Radio Resource Allocation for Device-to-Device Communications Underlaying Cellular Networks

by

Mohammad Tauhidul Islam

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Abstract

Inexpensive connectivity and computing power have caused the number of communicating devices to explode in the last decade. New applications are emerging every day to take advantage of the proximity and abundance of these devices. Device-to-Device (D2D) communication using cellular spectrum to increase spectral efficiency of the network is a technology component of Long Term Evolution - Advanced (LTE-A). In D2D communication underlaying cellular networks, devices communicate with each other using a direct link using cellular resources without going through the evolved Node B (eNB) but remaining under the control of it. D2D communication is expected to be one of the prominent features supported by future cellular networks because of reusing the cellular spectrum to increase the system performance of cellular networks. However, due to the limitations of a licensed spectrum when these devices share a cellular spectrum to communicate directly among themselves, the same resource may need to be shared among cellular and D2D communicating pairs. This resource sharing introduces a new interference scenario, which needs to be coordinated through a new resource allocation scheme.

We investigate this problem of interference coordination and explore three different perspectives from which this problem can be viewed, namely a) interference minimization; b) fair allocation while minimizing interference; c) Quality of Service (QoS) satisfaction while maximizing total system sum rate of the cellular network. We show that the proposed schemes are suitable for the short LTE scheduling period of 1 ms as they are computationally tractable. Our schemes can allocate radio resources to D2D pairs underlaying a cellular network in a short time, ensuring fairness in allocation while minimizing interference, and increasing the total system sum rate of the network while maintaining a QoS target.

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Statement of Originality

I hereby certify that this Ph.D. thesis is original and that all ideas and inventions attributed to others have been properly referenced.

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List of Acronyms

3GPP Third Generation Partnership Project

BS Base Station

CU Cellular User

D2D Device-to-Device

DARA Deferred Acceptance based Resource Allocation

eNB evolved Node B

Hetnet Heterogenous Networks

LTE Long Term Evolution

MIKIRA MInimum Knapsack-based Interference-aware Resource Allocation

MINLP Mixed Integer Non-Linear Program

MLOC Maximum improvement LOCal search based resource allocation

OFDMA Orthogonal Frequency Division Multiple Access

QoS Quality of Service

RA Resource Allocation

RB Resource Block

SC-FDMA Single Carrier Frequency Division Multiple Access

SINR Signal to Interference and Noise Ratio

SLOC Simple LOCal search based resource allocation

TAFIRA Two-phase Auction-based Fair and Interference-aware Resource Allocation

UE User Equipment

List of Notations

D_j^t	Transmitter of D2D pair D_j
D_j^r	Receiver of D2D pair D_j
P^B	Transmission power of base station or eNB
P^D	Transmission power of D2D devices
P^C	Transmission power of cellular users
$G^{i,eNB}$	Channel gain of the cellular link from cellular user CU_i to the eNB in Uplink
$G^{jt,eNB}$	Interference from the transmitter of D2D pair D_j to eNB in Uplink
$G^{jt,jr}$	Channel gain from the transmitter of D2D pair D_j to the receiver of D2D pair D_j in Uplink
$G^{i,jr}$	Interference from the cellular user CU_i to the receiver of D2D pair D_j in Uplink
$SINR_{i,j,1}$	SINR at the eNB when CU_i shares the channel with D2D pair D_j

$SINR_{i,j,0}$	SINR at the eNB when the CU_i does not share the channel with any D2D pair
$SINR_{i,j}$	SINR at the receiver of the D2D pair D_j when it shares the channel with CU_i
$SINR_c^{DL}$	Downlink SINR of cellular user c
$SINR_d^{DL}$	Downlink SINR of the receiver of D2D pair d
$SINR_{c,target}^{DL}$	Downlink SINR target at cellular user c
$SINR_{d,target}^{DL}$	Downlink SINR target at the receiver of D2D pair d
$G^{B,c}$	Channel gain between the eNB and the cellular user c in Downlink
$G^{d_t,c}$	Interference from the transmitter d_t of D2D pair d to the cellular user c in Downlink
G^{d_t,d_r}	Channel gain between the transmitter d_t and receiver D_r of D2D pair d in Downlink
G^{B,d_r}	Interference from the eNB to the receiver d_r of D2D pair d in Downlink
R_c^{DL}	Sum rate corresponding to $SINR_c^{DL}$ for cellular user c according to Shannon's capacity formula
R_d^{DL}	Sum rate corresponding to $SINR_d^{DL}$ for cellular user d according to Shannon's capacity formula

N_c	The number of RBs assigned to the cellular user c at a time slot in downlink

Chapter 1

Introduction

Recent advances in communication technologies and reduced production cost of smart devices have allowed the proliferation of devices in almost all areas of our day to day life. These devices can communicate with each other directly using an unlicensed spectrum or by sharing a licensed spectrum with cellular users. When the devices use dedicated licensed spectrum no additional interference occurs; but this is achieved at the cost of inefficient resource utilization. However, when they share the licensed spectrum with cellular users, it enables efficient utilization of spectrum resources. On the other hand, because of sharing the spectrum a previously non-existing intra-cell interference scenario arises. It becomes important to ensure that the communication scenario does not degrade the service quality to a level under an accepted threshold for the cellular users. Designing efficient resource allocation algorithms for allocating cellular resources to Device-to-Device (D2D) users is the main focus of this thesis.

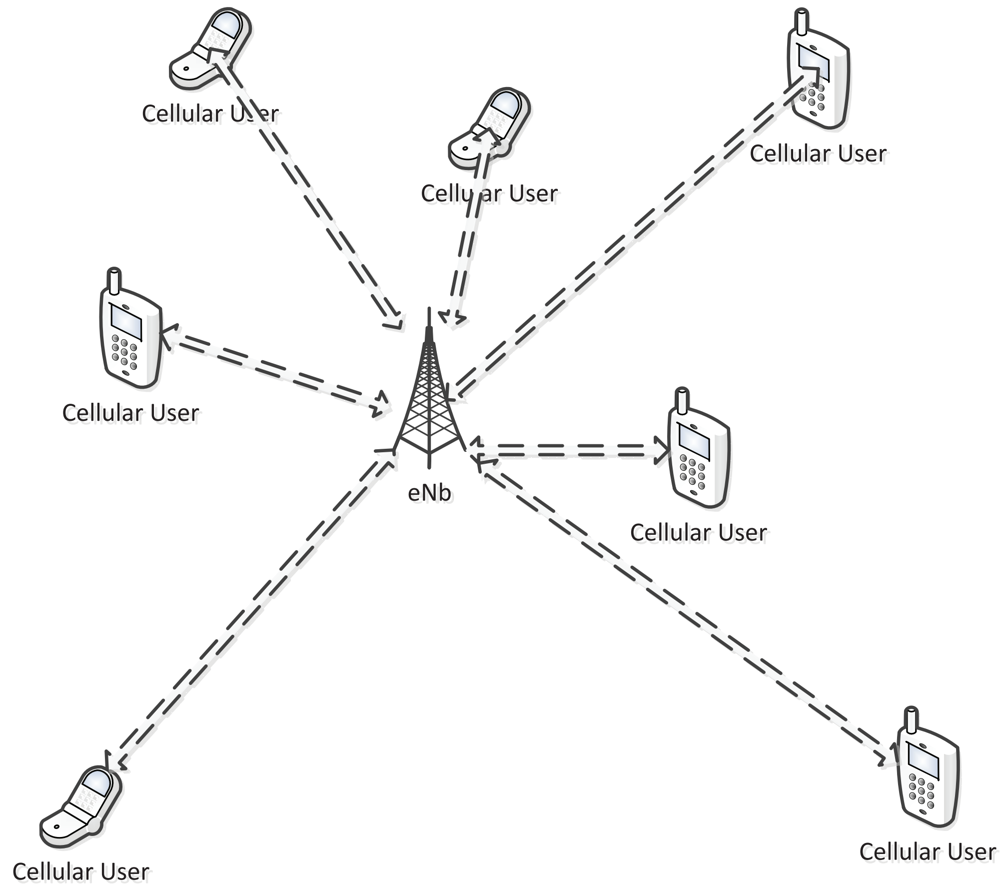

Figure 1.1: Traditional cellular communication.

1.1 Motivations

In traditional cellular communication, the Cellular Users (CU) have to communicate with each other via the evolved Node B (eNB) or the Base Station (BS) as shown in Fig. 1.1. In contrast, D2D communication allows direct communication between two devices without having to go through a BS or eNB as depicted in Fig. 1.2. Long Term Evolution-Advanced (LTE-A) as described in Third Generation Partnership

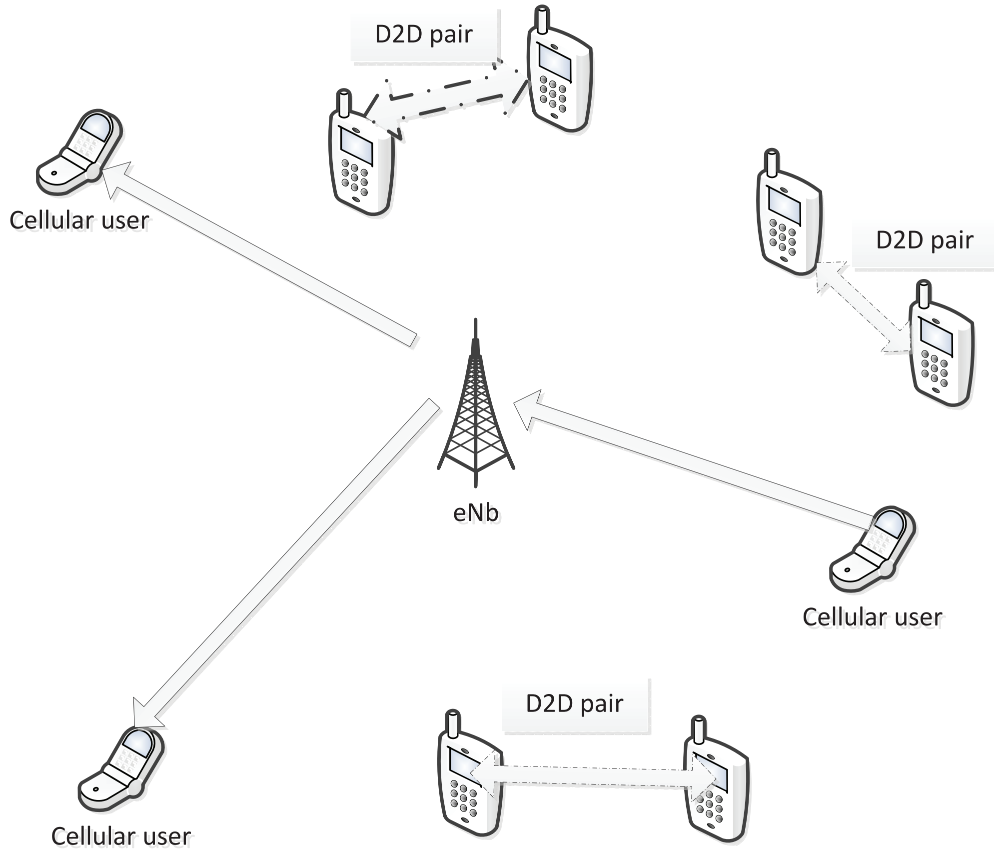

Figure 1.2: D2D communication.

Project (3GPP) [3gpa] considers D2D communication as one of the main players to address the expected huge mobile traffic in future as reported by different organizations [Nic; Sor15]. According to a report by the United States National Intelligence Council (NIC), by 2025 the Internet nodes will cover most of the everyday essentials including food packages, furniture, paper documents and more [Nic]. Furthermore, according to a research conducted by Juniper Research in 2015, by 2020, the number of connected devices will be 38.5 billion, up from 13.4 billion in 2015 a rise of

285% [Sor15]. These are all indicators of how a large number of devices and the traffic generated from applications running on them are going to dominate communication paradigms. Hence, D2D communication with its associated challenges needs to be considered a viable option. This expectation comes from the gains that can be achieved from adopting D2D communication in cellular networks [Fod+12]. These gains can be listed as: firstly, transmission-rate gain resulting from utilizing the proximity of the devices; secondly, frequency-reuse gain resulting from the simultaneous usage of the same resources by the cellular and D2D devices; thirdly, hop-gain resulting from reducing the number of hops when transmitting from one device to another in traditional cellular communication, and finally, coverage-gain resulting from increasing the coverage of the cellular network through the use of D2D communicating pairs.

D2D communication can be achieved by using the frequency allocated to the cellular spectrum (in-band D2D) or by using an unlicensed spectrum (out-band D2D) [Lin+13]. Here, band refers to a small selection of the spectrum of the cellular frequencies used for communication. Furthermore, within in-band D2D some cellular resources may be dedicated for D2D communications, and some reserved for cellular users (overlaying a cellular network); whereas in the case of D2D communications underlaying a cellular network, the cellular resources may be shared and reused by D2D devices. The main purpose of overlaying D2D communication is to ensure dedicated radio resource for D2D communications and cellular communications but not share them.

D2D communication underlaying cellular networks has attracted a lot of attention in the past few years because of its potential to provide multifold benefits to the cellular network's users and providers. Though D2D communication can be used as an overlay to cellular networks having orthogonal (non-interfering and dedicated) radio resources, it can result into unused radio resources. In contrast, utilizing spectrum sharing to increase system capacity is possible only through underlaying cellular networks, since the resources are not orthogonal and need to be shared. The benefits arising from using resources in the underlaying cellular network come with the price of having intelligent resource sharing techniques. These techniques are needed to avoid or cancel the interference D2D communication causes to the existing cellular users or the interference that arises from the cellular users to the D2D pairs as a result of sharing the same radio resources.

3GPP LTE promises high data rate and system capacity. Furthermore, LTE-A was introduced to support new features for LTE to meet more demanding communication needs [Dop+09]. In recent times, proximity based services and information have become a significant area of interest for the social networks [Bry14]. A particular service can be of more value to a user if it can be made more relevant to him at a particular situation, time or place. Proximity based local area services is one of the demanding communication needs that requires further improvement, and reusing the spectrum increases the local data rates significantly. However, in case of unlicensed spectrum (small cells, WiFi, Bluetooth, ZigBee) sharing the eNB or BS or some other central node does not have control over the ad hoc network and the local service providers can not provide a stable, reliable and controlled environment. In ad hoc networks, individual network nodes forward packets to and from each other without relying on the BS to coordinate the flow of messages. As a result, sharing the licensed cellular spectrum with the D2D users has gained much attention in the research community.

Currently, the challenges associated with D2D communication cannot be readily addressed using the existing approaches for Heterogenous Networks (Hetnet). A HetNet consists of cells of different sizes that are referred to as macro-, micro-, pico- and femto-cells; listed in order of decreasing BS power. Authors in [Teh+14] present the technical challenges associated with D2D communication underlaying cellular networks and point out a few approaches that offer solutions as well as directions towards pricing schemes for the operators. Mirahmadi et al. [Mir+14] propose an interference model to be used to analyze and enhance the performance of existing interference mitigation and power control techniques in realistic heterogenous cellular network scenarios.

3GPP recognizes that D2D communication is a major contender in future communication systems and its status of standardization are mentioned by Lin et al. [Lin+14]. 3GPP specification regarding D2D proximity services is explained in [3gpb]. D2D communication underlaying 3GPP LTE-A network including session setup and management, resource allocation and interference management is described by Doppler et al. [Dop+09]. General design aspects of D2D communication underlaying cellular network are addressed by Fodor et al. [Fod+12] and Feng et al. [Fen+14].

In LTE, the smallest radio resource that can be shared or scheduled is the Resource Block (RB). Each RB occupies 1 timeslot (0.5 ms) in the time domain and 180 KHz in the frequency domain of LTE. LTE downlink frame structure is shown in

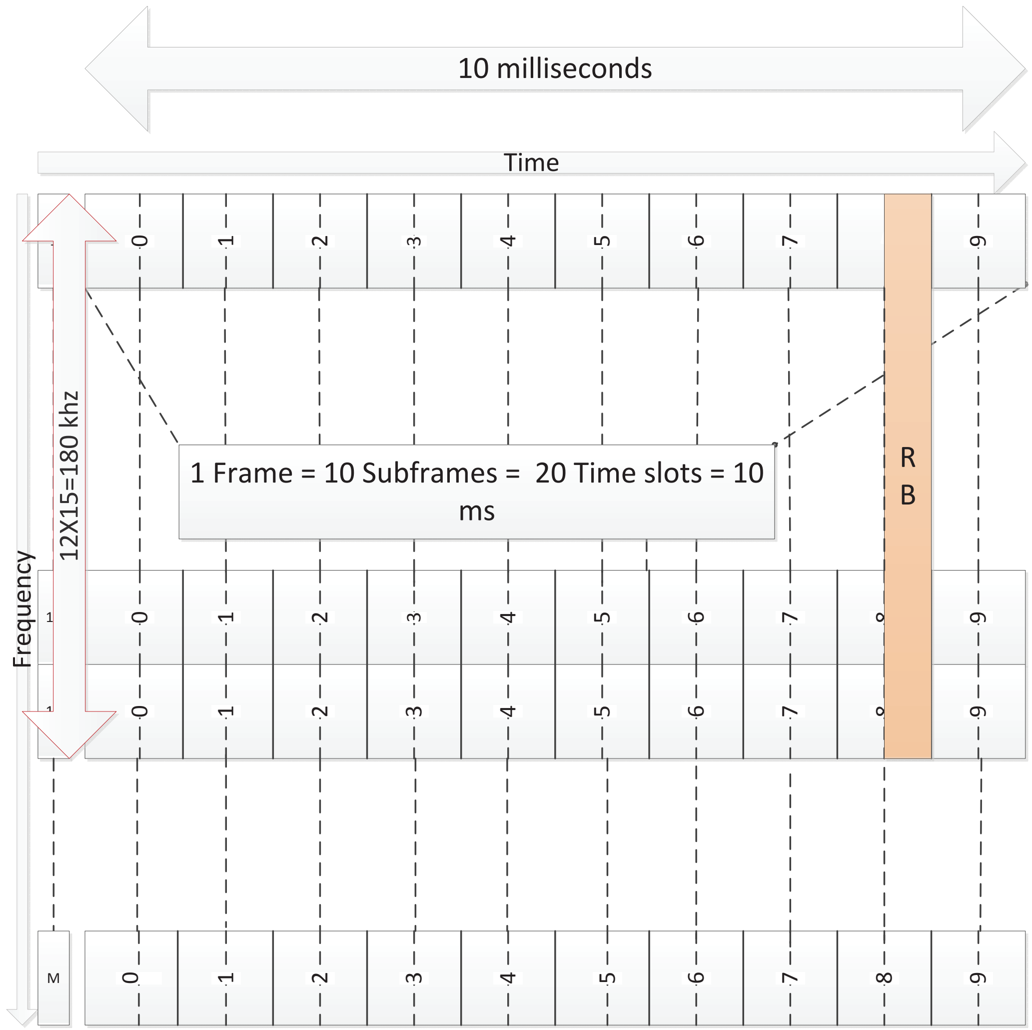

Figure 1.3: LTE downlink frame structure.

Fig. 1.3. The RBs are the radio resource units that the cellular users are allocated in a scheduling period, and the D2D pairs request the eNB to share for communication. The LTE scheduler assigns the RBs to cellular users in the scheduling period. A power efficient scheduler for LTE uplink is presented in Kalil et al. [Kal+15a] for delay sensitive traffic and a QoS aware scheduler is proposed in Kalil et al. [Kal+15b].

Dechene and Shami [DS14] propose energy-aware resource allocation strategies for LTE uplink. However, the adaptability of proposals when D2D underlays LTE networks was not explored in details. Kalil et al. [Kal+14] present a genetic algorithm based scheduling for LTE uplink to reduce the time to obtain the optimal solution. However, this was also not adapted to include D2D resource sharing in the scheduling procedure. To this end, we identify resource allocation for D2D underlaying cellular networks an interesting research problem with significant room for improvement.

1.2 Thesis Statement

The optimization problem of resource allocation for D2D underlaying cellular network, with the objective of maximizing overall system sum rate while maintaining minimum QoS target level and one-to-one allocation leads to a computationally intractable MINLP problem. Since, MINLPs are NP-hard to solve [KM78], the researchers in this area adopt alternate approaches to solve the problem sub-optimally such that the solution is not far off from the optimal solution and can be obtained in short time. These alternate approaches can be based on game theory, graph theory or heuristics. Based on these understandings, in this thesis we aim to design fast new algorithms to obtain solutions to the resource allocation problem, so that these algorithms can be used by the cellular networks in the short LTE scheduling period of 1 ms to schedule resources. Nonetheless, as we have discussed in the previous sections scheduling cellular resources to D2D users has some challenges associated with it. The objectives of the resource allocation algorithms may also vary depending whether the focus is on minimizing the interference, maximizing the system sum rate or allocating resources fairly among the D2D users.

In Chapter 3 and 4, our objective is to minimize the interference introduced and ensure a one-to-one channel mapping between CUs and D2D devices. In these two chapters we assume that, the uplink frame is divided into some orthogonal channels that are allocated to the cellular users. The techniques to orthogonalize the channels can vary based on separation in frequency, time or code, depending on whether the system follows orthogonal frequency division multiplexing, time division multiplexing or code division multiplexing. However, as long as one cellular user is served by one channel this technique is feasible. Thereafter, the task is to find out the allocation of the cellular channels to D2D users. This allocation algorithm is carried out at the eNB or BS. The eNB has the Channel State Information (CSI) associated with all the channels which is used by the algorithms to find an allocation of cellular resources to D2D users. After the allocation is completed, this allocation information is carried out to the D2D users and CUs from the eNB. We refer to this type of resource allocation as channel level resource allocation. The goal of the algorithm in Chapter 3 is to obtain an allocation with less interference introduced than another graph based algorithm while obtaining an equivalent system sum rate and signal quality than those of the latter. It also runs faster than the graph based algorithm and hence is more suitable for use in the LTE scheduling period. The algorithm in Chapter 4 has a dual focus of minimizing interference and at the same ensuring fair allocation of resources to all the D2D users. This is to eliminate the problem of starvation for D2D users. This algorithm tackles a very important issue of fair allocation for D2D which is not addressed comprehensively in the literature.

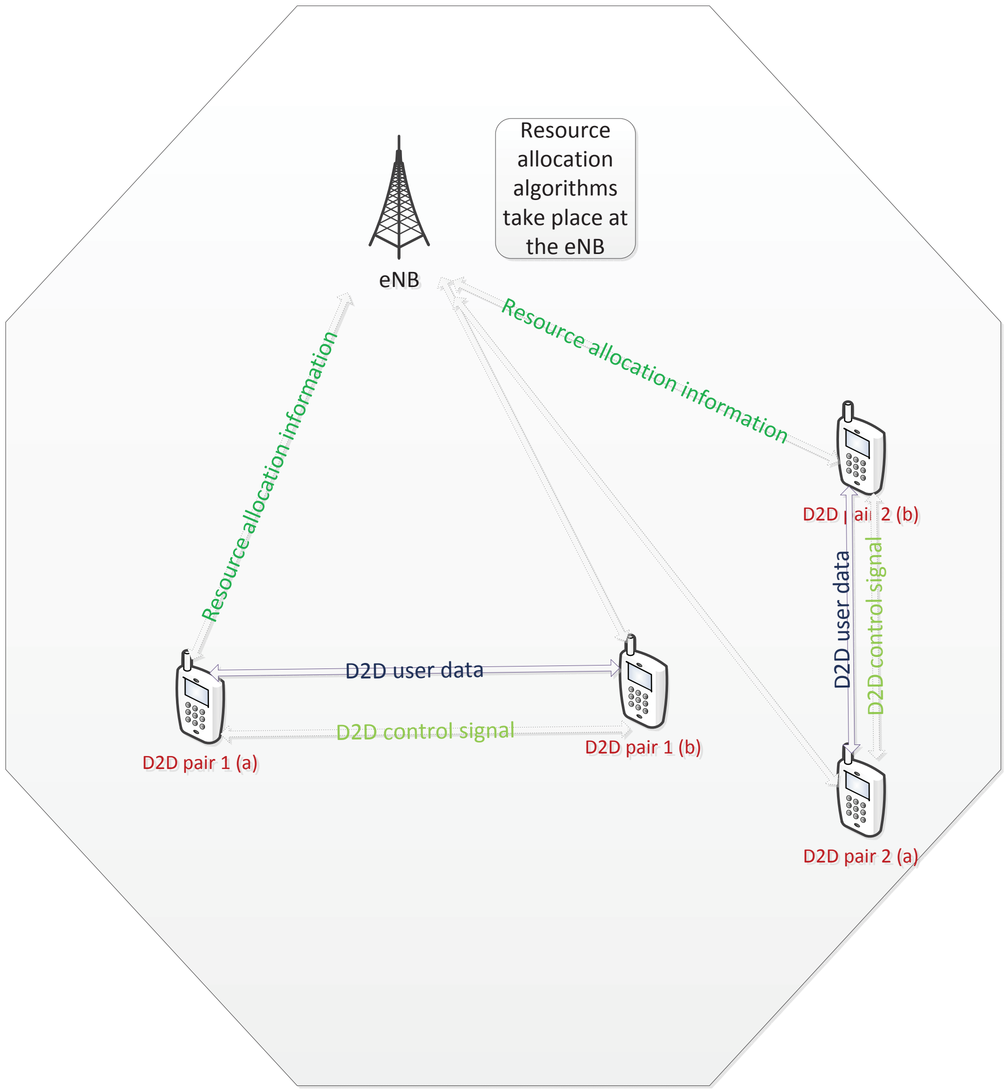

Figure 1.4: D2D resource allocation system diagram.

In Chapter 5, our goal is to maximize the system sum rate while ensuring a minimum QoS level and one-to-one RB mapping in LTE cellular networks. In LTE, RBs are allocated to cellular users in the scheduling period. D2D pairs can then share the RBs allocated to a cellular user for communication. The objective is to find the allocation of the RBs to the D2D users. The resource allocation algorithm in this case also runs at the eNB which has the RB allocation information for the CUs as well as the channel state information. After the RB allocation for the D2D users is completed the allocation details are conveyed to the CUs and the D2D users. We refer to this type of allocation as RB level resource allocation. Our proposed algorithms are aimed toward obtaining a better network efficiency in terms of system sum rate and signal quality than other approaches. To this end, we compare our algorithms with other known algorithms to validate our claim. The proposed algorithms allocate resources to D2D in short time and also obtain a better signal quality than other known algorithms in the process. Therefore, these algorithms address the core issue of resource allocation for D2D in short time while maintaining a satisfactory signal quality.

