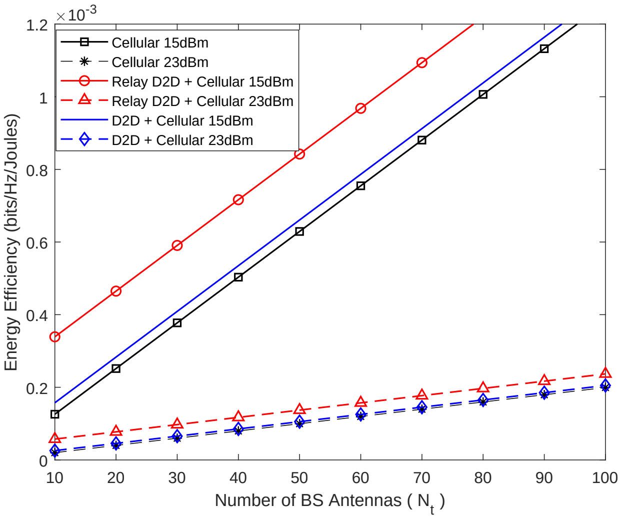

Figure C.2: Effect of number of antennas on EE for $P_t = 15dBm, 23dBm$

relay aided communication drops with D2D separation whereas when considered with cellular communication, there is no effect of the separation does not affect the total ASE. This can be explained from the fact that the drop in performance in relay aided communication is overshadowed by cellular communication.

Similarly, Fig. C.4 shows the EE performance as the separation between D2D pairs is increased. Separation between D2D pairs directly affects D2D communication performance and cellular communication. An increase in D2D separation will imply reduced interference for a cellular users with which the D2D pairs shares a resource, hence the rise in the plots. On the other hand a separation increase will reduce

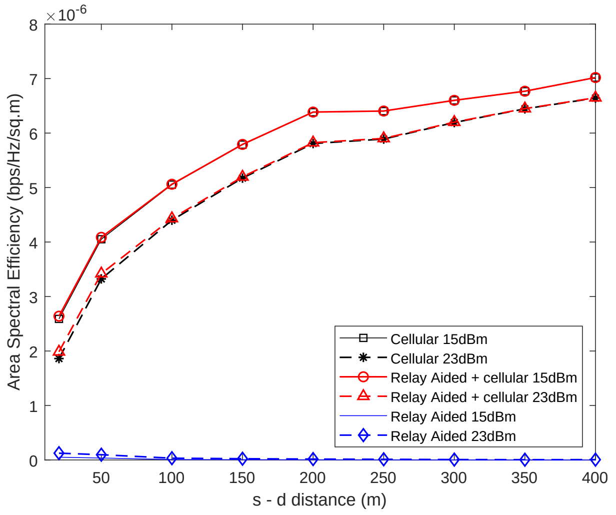

Figure C.3: Effect of s - d distance on ASE for $P_t = 15dBm, 23dBm$

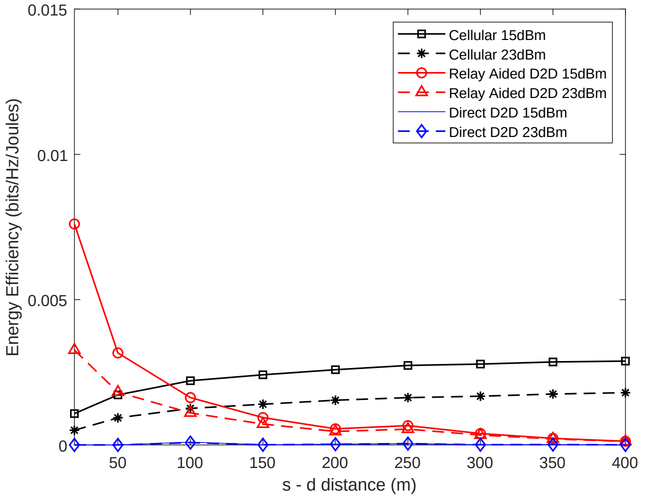

Figure C.4: Effect of s - d distance on EE for $P_t = 15dBm, 23dBm$

the likelihood of successful reception for D2D communication. Conclusively having more antennas can improve the overall energy efficiency and energy efficiency of an underlay D2D communication with suitable mode selection technique.

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