Fig. 1.4 shows the D2D resource allocation system diagram. From Fig. 1.4 we observe that the resource allocation algorithms are carried out at the eNB and the allocation information is conveyed to the D2D pairs. After a D2D pair receives the allocation information it can start using the allocated cellular resource to communicate directly without any control from the eNB.

The resource allocation algorithms proposed in this thesis can be adopted by the cellular service providers for use in the scheduling period at the eNB. This will allow them to increase the network system sum rate while maintaining QoS target levels at the cellular users and D2D users. The algorithm in Chapter 4 also ensures that the service providers can allocate resources fairly among the D2D devices to increase user satisfaction. The service provider can adopt one or more of these algorithms that better suits its service priority design.

1.3 Thesis Contributions

Our research aims at minimizing the interference while satisfying the system sum rate demand in the process. System sum rate is the sum of the channel data or transmission rates for all communication channels including the cellular communication links and the D2D links over a given bandwidth. Ensuring a minimum system sum rate gives a lower bound to the overall cellular network efficiency achievable. We choose satisfy the sum rate demand instead of individual rates as this will give an indication of the minimum overall system performance achievable rather than a connection specific rate. We formulate the optimization problem as either minimizing interference or maximizing the system sum rate problem. However, the resource allocation needs to satisfy QoS constraints associated with the victims of the interference. To this end we present novel schemes to allocate cellular resources to D2D pairs in the short LTE scheduling period of 1 ms.

The primary contributions of this thesis are as follows:

1. We reduce the resource allocation problem to a simple variant of the knapsack problem. This insight allowed us to use efficient techniques for solving the problem in shorter time.

2. We present an auction based algorithm for the similar problem formulation ensuring that cellular resources are allocated to the D2D pairs in a fair manner and no particular D2D pair is starved. In this algorithm we incorporate fairness

in allocating resource among the D2D pairs.

3. We solve the optimization problem for maximizing system rate while maintaining a target signal quality using a novel local search algorithm. This optimization problem is a Mixed Integer Non-Linear Programming (MINLP) problem. Our local search algorithm is fast and suitable for use in the short LTE scheduling period of 1 ms. We also design and elaborate on an extended version of the local search algorithm to further refine the solution obtained.

4. We present a new greedy approach motivated from another well known greedy approach mentioned in [Zul+10] while not having the pitfalls associated with it to solve the problem mentioned in the last contribution.

5. We present a polynomial time stable matching algorithm for allocating resources to the D2D pairs. This scheme can be useful for D2D applications requiring a steady solution by providing a stable final allocation of resources.

1.4 Organization of Thesis

The thesis is organized as follows. In Chapter 2, we present a classification of the D2D resource allocation algorithms, and related background work descriptions. We also present our research focus, some general assumptions of our algorithms and how industry can benefit from our work. In Chapter 3, we present a polynomial time approximation algorithm to solve the resource allocation problem modeled as a variant of the knapsack problem. In Chapter 4, we present an auction based and fair resource allocation algorithm to minimize interferences introduced in the system.

We also prove the fairness of this approach mathematically and experimentally. We present four novel schemes for resource block level resource allocation in Chapter 5. This includes a novel local search algorithm for D2D resource allocation, an extension of the local search to further refine the solution, a new greedy algorithm and a deferred acceptance based stable matching algorithm. Finally, in Chapter 6, we conclude the thesis by summarizing our findings and highlighting the possibilities for future work.

Chapter 2

Background

The recent interest in D2D communication underlaying cellular networks is motivated by the increasing popularity of proximity based services in social networks and the problems associated with technologies (WiFi and Bluetooth) using unlicensed spectrum such as, the manual pairing of devices and the lack of security features in these technologies. Some examples of proximity based services are, a Facebook user being notified of the presence of a relative or a friend in a nearby shopping mall, a sports enthusiast being alerted of special discounts going on a local sports shop on her way to home or a food lover being informed about new items in a restaurant as she passes by it. These proximity based services utilize the location of the devices to communicate relevant information to them.

The rest of the chapter is organized as follows. We first present our research focus and what makes it challenging and interesting to work on in Section 2.1. In the next section, for the purpose of gaining a better understanding of D2D resource sharing approaches we classify the D2D resource allocation proposals based on the way they tackle the resource allocation problem (auction based, game theory based, graph based, greedy, centralized, distributed, local search based, etc.). These proposals also differ in the focus of the allocation algorithm (interference minimization, sum rate maximization, energy consumption minimization, etc.) and the scope of resource allocation (UL, DL or both). This classification aids in providing useful insights on how to approach the resource allocation problem for D2D. The classification is described in Section 2.2. In Section 2.3, we compare the proposals based on different criteria. A brief summary of the chapter is presented in Section 2.4.

2.1 Research Focus

In regular cellular communications, the cellular users (CU) communicate with each other through a central node such as eNB or BS. In this process, the resource allocation and total communication procedure occurs under the direct supervision of the central entity such as an access point or BS. As non-cellular devices start to share cellular spectrum, the scarcity of licensed cellular spectrum makes it very difficult for the cellular network to maintain a satisfactory QoS for the CUs because of the interferences introduced to the traditional CUs by the newly admitted devices. Using an unlicensed spectrum (small cells, WiFi, Bluetooth, ZigBee) poses another challenge for the service providers in terms of reliability, as the central nodes (eNB or BS) do not have control over the ad hoc network.

In this research we focus on resource allocation for D2D underlaying a cellular network. In D2D communication the devices can communicate with each other directly without having to go through a central node but operating under the control of it. The central node bears the responsibility of allocating resources to the devices which are to be shared with other traditional CUs. This scenario introduces some new challenges such as; firstly, the interference introduced to the regular CUs from the D2D devices; secondly, the degraded QoS of the CUs because of this interference, and thirdly, difficulty in ensuring a fair allocation of resources to the D2D devices from CUs such that no D2D device starves.

Traditional interference management techniques for cellular networks will not work for a D2D underlaying a cellular network for two main reasons; firstly, D2D users are only assigned a resource that has already been assigned to a CU in a previous time-slot unlike CUs that can be assigned a previously unassigned resource, and secondly, the D2D users have lower priority than the traditional CUs because CUs are the primary users of the cellular network and their service quality cannot be compromised because of secondary D2D users. Resource allocation for D2D underlaying cellular networks should address the aforementioned issues.

One of the main purposes of using cellular resources for D2D communication is to increase the system sum rate while maintaining a satisfactory signal quality. System sum rate is the sum of the channel rates for all communication channels including the cellular communication links and the D2D links over a given bandwidth. Therefore, the problem of resource allocation in D2D becomes an optimization problem with the goal of maximizing system sum rate or minimizing interference, and the constraints are maintaining a satisfactory signal quality for the CUs and D2D receivers. This optimization problem, which we will later show to be a mixed integer non-linear programming (MINLP) problem, takes exponential time to solve optimally. Hence, alternative sub-optimal approaches are often adopted for use in the short

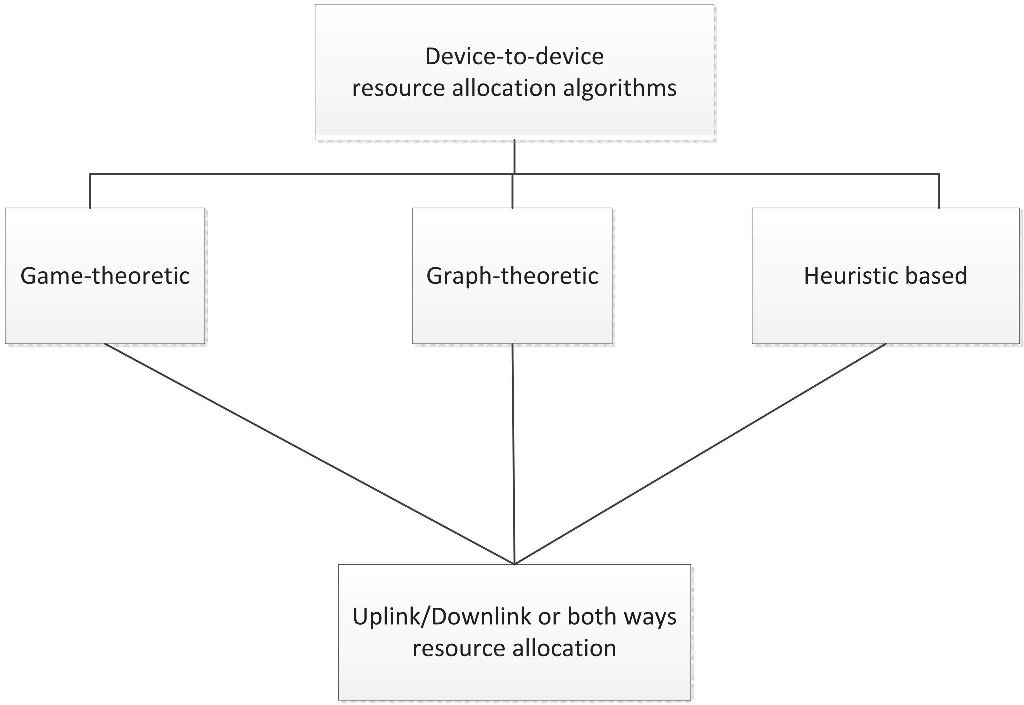

Figure 2.1: A classification of D2D resource allocation proposals.

LTE scheduling period of 1 ms.

In the next section we detail the classification of resource allocation proposals.

2.2 Classification of proposals

The classification for the resource allocation techniques is depicted in Fig. 2.1. In this section we describe the resource allocation proposals according to our classification.

2.2.1 Game-theoretic proposals

In this subsection, we present the proposals that are based on game theory.

Huang et al. [Hua+15], propose a game theoretic resource allocation technique, where complete information about the transmission parameters may not be available. The objective of this proposal is to improve on the sum rate gained over spectrum sharing even when complete information about the other players is available. A coalitional game is formed by Wang et al. [Wan+15] for community aware resource allocation. In a coalitional game the players form a group or coalition with a goal of reaching stability where the deviation of a player from its current coalition will result in decreased utility. According to game theory, for a game to be fully specified three elements need to be mentioned clearly. Firstly, the players participating in the game, secondly, the information and actions available to each player at each decision point in the game, and thirdly, the utility/payoff of each action taken in the decision points [Saa+09]. Ties in human formed social networks are exploited for resource sharing by Wang et al. [Wan+15]. This approach projects the D2D communication in both the physical and social domains. The community aware resource allocation problem is then formulated as a coalitional game and solved using a merge-and-split based approach. The performance improvement is shown in terms of inter-cell interference. Interference in a communication system refers to a disruption or modification of a signal transmitted from some source caused by signals originating from other objects on its way to the destination. Interference can be of four different types, (1) intra-cell interference, where the interference under consideration happens inside a single cell, (2) inter-cell interference, where the interference under consideration is across different adjacent cells, (3) cross-tier interference, where the aggressor and the victim are in different tiers of communication (D2D device and cellular user), and (4) co-tier interference, where the aggressor and the victim are of the same tier (both from D2D devices).

Xu et al. [Xu+12b] aim at proposing an auction based scheme to optimize system sum rate over the radio resource allocation for D2Ds and cellular User Equipments (UEs). The system model consists of a single cell with multiple users where the users are equipped with a single omni-directional antenna. In the proposed auction based approach, the spectrum resources act as the bidders to obtain packages of D2D pairs which are auctioned off as goods in each round. The auction process terminates when all the D2D links are auctioned off or every cellular channel buys a package. The authors also prove that the RA based on the reverse auction is cheat proof, i.e., it is in the best interest of all bidders to bid based on true demand, otherwise bidders may lose on the channel rate. Since the algorithm has exponential complexity, Xu et al. [Xu+12b] did not proceed with running simulations with a higher number of D2D pairs and resource units.

Xu et al. [Xu+12a] aim to mitigate additional interference introduced through spectrum sharing using a sequential second price auction. Performance result improvements are reported using system sum rate, system efficiency and system fairness improvement. The objective of Zhang et al. [Zha+13b] is to treat the problem of resource allocation in D2D communication underlaying cellular network in a distributed and cooperative manner through the use of a coalitional game. In this work, Zhang et al. [Zha+13b] view the problem of distributed allocation of resource to the D2D pairs and cellular users as a coalitional game with transferable utility. They do not show resulting interference evaluation at the network nodes. The primary goal of Huang et al. [Hua+14] is to propose a repeated game model under three different communication scenarios involving inter-cell interference to increase the system sum-rate of a D2D underlaying cellular network. Repetition is performed to fine tune the performance of the proposed game model. In the proposed game-theoretic approach for handling inter-cell interference at the neighboring BSs, the BSs act as players unlike most other game-theoretic approaches where the D2D links act as players. However, Huang et al. [Hua+14] do not mention how many D2D and cellular users were deployed and also what the traffic percentage of D2D over all the traffic was.

2.2.2 Graph-theoretic proposals

In this subsection, we present the proposals that are based on graph theory. We describe the basic ideas introduced in the proposals and make note of observations. Graph theory has attracted the attention of many researchers, in the resource allocation domain, as a powerful tool to solve this problem. In this approach, resource allocation problems are initially modeled as a graph theory based problem and then solutions to the newly modeled problem are proposed to solve the original problem.

Graph theory is used by Cai et al. [Cai+15], Zhang et al. [Zha+13c], Zhang et al. [Zha+13a], and Mou et al. [Mou+14] for obtaining D2D resource allocation. Cai et al. [Cai+15] use a graph coloring approach for resource allocation in D2D, but this approach does not mention the signal quality obtained by the interference victims. In this paper, D2D pairs in the system are viewed as a set of vertices and the resources of cellular users are viewed as a set of colors to model the resource allocation problem as a graph coloring problem. The objective of Zhang et al. [Zha+13c] is to find interference aware resource allocation graph for allocating resource to D2D users underlaying a cellular network and then using the graph to devise an algorithm to find a resource assignment for the D2D users. Zhang et al. [Zha+13c] first define the resource allocation problem and formulate the non-deterministic polynomial time hard (NP-hard) optimization problem resulting from the resource allocation problem. To reduce the complexity of resource allocation they opted for an alternate graph based approach. Another graph based approach was described by Zhang et al. [Zha+13a] for uplink channel level resource allocation yet does not address RB level resource allocation. The focus of this approach was on system sum rate improvement only.

Mou et al. [Mou+14] analyze the performance of three types of radio resource allocation schemes for D2D communications for bursty traffic. They formulate three different types of resource allocation schemes for D2D communications: 1) full reuse (FR) method where D2D links share the same resources simultaneously, and links with backlogged packets in the queue can transfer simultaneously, 2) orthogonal reuse (OR), where D2D links use dedicated resources and a link can transmit only when it is scheduled in the time slot, and 3) partial reuse (PR), where D2D links are partitioned into different groups and only D2D links that are in the same reuse group can share the resources. This paper proposes a graph based interference allocation scheme to address this grouping problem.

2.2.3 Heuristics-based proposals

In this subsection, we present heuristics-based proposals. An insight into the D2D resource allocation problem and the participating network entities can lead to a heuristic-based resource management approach for D2D underlaying cellular network. The heuristic can be a greedy approach based on an intuition, an observation over time or simply experimental.

Zulhasnine et al. [Zul+10] aim to provide UL and DL resource sharing schemes for D2D underlaying cellular network to increase system throughput. They start with formulating the resource allocation problem for D2D in UL and DL as two MINLPs. However, these MINLPs are exceedingly difficult to solve in the short scheduling time of 1 ms in LTE. Therefore, Zulhasnine et al. [Zul+10] propose two similar greedy approaches for resource sharing among the D2D and cellular uses in UL and DL. The objective of Janis et al. [Jan+09] is to propose a practical scheme for generating local awareness of interferences among the D2D users and cellular users at the BS for resource allocation. It also exploits the multiuser diversity to minimize the interference. Identical splitting between uplink and downlink resources is assumed so that no interference is generated between uplink and downlink transmissions.

Naderializadeh and Avestimehr [NA14] propose a novel, computationally inexpensive spectrum sharing approach for D2D communications to improve network efficiency in terms of sum rate gain. The authors present a new concept of information-theoretic independent sets (ITIS) to identify the sets of links for which simultaneous communication and treating interference from each other as noise is information theoretically optimal to within a constant gap. Noise in a communication channel refers to an undesirable random disturbance of a transmitted signal. Following this idea they present a spectrum sharing technique called information theoretic link scheduling (ITLinQ) which schedules links in an ITIS. The work by Malandrino et al.

[Mal+14] provides a fast approximate dynamic programming solution to the resource allocation problem in heterogeneous networks supporting D2D communication. Dynamic programming is a mathematical programming technique for solving complex problems by breaking them into smaller overlapping sub problems and with optimal substructure. It takes less time to solve these problems using dynamic programming than using the naive method of solving it by a brute force method that does not exploit the overlap. For more information on dynamic programming please see [KT06]. Resource allocation in LTE networks can be computationally very expensive if optimal allocation is sought after. Malandrino et al. [Mal+14] try to reduce this complexity without making room for trivial assumptions. The approximate dynamic programming approach adopted provides a suboptimal solution in polynomial time and runs in linear time to the total number of network nodes.

The primary objective of Bansal et al. [Ban+14] is to propose a two time-scale solution for the resource allocation problem for D2D: a coarse time-scale (epoch level-lasting several tens of frames) dynamic fractional frequency reuse (FFR) scheme to leverage the flexibility of D2D traffic and also a finer time-scale (frame-level) scheduling solution for the cellular and D2D traffic jointly across both DL and UL directions. FFR is an interference management technique for OFDMA (Orthogonal Frequency Division Multiple Access) based cellular networks where different spatial parts of the cells use the spectrum with different frequency reuse factors [Nov+11]. The rate at which the same frequency can be used in the cellular network is called the frequency reuse factor.

The objective of Xu et al. [Xu+10] is to leverage the LTE cellular network peculiarities in order to devise a novel method for uplink resource allocation in D2D communication underlaying cellular network and also avoids interference in the process. The authors use the fact that in LTE UL a cellular UE sends data after several transmission time intervals (TTI) on receipt of resource allocation information from eNB. The D2D users may finish their resource management by using related cellular information within this time (order of milliseconds). The overhead involved in the extra sensing and signaling is not mentioned in the measurements presented in the paper. Peng et al. [Pen+09] in [Pen+09] propose new techniques for interference management while sharing resources between cellular and D2D users in the UL. The paper proposes two mechanisms for interference management in the UL. The first one is to mitigate the interference caused by the cellular user to the D2D receiver through an interference tracing approach and the second one is to avoid interference caused by the D2D transmitter on the cellular receiver through a tolerable interference broadcasting method.

The goal of Golrezaei et al. [Gol+12] is to propose a novel technique for increasing throughput of video files in cellular communication through caching in user devices. The proposal introduces architecture for improving the throughput of video transmission in cellular networks by caching popular video files in cellphones in BS controlled D2D communications. They propose dividing the microcells into virtual clusters, and the size of the cluster plays a vital role in the system performance. Assuming that the transmission within a cluster does not interfere with other clusters is not realistic. The authors did not present any information on what could happen if the simplified assumptions are lifted and how this would introduce additional interferences.

Yu and Tirkkonen [YT12] adopt a rate splitting approach to maximize system sum rate for D2D communication underlaying cellular networks. In this paper the authors propose an approach similar to Han and Kobayashi [HK81], a scheme where a message is split into two parts: a private message to be decoded only at the intended receiver and a public message decoded at all receivers. An arbitrary power splitting between the public and private messages is also taken into account. Decoding the public message cancels the interference to an extent. In addition to the proposed rate-splitting method the authors also mention three more traditional approaches: interference-as-noise mode (INM), orthogonal sharing mode (OSM) and the cellular mode (CM). In the INM, the D2D and cellular users reuse the same resources causing interferences to each other; and the BS coordinates the power of transmission taking these interference values into consideration. In the OSM, orthogonal resource sharing ensures non-interference. In the CM, the D2D devices communicate through BS that acts as a relay node. Therefore, no direct D2D is available in CM mode.

Lee et al. [Lee+14] propose a semi-distributed resource management approach for D2D communications in cellular networks to achieve the performance gains of both centralized and distributed approaches, i.e., increase system throughput and decrease computational or control overload. In the first of two stages of resource management, the BS allocates resources to the base station to user-device (B2D) and D2D links based on limited channel information which is the path loss of all relevant links. In the second stage, the devices of the D2D links determine the modulation and coding scheme (MCS) level and the transmission power associated with the link. In the meantime, the BS schedules the transmissions to and from the cellular users on the B2D links. The BS uses the MCS index to let a terminal know the modulation and coding scheme to use in sending (or transmitting) a particular transport block.

Moubayed et al. [Mou+15] divide the problem of wireless resource visualization with D2D communication underlaying the LTE network into two smaller integer linear programs and then propose two lower complexity heuristics based algorithms to obtain close to optimal results.

2.3 Comparison of the proposals

In this section we provide a comparison of the existing resource allocation proposals for D2D communication underlaying cellular network based on some performance metrics. We found that in the majority of the literature, several performance metrics are common, for example system sum rate and system throughput. Yet some proposals define new performance metrics based on their problem formulation or the metric that best reflects their specific contribution.

One needs to have a clear understanding of the metrics to realize the true gain achieved from these techniques. Therefore, we define the metrics that have been used to evaluate the performances of proposals:

- Signal-to-Interference-and-Noise Ratio (SINR) -

  SINR refers to the ratio of the signal to the sum of all the interferences and noise in the communication channel.

$$SINR = \frac{S}{I+N}$$

Here S refers to the signal, I refers to all the interferences in the channel and N refers to the noise in the channel. SINR is expressed in decibels of dB.

- Signal-to-Noise Ratio (SNR) - SNR refers to the ratio between the transmitted signal and noise in the communication channel. Therefore,

$$SNR = \frac{S}{N}$$

- Spectral efficiency - The information rate that can be achieved to communicate in a communication system over a given bandwidth in a defined geographic area.

- System throughput - The sum of the data rates that are delivered to the devices in the network.

- System sum rate - The sum of the channel rates for all communication channels including the cellular communication links and the D2D links over a given bandwidth.

- Cell throughput - the throughput achieved in one cell rather than the whole cellular network.

- Control overhead - the signaling required for the control information and other tasks of the proposal which is more than that is required by the adopted technology (e.g. LTE) standard.

- Sum rate gain - the ratio of the sum of the rate obtained at the BS and the sum rate of D2D communication to the sum rate obtained in cellular communication except the D2Ds [Hua+14].
- System efficiency - the ratio of the obtained sum rate to the optimal sum rate [Xu+12b].
- System utility - sum of the payoff of each community [Wan+15].
- Dropping probability - the probability with which a D2D link packet is dropped from the queue of the queueing model [Mou+14].
- Maximum average number of active clusters - the average number of parallel links in the cell [Gol+12].
- Sum rate ratio - the ratio of the sum rate obtained by the rate splitting method, to the sum rate of the best mode selection among traditional resource sharing modes (as defined in [YT12]).
- Interference CDF (Cumulative Distribution Function) - CDF(x) means the probability with which the interference is less than or equal to x.
- Probability of D2D link - the probability of a D2D link existing on one of the cellular channels [KA08].
- Probability of a clustered D2D link - the probability of a link between a D2D transmitter and a D2D receiver inside a randomly placed cluster [KA08].

- CDF of completion times - the probability with which the completion time of a download is less than or equal to a given value [Mal+14].
- Transmission length - the number of time-slots required in which a feasible access pattern of D2Ds is scheduled in a frame [Phu+13].

Table 2.1 shows the comparison of the D2D resource allocation (RA) proposals based on five different criteria:

1. Direction - whether the proposal addresses resource allocation in only UL or DL or in both spectrums.
2. Analytical tools used - this column lists the analytical tools used by the proposal in question.
3. Main Objective - the main goal of the proposed technique.
4. Complexity - the computational complexity of the proposed resource allocation technique. This is of particular importance as in LTE resources are allocated on frame level (10 ms). Therefore, fast resource allocation algorithms are desirable. In some of the cases only LTE system level simulations were performed with some changes in the original standard but no algorithms were presented to account for actual complexity. These entries in the Table 2.1 are written as system level simulation.
5. Evaluation metrics used - the main performance metrics used in the proposal to evaluate the efficiency of the proposal.

Table 2.1: Performance comparison of resource allocation algorithms.

Metric → **Proposal ↓**	**Direction**	**Analytical Tools Used**	**Main Objective**	**Complexity**	**Evaluation Metrics Used**
[Hua+15]	UL/DL	Game theory	Increase system sum rate	Non-trivial to determine	System sum rate
[Wan+15]	UL	Game theory	Community aware resource allocation	Non-trivial to determine	System utility
[Xu+12b]	DL	Game theory	Optimize system sum rate	$\mathcal{O}(n(2^m-1)+t)$, where t is the total number of iterations, m is the number of items to be allocated and n is the number of bidders	System sum rate and system efficiency =obtained rate/optimal rate
[Xu+12a]	UL	Game theory	Optimize system sum rate	Non-trivial to determine	System sum rate
[Zha+13b]	DL	Coalitional Game	Formulate coalitional game with lower complexity to improve sum rate.	For merge $\mathcal{O}(m^2)$ where m is the total number of cellular and D2D pair users and for split $\mathcal{O}(2^{\lvert S \rvert})$ for coalition S.	System sum rate

Table 2.1 – *Continued from previous page*

Metric → **Proposal ↓**	**Direction**	**Analytical Tools Used**	**Primary Objective**	**Complexity**	**Evaluation Metrics Used**
[Hua+14]	UL/DL	Game theory based	Handle inter-cell interference to increase system sum rate	$\mathcal{O}(t_{max} * B^3)$, where t_{max} is the maximum number of iterations and B is the number of interfering base stations	Sum rate and Sum rate gain
[Cai+15]	DL	Graph theory	maximize system sum rate	$\mathcal{O}(2^n n)$, where n is the number of vertices or devices in the graph to be colored	System sum rate
[Zha+13c]	DL	Graph theory based	Obtain near-optimal resource assignment solutions at the BS with low computational complexity	$\mathcal{O}(\frac{(M+N+1)(M+N)K}{2})$, Where M, N and K correspond to the number of cellular UEs, number of D2D pairs and total number of RBs	Network sum rate

Table 2.1 – *Continued from previous page*

Metric → **Proposal ↓**	**Direction**	**Analytical Tools Used**	**Primary Objective**	**Complexity**	**Evaluation Metrics Used**
[Zha+13a]	UL	Graph theory	Optimize system capacity	$\mathcal{O}(mn^2)$, where m and n are the number of D2D pairs and cellular users respectively	System capacity
[Mou+14]	UL/DL	Graph theory	Use queueing model for RA to control interference among devices of different colors in the interference graph	$\mathcal{O}(2^n n)$, where n is the number of vertices or devices in the graph to be colored	Mean Throughput and dropping probability
[Zul+10]	UL/DL	Mixed Integer Non-linear Programming and Greedy heuristic	Lessen the interference to the cellular network by utilizing the channel gain information	$\mathcal{O}(max\|C\|, \|D\|)$, where C and D are the list of all DL/UL UEs and the list of all D2D connections yet to be assigned	Network throughput

Table 2.1 – *Continued from previous page*

Metric → **Proposal ↓**	**Direction**	**Analytical Tools Used**	**Primary Objective**	**Complexity**	**Evaluation Metrics Used**
[Jan+09]	UL/DL	Convex optimization	Minimize interference by exploiting multi-user diversity	$O(n!)$ where n is the number of active UL transmitters and D2D receivers in a cell	Cellular link SINR CDF, D2D link SINR CDF, cell capacity CDF
[NA14]	UL/DL	Information theory -based independent sets	Distributed allocation with proportional fairness to increase system sum rate	$\mathcal{O}(n^2)$, where n is the total number of links in the network	Average achievable system sum rate
[Mal+14]	DL	Approximate Dynamic Programming	Increase system throughput and reduce energy consumption	$\mathcal{O}(\|U\|)$, where U is the total number of network nodes	CDF of completion times, downloaded data and energy consumed
[Ban+14]	UL/DL	Greedy heuristics and approximation algorithms	Leverage the flexible nature of D2D traffic to intelligently schedule resources	$\mathcal{O}(N^2K^3)$, $\mathcal{O}(N^2K)$ and $\mathcal{O}(N^4K^3)$ where N and K are the number of OFDMA resource	Throughput

Table 2.1 – *Continued from previous page*

Metric → Proposal ↓	Direction	Analytical Tools Used	Primary Objective	Complexity	Evaluation Metrics Used
				blocks and the number of users in each sector respectively	
[Xu+10]	UL	NA	Avoid interference by exploiting network peculiarity of a hybrid network	System level simulation	System average throughput, interference CDF
[Pen+09]	UL	NA	Mitigating interference to improve system performance	System level simulation	Throughput and interference
[Gol+12]	DL	Zipf distribution	Increase throughput of video files	Numerical Simulation	Spectral efficiency of active clusters maximum average number of active clusters
[YT12]	DL	Han-Kobayashi	Increase system efficiency by deriving an optimal	Numerical optimization of splitting factors	Sum rate ratio and per user spectral efficiency

Table 2.1 – *Continued from previous page*

Metric → **Proposal ↓**	**Direction**	**Analytical Tools Used**	**Primary Objective**	**Complexity**	**Evaluation Metrics Used**
			rate splitting factors		
[Lee+14]	UL/DL	Linear programming, Greedy heuristic and column generation technique	Combine performance gains of both centralized and distributed approach	Greedy: $\mathcal{O}(L^4)$, where L is the number of D2D links. Column generation: $\mathcal{O}(L^3k)$, where k is the average number of iterations.	Cell throughput and control overhead
[Mou+15]	DL	Heuristic based technique	Increase system throughput	First phase: $\mathcal{O}(L * \lvert C \rvert)$, where L is the number of RBs available and $\lvert C \rvert$ is the total number of cellular users in the system. Second Phase: $\mathcal{O}(\lvert D_m \rvert * \lvert C_m \rvert)$, where $\lvert D_m \rvert$ is the number of D2D pairs and $\lvert C_m \rvert$	Cell throughput and control overhead

Table 2.1 – *Continued from previous page*

Metric → Proposal ↓	Direction	Analytical Tools Used	Primary Objective	Complexity	Evaluation Metrics Used
				is the number of cellular users per service provider.	

From Table 2.1 we can have an idea about the current literature addressing the radio resource allocation for D2D communication underlaying cellular networks. However, in the literature there is hardly any approach addressing the fair allocation of radio resources to D2D specifically. In some cases fairness is used as a metric to compare performance results, however to ensure fairness was not an integral part of these approaches. We identify this research gap and address this issue of fair allocation of resources among D2D pairs. In the process we also minimize interference and satisfy a system sum rate demand. We also observe that, in the literature system sum rate demand is rarely used as a constraint that needs to be fulfilled. In the first two chapters of this thesis we formulate the problem as an interference minimization problem while ensuring a system sum rate demand is satisfied. This constraint ensures a minimum service rate guarantee for a cell.

Furthermore, we also identify that local search based approaches can be an efficient way to solve the resource allocation problem for D2D underlaying cellular networks. These algorithms are simple in working principle and can be solved by performing only local computations. To our knowledge, no local search based approach for D2D resource allocation underlaying cellular networks exists in the literature and therefore the local search algorithms proposed in this thesis can serve as the basis for future local search based resource allocation algorithms for D2D underlaying cellular networks.

Additionally, in the literature there is rarely any mention of a stable resource allocation in D2D. However, a stable allocation may be useful for D2D communication when D2D devices are relatively stationary and do not need to be rescheduled frequently. To this end, we propose a deferred acceptance based resource allocation that can provide a stable allocation of cellular resources to D2D pairs. By stable allocation we mean that changing the current allocation will affect the cellular network in a negative manner and it is of best interest of the cellular network to maintain in the current allocation unless some parameters are changed.

2.4 Summary

In this chapter, we classified the resource allocation proposals based on the approach used and then compared them based on different criteria as shown in Table 2.1. The resource allocation problem of D2D devices is a computationally expensive problem. Therefore, most of the proposals try to derive heuristic based observations and intuitions and work on these to design an algorithm for allocating resources. These algorithms do not guarantee optimal solution; however, run faster than the exhaustive approach to obtain optimal solution and provide close to optimal solutions for practical use in the short scheduling period of LTE. We also identified some research gaps that we addressed in this thesis. In the next chapter we present our first channel level resource allocation algorithm.

Chapter 3

Channel Level Resource Allocation

Simultaneous usage of LTE cellular spectrum with D2D devices comes with the price of additional interference being introduced. In this chapter, we present a channel level resource allocation scheme which uses channels of LTE that cellular users can share with D2D devices, without incurring expensive computation and at the same time increasing total system sum rate. This interference coordination based resource allocation scheme can mitigate the problem of newly introduced interference because of spectrum sharing.

We propose a novel scheme called Minimum Knapsack-based Interference-aware Resource Allocation (MIKIRA) for minimizing the interference and increasing the SINR (Signal to Interference and Noise Ratio) at the eNB while sharing the cellular channels with the D2D pairs in an LTE cellular network. In this work, we show that this allocation problem can be modeled as a minimum knapsack problem and we use this approach to find an allocation of resources for the D2D pairs such that the signal quality at the eNB is improved. The contribution here is multi-fold. Firstly, the proposed scheme obtains a better signal quality at the eNB while maximizing the

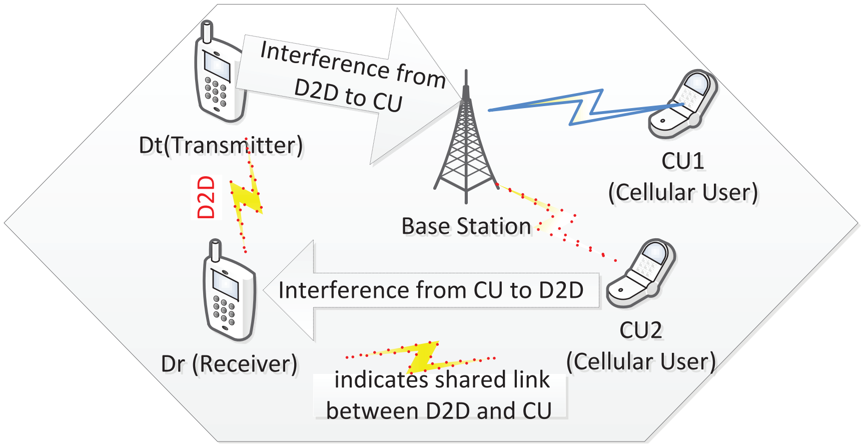

Figure 3.1: Co-channel interference scenario in D2D communication underlaying LTE cellular network (Uplink Resource Sharing - redrawn based on [Zha+13a]).

system sum rate. Secondly, the complexity of the proposed approach is polynomial and suitable for the short scheduling period (1 ms) of LTE.

The rest of this chapter is organized as follows. We describe the system and channel model in Section 3.1. Problem formulation is presented in Section 3.2. The detailed working procedure of the proposed scheme is described in Section 3.3. Experimental results are presented in Section 3.4. Finally, we provide a summary of the chapter in Section 3.5.

3.1 System and Channel Model

3.1.1 System Model

Consider the scenario in Figs. 3.1 and 3.2. As shown in Fig. 3.1, when an uplink resource is shared between a D2D pair and a Cellular User (CU) then the victims of the interferences are the eNB from the D2D transmitter and the D2D receiver

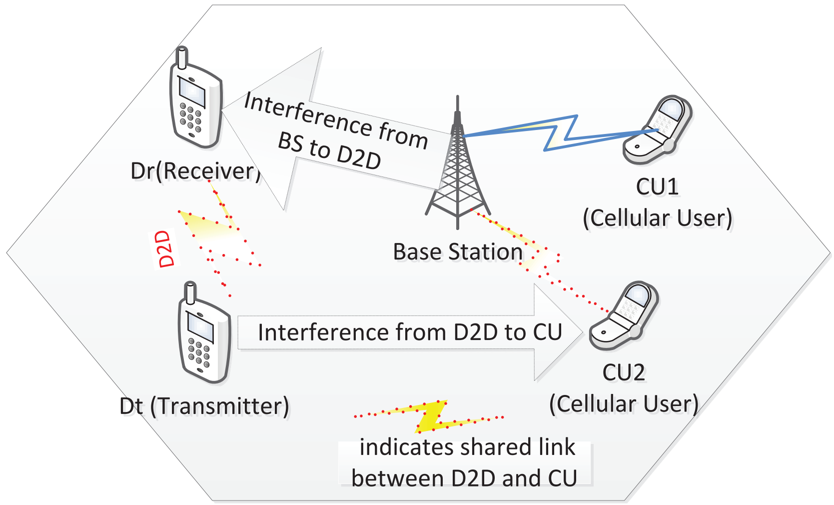

Figure 3.2: Co-channel interference scenario in D2D communication underlaying LTE cellular network (Downlink Resource Sharing - redrawn based on [Zha+13a]).

from the CU. In Fig. 3.1, CU2 shares the channel with the D2D pair and causes interference at the D2D receiver. The shared link is represented by the red-dotted line. The dark-outlined link shows that the cellular link is not shared.

Similarly, when a downlink resource is shared between a D2D pair and a CU then the victims of the interferences are the D2D receiver from the eNB and the CU (in this case CU2) from the D2D transmitter as depicted in Fig. 3.2. In this chapter we address the uplink resource sharing scenario between D2D and CU.

We consider an uplink scenario in our work with m D2D pairs and n CUs. The D2D pairs can share the channel with the CUs. Based on the requests from the D2D pairs the eNB knows which connections are to be treated as D2D and which are regular cellular cellular connections. However, the eNB decides which D2D pair to coordinate with which CU. In our case we are assuming orthogonal channels.

Therefore only intra-channel interference comes into play due to the channel sharing. The cellular users are represented by CU_i, where $1 \leq i \leq n$, and D2D pairs are represented by D_j, where $1 \leq j \leq m$. To differentiate between the transmitter and the receiver in the D2D pair D_j we denote the transmitter using D_j^t and receiver using D_j^r. The transmit powers of the D2D devices and the CUs are P^D and P^C respectively.

3.1.2 Channel Model

In our system, the channel is modeled as a Rayleigh fading channel [Skl97]. Accordingly, the individual channel responses follow an independently and identically distributed gaussian process. The path loss model we used is described in [IR08] for Urban Micro systems (UMi). For UMi the distance dependent path loss model we used is as follows-

$$PL = 36.7log_{10}(d) + 22.7 + 26log_{10}(f_c)$$

Here, d is the distance between the transmitter and the receiver (in metres) and f_c is the frequency (in GHz).

The channel gains of the cellular link from CU_i to the eNB and of the D2D link from D_j^t to D_j^r are denoted by $G_i^{CU,eNB}$ and $G_j^{D_t,D_r}$ respectively. The corresponding co-channel interferences as shown in Fig. 3.1 are represented by $G_j^{D_t,eNB}$ and $G_{i,j}^{CU,D_r}$ for the interferences caused by the D2D transmitter on the eNB and by the CU on the D2D receiver respectively. The channel gains are expressed as a function of distance dependent path loss and a small scale fading and take the following form.

$$G^{a,b} = PL^{a,b}h^{a,b}$$

Here, $PL^{a,b}$ is the distance dependent path loss between a and b and $h^{a,b}$ is the small scale fading between a and b.

3.2 Problem Formulation

In our approach, we opt to fit the interference minimization problem into a minimum knapsack problem. The objective of the minimum knapsack problem is to find the least costly set of items such that the total value of the selected items is at least the demand D. The minimum knapsack problem can be formulated as the following integer program:

MIN-KNAPSACK:

$$\text{minimize} \sum_{i=1}^{n} C_i x_i \tag{3.1}$$

$$\text{subject to} \sum_{i=1}^{n} W_i x_i \geq D \tag{3.2}$$

$$x_i \in \{0, 1\}, \forall \quad i \in \{1, ..., n\} \tag{3.3}$$

In (3.1), (3.2) and (3.3), C_i and W_i denote the cost and value associated with each item respectively and x_i is a binary variable representing whether the item was selected in the optimal solution. The values of the selected items should meet the demand value D while keeping the cost to a minimum.

We denote the matrix representing whether a cellular user CU_i shares resources with a D2D pair D_j using $S_{n\times m} = [a_{i,j}]$. The entries in the matrix are binary variables representing whether the corresponding D2D pairs and CUs share resources. The objective of our optimization problem MIN-INTERFERENCE is to minimize the interference introduced in the process.

MIN-INTERFERENCE:

$$\text{minimize} \sum_{i=1}^{n}\sum_{j=1}^{m} a_{i,j} I_{i,j} \tag{3.4}$$

$$\text{subject to} \sum_{i=1}^{n}\sum_{j=1}^{m} a_{i,j} C_{i,j} \geq R \tag{3.5}$$

$$\sum_{i=1}^{n} a_{i,j} \leq 1, \forall \quad j \in \{1, ..., m\} \tag{3.6}$$

$$\sum_{j=1}^{m} a_{i,j} \leq 1, \forall \quad i \in \{1, ..., n\} \tag{3.7}$$

$$a_{i,j} \in \{0, 1\}, \forall \ i \in \{1, ..., n\} \text{ and } \forall \ j \in \{1, ..., m\} \tag{3.8}$$

Here, $I_{i,j}$ and $C_{i,j}$ indicate the interference introduced if CU_i and D2D pair D_j share the uplink resources and the associated channel rate respectively and R indicates the total expected system sum rate. Here $a_{i,j}$ is a binary decision variable indicating whether the cellular channel associated with CU_i was shared with D2D pair D_j. Constraints (3.6) and (3.7) ensure that, one D2D pair is assigned only one cellular channel and one cellular channel is assigned to at most one D2D pair. If more than one sharing is allowed on the same resource then the interference coordination becomes much more difficult to handle. The value of $I_{i,j}$ is calculated from the interference part of the denominator of the following equations (3.10), (3.11) and (3.12). The value of $I_{i,j}$ is calculated using the following equation:

$$I_{i,j} = P^D G^{jt,eNB} + P^C G^{i,jr} \tag{3.9}$$

$$SINR_{i,j,1} = \frac{P^C G^{i,eNB}}{N + P^D G^{jt,eNB}} \tag{3.10}$$

$$SINR_{i,j,0} = \frac{P^C G^{i,eNB}}{N} \tag{3.11}$$

$$SINR_{i,j} = \frac{P^D G^{jt,jr}}{N + P^C G^{i,jr}} \tag{3.12}$$

Where, $SINR_{i,j,1}$ denotes the SINR at the eNB when CU_i shares the channel with D2D pair D_j. $SINR_{i,j,0}$ denotes the SINR at the eNB when the CU_i does not share the channel with any D2D pair and $SINR_{i,j}$ denotes the SINR at the receiver of the D2D pair D_j when it shares the channel with CU_i. N represents the noise in the channel. The final interference of an item in $S_{n\times m}$ is calculated by the sum of the two types of interferences: interference at eNB from 3.10 and interference at D2D receiver from 3.12. Here one item in $S_{n\times m}$ indicates one particular combination of a CU_i and a D2D pair D_j.

The terms $G^{i,eNB}$, $G^{jt,eNB}$, $G^{jt,jr}$ and $G^{i,jr}$ denote the channel gain obtained from the cellular device CU_i to the eNB, the interference from the transmitter of D2D pair D_j to the eNB, the channel gain from the transmitter of the D2D pair D_j to the receiver of the same D2D pair D_j, and the interference from the cellular user CU_i to the receiver of the D2D pair D_j. The channel rate of the cellular channel associated with CU_i when it is shared with a D2D pair D_j is calculated by the following formula.

$$C_{i,j} = \log_2(1 + SINR_{i,j,1}) + \log_2(1 + SINR_{i,j}) - \log_2(1 + SINR_{i,j,0}) \tag{3.13}$$

The channel rate is indicated by $C_{i,j}$ when the CU_i and D2D pair D_j share the uplink resources. The value of R in (3.5) can be based on heuristics depending on the number of cellular users and the number of D2D pairs participating in the communication. This can also be a fraction of the theoretical maximum system sum rate possible for the network configuration. In our case we set the value of R as a fraction of the system sum rate obtained from a Graph-based Resource Allocation scheme (GRA) [Zha+13a] because it gives a near optimal sum rate value. Now that we have R, we can formulate the channel sharing scheme as a minimum knapsack problem as in MIN-INTERFERENCE.

3.3 Minimum Knapsack-based Interference-aware Resource Allocation Scheme (MIKIRA)

The knapsack problem is listed as one of the 21 NP-Complete problems in the original list by Karp [Kar72]. For an input of size n, the $0-1$ minimum knapsack problem can be solved using any of the several constant factor approximation algorithms. It can be solved in $\mathcal{O}(n \log n)$ time with an approximation ratio of 2 or it can also be solved in $\mathcal{O}(n^2)$ time with an approximation ratio of 1.5 [Csi+91]. Depending on the time/accuracy requirement the user the can choose an approach to solve the minimum knapsack problem. We have used the approximation algorithm presented in [Csi+91] for solving the minimum knapsack problem formulated.

3.3.1 Pseudocode of MIKIRA

In MIKIRA, at first an $n \times m$ matrix $S_{n\times m}$ is formed for the n cellular users and m D2D pairs and all the elements are initialized to 0 (line 2 of Algorithm 1). From line 3 to 7 all the $I_{i,j}$ values are calculated, which is the interference part of the denominators of (3.10), (3.11) and (3.12). Then from line 8 to 15 the values for $SINR_{i,j,1}$, $SINR_{i,j,0}$, $SINR_{i,j}$ and $C_{i,j}$ are calculated. From line 16 to 18 the entries in matrix $S_{n\times m}$ are filled with the solution obtained by Algorithm 2 [Csi+91]. However, to ensure that the constraints (3.6) and (3.7) hold, we modify Algorithm 2 to include only the solutions that do not violate (3.6) and (3.7).

In Algorithm 2 we have a total of $\mathbb{M} = n \times m$ elements. Each of the elements has an associated interference and channel rate as explained in Section 3.2. The items are first sorted based on their relative interferences which is calculated by taking the ratio of total interference and the rate associated with it. Sorting is an integral part of selection in this approach. The greedy approximation algorithm [Csi+91] for the minimum knapsack problem is presented in Section 3.3.2.

Algorithm 1 Minimum Knapsack-based Interference-aware Resource Allocation Scheme (MIKIRA)

procedure MIKIRA($C(c_1, c_2, ..., c_N), D(d_1, d_2, ..., d_M)$) ▷ An allocation from C to D
    $S_{n\times m} \leftarrow [a_{i,j}] \leftarrow 0$ ▷ Initially none of the links are shared
    for each $i \in C$ **do** ▷ All cellular users
        for each $j \in D$ **do** ▷ All D2D devices
            Calculate the values of $I_{i,j}$. This is the denominator (excluding the noise part N of (3.10), (3.11) and (3.12)).
        end for
    end for
    for each $i \in C$ **do** ▷ All cellular users
        for each $j \in D$ **do** ▷ All D2D devices
            $SINR_{i,j,1} \leftarrow$ value from (3.10) using $I_{i,j}$
            $SINR_{i,j,0} \leftarrow$ value from (3.11) using $I_{i,j}$
            $SINR_{i,j} \leftarrow$ value from (3.12) using $I_{i,j}$
            $C_{i,j} \leftarrow$ value from (3.13)
        end for
    end for
    $S_{n\times m} \leftarrow$ GreedyApprox($C_{i,j}, I_{i,j}, R$)
    Report $S_{n\times m} = [a_{i,j}]$ as the final allocation
end procedure

3.3.2 Greedy approximation algorithm for minimum knapsack problem

Csirik et al. [Csi+91] proposed a greedy heuristic for the 0-1 min-knapsack based on the heuristic for max-knapsack by Gens and Levner [GVG79]. Let us assume there are n items each with interference I_i and capacity C_i. These n items are first sorted in nondecreasing order of their relative interferences. Relative interference of an item i is defined as the ratio of the interference I_i of the item to the capacity C_i of the item. After sorting,

Algorithm 2 Greedy approximation algorithm for Minimum Knapsack [Csi+91]

procedure GreedyApprox($C(C_1, C_2, ..., C_{\mathbb{M}}), I(I_1, I_2, ..., I_{\mathbb{M}}), R$)
    for each $i \in \mathbb{M}$ **do** ▷ All $\mathbb{M} = n \times m$ items
        $RelativeInterference_i \leftarrow \frac{I_i}{C_i}$
    end for
    Based on $RelativeInterference$ values non-decreasingly sort $\mathbb{M}$ items in a list L.
    $finalSolution \leftarrow \phi$
    $CandidateSolutions \leftarrow \phi$
    Find the first index k_1 which $\sum_{i=1}^{k_1} C_i < R \leq \sum_{i=1}^{k_1+1} C_i$.
    $S_1 \leftarrow (1, 2, ..., k_1)$ ▷ Small items
    $CandidateSolutions \leftarrow S_1 \cup \{k_1 + 1\}$ ▷ Candidate solutions
    repeat
        Find k_2 such that, $\forall j \in [k_1 + 2, ..., k_2 - 1]$: $\sum_{i=1}^{k_1} C_i + C_{k_2} < D$ and $\sum_{i=1}^{k_1} C_i + C_j \geq D$ hold true.
        $B_1 \leftarrow (k_1 + 1, ..., k_2 - 1)$ ▷ Big items
        $CandidateSolutions \leftarrow S_1 \cup \{j\}, \forall j \in [k_1 + 2, ..., k_2 - 1]$
        Find $k_3 \geq k_2$ such that, $\sum_{i=1}^{k_1} C_i + \sum_{i=k_2}^{k_3} C_i < R \leq \sum_{i=1}^{k_1} C_i + \sum_{i=k_2}^{k_3+1} C_i$.
        $S_2 \leftarrow \{k_2, ..., k_3\}$ ▷ Second set of small items
        $CandidateSolutions \leftarrow S_1 \cup S_2 \cup \{k_3 + 1\}$.
    until The end of L using k_{2i+1} instead of k_1 and k_{2i+2} instead of k_2 in the i^{th} iteration
    $finalSolution \leftarrow CandidateSolutions$ element with minimum interference that does not violate constraints (3.6) and (3.7).
    return $finalSolution$
end procedure

$$I_1/C_1 \leq I_2/C_2 \leq I_3/C_3 \leq ... \leq I_n/C_n$$

The greedy approach first scans through the items sorted according to their relative interferences to find the first index k_1 for which,

$$\sum_{i=1}^{k_1} C_i < R \leq \sum_{i=1}^{k_1+1} C_i,$$

where R is the demand or in our case total expected system sum rate. Now we have the first candidate solution in the sublist of items $(1, 2, ..., k_1 + 1)$. The set of items for which the total capacity of the set is less than the expected system sum rate are denoted as as the set of *small items*. Therefore, $S_1 = (1, 2, ..., k_1)$ is the first set of *small items*. The first candidate solution is, $S_1 \cup \{k_1 + 1\}$.

First phase: Starting from the next item $k_1 + 2$ we scan through the items and let k_2 be the next item for which $\sum_{i=1}^{k_1} C_i + C_{k_2} < R$. Therefore, for all the items $j \in [k_1 + 2, ..., k_2 - 1]$ the following holds,

$$\sum_{i=1}^{k_1} C_i + C_j \geq R$$

All items from $k_1 + 1$ to $k_2 - 1$ are denoted as *big items* and let the first set of *big items* be $B_1 = (k_1 + 1, ..., k_2 - 1)$. Now all sets $S_1 \cup \{j\}, j \in [k_1 + 2, ..., k_2 - 1]$, are candidate solutions.

Second phase: Scan again from next item for the first index $k_3 \geq k_2$ for which the following holds,

$$\sum_{i=1}^{k_1} C_i + \sum_{i=k_2}^{k_3} C_i < R \leq \sum_{i=1}^{k_1} C_i + \sum_{i=k_2}^{k_3+1} C_i$$

Now we have the second set of *small items* in $S_2 = \{k_2, ..., k_3\}$. At this stage, $S_1 \cup S_2 \cup \{k_3 + 1\}$ is also a candidate solution having only one big item at the end. We repeat phase one and phase two until the end of the list using k_{2i+1} instead of k_1 and k_{2i+2} instead of k_2 in the i^{th} iteration. The final solution will be the one with smallest interference amongst all the candidate solutions.

The sorting step takes $\mathcal{O}(n \log n)$ and the later steps take $\mathcal{O}(n)$ time. This greedy approximation algorithm has an approximation ratio of 2 [Csi+91]. The procedure is shown in Algorithm 2. This can be further improved to have an approximation ratio of 1.5 in $\mathcal{O}(n^2)$ time 2.

3.3.3 Complexity Analysis

Our approach solves a minimum knapsack problem with $n \times m$ elements. Here, n is the number of cellular users and m is the number of D2D pairs. The approximation technique described in [Csi+91] can solve the minimum knapsack problem with n items with computational complexity $\mathcal{O}(n \log n)$ time, our minimum knapsack problem having $\mathbb{M} = n \times m$ elements has the computational complexity of $\mathcal{O}(\mathbb{M} \log \mathbb{M})$ which is better than Zhang et al. [Zha+13a] that solves the allocation problem by mapping it into a matching problem where each D2D pair can be associated with only one CU and vice versa. The complexity of the approach in Zhang et al. [Zha+13a]

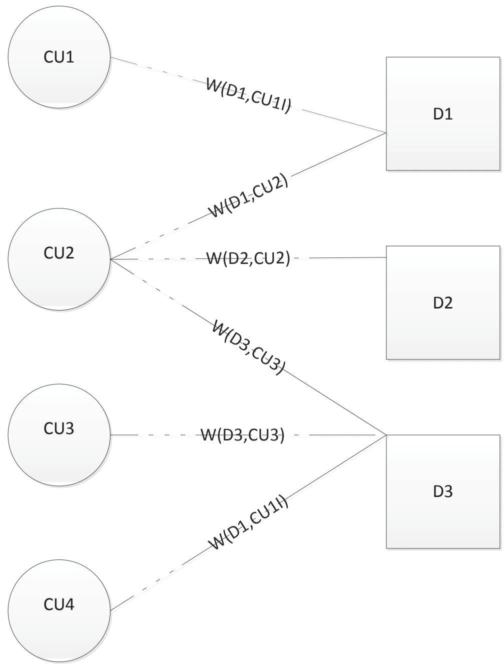

Figure 3.3: An example illustration of a bipartite graph (not all edges are shown). Here the edges represent the shared channels between cellular user CU_i and D2D pair D_j.

is $\mathcal{O}(mn^2)$ or $\mathcal{O}(\mathbb{M}n)$. Therefore, our approach is more efficient in terms of time as $m << n$ in a real network scenario. For more details on the proof of the complexity analysis of the approximation algorithm for minimum knapsack problem please refer to Csirik et al. [Csi+91].

3.4 Performance Evaluation

3.4.1 Reference algorithms for performance comparison

We chose two baseline algorithms to cover both ends of the performance spectrum: GRA [Zha+13a] and a random resource allocation scheme to compare against

MIKIRA. GRA gives a near optimal allocation when considered only for system sum rate. Therefore, it is the most appropriate approach to compare to in terms of satisfactory system sum rate results. Our second baseline algorithm, the random resource allocation is the most basic channel sharing approach with a rudimentary technique for allocating resources and is easy to understand.

Graph based resource allocation scheme

The cellular devices and the D2D pairs are considered to be two sets of nodes of a bipartite graph. The bipartite graph $G = \{V_c, V_d, E\}$ is formed such that, $V_i \in V_c$ and $V_j \in V_d$, where V_c is the set containing n cellular devices and V_d is the set containing m D2D pairs, and $e_{i,j} \in E$ connects the vertices $V_i \in V_c$ and $V_j \in V_d$. An edge $e_{i,j} \in E$ implies that the cellular user $V_i \in V_c$ and the D2D pair $V_j \in V_d$ share the channel associated with $V_i \in V_c$. The weight $W_{i,j}$ of the edge $e_{i,j} \in E$ is the difference between the rate of the channel when it is shared between cellular device $V_i \in V_c$ and D2D pair $V_j \in V_d$, and when the channel allocated to the cellular device $V_i \in V_c$ is not shared with D2D pair. This results in the weight $W_{i,j}$ of the edge $e_{i,j} \in E$ to be as follows:

$$W_{i,j} = \log_2(1 + SINR_{i,j,1}) + \log_2(1 + SINR_{i,j}) - \log_2(1 + SINR_{i,j,0})$$

Here, $SINR_{i,j,1}, SINR_{i,j,0}$, and $SINR_{i,j}$ are calculated from (3.10), (3.11), and (3.12) respectively. Now once we have a bipartite graph with m nodes in one part and n nodes in another with weighted edges among them we can use the Hungarian

Table 3.1: Simulation Parameters of Chapter 3.

Parameter	Value
Cell Radius	1000 metres
Cellular Users	50 (first and second set) 70 (third set)
D2D pairs	(first set) 5 to 50 (increments of 5) (second set) 5 to 40 (increments of 5) (third set) 5 to 35 (increments of 5)
Maximum D2D pair distance	15 metres
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Noise power	-174 dBm
Pathloss Model	Umi pathloss model for NLOS hexagonal cell layout [IR08]
Carrier Frequency	1.7 GHz for LTE

method [Mun57] to find the maximum weighted matching between the D2D pairs and cellular devices. Hence the result of the matching is channel allocation for the cellular users with D2D pairs. Fig. 3.3 shows an example bipartite graph with four cellular users and three D2D pairs.

Random resource allocation scheme

In this approach, the cellular user channels are assigned randomly to the D2D pairs with no specific objective.

3.4.2 Simulation Environment Setup

In the simulation, we placed the eNB at the center of the cell and placed cellular users and D2D pairs randomly such that the maximum distance between the devices of a D2D pair is 15 metres. The simulation parameters are shown in Table 3.1 [IR08; Hak+10]. We consider a single cell scenario where D2D communication and cellular communication co-exist and can share the channels. The frequency is set to 1.7 GHZ as we are considering an LTE cellular network. We used Network Simulator 3 (NS-3) for evaluating all the resource allocation algorithms to obtain the simulation results [Ns3]. Each point in the graphs in this chapter is an average of the 20 results to eliminate the effects resulting from extreme outlier cases.

3.4.3 Results and Analysis

We conduct three different sets of experiments to verify our claims. In the first set we fix the number of cellular users to 50 and increase the number of D2D pairs from 5 to 50, which is equal to the number of cellular users. In the second set of experiments, we explore what happens if the maximum number of D2D pairs does not reach the maximum number of cellular users and let the number of D2D pairs to increase up to 40 only. Finally, in the third set of experiments, we fix the total number of cellular users to 70 and let the number of D2D pairs to increase up to only the 50% of the total number of cellular users. These three scenarios reflect our assumptions about the number of D2D pairs to be less than the number of cellular users.

Experiment with $n = 50$ and $5 \leq m \leq 50$

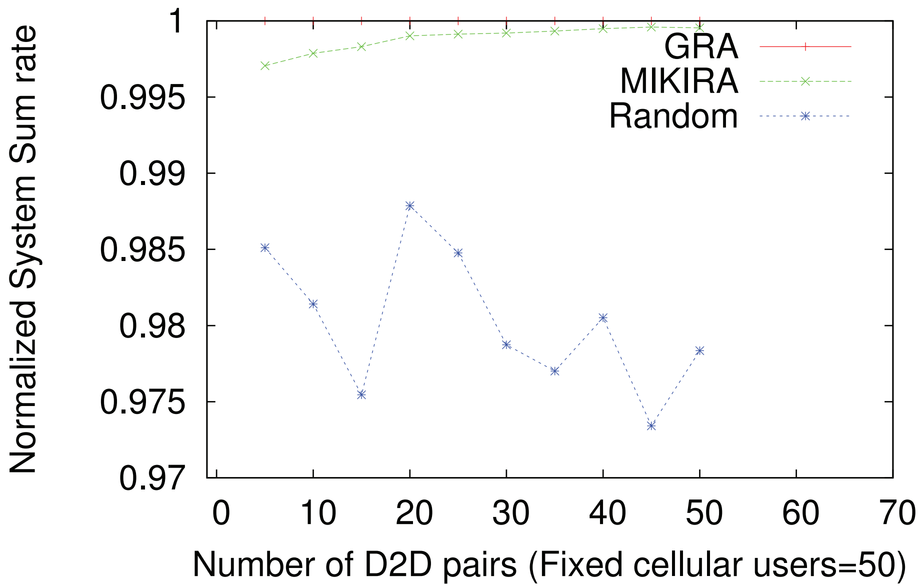

Figure 3.4: Normalized system sum rate of the three approaches (normalized with respect to GRA and for $n = 50$ and $5 \leq m \leq 50$).

In Fig. 3.4 we illustrate the system sum rates of the three approaches normalized to the sum rate obtained by the GRA. We see that MIKIRA is very close to the optimal sum rate obtained by GRA but the random based approach is less than both of the other two approaches. The random allocation does not follow any trend as the number of D2D pairs increases, meaning that the devices selected in the random allocation do not guarantee any type of optimization.

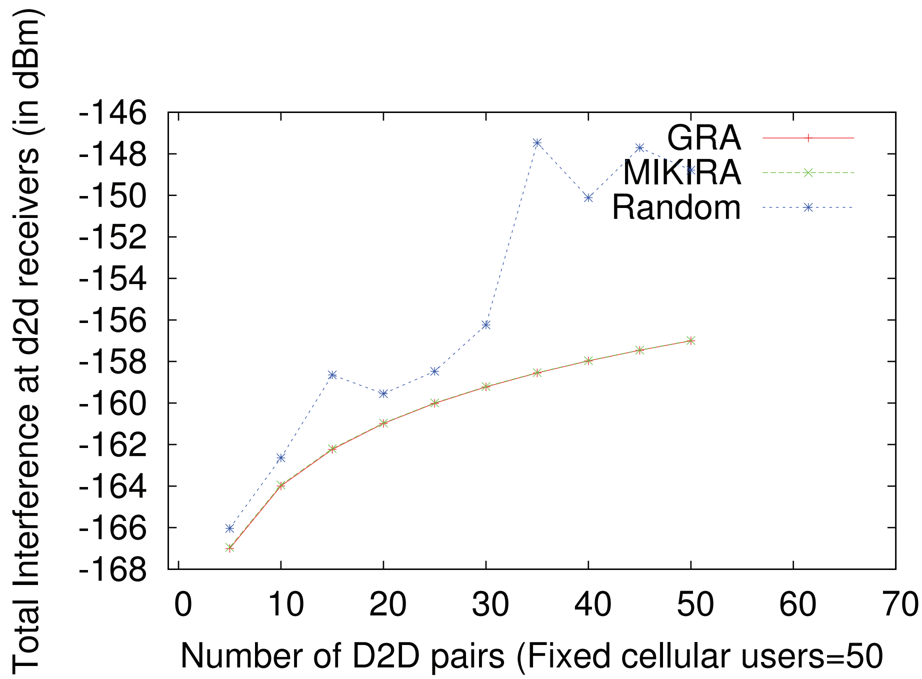

Figure 3.5: Interference introduced at the D2D receivers for channel sharing ($n = 50$ and $5 \leq m \leq 50$).

Fig. 3.5 shows the interferences caused at the D2D receiver by the three approaches. It is clear that, GRA and MIKIRA account for less interference at the D2D receiver than the random approach. This is because both MIKIRA and GRA select the channels to be shared in a way that devices with less interference are selected. However, for random allocation no such objective is in place. As a result, the selected shared channels cause increased interference at the receiver of the D2D pairs.

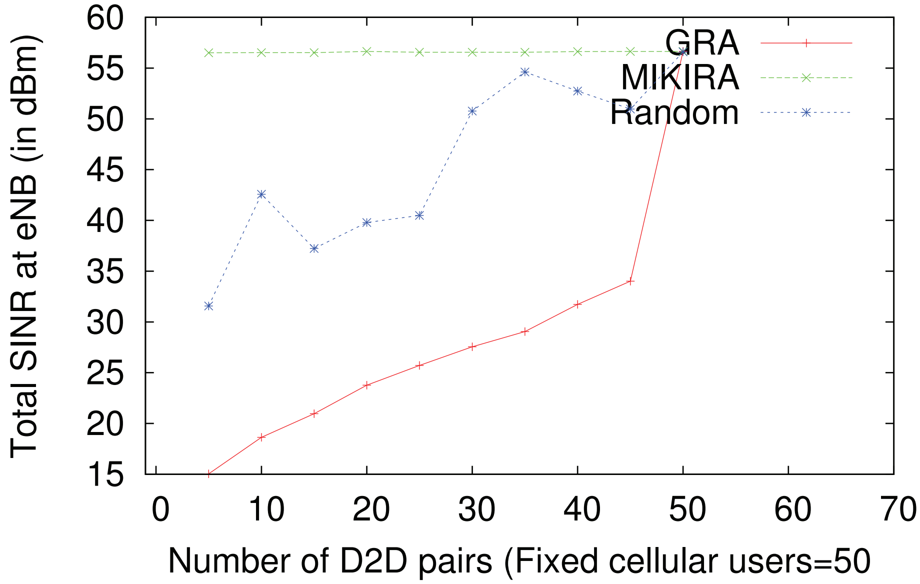

Figure 3.6: SINR at the eNB of the three approaches ($n = 50$ and $5 \leq m \leq 50$).

In Fig. 3.6, we see that MIKIRA experiences much better SINR than GRA or the random approach when the numbers of D2D pairs are smaller than the numbers of cellular users. As the number of D2D pairs approaches the number of cellular channels, then the number of shared channels increases. When the number of D2D pairs and number of cellular users are equal, all three approaches have the same SINR at the eNB.

Moreover, one very interesting thing to notice in Fig. 3.6 is that the knapsack based approach shows almost constant SINR at the eNB regardless the number of D2D pairs, whereas in the other two approaches the SINR increases as the number of D2D pairs increases. This is due to the fact that in the knapsack based approach the items are first sorted according to their relative interferences before being considered for inclusion in the final solution in the greedy approach; this results in a better overall SINR. This means that as long as the number of D2D pairs is smaller than the number of cellular users MIKIRA will have better signal quality at the eNB than the other two approaches.

Experiment with $n = 50$ and $5 \leq m \leq 40$

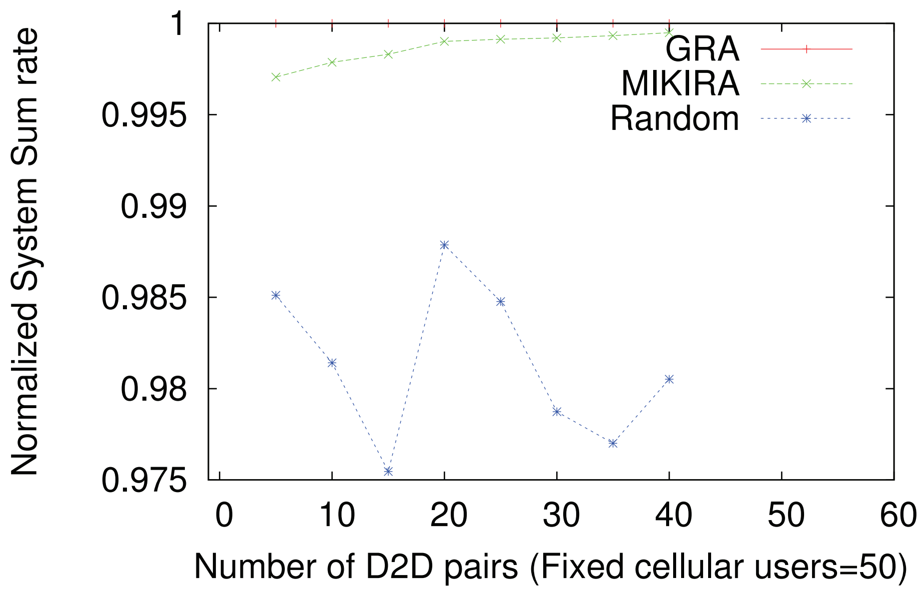

Figure 3.7: Normalized system sum rate of the three approaches (normalized with respect to GRA, and for $n = 50$ and $5 \leq m \leq 40$).

From Fig. 3.7, we find that the system sum rate graphs for the algorithms follow similar pattern as it was for the first set of experiments. However, one interesting thing to note is that as the number of D2D pairs approach the number of cellular users, the system sum rate of MIKIRA approaches closer to GRA. In the previous set of experiments when the number of D2D pairs became equal to the number of cellular users then the graphs were very close to each other. In this case, as we do not further increase the number of D2D pairs after 40 the graph for MIKIRA could not reach as close as it did in the previous case.

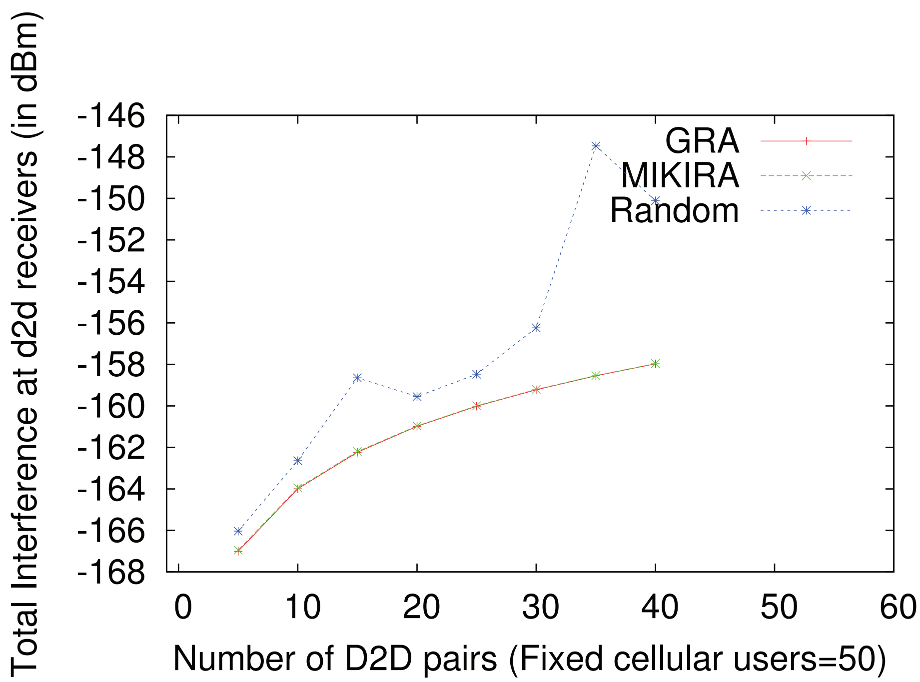

Figure 3.8: Interference introduced at the D2D receivers for channel sharing ($n = 50$ and $5 \leq m \leq 40$).

Fig. 3.8, does not provide any further observations or analysis except for those mentioned in the first experiment set. MIKIRA and GRA experience similar interference at the D2D receivers. But random allocation experiences the worst interference at the D2D receivers.

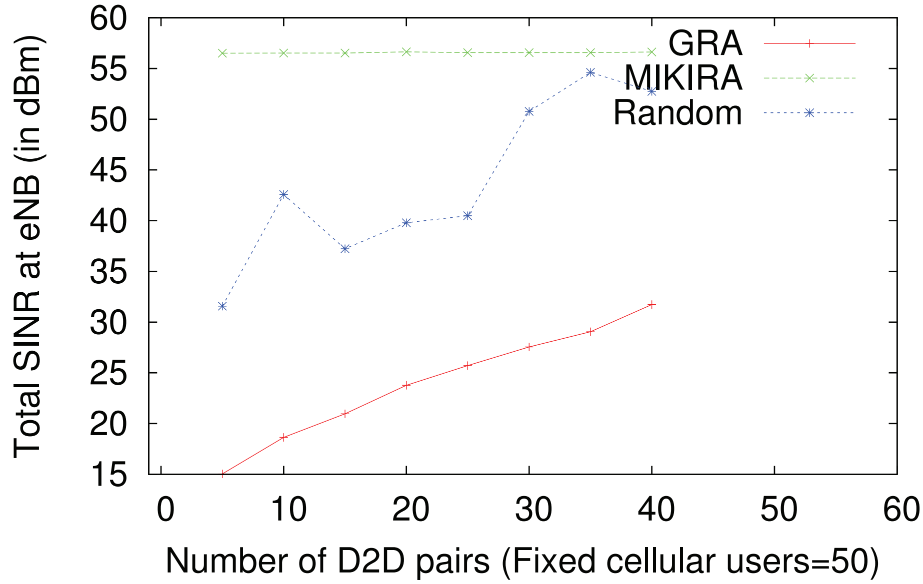

Figure 3.9: SINR at the eNB of the three approaches ($n = 50$ and $5 \leq m \leq 40$).

From Fig. 3.9 we observe that, when the number of D2D pairs is equal to 40 then there is a significant gap in the SINR obtained at the eNB by MIKIRA, GRA and the random approach. This supports our claim made at the end of the first set of experiments that as long as the number of D2D pairs is less than the number of cellular users MIKIRA will continue to obtain better signal quality at the eNB. This is because in MIKIRA items are first sorted according to their relative interferences before being considered for inclusion in the solution. This in turn results in a better SINR at the eNB.

Experiment with $n = 70$ and $5 \leq m \leq 35$

In these set of experiments we only allow the number of D2D pairs to increase up to 50% of the total number of cellular users. We changed the number of cellular users from 50 to 70 and allowed the number of D2D pairs to increase from 5 to 35.

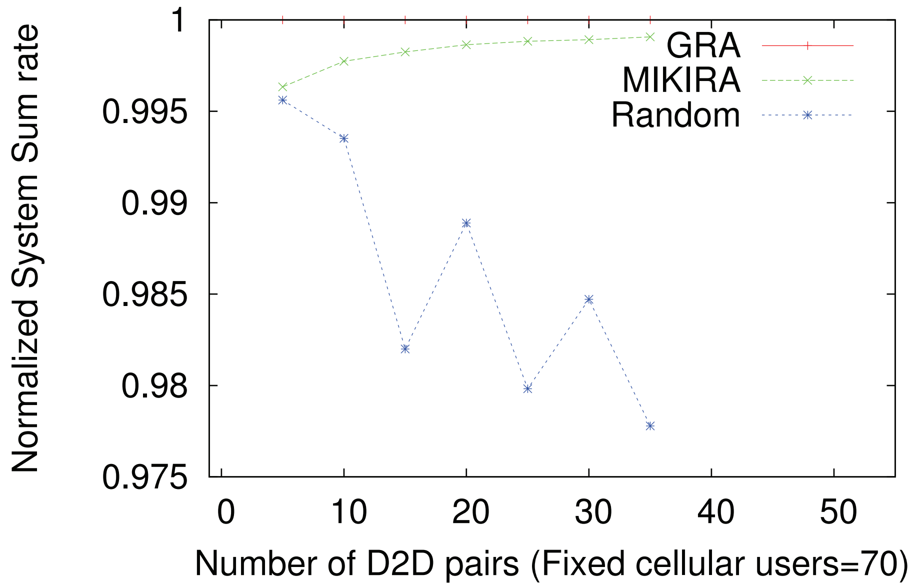

Figure 3.10: Normalized system sum rate of the three approaches (normalized with respect to GRA and $n = 70$ and $5 \leq m \leq 35$).

The system sum rate observations from Fig. 3.10 is similar to Fig. 3.4 and Fig. 3.7. In this case, as the number of D2D pairs do not come close to the number of cellular users the gap between achieved system sum rates of MIKIRA and GRA is more than that of Figs. 3.4 and 3.7.

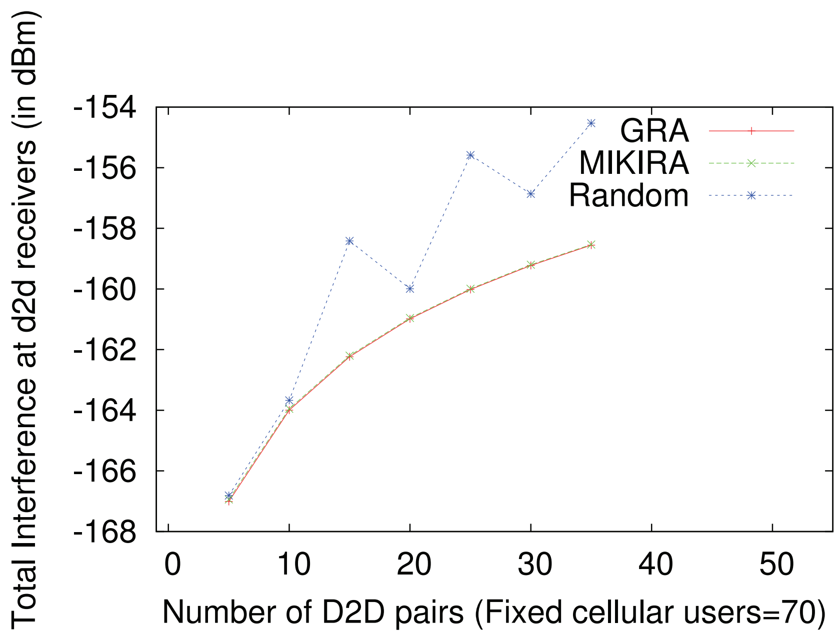

Figure 3.11: Interference introduced at the D2D receivers for channel sharing ($n = 70$ and $5 \leq m \leq 35$).

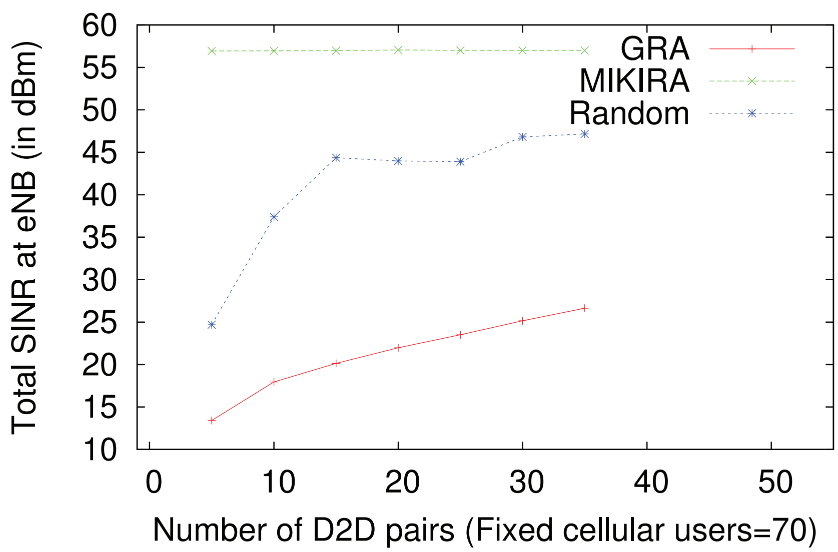

Figure 3.12: SINR at the eNB of the three approaches ($n = 70$ and $5 \leq m \leq 35$).

From Fig. 3.11 we find that even when the number of D2D pairs is much less than the number of cellular users the interference at the D2D receivers experienced by MIKIRA and GRA are almost the same and much less than that of the random algorithm.

Fig. 3.12 shows that, as the numbe rof D2D pairs fall far below the number of cellular users the difference between the SINR obtained at the eNB by MIKIRA and GRA also increases. In this case, MIKIRA obtains a much better SINR than the GRA or the random algorithm.

From the three different sets of experiments we observe that, as the number of D2D pairs approaches the number of cellular users the system sum rate obtained by the MIKRIA approaches that of GRA, and SINR at the eNB obtained by GRA approaches that of MIKIRA. However, according to our assumptions when the number of D2D pairs is less than the number of cellular users MIKIRA obtains a much better signal quality at the eNB than GRA and the random algorithm but the system sum rate remains very close to that of GRA.

3.5 Summary

In this chapter, we presented a channel level resource allocation scheme for D2D communication underlaying cellular network. We formulated the resource allocation problem as a minimum knapsack problem and then solve it using a greedy approximation algorithm. The simulation results showed that this approach can obtain good signal levels at the eNB while maintaining a satisfactory system sum rate. The running time of this approach is also polynomial which makes it particularly suitable for the short LTE scheduling period. In the next chapter we discuss another channel level resource allocation algorithm with a focus on fair allocation.

Chapter 4

Fair Participation Channel Level Resource Allocation

In this chapter, we propose a polynomial time, Two-phase Auction based, Fair and Interference aware Resource Allocation algorithm (TAFIRA) for D2D communication underlaying cellular networks. TAFIRA can be used to minimize the interference both at the eNB and the receiver of the D2D pairs while simultaneously maintaining a target system sum rate and ensuring fair allocation of cellular resources among D2D pairs.

TAFIRA is aimed towards minimizing the total interference introduced in the system when cellular spectrum is shared with D2D pairs and at the same time ensure fairness in resource allocation. If an allocation is not found in the first phase of the auction, then a second phase of the algorithm starts to find an allocation that satisfies the system sum rate demand. The main contribution of this chapter is an efficient, polynomial time, and interference minimizing resource allocation algorithm suitable for the LTE scheduling period (1 ms) that also maintains fairness in the process.

We also provide a detailed complexity analysis of this approach to prove that this is indeed a fast interference coordination technique. TAFIRA ensures fairness at the time of allocation and does not allow any D2D pair to starve from not getting cellular resources; rather it allows every D2D pair to share cellular resources with equal opportunity.

The rest of the chapter is organized as follows. We describe the system and channel model in Section 4.1. We formulate the problem in Section 4.2. Then we describe the detailed working procedure of the proposed scheme in Section 4.3. Experimental results are presented in Section 4.4. Finally, we provide a summary of the chapter in Section 4.5.

4.1 System and Channel Model

4.1.1 System Model

We show the interference scenario in the uplink direction for D2D communication underlaying a cellular network in Fig. 4.1. The red dotted line indicates a shared link between a CU and a D2D pair, and a blue solid line indicates a dedicated link allocated to only a cellular user. In the uplink scenario, CU1 is using a dedicated link, CU2 is sharing its link with D2D pair 1 and CU3 is sharing its link with D2D pair 2. Victims of interference in the uplink direction are the D2D receivers from cellular users, and eNB from the D2D transmitter as indicated by dotted arrows from both of the shared links. The D2D pairs are shown inside a shaded elliptical region in Fig. 4.1 to emphasize the fact that, there is a maximum distance requirement for the transmitter and receiver of a D2D pair. In this chapter we address the uplink

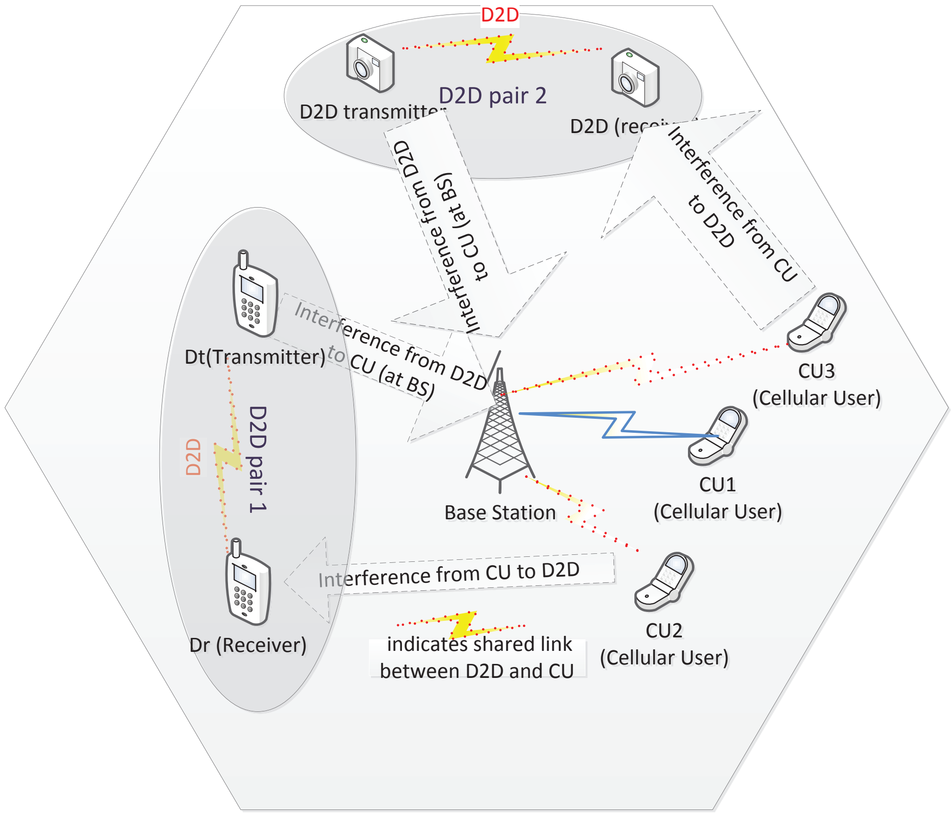

Figure 4.1: Uplink interference scenario in D2D communication underlaying LTE cellular network.

resource sharing scenario between D2D and CU.

In our system model, we consider an uplink scenario with n cellular users and m D2D pairs. Also as in real network situations the number of cellular users is much more than the number of D2D pairs, i.e., $m << n$. Please note that we only take into account intra-channel interference as we assume the channels to be orthogonal to each other. We denote the cellular users by c_i for each $1 \leq i \leq n$ and D2D pairs by d_j for each $1 \leq j \leq m$. The transmit power of the D2D devices and the CUs are P^D and P^C respectively. The transmitter and the receiver in D2D pair d_j are denoted by d_j^t and d_j^r respectively.

4.1.2 Channel Model

According to our assumptions, the channels are Rayleigh fading channel, and therefore, the individual channel responses follow an independently and identically distributed gaussian process. The path loss that the cellular users and the D2D pairs experience follow the path loss for UMi [IR08]. Therefore, the path loss model is as follows.

$$PL = 36.7log_{10}(d) + 22.7 + 26log_{10}(f_c)$$

where, PL is the experienced path loss, d is the distance between the source and destination (in metres) and f_c is the frequency in GHz.

The channel gain between source a and destination b are expressed as a function of distance dependent path loss and a small scale fading.

$$G^{a,b} = PL^{a,b}h^{a,b}$$

where, $G^{a,b}$ denote the channel gain between a and b, $PL^{a,b}$ is the distance dependent path loss between a and b and $h^{a,b}$ is the small scale fading between a and b.

4.2 Problem Formulation

We formulate the resource allocation problem as an interference minimization problem. We also assume that there is a system sum rate target that needs to be attained in order for a satisfactory level of system efficiency. As system sum rate increase is one of the main advantages of spectrum sharing between cellular and D2D pairs, the sum rate target fulfilment is an important part of our problem formulation. Therefore, our problem is designed to minimize interferences while satisfying a sum rate target and at the same time ensure that one cellular users channel is shared by only one D2D pair and one D2D pair can share the resources of only one cellular user.

The formulation of our optimization problem MIN-INTERFERENCE looks as follows.

MIN-INTERFERENCE:

$$\text{minimize} \sum_{i=1}^{n}\sum_{j=1}^{m} a_{i,j} I_{i,j} \tag{4.1}$$

$$\text{subject to} \sum_{i=1}^{n}\sum_{j=1}^{m} a_{i,j} C_{i,j} \geq R \tag{4.2}$$

$$\sum_{i=1}^{n} a_{i,j} \leq 1, \forall \quad j \in \{1, ..., m\} \tag{4.3}$$

$$\sum_{j=1}^{m} a_{i,j} \leq 1, \forall \quad i \in \{1, ..., n\} \tag{4.4}$$

$$a_{i,j} \in \{0, 1\}, \forall\ i \in \{1, ..., n\} \text{ and } \forall\ j \in \{1, ..., m\} \tag{4.5}$$

where, $I_{i,j}$ and $C_{i,j}$ indicates the interference introduced if c_i and D2D pair d_j share the uplink resources and the associated channel rate respectively. R indicates the total expected system sum rate. Here $a_{i,j}$ is a binary variable indicating whether the cellular channel associated with c_i was shared with D2D pair d_j. Constraint (4.2) ensures that the target system sum rate level is fulfilled. Constraints (4.3) and

(4.4) ensure that each D2D pair can share only one cellular channel and each cellular channel can share only one D2D pair respectively. The final constraint (4.5) ensures that $a_{i,j}$ can hold only binary values.

The value of $I_{i,j}$ is calculated using the following equation:

$$I_{i,j} = P^D G^{jt,eNB} + P^C G^{i,jr} \tag{4.6}$$

where, $G^{jt,eNB}$ and $G^{i,jr}$ denote the interference from the transmitter of D2D pair d_j to the eNB and the interference from the cellular user c_i to the receiver of the D2D pair d_j. Therefore, this interference value captures both the interference at the eNB and the interference at the receiver of the D2D pair. Our goal in MIN-INTERFERENCE is to minimize this interference.

The channel rate of the cellular channel associated with c_i when it is shared with a D2D pair d_j is calculated by the following formula:

$$C_{i,j} = \log_2(1 + SINR_{i,j,1}) + \log_2(1 + SINR_{i,j}) - \log_2(1 + SINR_{i,j,0}) \tag{4.7}$$

The channel rate is indicated by $C_{i,j}$ when the c_i and D2D pair d_j share the uplink resources. The value of $SINR_{i,j,1}$, $SINR_{i,j}$ and $SINR_{i,j,0}$ are calculated from (4.8), (4.9) and (4.10) respectively.

$$SINR_{i,j,1} = \frac{P^C G^{i,eNB}}{N + P^D G^{jt,eNB}} \tag{4.8}$$

$$SINR_{i,j,0} = \frac{P^C G^{i,eNB}}{N} \tag{4.9}$$

$$SINR_{i,j} = \frac{P^D G^{jt,jr}}{N + P^C G^{i,jr}} \tag{4.10}$$

where, $SINR_{i,j,1}$ denotes the SINR at the eNB when c_i shares the channel with D2D pair d_j. $SINR_{i,j,0}$ denotes the SINR at the eNB when the c_i does not share the channel with any D2D pair and $SINR_{i,j}$ denotes the SINR at the receiver of the D2D pair d_j when it shares the channel with c_i. N represents the noise in the channel. The final interference of an allocation is calculated by the sum of the two types of interferences: interference at eNB from (4.8) and interference at D2D receiver from (4.10).

The terms $G^{i,eNB}$, $G^{jt,eNB}$, $G^{jt,jr}$ and $G^{i,jr}$ denote the channel gain obtained from the cellular device c_i to the eNB, the interference from the transmitter of D2D pair d_j to the eNB, the channel gain from the transmitter of the D2D pair d_j to the receiver of the same D2D pair d_j, and the interference from the cellular user c_i to the receiver of the D2D pair d_j.

Expected system sum rate R in (4.2) can be based on heuristics depending on the number of cellular users' resources are being utilized and the number of D2D pairs participating in the communication. This can also be a fraction of the theoretical maximum system sum rate possible for the network configuration. The network administrator may also have an expected system sum rate based on the network settings. In our case we used a fraction of the maximum theoretical system sum rate possible.

4.3 Two-phase Auction-based Fair and Interference-aware Resource Allocation (TAFIRA)

We propose an auction-based algorithm in this section for the channel level resource allocation purpose. This auction based approach consists of two phases and we describe the two phase of TAFIRA as follows.

4.3.1 Phase one of TAFIRA

Our auction based approach has a set of bidders $\mathbb{B}$ and a pool $\mathbb{P}$ of bidding items. Initially, all the cellular channels $C(c_1, c_2, ..., c_n)$ are added to the bidding pool $\mathbb{P}$ and all the D2D pairs $D(d_1, d_2, ..., d_m)$ are added to the bidders set as indicated in line 3 of algorithm 3. Each bidder $d_j \in \mathbb{B}$ has a strategy to bid for the channel $c_i \in \mathbb{P}$ that results in minimum interference $I_{i,j}$ calculated from 4.6. This strategy is mentioned in line 4 and later used by the bidders in line 6. The while loop in line 5 continues until no bidder is left without an item from the bidding pool $\mathbb{P}$. In line 6 all the bidders in $\mathbb{B}$ bid according to their bidding strategy. The for loop from line 7-13 allocates each bidden channel c_i to the bidder $d_j \in \mathbb{B}$ that causes the minimum interference according to 4.6. If more than one d_j incurs the same interference then choose the one that produces maximum sum rate according to 4.7. If this value is still the same then break the tie in an arbitrary manner. Once the new allocation is done, c_i is removed from the bidding pool $\mathbb{P}$ and the winning bidder d_j of c_j is removed from $\mathbb{B}$. This procedure will continue until all the bidders in $\mathbb{B}$ are allocated with an item from $\mathbb{P}$.

In line 15, we calculate the total sum rate of the current allocation and check if it satisfies the demand R in line 16. If the demand is satisfied then we report the current allocation as the final allocation. Otherwise, we go to phase 2 of TAFIRA. Phase one of TAFIRA ensures fairness of resource allocation as it allocates every D2D pair cellular resource and does not allow any D2D to starve because of channel conditions and this fairness continues in phase two.

4.3.2 Phase Two of TAFIRA

The algorithm for phase two of TAFIRA is shown in algorithm 4. Line 1 stores the current sum rate value obtained from algorithm 3 in *curSumRate*. The while loop from line 3-15 runs until the demand R is satisfied. In line 4 of algorithm 4 we add the unallocated channels after the phase one in $\mathbb{P}$ and all $d_j \in D$ in bidders set $\mathbb{B}$. Please note that, at this phase all the bidders already have a previously allocated c_i to them. But, the pool $\mathbb{P}$ now contains only previously unallocated channels. In line 5, each d_j now tries to find a $c_k \in \mathbb{P}$ for which the bidding amount is maximum among all the bidding amounts. The bidding amount for c_k is $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}}$ and the value of it should be positive to ensure that the sum rate (nominator of bidding amount) is increased with incurring least interference (denominator of bidding amount) increase.

From line 6-8 we check if any channel is bidden for with a positive bidding amount. If no such channel exists then we report that the demand R cannot be satisfied and exit the algorithm. Otherwise, it means we can allocate at least one channel from the pool to one of the bidders after they release their old allocation. From line 9-13, each bidden channel c_k is allocated to the bidder d_j having the maximum bidding amount for it. d_j releases its old allocation c_i in line 11. A released c_i is added to the bidding pool in line 12. After each bidden channel is allocated to the maximum bidder the total sum rate is calculated in line 14 for the next iteration. If the value is greater than or equal to R then we have found the allocation. Otherwise, the while loop from line 3 starts over again.

Algorithm 3 Phase One of TAFIRA (TAFIRA-1)

1: **procedure** TAFIRA-1($C(c_1, c_2, ..., c_N), D(d_1, d_2, ..., d_M)$) ▷ An allocation from C to D
2: Let $\mathbb{P}$, $\mathbb{B}$ denote the bidding pool and bidder set.
3: $\mathbb{P} \leftarrow C(c_1, c_2, ..., c_N)$ and $\mathbb{B} \leftarrow D(d_1, d_2, ..., d_M)$.
4: Bidding strategy for each bidder $d_j \in \mathbb{B}$ is to bid for the channel $c_i \in \mathbb{P}$ that results in minimum interference $I_{i,j}$ calculated from 4.6.
5: **while** $\mathbb{B} \neq \phi$ **do** ▷ Repeat until all the bidders are allocated
6: Each bidder $d_j \in \mathbb{B}$ will bid according to their bidding strategy.
7: **for** each bidden channel$c_i \in \mathbb{P}$ **do**
8: Allocate c_i to the bidder $d_j \in \mathbb{B}$ that causes the minimum interference according to 4.6.
9: If more than one such $d_j \in \mathbb{B}$ exists then allocate c_i to the one that cause maximum sum rate according to 4.7.
10: If ties still remain allocate c_i randomly to any one of the tied bidders to break the tie.
11: Remove c_i from $\mathbb{P}$.
12: Remove d_j from $\mathbb{B}$ to which c_i was allocated.
13: **end for**
14: **end while**
15: Calculate the current total sum rate $curSum$.
16: **if** $curSum \geq R$ **then**
17: **return current allocation** ▷ Allocation complete satisfying (4.2)
18: **else**
19: Go to second phaseTAFIRA-2.
20: **end if**
21: **end procedure**

Figure 4.2 shows the two phases of TAFIRA in a simplified flow chart.

Algorithm 4 Phase Two of TAFIRA (TAFIRA-2)

procedure TAFIRA-2($C(c_1, c_2, ..., c_N), D(d_1, d_2, ..., d_M)$) ▷ An allocation from C to D
  $curSumrate \leftarrow$ current sum rate obtained from TAFIRA-1.
  while $curSumrate < R$ **do**
    Put all unallocated channels after TAFIRA-1 in bidding pool $\mathbb{P}$ and all $d_j \in D$ in bidders set $\mathbb{B}$.
    Each $d_j \in \mathbb{B}$ that currently is allocated to c_i bid for another $c_k \in \mathbb{P}$ which gives the maximum bidding amount $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}}$. This amount should be greater than 0.
    if no $c_k \in \mathbb{P}$ is bidden for **then**
      return Allocation satisfying R is not possible.
    end if
    for each bidden channel$c_k \in \mathbb{P}$ **do**
      Allocate c_k to the d_j that gives the maximum bidding amount.
      Release the winner d_j from its previous allocation c_i.
      Add c_i in the bidding pool $\mathbb{P}$.
    end for
    $curSumrate \leftarrow$ calculate total sum rate according to Eq. (4.7).
  end while
  return current allocation ▷ Allocation complete satisfying (4.2)
end procedure

4.3.3 Complexity Analysis

We will derive the worst case analysis of TAFIRA. In the worst case, the while loop at line 5 of algorithm 3 executes in $\mathcal{O}(m)$ time at each step we are removing a bidder from the bidder set. Line 6 will take $\mathcal{O}(mn)$ for each bidder to bid according to the bidding strategy in line 4. The loop from lines 7-11 will run at most $\mathcal{O}(m)$ times as the total number of bidden channel is at most m and one bidder can bid at most one channel at each round. Calculating the sum rate at line 15 takes $\mathcal{O}(mn)$ time. Therefore, the total running time for first phase of TAFIRA is $\mathcal{O}(mn + m)m$, which can be written as $\mathcal{O}(m^2n)$.

Please note that algorithm 4 will run only when the allocation could not be done

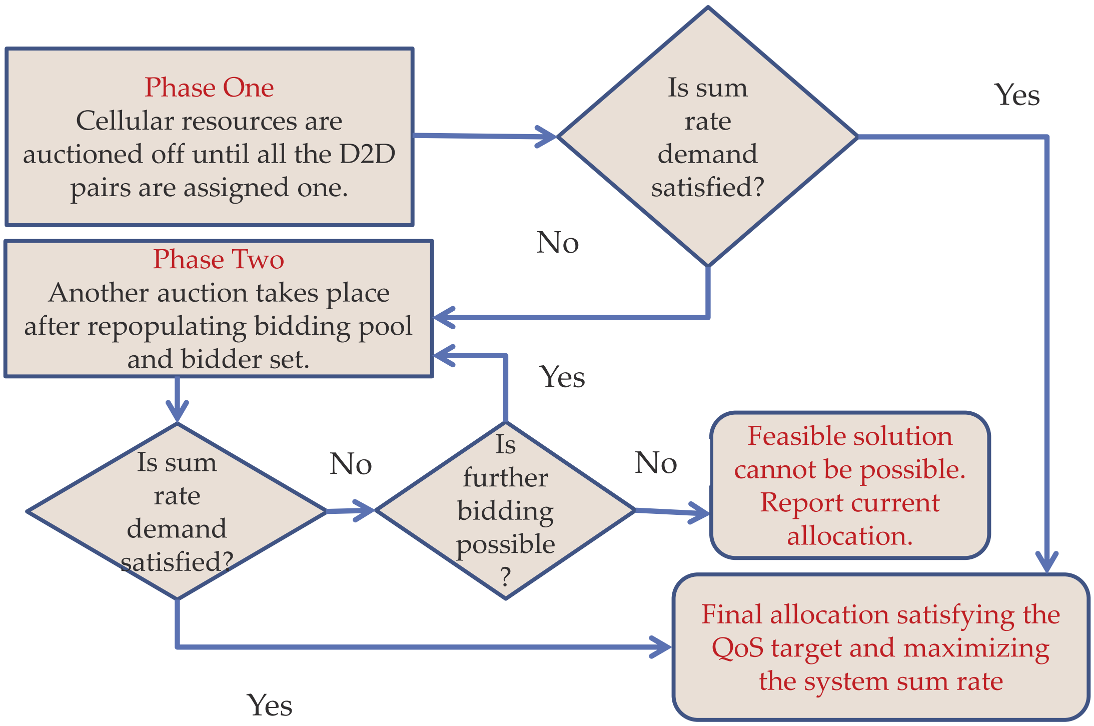

Figure 4.2: Flow Chart of TAFIRA.

in algorithm 3 to achieve R. Consequently, after running algorithm 3 if the system sum rate is R_1, then the running time of phase 2 is $\mathcal{O}(R - R_1)$, which is $\mathcal{O}(R)$.

Combining both the phases of TAFIRA the total running time in worst case becomes $\mathcal{O}(m^2n + R)$. However, in practice R is very close to R_1 and the running time will be mostly dominated by the first phase of the algorithm. Consequently, the average complexity of TAFIRA becomes $\mathcal{O}(m^2n)$.

4.3.4 Theorem and Lemmas

From algorithms 3 and 4 we can derive the following theorem and lemmas.

Lemma 4.3.1. *At the end of phase 1, each D2D pair is guaranteed to be assigned* *in a cellular channel.*

Proof. According to our assumptions in 4.1.1, $|\mathbb{B}| < |\mathbb{P}|$. The while loop at line 5 of algorithm 3, runs until $\mathbb{B} = \phi$. In line 12 of algorithm 3, the minimum bidder of a channel is declared the winner and is removed from $\mathbb{B}$. Therefore, at each iteration of the while loop at line 5 one bidder is assigned a resource and is removed from $\mathbb{B}$. As there is only a finite number of bidders in $\mathbb{B}$, at the end of algorithm 3 all the D2D pairs (bidders) are guaranteed to be assigned in a cellular channel. □

Lemma 4.3.2. *In phase 2 of TAFIRA, for any D2D pair j and any unallocated channel k, $I_{k,j} \geq I_{i,j}$, when i is the channel already assigned to the D2D pair j.*

Proof. Let us assume that, there exists an unallocated channel k after the first phase of TAFIRA for which $I_{k,j} < I_{i,j}$ where, i is the channel already assigned to the D2D pair j. However, according to line 6 of algorithm 3 each D2D pair j bids for the unallocated channel i that has minimum interference. Hence, our assumption that $I_{k,j} < I_{i,j}$ is wrong for any unallocated channel k.

Therefore, for any D2D pair j and any unallocated channel k, $I_{k,j} \geq I_{i,j}$, when i is the channel already assigned to the D2D pair j. □

Theorem 4.3.3 (Improvement theorem)**.** *In phase 2 of TAFIRA, if we do not find any pair of channels i and k, and any D2D pair j such that, i is currently allocated to j and, $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}} > 0$, then we cannot improve current system sum rate by assigning any unallocated channel to any D2D pair.*

Proof. Let us assume that, a channel k exists for which $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}} < 0$, where D2D pair j is currently allocated to channel i. And reallocating j to k from i improves the system sum rate.

For $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}} < 0$ to be true, either $C_{k,j}-C_{i,j}$ or $I_{k,j}-I_{i,j}$ needs to be smaller than 0 but both can not be smaller than 0. However, from Lemma 4.3.2 we know that, $I_{k,j} \geq I_{i,j}$. Therefore, it must be the case of $C_{k,j} - C_{i,j} < 0$. This means that the current channel rate is greater than the channel rate that would result if D2D pair i swapped its allocation from channel j to k. That means, our initial assumption that reallocating j to k from i improves the system sum rate is wrong.

The case where $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}} = 0$ is trivial, as in this case, we know that $C_{k,j}-C_{i,j} = 0$. This indicates that no channel rate improvement is possible by reallocating.

Therefore, if we do not find any pair of channels i and k, and any D2D pair j such that, i is currently allocated to j and $\frac{C_{k,j}-C_{i,j}}{I_{k,j}-I_{i,j}} > 0$, then we cannot improve the current system sum rate by assigning any unallocated channel to any D2D pair.

□

4.4 Performance Evaluation

4.4.1 Simulation Environment

In our simulation environment the eNB is placed in the middle and the cellular users and D2D pairs are uniformly distributed in the cellular region. We fix the total number of cellular users to 200 and vary the D2D pairs from 20 to 150. Also the transmitter and receiver of a D2D pair are distance restricted to be placed within 15 meters of each other to ensure effective D2D communication [Xu+13]. Other details of simulation parameters are listed in Table 4.1. We used NS3 [Ns3] for all

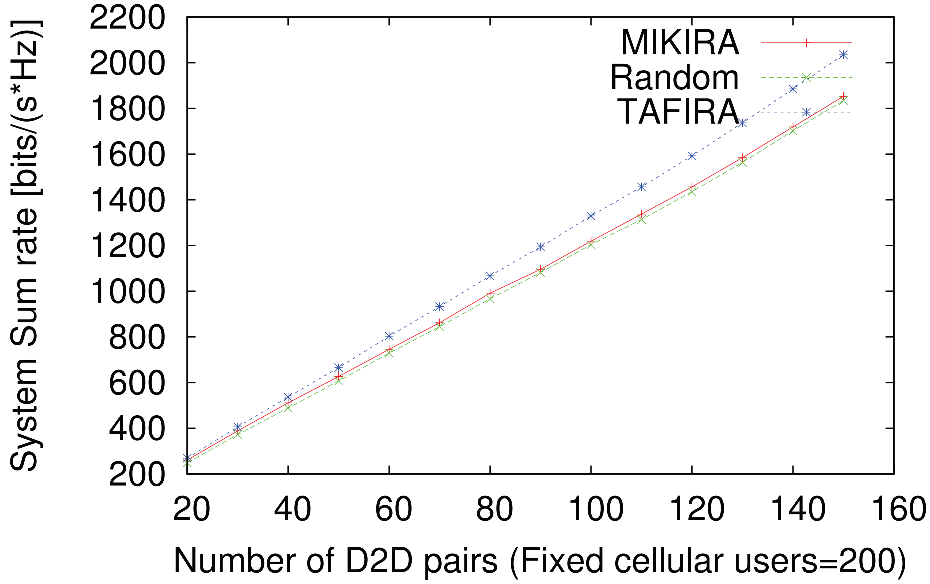

Figure 4.3: System sum rate of the four RA approaches.

Table 4.1: Simulation Parameters of Chapter 4.

Parameter	**Value**
Cell Radius	1000 metres
Cellular Users	200
D2D pairs	20 to 150 (increments of 10)
Maximum D2D pair distance	15 metres
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Noise power	-174 dBm
Pathloss Model	Umi pathloss model for NLOS hexagonal cell layout [IR08]
Carrier Frequency	1.7 GHz for LTE

our simulations and every point in Figs. 4.3, 4.4, 4.5 and 4.6 is taken as an average of 25 runs of the algorithms.

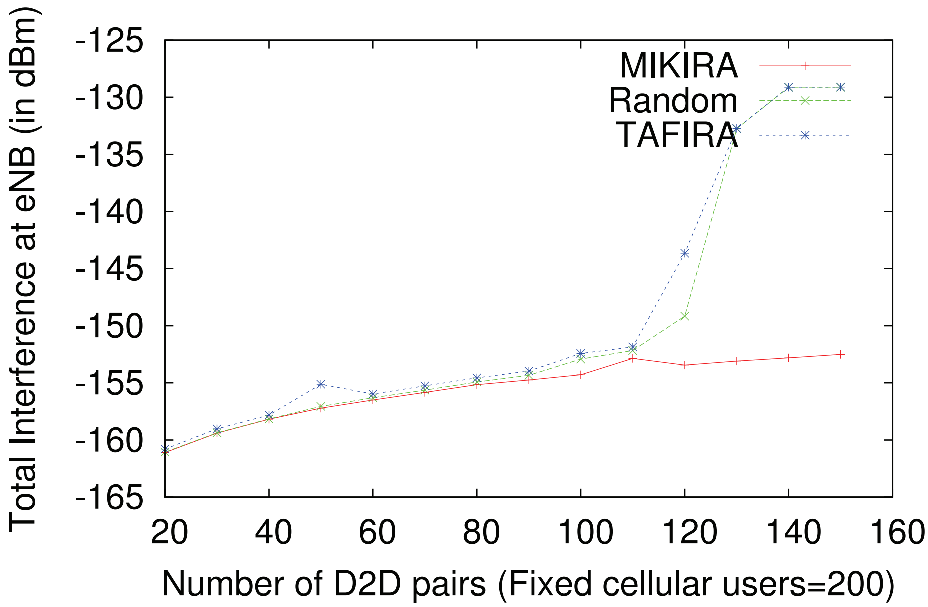

Figure 4.4: Interference at the eNB of the three RA approaches.

4.4.2 Baseline Algorithms

We compared TAFIRA with two other resource allocation algorithms in terms of the sum rate obtained and the interferences generated at the eNB and D2D receivers. We chose a knapsack based approach [Isl+15b] and a random allocation approach as baseline algorithms. We chose the knapsack based approach MIKIRA as this is similar to our problem formulation and also tries to minimize the interference while satisfying the system sum rate demand. MIKIRA is explained in details in Chapter 3. We use random allocation as it is easy to understand.

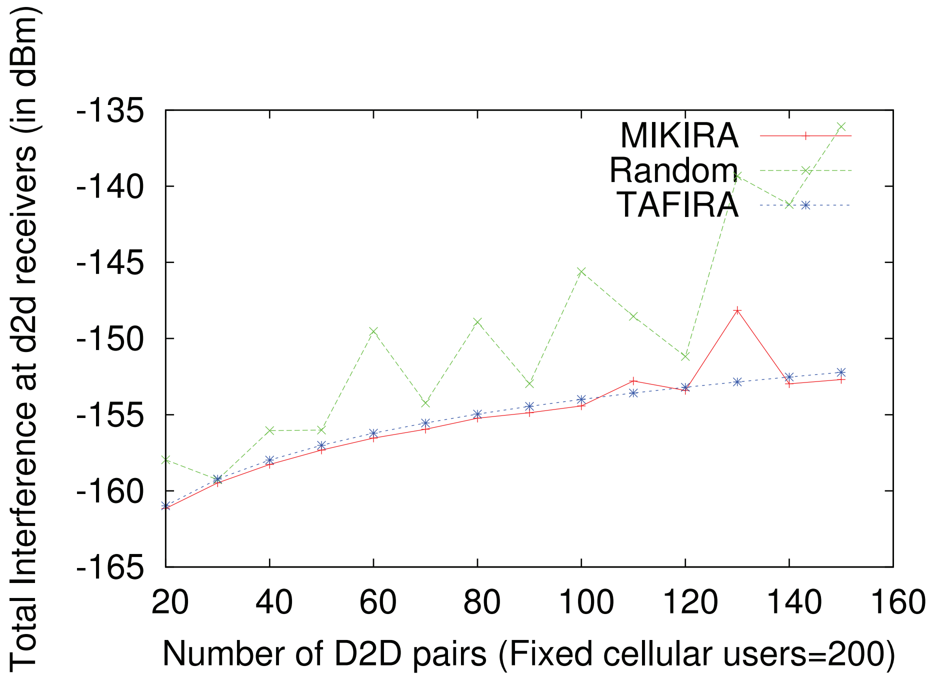

Figure 4.5: Interference at the D2D receivers of the three RA approaches.

Minimum Knapsack Based Interference Aware Resource Allocation (MIKIRA)

MIKIRA first formulates the resource allocation problem as a variant of the knapsack problem and then solves it using an approximation algorithm to obtain a close to optimal solution. The goal of this approach is to satisfy a sum rate demand while minimizing the interference. The details of this algorithm can be found in Chapter 3.

Random Resource Allocation

In the random resource allocation algorithm, cellular resources are allocated randomly to D2D pairs without any regards to whether they incur a lot of interferences

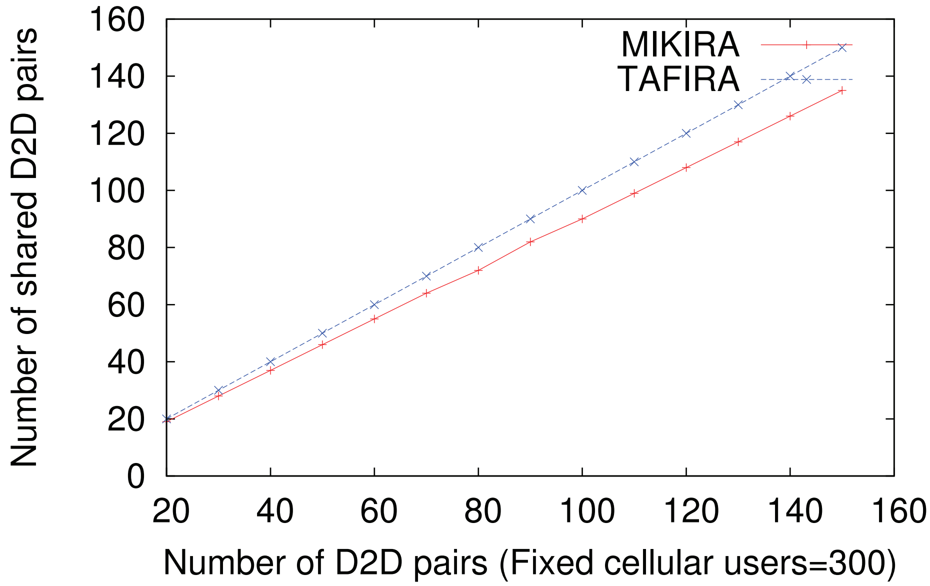

Figure 4.6: Number of D2D pairs that share cellular resources.

or not. Allocation stops as soon as the sum rate demand is met to avoid incurring more interferences.

4.4.3 Results and Performance Analysis

Fig. 4.3 depicts the system sum rate results for the three allocation algorithms. It is clear from the figure that TAFIRA obtains a better sum rate than MIKIRA or the random approach, while random is the worst of these three algorithms. However, please note that all three algorithms needed to satisfy a target system sum rate demand. TAFIRA performs better than the rest of the algorithms in terms of system sum rate because it first allocates all the D2D pairs to a channel based on a bidding strategy and then checks if the demand is met or not. However, for MIKIRA or random allocation, once the sum rate demand is met, allocation is no longer performed. TAFIRA only goes into phase two if the target was not fulfilled in phase one. TAFIRA then also reallocates strategically to incur the least interference and gain a high increase in sum rate.

Figs. 4.4 and 4.5 show the total interference generated by the algorithms at the eNB and the D2D receivers in the uplink direction. We observe from Fig. 4.4 that MIKIRA generates least interference at the eNB and random and TAFIRA generates similar interferences at the eNB. In general, eNB is more interference resistant than the D2D receivers due to more advanced and sophisticated interference avoidance algorithms deployed and hence interference at the eNB is not of a major concern. Nonetheless, this increased interference at the eNB for TAFIRA is expected as according to the algorithm it first allocates all the D2D pairs and then only checks if the demand is met or not; it does not stop before that, thereby obtaining a much better system sum rate with a little increase in the interference. Fig. 4.5 shows that random allocation generates the worst level of interference at the D2D receivers and that MIKIRA obtains the best level of interference. TAFIRA runs very close to MIKIRA while obtaining much better system sum rate.

Prior to a discussion on the performance results of Fig. 4.6 we need to define “fairness”. In our notion of fairness, one approach is more fair if it allocates more D2D pairs to share cellular resources to obtain a target system sum rate. Fig. 4.6 shows the number of D2D pairs that share the cellular resources as obtained by MIKIRA and TAFIRA. It is clear from this graph that TAFIRA is more fair in terms of sharing resources as it allows all the D2D pairs to share cellular channel resources whereas MIKIRA stops allocating as soon as demand is met.

To summarize the results obtained from Figs. 4.3, 4.4, 4.5 and 4.6, we observe that, TAFIRA obtains a much better system sum rate than the other two algorithms while incurring very little increased interference at the eNB and D2D receivers and also ensures a fair allocation of resources among the D2D pairs.

4.5 Summary

In this chapter, we proposed a fair, fast and efficient resource sharing algorithm for D2D communication underlaying a cellular network. The proposed approach aims at minimizing interference while obtaining a target system sum rate and maximizing fairness in the allocation. Simulation results showed the effectiveness of this approach to obtain an increased system sum rate with a fair allocation while minimizing the interferences when compared with two other approaches. We also proved the fairness of the allocation theoretically. This algorithm runs fast and is suitable for an LTE scheduling period of 1 ms. Based on these findings, we can conclude that TAFIRA has a great potential for use in LTE scheduling period for efficient D2D resource allocation. In the next chapter we present some algorithms for RB level resource allocation for D2D while satisfying the QoS target at interference victims.

Chapter 5

Resource Block Level Resource Allocation

One major challenge in allocating resources for devices participating in D2D communication underlaying cellular networks is to ensure the QoS. Since the newly introduced interference can degrade the signal quality an effective resource allocation scheme should make sure that satisfactory QoS target levels are met in the allocation process.

In this chapter, we present firstly, a simple local search based resource allocation algorithm, secondly, an extension of the local search algorithm, thirdly, a greedy algorithm, and finally, a deferred acceptance based stable matching algorithm for obtaining an allocation to maximize system sum rate and at the same time satisfying the QoS target levels.

We first formulate the problem as an MINLP. However, as the computational complexity of MINLP is very high, it is not suitable for adoption in the short LTE scheduling period of 1 ms. Consequently, we propose a Simple LOCal search based resource allocation algorithm (SLOC) to solve this problem. SLOC improves the system sum rate while satisfying the QoS constraints. Local search is a very well-known technique to solve optimization problems. It has been used successfully to solve resource allocation, scheduling, and facility location problems in different research domains [Ary+01; PF05]. It has also been used to solve different optimization problems in the telecommunications area [Tio+00]. The first contribution of this work is an improved solution to the downlink D2D resource allocation problem in LTE cellular networks using a local search technique. Our algorithm is computationally inexpensive and is suitable for the short scheduling period (1 ms) of LTE. To our knowledge, this is the first local search approach to handle the resource allocation problem for D2D enabled LTE cellular networks. We also propose an extension of the local search algorithm named Maximum improvement LOCal search based resource allocation algorithm (MLOC) to further refine the solution.

The second contribution is a greedy resource allocation algorithm that is computationally inexpensive. This approach is motivated from another greedy resource allocation algorithm [Zul+10]; however, it does not suffer from getting stuck in a infinite loop while allocating resources when the feasibility condition is not satisfied.

The final contribution in this chapter is the design of a polynomial-time deferred selection algorithm in which association of cellular users and D2D pairs is based on a proximity-based matching game.

All of the above mentioned approaches are computationally inexpensive and suitable for the short LTE scheduling period (1 ms). These algorithms maximize the overall system sum rate while maintaining a satisfactory signal quality at the cellular users and the D2D receivers.

The remainder of this chapter is organized as follows. We describe the system and

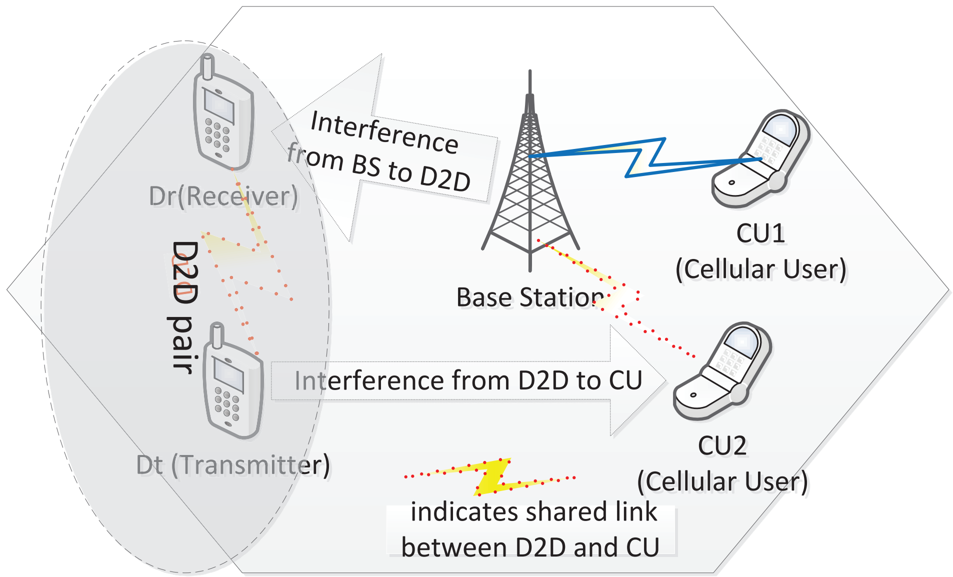

Figure 5.1: Co-channel interference scenario in Downlink in D2D communication underlaying LTE cellular network [Isl+15a].

channel model in Section 5.1. Problem formulation is presented in Section 5.2. The detailed working procedure of SLOC, MLOC and the greedy algorithm is described in Section 5.3. The motivated greedy algorithm is presented in Section 5.4 along with the improvements obtained when compared to the original greedy heuristic algorithm. We present the Deferred Acceptance based Resource Allocation (DARA) algorithm in Section 5.5. Experimental results of all these algorithms are presented in Section 5.6. Finally, we provide a summary of the chapter in Section 5.7.

5.1 Network and Channel Model

In the next three subsections we discuss the network model, radio resource and access technology for the LTE and channel model.

5.1.1 Network Model

In our model, the network consists of one BS or eNB, a set of n CU, $C = c_1, c_2, c_3, ..., c_n$ and a set of m D2D pairs, $D = d_1, d_2, d_3, ..., d_m$. The D2D devices can communicate directly through the D2D links. However, the eNB assumes the responsibility of establishing D2D connection and controlling the resource allocation to minimize the interference incurred to the CUs. The maximum distance between the two D2D devices in a pair is 15 metres. Also as in real network situations the number of cellular users is much more than the number of D2D pairs, i.e., $m << n$. Our network model has cellular users and D2D users uniformly distributed in a cell with one eNB.

5.1.2 Radio Resource and Access Technology for LTE

In LTE, total bandwidth is divided into a number of equal sized Resource Blocks (RB). In LTE, one RB occupies 0.5 milliseconds in time domain and 180 kHz in frequency domain. Fig. 1.3 in Chapter 1 depicts the LTE DL physical resources in the time and frequency domain. One major difference between LTE uplink and downlink resource allocation lies in the radio access technology used. In the DL, LTE uses OFDMA and in the UL, the radio access technology is Single Carrier Frequency Division Multiple Access (SCFDMA). The minimum scheduling period in the frequency domain is one RB and one sub-frame is 1 ms (1 RB = 0.5 ms). Therefore, the smallest unit of resource that can be assigned to a user is two RBs.

5.1.3 Channel Model

In the downlink resource sharing scenario, the victims of interference are the D2D receiver and the CU from the eNB and the D2D transmitter respectively as shown in Fig. 5.1. The dotted red line indicates a shared link or resource and the solid blue line indicates a non-shared link or resource in Fig. 5.1. The shaded circled in Fig. 5.1 indicates a D2D pair containing a transmitter and a receiver.

We model the channel as a Rayleigh fading channel. The individual channel responses thus follow an independently and identically distributed Gaussian process. The path loss model used is for Urban Micro systems (UMi) [IR08].

$$PL = 36.7log_{10}(d) + 22.7 + 26log_{10}(f_c) \tag{5.1}$$

Here d is the distance between the transmitter and the receiver (in meters) and f_c is the frequency (in GHz). The channel gains are expressed as a function of distance dependent path loss and a small scale fading and take the following form.

$$G^{a,b} = PL^{a,b}h^{a,b} \tag{5.2}$$

Here $PL^{a,b}$ is the distance dependent path loss between a and b and $h^{a,b}$ is the small scale fading between a and b.

5.2 Problem Formulation

In the downlink phase of interference calculation, the victims of interferences are the D2D receiver from the base station and the cellular user from the D2D transmitter when they are using the same allocated sub band. The total amount of SINR of a cellular user c depends on the channel gain between the eNB and c. The transmission power of the eNB, D2D devices and the CUs are P^B, P^D and P^C respectively. Thermal noise of the channel is represented using N. Therefore, the DL SINR of cellular user c is

$$SINR_c^{DL} = \frac{P^B G^{B,c}}{N + \sum_d a_d^c P^D G^{d_t,c}} \tag{5.3}$$

Here, a_d^c is a binary variable indicating whether the RBs assigned to cellular user c are shared with the D2D pair d. $a_d^c = 1$ indicates the RBs were shared with d, and $a_d^c = 0$ otherwise. P^B and P^D indicates the transmission powers of the eNB and the D2D transmitter d respectively. $G^{B,c}$ indicates the channel gain between the eNB and the cellular user c, and $G^{d_t,c}$ indicates the channel gain between the transmitter d_t of the D2D pair d and cellular user c. Similarly, the SINR at the D2D receiver d is-

$$SINR_d^{DL} = \frac{\sum_c a_d^c P^D G^{d_t,d_r}}{N + P^B G^{B,d_r}} \tag{5.4}$$

Here G^{d_t,d_r} indicates the channel gain between the transmitter d_t and receiver d_r of the D2D pair d, and G^{B,d_r} indicates the channel gain between the eNB and the D2D receiver d_r of the D2D pair d. Our goal is to maximize the system sum rate which is the sum of the rates obtained from the cellular users and the D2D users. Let the sum rate obtained from the Shannon's capacity formula for the cellular user c and

D2D pair d be R_c^{DL} and R_d^{DL} corresponding to the $SINR_c^{DL}$ and $SINR_d^{DL}$. N_c is the number of RBs assigned to the cellular users at a time slot in downlink. The optimization problem to maximize the system sum rate is given below and description of the constraints is provided after the formulation.

$$\text{maximize} \sum_{c}^{C} R_c^{DL} N_c + \sum_{c}^{C} \sum_{d}^{D} a_d^c R_d^{DL} N_c \tag{5.5}$$

$$\text{subject to} \ \frac{P^B G^{B,c}}{N + \sum_d a_d^c P^D G^{d_t,c}} \geq SINR_{c,target}^{DL}, \forall \ \ c \in C \tag{5.6}$$

$$\frac{\sum_c a_d^c P^D G^{d_t,d_r}}{N + P^B G^{B,d_r}} \geq SINR_{d,target}^{DL}, \forall \ \ d \in D \tag{5.7}$$

$$\sum_c a_d^c \leq 1, \forall \ \ c \in C \tag{5.8}$$

$$\sum_d a_d^c \leq 1, \forall \ \ d \in D \tag{5.9}$$

$$a_d^c \in \{0, 1\} \ , \forall \ c \in C \text{ and } \forall \ d \in D \tag{5.10}$$

This objective function ensures maximization of the system sum rate whereas (5.6) and (5.7) ensure that satisfactory SINR target levels are fulfilled. (5.8), (5.9) and (5.10) ensure that RBs allocated to one cellular user can be shared with only one D2D pair and one D2D pair can share the RBs of only one cellular user respectively.

5.3 Local Search Algorithms

Local search algorithms are used for solving computationally hard optimization problems [PS82]. In a local search algorithm, we start with a feasible solution and then try to improve it by moving to a neighboring solution. The solution we get using this approach is called a local optimum. In an efficient local search algorithm, a local optimum is generally very close to the global optimum.

5.3.1 Simple local search based resource allocation (SLOC)

In our local search algorithm, we start with a feasible solution which is a one to one feasible assignments of d_i where $i = 1, 2, ..., m$ to one of c_i where $i = 1, 2, ..., n$. For getting an initial feasible solution, we can implement MINLP [Chv83] described in Section 5.2 ((5.5)-(5.10)) in CPLEX [Cpl]. Alternatively, we can also use the final result greedy heuristic of Zulhasnine et al. [Zul+10] or that of a random allocation that satisfies the feasibility constraints.

Please note that, getting an initial feasible solution using MINLP is not computationally expensive [Chv83]. Once we have the initial solution, then we pick a pair (c_i, c_j) where $i \neq j$ and $i, j = 1, 2, ..., n$, that try to swap their D2D pair mappings if it improves the corresponding system sum rate while satisfying (5.6) and (5.7). We repeat this step until we find no such improvement for any pair of (c_i, c_j).

At the start of Algorithm 5, no D2D pair is allocated to any cellular user. So, after getting the initial feasible solution from line 2, we continue using the loop at line 5 until we reach a state where no improvement is possible in terms of the system sum rate. We check this improvement on a pair by pair basis from line 7 using the for loop. In this loop, we pick a pair $(c_i, c_j) \in C$, and swap their D2D pairs $(d_i, d_j) \in D$ (i.e., both cellular users have D2D pairs allocated) if it improves their sum rate (line 11) maintaining the SINR conditions (5.6) and (5.7) using Algorithm 6. If one of the cellular users has a D2D pair allocated and the other does not then it will allocate

Algorithm 5 Simple Local Search-based Resource Allocation Algorithm (SLOC)

procedure SLOC($C(c_1, c_2, ..., c_n), D(d_1, d_2, ..., d_m)$) ▷ An allocation from C to D
    Find an initial feasible allocation $allocation[c_1, c_2, ..., c_n]$ from
    C to D satisfying (5.6) and (5.7)
    $improved \leftarrow true$
    while $improved = true$ **do** ▷ Otherwise we have a final allocation
        $improved \leftarrow false$
        for each pair $(c_i, c_j) \in C$ where $i \neq j$ **do** ▷ Pairwise check
            $d_i \leftarrow allocation[c_i]$
            $d_j \leftarrow allocation[c_j]$
            if $d_i \in D$ and $d_j \in D$ **then**
                $swapResult \leftarrow \text{CALCRESULTS}(c_i, d_i, c_j, d_j)$
                if $swapResult \neq -1$ **then**
                    $improved \leftarrow true$
                    Allocate d_i to c_j and d_j to c_i. ▷ Swap
                end if
            else if $d_i \in D$ and $d_j \in \emptyset$ **then**
                $swapResult \leftarrow \text{CALCRESULTS}(c_i, d_i, c_j, -1)$
                if $swapResult \neq -1$ **then**
                    $improved \leftarrow true$
                    Deallocate d_i from c_i and assign it to c_j. ▷ Reallocation
                end if
            else if $d_i \in \emptyset$ and $d_j \in D$ **then**
                $swapResult \leftarrow \text{CALCRESULTS}(c_i, -1, c_j, d_j)$
                if $swapResult \neq -1$ **then**
                    $improved \leftarrow true$
                    Deallocate d_j from c_j and assign it to c_i. ▷ Reallocation
                end if
            end if
        end for
    end while
end procedure

Algorithm 6 Procedure for calculating allocation swap results

```
procedure CALCRESULTS(c_i, d_i, c_j, d_j)
    if (5.6) and (5.7) are satisfied for (c_i, d_j) and (c_j, d_i) then
        ifSwapped ← value of (5.5) for (c_i, d_j) and (c_j, d_i)
        current ← value of (5.5) for (c_i, d_i) and (c_j, d_j)
        if ifSwapped > current then
            improvement ← (ifSwapped − current)
            return improvement                          ▷ Improvement if swapped
        else
            return −1                                   ▷ not a valid swap
        end if
    else
        return −1                                       ▷ not a valid swap
    end if
end procedure
```

the D2D pair to the one that is not currently allocated any D2D pair if it improves the sum rate and also (5.6) and (5.7) are satisfied (line 16-26).

The loop started at line 7 will consider every possible pair of cellular users and the outer while loop at line 5 will terminate when no improvement for any possible pair is found in the inner loop in line 7.

Finally, our algorithm will terminate as at each swap we are strictly improving the total system sum rate. Therefore, in the worst case it will run for $\mathcal{O}(Wn^2)$, where W is the total sum rate of the system and n is the total number of cellular users, making this a pseudo-polynomial time algorithm. In theory, we can get a $(1-\frac{1}{\epsilon})$ approximate solution for any local search algorithm in time that is polynomial in input size and $(1-\frac{1}{\epsilon})$ [Orl+04]. It means, for small values of ϵ we can get an approximate solution within $(1-\frac{1}{\epsilon})$ of the optimal solution.

5.3.2 Maximum improvement local search based resource allocation (MLOC)

The algorithms for maximum improvement local search is as follows:

Algorithm 7 Maximum Improvement Local Search-based Resource Allocation Algorithm (MLOC)

```
procedure MLOC(C(c_1, c_2, ..., c_n), D(d_1, d_2, ..., d_m))        ▷ An allocation from C to D
    Find an initial feasible random allocation allocation[c_1, c_2, ..., c_n] from
    C to D satisfying (5.6) and (5.7)
    improved ← true
    while improved = true do                                  ▷ Otherwise, found final allocation
        maxPair ← φ
        max ← 0
        improved ← false
        for each pair (c_i, c_j) ∈ C where i ≠ j do                            ▷ Pairwise check
            d_i ← allocation[c_i]
            d_j ← allocation[c_j]
            if d_i ∈ D and d_j ∈ D then
                swapResult ← calcResults(c_i, d_i, c_j, d_j)
                if swapResult ≠ −1 then
                    improved ← true
                    current ← swapResult
                    if current ≥ max then
                        maxPair ← c_i, c_j
                        max ← current
                    end if
                end if
            else if d_j ∈ ∅ and d_i ∈ D then
                swapResult ← calcResults(c_i, d_i, c_j, −1)
                if swapResult ≠ −1 then
                    improved ← true
                    current ← swapResult
                    if current ≥ max then
                        maxPair ← c_i, c_j
```

```
                max ← current
            end if
        end if
    else if d_i ∈ ∅ and d_j ∈ D then
        swapResult ← CALCRESULTS(c_i, −1, c_j, d_j)
        if swapResult ≠ −1 then
            improved ← true
            current ← swapResult
            if current ≥ max then
                maxPair ← (c_i, c_j)
                max ← current
            end if
        end if
    end if
  end for
  Swap the allocation of maxPair(c_i, c_j)                    ▷ Perform swap
 end while
end procedure
```

Algorithms 5 and 7 are quite similar in terms of working procedure. However, they have some major differences in the way they select a pair of cellular users to swap the D2D devices allocated to them. The differences are described in the following subsection.

5.3.3 Differences between SLOC and MLOC

At each iteration of MLOC, like SLOC, we consider all possible cellular user pairs. But unlike SLOC, we only calculate the improvement for each pair and do not swap their devices if we find the improvement. Instead, we keep track of the maximum improvement obtained for different pairs of users and finally, at the end of an iteration, we choose the one that gives us the maximum improvement and satisfies feasibility constraints (5.6) and (5.7) and then repeat the process. If for any iteration we do not find an improvement for any pair of users, we terminate the algorithm. So considering the previous example, first we calculate the improvement for c_1 and c_2

and we do not swap it right away (main difference with SLOC), we keep calculating the improvements for other pairs such as c_2, c_3 (in the previous case of SLOC we consider the new device pair for c_2 when we compare this pair). Once we find improvements for all possible pairs then we swap the users for which we find the maximum improvement. Therefore, swaps are only performed at line 44 of Algorithm 7.

In each iteration of SLOC, we can make multiple swaps/reallocations. However, at each iteration of MLOC we are choosing a particular swap/reallocation (greedily). If we compare the running time on average then SLOC should be faster as it might reach the local optima earlier. However, in the worst case analysis, theoretically the running time will be the same. Moreover, in practice we have a better chance of getting an improved solution in MLOC which is reflected in the experimental results section.

In the next section we describe two greedy approaches to solve the problem formulated in Section 5.2. The first one is our proposed approach and the second one is the greedy algorithm from which our approach was motivated.

5.4 Greedy Algorithms

In the next three subsections we present, firstly, the proposed greedy algorithm, secondly, the greedy algorithm from which this was motivated, finally, the differences between the two algorithms and how our approach removes the problems associated with the existing approach.

Algorithm 8 Proposed greedy heuristic-based resource allocation for D2D (PGRA)

1: **procedure** GreedyRA($C(c_1, c_2, ..., c_n), D(d_1, d_2, ..., d_m)$) ▷ An allocation from C to D
2: **for** e **do**ach cellular user c_i
3: **for** e **do**ach D2D pair d_j
4: $R_{ij} \leftarrow$ FCRA(c_i, d_j) ▷ n× m combinations in one list
5: **end for**
6: **end for**
7: Sort R is descending order
8: $maxVal \leftarrow -1$
9: **while** $R \neq \phi$ **do**
10: $maxVal \leftarrow$ First feasible entry R_{ij}in R
11: Allocate d_j to c_i
12: Remove all R_{xy} where $x = i$ or $y = j$
13: **end while**
14: **end procedure**

5.4.1 Proposed new Greedy Resource Allocation algorithm (PGRA)

In this section we present a greedy approach to solve the resource allocation problem defined in Section 5.2. This greedy approach is similar to the greedy approach proposed in Zulhasnine et al. [Zul+10]; however, some differences in their working principle demand a separate mention. This algorithm works greedily by allocating those cellular RBs to D2D pairs for which the feasible channel rate is maximum. Here, feasibility means satisfying the SINR constraints (5.6) and (5.7).

In Algorithm 8, at first all possible resource allocation combinations among n cellular users and m D2D pairs are calculated (line 2-6) using Algorithm 9. Now all the feasible channel rates are sorted in a descending order (line 7) in list R. In the loop at line 9, starting from the first element of the sorted list R we start allocating D2D pairs to cellular users (line 11). Now for maintaining the constraints (5.8), (5.9) and (5.10), we remove all the elements from R where the cellular user or the D2D

Algorithm 9 Feasible channel rate calculation

1: **procedure** FCRA(c_i, d_j) ▷ Feasible channel rate between c_i and d_j
2: $rate \leftarrow$ resulting rate from (5.5) if c_i is allocated to d_j ▷ n× m combinations
3: $validChannel \leftarrow false$
4: **if** (5.6) and (5.7) are satisfied for (c_i, d_j) **then**
5: $validChannel \leftarrow true$
6: **else**
7: $validChannel \leftarrow false$
8: **end if**
9: **if** $validChannel = true$ **then**
10: **return** $rate$ ▷ Return feasible channel rate
11: **else**
12: **return** -1 ▷ Not a feasible channel
13: **end if**
14: **end procedure**

pair is already part of a previous allocation (line 12).

Algorithm 9 is very straight forward and it calculates the channel rate between a cellular user and a D2D pair using (5.5) (line 2). From line 4-12 it checks the validity of the SINR constraints for the cellular user and the D2D pair sharing the channel. If the SINR constraints (5.6) and (5.7) are satisfied then the corresponding channel rate is returned (line 10), otherwise -1 is returned to indicate an infeasible allocation.

The worst case complexity of line 2-6 of Algorithm 8 is $\mathcal{O}(\mathbb{N})$ where $\mathbb{N} = n \times m$, as we are checking the feasibility of each D2D pair with each cellular user. However, the sorting step of R at line 7 is bounded by $\mathcal{O}(\mathbb{N}log\mathbb{N})$. The while loop at line 9-13 in Algorithm 8 continues until R is empty. R contains at most $n \times m$ items to start with and at each iteration at least one item from R is removed. Therefore the running time of the while loop at line 9 is bounded by $\mathcal{O}(\mathbb{N})$. Therefore, the overall complexity of PGRA is $\mathcal{O}(\mathbb{N}) + \mathcal{O}(\mathbb{N}log\mathbb{N}) + \mathcal{O}(\mathbb{N}) = \mathcal{O}(\mathbb{N}log\mathbb{N})$, where $\mathbb{N} = n \times m$.

5.4.2 Greedy heuristic resource allocation (GHRA) [Zul+10]

In this approach, all the UE are first sorted in a decreasing order based on the channel quality identifier (CQI) and then they are tried out in order to match with a D2D pair that is not yet assigned to share RBs with any other cellular user. A target SINR has to be maintained to enable a successful association of a D2D pair to a cellular user RBs.

From (5.3), it is clear that, a cellular user with a higher CQI can share the RBs allocated to them with a D2D transmitter with low channel gain between them. This will result in a higher value of $SINR_c^{DL}$ in (5.3). This approach greedily tries to allocate cellular users RBs to D2D transmitters and this process sometimes may not allocate optimally and miss some opportunity to allocate some D2D pairs. Moreover, the algorithm as described in Zulhasnine et al. [Zul+10] may not always terminate. Therefore, we changed the terminating condition of algorithm for it to be able to terminate in all cases without compromising the intended working principle.

5.4.3 Differences between PGRA and GHRA

There are some major differences between PGRA and the GHRA [Zul+10]. The main problem with Algorithm 10 is that it may get stuck in an infinite loop as it does not change the loop variables if the feasibility condition is not satisfied (line 17). However, it is very likely that the feasibility condition may not be satisfied for many of the cases if SINR target is not satisfied. In case of PGRA as described in algorithm 8, when we create the list of possible allocations we only consider those channels that satisfy the SINR constraints. Therefore, no further checking is required

Algorithm 10 GHRA as in [Zul+10]

1: **procedure** GHRA(C, G_{cd}, D, m_c) ▷ An allocation from C to D
2: C : Sorted list of all CQIs for all downlink UEs in decreasing order
3: G_{cd} : Channel gain matrix
4: D : List of D2D pairs yet to be assigned RBs
5: m_c : Number of RBs assigned to cellular UE c
6: $c \leftarrow 1$
7: **while** $D \neq \phi$ or $c == C$ **do**
8: Pick RBs with c^{th} largest value.
9: Find the D2D transmitter d for which channel gain is minimum
10: $SINR_c^{DL} \leftarrow \frac{P^B G^{B,c}}{N+I+P^D G^{c,d}}$
11: $SINR_d^{DL} \leftarrow \frac{P^D G^{d,d}}{N+I+P^B G^{d,B}}$
12: **if** $SINR_c^{DL} \geq SINR_{c,target}^{DL}$ and $SINR_d^{DL} \geq SINR_{d,target}^{DL}$ **then**
13: Share all RBs of UE c with D2D pair d
14: $D \leftarrow D - \{d\}$
15: $c \leftarrow c + 1$
16: **else**
17: Do not assign RBs to D2D connection d
18: **end if**
19: **end while**
20: **end procedure**

for the SINR constraints.

To fix the problem of a possible non-terminating loop at line 7 of Algorithm 10, if we increase one of the loop variables in line 17 (either remove an element from D as in line 14 or increase c as in line 15) we may not get the best possible channel rate in the greedy approach. In Algorithm 8, no such problem exists as we are not losing any information regarding possible channel rates of an allocation as they are sorted in descending order after satisfying the feasibility condition, and at each iteration of the Algorithm 8 at line 9 at least one element is removed that guarantees termination of the loop.

5.5 Deferred Acceptance based Algorithm for Resource Allocation (DARA)

In the deferred acceptance based matching algorithm, we start with a preference matrix calculated based on the location of the D2D devices and the cellular users. Let the preference matrix $Pref$ have $2n \times n$ elements. Here, n is the number of cellular users and we assume $n > m$ where m is the number of D2D pairs. Therefore, the $Pref$ matrix contains $n+m$ valid rows and $n-m$ invalid rows that do not correspond to any D2D or cellular devices. Each valid row for D2D pairs in the $Pref$ matrix contains the list of the cellular users in ascending order of their proximity to the D2D pair. Each valid row for cellular users contains m valid entries for the list of the D2D pairs in ascending order of their proximity to the cellular user and the remaining $n - m$ entries are invalid and do not affect the calculation. For each valid row the highest preferred item is at the beginning of the row. An example $Pref$ matrix is shown in Table 5.1 with 3 D2D devices and 4 cellular devices. In this example, for row 1 the highest preferred item 6 is at the beginning of the row.

Similarly, we maintain another list, *Association*, with $2n$ elements to contain the current association of the items. In this list $n + m$ items are valid entries and the rest are invalid and will not affect our calculation. The invalid entries do not affect the computation of correct results and are used to maintain the generality of the originally proposed solution that has equal elements in either side of the matching game [MW70]. Initially there is no association among the D2D and cellular users.

We describe the deferred acceptance based resource allocation approach in algorithm 11.

At the start of Algorithm 11, in line 2 we declare and initialize the $Pref$ matrix

Algorithm 11 Deferred acceptance based Resource Allocation Algorithm (DARA)

```
procedure DARA(C(c_1, c_2, ..., c_n), D(d_1, d_2, ..., d_m))        ▷ An allocation from C to D
    Pref[2n][n] ← calculatePreference()                             ▷ Populate the Preference matrix
    for each i ∈ (1...2n) do
        Association[i] ← free
    end for
    for each d_i ∈ D do
        Q.push(d_i)                                                 ▷ Initialize Q with all un-associated devices
    end for
    while Q! = empty do                                             ▷ Continue until all the devices are associated
        Front ← Q.pop()
        for each i ∈ n do                                           ▷ Check all priorities
            temp ← Pref[Front][i]
            if Association[temp] = free then
                Association[temp] ← Front
                Association[Front] ← temp
            else
                p1 ← Preference of Association[temp] with respect to temp
                p2 ← Preference of Front with respect to temp
                                                                    ▷ lower preference index means it has higher priority
                if p1 > p2 and isValid(Front, temp) then
                    nowFree ← Association[temp]                     ▷ Release old association
                    Association[temp] ← Front
                    Association[Front] ← temp
                    Association[nowFree] ← free
                    Q.push(nowFree)
                end if
            end if
        end for
    end while
    Report Association list as the final allocation of resources.
end procedure
```

Table 5.1: Example $Pref$ matrix.

Devices	**preference**			
⇓	0	1	2	3
0 (D2D)	5	4	7	6
1 (D2D)	6	5	7	4
2 (D2D)	7	6	5	4
3 (invalid)	invalid	invalid	invalid	invalid
4 (cellular)	0	1	2	invalid
5 (cellular)	0	2	1	invalid
6 (cellular)	1	0	2	invalid
7 (cellular)	2	0	1	invalid

Algorithm 12 Procedure for finding if the allocation satisfies the QoS constraints

```
procedure isValid(d2d, cellular)
    valid ← false
    if (5.6) and (5.7) are satisfied for (d2d, cellular) then
        valid ← True
    end if
    return valid
end procedure
```

as explained previously. From line 3-5 we initialize the list *Association* as explained previously. From line 6-8 we create a queue Q to contain all the un-associated or free D2D pairs until now and is initialized with all the D2D pairs.

The while loop from line 9-27 contains the core part of the algorithm. It runs as long as there is a free D2D pair. In line 10 we pop the front element from the queue Q and use it as $Front$ for the rest of the loop. The for loop at line 11 runs for all the priorities starting with the highest priority. In Line 12, *temp* contains the cellular user index associated with $Front$ with priority i. From line 13-15 if the cellular user is free then it allocates it to the $Front$ and $Front$ to it. Otherwise, the algorithm goes into the else in line 16. $p1$ and $p2$ in line 17 and line 18 contain the preferences of the currently associated cellular user and the $Front$ respectively. Line 19 checks if the preference of the current association is less than that of $Front$ and if the QoS constraints (5.6) and (5.7) are satisfied. If both the conditions are true then from line 20-23 the reallocation is performed and the recently freed D2D pair is added to Q.

Finally, this algorithm will terminate as at each step an item is removed from Q. We add an item to Q only when it is freed and at each step we are allocating one D2D pair to a cellular user. In the worst case the algorithm will run in $\mathcal{O}(n^2)$, where n is the number of cellular users. However, in average case analysis the algorithm runs is $\mathcal{O}(n \log n)$ time as shown in Knuth [Knu76].

Our resource allocation algorithm can be adopted at the eNB and the devices trying to communicate will use LTE features and protocols as per 3GPP specifications when they are sharing resources from cellular users.

5.6 Performance Evaluation

In our experimental evaluation, we conduct two different sets of experiments. In the first experiment set we compare the SLOC, MLOC and the new greedy algorithm with the existing Greedy Heuristic Resource Allocation (GHRA) algorithm and a random resource allocation (random RA) algorithm. From here on we will refer to this set of experiments as first experiment. In the second set of experiments, we compare DARA with SLOC, GHRA and random RA. From the previous sections

Table 5.2: Simulation Parameters of Chapter 5.

Parameter	Value
Cell Radius	1000 metres
Cellular Users	250 (experiment set one) 300 (experiment set two)
D2D pairs	10 to 200 (increments of 10 for experiment set one 50 to 250 (increments of 10 for experiment set two)
% of D2D users	4% to 45% (experiment set one) 14% to 46% (experiment set two)
Maximum D2D pair distance	15 metres
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Noise power	-174 dBm
Pathloss Model	Umi pathloss model for NLOS hexagonal cell layout [IR08]
Carrier Frequency	1.7 GHz for LTE

we identified that, MLOC is derived from SLOC and PGRA is derived from GRA. Therefore, in the second experiment we do not compare the derived algorithms rather compare only the original algorithms along with DARA. In the first experiment we consulted every algorithm except for DARA for a clearer view of the graphs as more graphs would make the graph cluttered and hard to read and comprehend.

5.6.1 Simulation environment setup

In our simulation set up, we place the eNB at the center of the cell. The cellular and D2D pairs are distributed uniformly in a cellular region. However, in the case of D2D pairs, it is made sure that the maximum distance between the transmitter and the receiver of a pair of D2D devices is at most 15 metres. The simulation parameters are shown in Table 5.2 [IR08]. We consider a single cell in a LTE cellular network and we also assume the co-existence of D2D and cellular communication for the spectrum sharing purpose.

5.6.2 First Experiment

We fix the total number of cellular users to 250 and vary the number of D2D pairs from 10 to 200, i.e., the D2D user varies from 4% to 45% of the total users. This is in accordance with the fact that the number of cellular users is larger than the number of D2D pairs. We use NS-3 [Ns3] for evaluating all resource allocation algorithms for performance comparison in the downlink direction. For all simulation results mentioned in this chapter, an average over 20 simulations are reported to remove the possible effects of any kind of extremity. In our simulations for SLOC and MLOC, we consider a random feasible solution as the initial feasible solution (line 2 of Algorithm 5 and 7).

Reference algorithms for performance comparison

We choose GHRA [Zul+10] and a random resource allocation algorithm to compare with SLOC, MLOC and the proposed greedy algorithm. We choose GHRA as one of the baseline algorithms as this is also used to maximize the system sum rate through intelligent resource allocation without incurring exponential time. SLOC, MLOC and the new greedy algorithms are also motivated from the need to design a fast algorithm to solve the problem formulation (5.5) to (5.10) which is similar to [Zul+10]. We choose random resource allocation as this is one of the easiest to understand approaches to allocate resources. GHRA is already explained in subsection 5.4.2, therefore we only explain the random resource allocation algorithm in the following paragraph.

Random Feasible Resource Allocation Algorithm (Random RA) Cellular user RBs are assigned to D2D pairs randomly as long as they satisfy the target SINR threshold values. This allocation has only one condition of satisfying the SINR threshold. As long as this condition is satisfied an allocation is assumed to be successful. We used the final result of this simplistic random allocation as the initial feasible solution for our local search algorithm.

5.6.3 Results and Analysis of First Experiment

To compare the performance of the resource allocation algorithm we plot the system sum rate obtained by the five resource allocation algorithms in Fig. 5.2. From this figure it is quite clear that SLOC, MLOC, GHRA and the new greedy algorithm all obtain a much better system sum rate than the random allocation algorithm. However, to have a closer look at the sum rate results of these four resource allocation algorithms we plot the sum rates obtained by these four algorithms except for the random allocation in Fig. 5.3. From Fig. 5.3, we find some interesting observations;

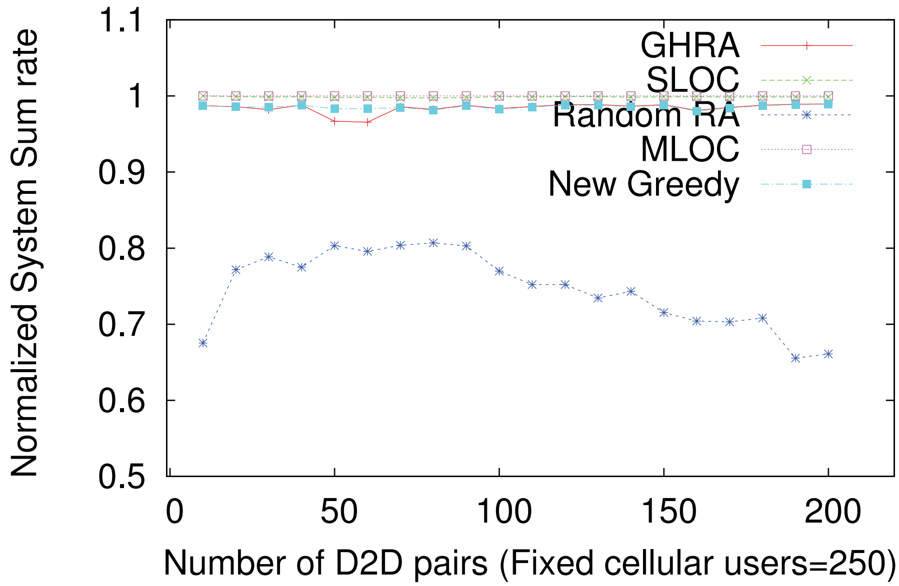

Figure 5.2: Normalized system sum rate of the five RA approaches (Normalized with respect to MLOC).

the two local search approaches and the two greedy approaches obtain similar system sum rates, but both the local search approaches clearly obtain better system sum rates than the greedy approaches.

To further investigate the system sum rates obtained for the local search algorithms we find that the MLOC performs better than the SLOC. This is expected because in case of MLOC we swap only the pair with maximum improvement in each iteration whereas in case of SLOC we perform swap as soon as we find a feasible swap that improves the system sum rate. Now as we look into the performances of the greedy approaches, we observe that their performances are similar except for a few cases (number of D2D pairs = 30, 50 and 60) where the proposed greedy approach performs better than GHRA which is expected. This is because of the problem with

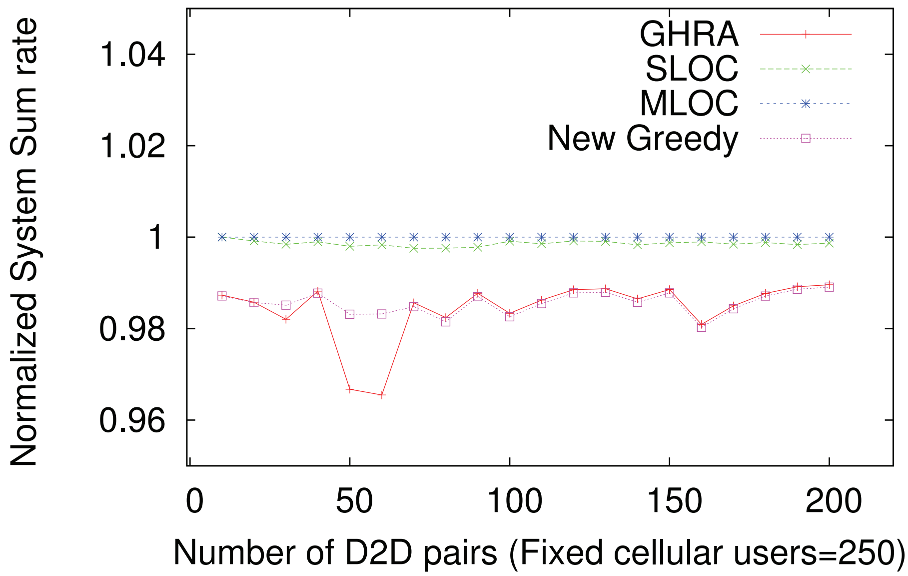

Figure 5.3: Normalized system sum rate of the four RA approaches (Normalized with respect to MLOC).

GHRA explained in subsection 5.4.3. Due to the looping condition problem in Algorithm 10, some D2D pairs remained unassigned causing the system sum rate to be less than the proposed greedy approach.

Figs. 5.4 and 5.5 show the SINR achieved by the resource allocation algorithms at the D2D receivers and cellular users respectively. Fig. 5.4 suggests that there is hardly any difference among the signal qualities achieved by the RA algorithms. However, from Fig. 5.5 we observe that all the RA algorithms obtain better SINRs at the cellular users than the random allocation. Therefore, to depict the SINR performance of the algorithms more clearly we show the SINRs at the cellular users obtained by the four algorithms except for the random allocation in Fig. 5.6.

From Fig. 5.6 it is clear that, the SINRs at the cellular users obtained by the SLOC and MLOC are hard to separate and the greedy approaches are also very close

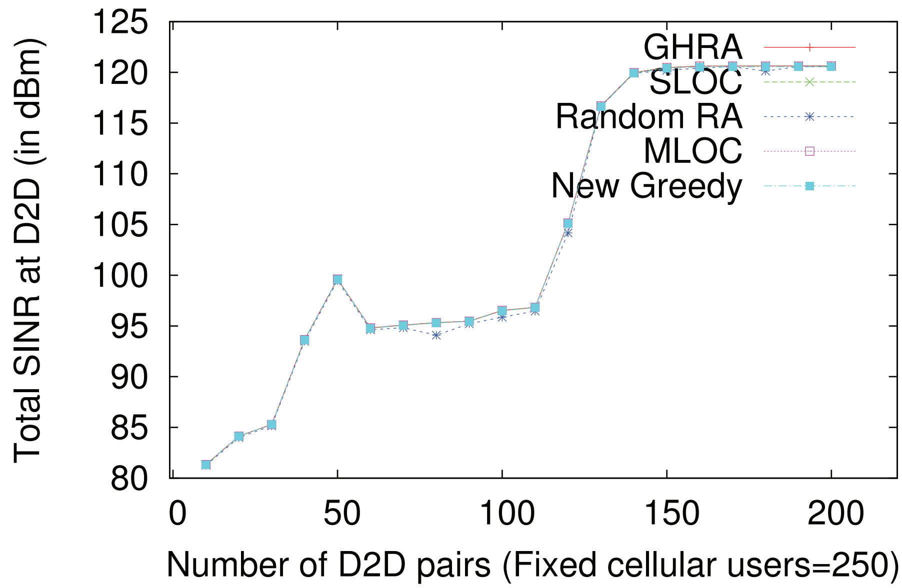

Figure 5.4: SINR at the D2D receivers of the five RA approaches.

to each other in terms of SINR at the cellular users. However, it is obvious from Fig. 5.6 that both the local search approaches obtain better quality signals at the cellular users than the greedy approaches.

Summarizing from Figs. 5.2, 5.3, 5.4, 5.5 and 5.6, we observe that both the local search algorithms achieve better system sum rates and better signal qualities at the cellular users than the greedy algorithms and the random algorithm; and the proposed greedy algorithm is on par with the GHRA in terms of system sum rate and signal quality at the cellular users but avoids the accidental missed allocation as experienced by GHRA.

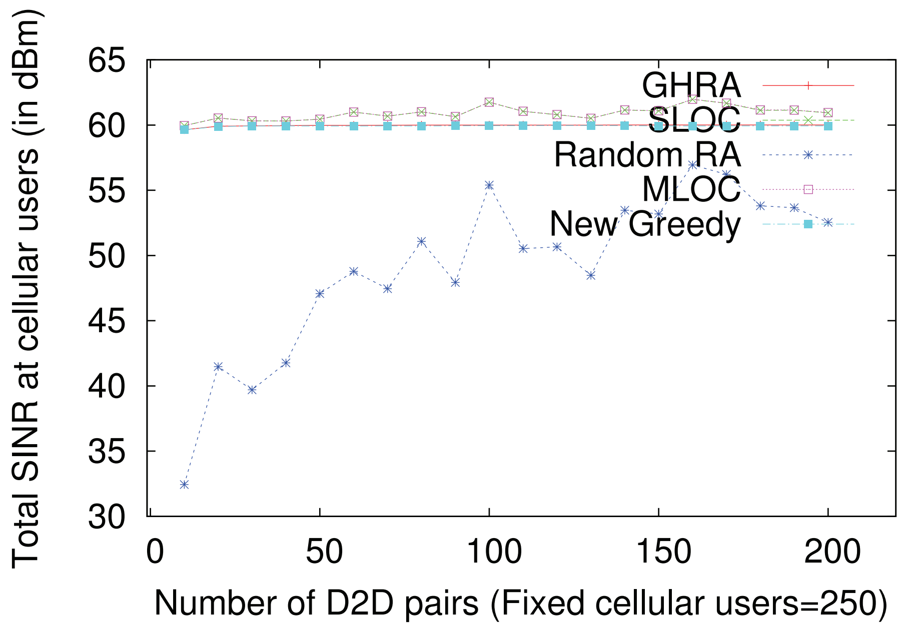

Figure 5.5: SINR at the cellular users of the five RA approaches.

5.6.4 Second Experiment

In these experiments, the total number of cellular users is fixed to 300 and the number of D2D pairs vary from 50 to 250, i.e., the percentage of D2D pairs ranges from 14% to 46% of the total number of devices. This is also in accordance with the fact that the number of cellular users is larger than the number of D2D pairs like experiment set up one. As experiment set up one, all simulation results reported is an average over 20 simulations in order to remove the possible effect of any kind of extremes that may result from outlier cases.

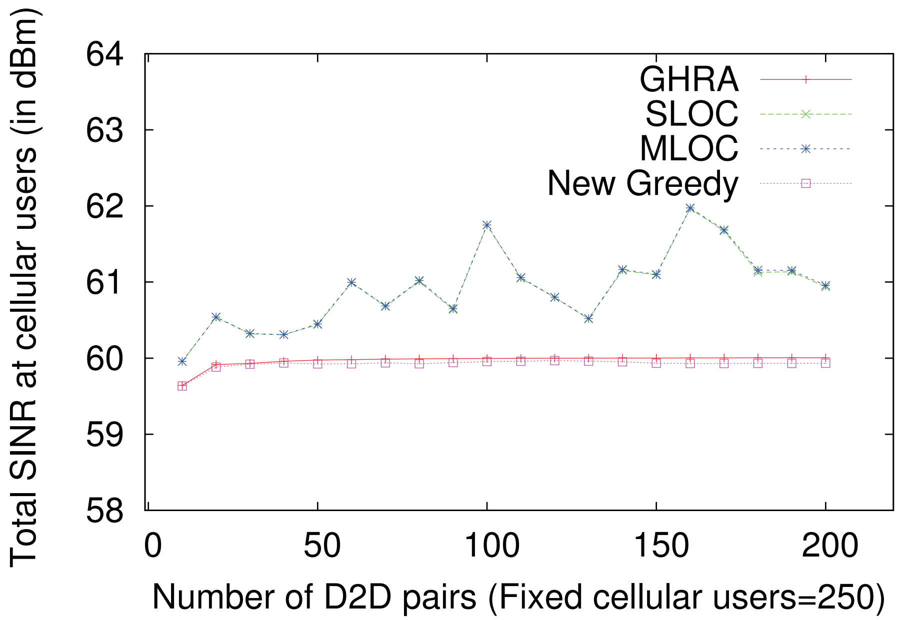

Figure 5.6: SINR at the cellular users of the four RA approaches.

Reference algorithms for performance comparison

We choose SLOC by Islam et al. [Isl+15a], GHRA by Zulhasnine et al. [Zul+10] and a random RA to compare with DARA. We choose SLOC as a reference algorithm as it is the only local search algorithm known to our knowledge to solve the resource allocation algorithm underlaying D2D and also it provides a locally optimal solution in terms of system sum rate when compared with other reference algorithms. We choose GHRA as one of the baseline algorithms as this is also used to maximize system sum rate through intelligent resource allocation without incurring exponential time. DARA is also motivated from the need to design a faster algorithm to solve the problem formulation (5.5) to (5.10) which is similar to SLOC [Isl+15a] and GHRA [Zul+10]. Random resource allocation is chosen as it is simple to understand and

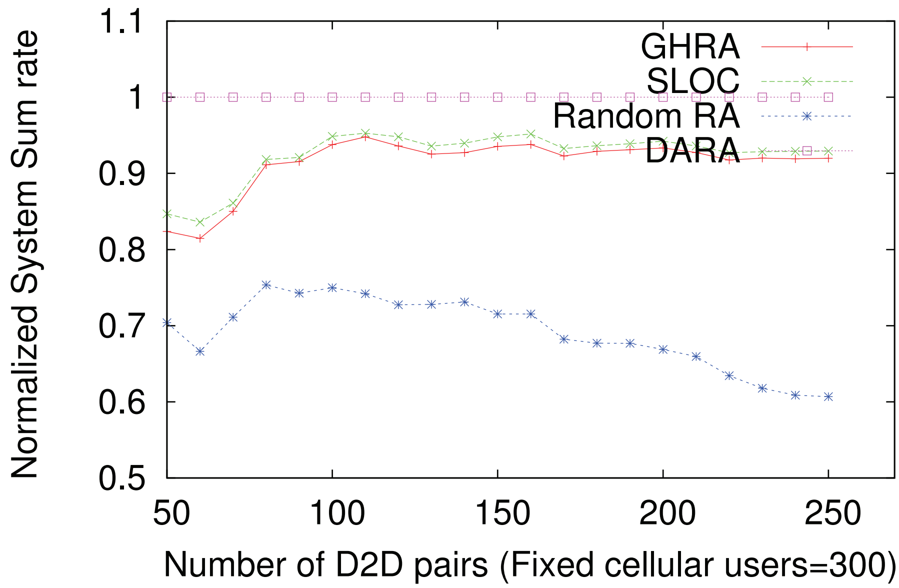

Figure 5.7: Normalized system sum rate of the four RA approaches (Normalized with respect to DARA).

can be used as a worst performance indicator.

5.6.5 Results and Analysis of Second Experiment

In Fig. 5.7, we plot the system sum rate obtained all the four resource allocation algorithms. The obtained system sum rates are normalized with respect to the sum rate obtained by DARA to have a clearer view of the performances of the algorithms. Otherwise, the difference between sum rates obtained from SLOC and GHRA is difficult to identify as they are very close to each other. From Fig. 5.7 it is evident that, the random allocation performs the worst of all the approaches as expected, since it does not have any kind of optimization objective and rather randomly allocates the first feasible assignment. It is also clear that the SLOC and

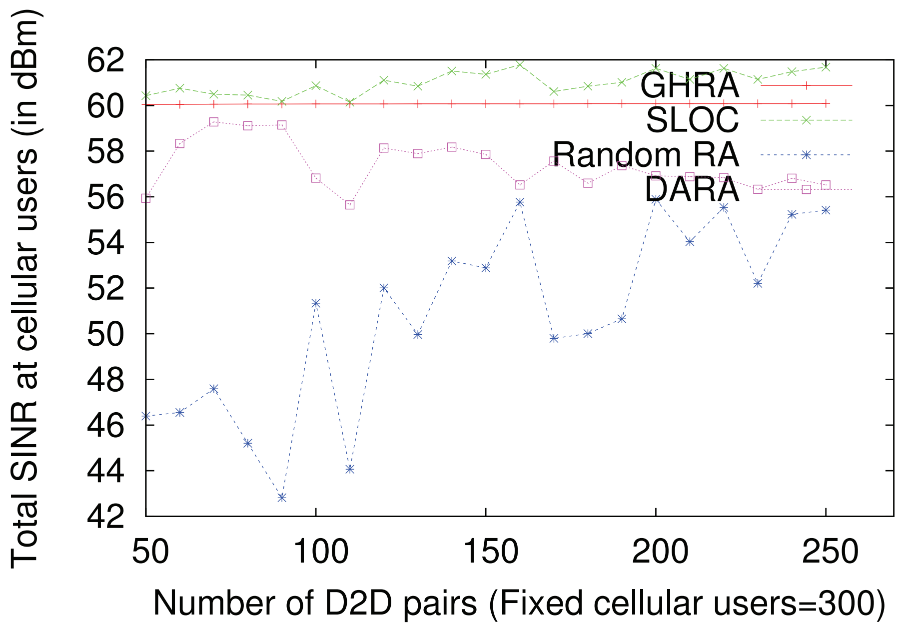

Figure 5.8: SINR at the cellular users of the four RA approaches.

GHRA are close to each other in terms of sum rate; however, SLOC consistently outperforms GHRA for a varying number of D2D pairs. The improvement in SLOC results from the fact that it performs local improvements until no such improvements are possible. However, DARA achieved 5% to 20% higher system sum rate compared to SLOC or GHRA for all different values of D2D pairs. This results from the fact that the deferred acceptance approach does not get stuck in a local optimum like the local search approach, and instead reaches a globally stable solution. A stable solution is a solution when swapping two matching pairs is not of interest to any of the pairs.

We plot the SINR obtained at the cellular users from the allocation in Fig. 5.8. We find that the SINR at the cellular users is the worst for the random allocation as expected. DARA will result in cellular users having lower SINR values than those

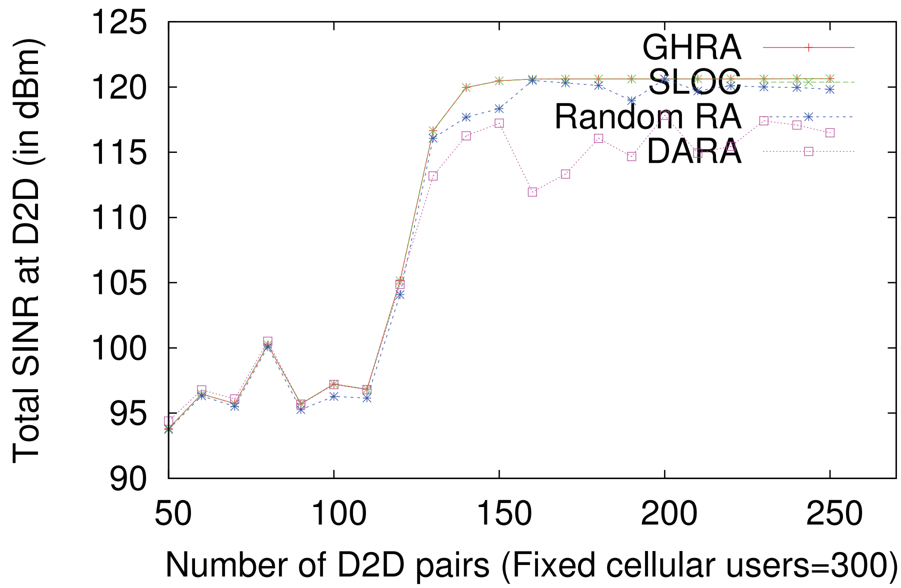

Figure 5.9: SINR at the D2D receiver of the four RA approaches.

produced by SLOC and GHRA. This is due to the fact that the preference function is calculated based on proximity measurements only and does not incorporate actual channel conditions. The SLOC obtains the best SINR and the GHRA is close to that of SLOC. The close SINR values for SLOC and GHRA result from the fact that they both have similar allocations when the feasibility condition of SINR target satisfaction is checked for. However, SLOC always obtains a better SINR at cellular users than that of GHRA. From Fig 5.9, we find the SINR at the D2D receivers for the four approaches. The results are hard to differentiate for cellular users number less than 150. Even after that, the results are very close and within 2% to 6% of each other.

In summary, from Figs. 5.7, 5.8 and 5.9, we observe that, DARA can achieve much better overall system sum rate than the other three approaches maintaining the

QoS constraints at the cellular users or at the D2D receiver with varying percentages (14% to 46%) of D2D pairs of the total number of users.

5.7 Summary

In this chapter, we presented three different approaches to the D2D resource allocation problem at the RB level to maximize system sum rate. We first formulated the problem as an MINLP and then propose different algorithms to solve this MINLP approximately in a computationally efficient manner. The simulation results showed that, all the three approaches, SLOC (and its extension MLOC), the new greedy approach and DARA obtain a better system sum rate than GHRA and random RA while satisfying the SINR constraints. These computationally efficient approaches can be adopted by the 3GPP for inclusion in LTE to allocate resources for D2D underlaying a cellular network that requires a minimum level of QoS satisfaction.

Chapter 6

Summary and Conclusions

In the current age of automation, most of the services in our day-to-day lives, military routines, environmental routines and industrial production routines are shifting towards a total mechanization phase. Consequently, a large number of machines are being deployed to accomplish this transition. To this end, it is necessary to realize effective communication between the machines or devices. Allowing the large number of devices to seamlessly communicate with each other based on their proximity to each other is the backbone of D2D communication. For example, home automation allows to control the devices at home from a mobile device from a distant location. However, it is also beneficial for the devices to communicate directly with each other without being under control of a central node such as eNB. From the cellular networks perspective, allowing the cellular users to share radio resources allocated to them with other D2D communicating pairs results in increasing the cellular throughput. The interference coordination challenge associated with resource sharing is the primary focus of research in this thesis.

We provide a summary of the schemes presented in this thesis in Section 6.1.

Some future research directions are outlined in Section 6.2.

6.1 Summary

The schemes proposed in this research focus on four main aspects of interference coordination. Firstly, increase the system sum rate while allocating resources or maintain a minimum system sum rate demand; secondly, maintain a certain level of signal quality; thirdly, allocate resources fairly among all the devices and, finally ensure that the allocation procedure is performed performed within a short period of time to be able to be used in an LTE scheduling period of 1 ms.

In Chapter 3, we modeled the allocation problem as an interference minimization problem that needs to satisfy a system sum rate demand. We solved this problem by reducing it to a variant of the knapsack problem. The solution is a polynomial time sub-optimal allocation that makes it suitable for use in an LTE scheduling period.

In Chapter 4, we used a similar formulation as the one in Chapter 3 with a dual purpose in mind: minimizing the interference, and ensuring a fair allocation of resources among the D2D pairs. This scheme prevented a particular set of D2D pairs from starvation.

In Chapter 5, we formulated the problem as a sum rate maximization problem that needs to satisfy a QoS target at the interference victims. We proposed four different schemes to address this problem showing how this problem can be approached from different perspectives. A first of its kind local search scheme for D2D resource allocation is proposed, an extension of the local search scheme was then presented. Following these two local search approaches, a greedy scheme was proposed that is motivated by another greedy approach but does not suffer from the problems associated with it. Finally, we presented a stable matching solution inspired from the classical stable marriage problem.

Among these algorithms the solution based on deferred acceptance has the least computational cost and also obtains a better system sum rate when compared to SLOC, MLOC or GHRA. Though DARA incurs more interference than these approaches it should be noted that DARA still satisfies the QoS targets at the interference victims. Therefore DARA is the most preferred algorithm for RB level resource allocation.

6.2 Future Work

We can highlight several future research problems from our work so far. In our schemes we have considered the power level of the devices to be fixed. Residual energy can be taken into account to find a more energy efficient approach that takes advantage of different power levels. As the devices are putting strain on the battery more than ever because of the number and variety of applications running on them, it is important for the allocation algorithms to be energy efficient.

Prioritizing different applications running on the devices that participate in D2D communications can provide better user satisfaction in a practical world. For example, a D2D pair communicating real time data should be prioritized over another D2D pair not communicating real time data while allocating cellular resources to them. Furthermore, a composite scheme considering the different power levels and priority of the applications can be taken into account to provide a more comprehensive framework.

A utility based resource allocation scheme where utility is calculated as a composite metric combining residual energy of devices, last time-slot when a cellular resource was allocated to it, and also the priority of the applications running on the devices can provide a better reflection of the actual communication scenario. Each metric in the composite metric can be assigned a weight to contribute toward a final utility of a particular D2D pair.

Bibliography

[3gpa] *Overview of 3GPP Release 12 V0.1.4 (2014-09)*. Retrieved on 11^{th} November, 2014. URL: http://www.3gpp.org/ftp/Information/WORK_PLAN/Description_Releases/.

[3gpb] *Study on LTE device to device proximity services; Radio aspects*. Technical Report. Release 12. 3GPP TR 36.843 v12.0.1, 2014.

[Ary+01] V. Arya, N. Garg, R. Khandekar, A. Meyerson, K. Munagala, and V. Pandit. "Local Search Heuristic for K-median and Facility Location Problems". In: *Proceedings of the Thirty-third Annual ACM Symposium on Theory of Computing*. STOC '01. Hersonissos, Greece: ACM, 2001, pp. 21–29. ISBN: 1-58113-349-9. DOI: 10.1145/380752.380755. URL: http://doi.acm.org/10.1145/380752.380755.

[Ban+14] T. Bansal, K. Sundaresan, S. Rangarajan, and P. Sinha. "R2D2: Embracing device-to-device communication in next generation cellular networks". In: *2014 Proceedings IEEE INFOCOM*. 2014, pp. 1563–1571. DOI: 10.1109/INFOCOM.2014.6848092.

[Bry14] A. Brydon. *Opportunities and threats from LTE Device-to-Device (D2D) communication*. Retrieved on 31^{st} December, 2015 from website. 2014. URL: http://www.unwiredinsight.com/2014/lte-d2d.

[Cai+15] X. Cai, J. Zheng, and Y. Zhang. “A Graph-coloring based resource allocation algorithm for D2D communication in cellular networks”. In: *2015 IEEE International Conference on Communications (ICC)*. 2015, pp. 5429–5434. DOI: 10.1109/ICC.2015.7249187.

[Chv83] V. Chvatal. *Linear programming*. Macmillan, 1983.

[Cpl] *CPLEX Optimizer*. Retrieved on 10^{th}April, 2015. URL: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/.

[Csi+91] J. Csirik, J. B. G. Frenk, M. Labbé, and S. Zhang. “Heuristics for the 0-1 Min-knapsack Problem”. In: *Acta Cybern.* 10.1-2 (Sept. 1991), pp. 15–20. ISSN: 0324-721X. URL: http://dl.acm.org/citation.cfm?id=150385.150387.

[Dop+09] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl. “Device-to-device communication as an underlay to LTE-advanced networks”. In: *IEEE Communications Magazine* 47.12 (2009), pp. 42–49. ISSN: 0163-6804. DOI: 10.1109/MCOM.2009.5350367.

[DS14] D. J. Dechene and A. Shami. “Energy-Aware Resource Allocation Strategies for LTE Uplink with Synchronous HARQ Constraints”. In: *IEEE Transactions on Mobile Computing* 13.2 (2014), pp. 422–433. ISSN: 1536-1233. DOI: 10.1109/TMC.2012.256.

[Fen+14] D. Feng, L. Lu, Y. Yuan-Wu, G. Li, S. Li, and G. Feng. "Device-to-device communications in cellular networks". In: *IEEE Communications Magazine* 52.4 (2014), pp. 49–55. ISSN: 0163-6804. DOI: 10.1109/MCOM.2014.6807946.

[Fod+12] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Mikló s, and Z. Turányi. "Design aspects of network assisted device-to-device communications". In: *IEEE Communications Magazine* 50.3 (2012), pp. 170–177. ISSN: 0163-6804. DOI: 10.1109/MCOM.2012.6163598.

[Gol+12] N. Golrezaei, A. F. Molisch, and A. G. Dimakis. "Base-station assisted device-to-device communications for high-throughput wireless video networks". In: *2012 IEEE International Conference on Communications (ICC)*. 2012, pp. 7077–7081. DOI: 10.1109/ICC.2012.6364729.

[GVG79] E. V. Levner G. V. Gens. "Computational complexity of approximation algorithms for combinatorial problems". In: *Lecture Notes in Computer Science* 74 (1979), pp. 292–300.

[Hak+10] S. Hakola, T. Chen, J. Lehtomaki, and T. Koskela. "Device-To-Device Communication in Cellular Network - Performance Analysis of Optimum and Practical Communication Mode Selection". In: *2010 IEEE Wireless Communications and Networking Conference (WCNC)*. 2010, pp. 1–6. DOI: 10.1109/WCNC.2010.5506133.

[HK81] T. Han and K. Kobayashi. "A new achievable rate region for the interference channel". In: *IEEE Transactions on Information Theory* 27.1 (1981), pp. 49–60. ISSN: 0018-9448. DOI: 10.1109/TIT.1981.1056307.

[Hua+14] J. Huang, Y. Zhao, and K. Sohraby. "Resource allocation for intercell device-to-device communication underlaying cellular network: A game-theoretic approach". In: *2014 23rd International Conference on Computer Communication and Networks (ICCCN)*. 2014, pp. 1–8. DOI: 10.1109/ICCCN.2014.6911738.

[Hua+15] J. Huang, Y. Yin, Y. Sun, Y. Zhao, C. Xing, and Q. Duan. "Game theoretic resource allocation for multicell D2D communications with incomplete information". In: *2015 IEEE International Conference on Communications (ICC)*. 2015, pp. 3039–3044. DOI: 10.1109/ICC.2015.7248790.

[IR08] ITU-R. *Guidelines for evaluation of radio interface technologies for IMT-Advanced*. Tech. rep. report ITU-R M.2135, 2008.

[Isl+15a] M. T. Islam, A. M. Taha, S. Akl, and S. Choudhury. "A local search algorithm for resource allocation for underlaying Device-to-device communications". In: *2015 IEEE International Conference on Global Communications (GLOBECOM)(To appear)*. 2015, pp. 1–1.

[Isl+15b] M. T. Islam, A. M. Taha, and S. Akl. "Reducing the complexity of Resource Allocation for underlaying Device-to-Device communications". In: *2015 International Wireless Communications and Mobile Computing*

Conference (IWCMC). 2015, pp. 61–66. DOI: 10.1109/IWCMC.2015.7289058.

[Jan+09] P. Janis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler, and K. Hugl. “Interference-Aware Resource Allocation for Device-to-Device Radio Underlaying Cellular Networks”. In: *IEEE 69th Vehicular Technology Conference, 2009. VTC Spring 2009*. 2009, pp. 1–5. DOI: 10.1109/VETECS.2009.5073611.

[KA08] B. Kaufman and B. Aazhang. “Cellular networks with an overlaid device to device network”. In: *2008 42nd Asilomar Conference on Signals, Systems and Computers*. 2008, pp. 1537–1541. DOI: 10.1109/ACSSC.2008.5074679.

[Kal+14] M. Kalil, J. Samarabandu, A. Shami, and A. Al-Dweik. “Performance evaluation of genetic algorithms for resource scheduling in TLE uplink”. In: *Wireless Communications and Mobile Computing Conference (IWCMC), 2014 International*. 2014, pp. 948–952. DOI: 10.1109/IWCMC.2014.6906483.

[Kal+15a] M. Kalil, A. Shami, A. Al-Dweik, and S. Muhaidat. “Low-Complexity Power-Efficient Schedulers for LTE Uplink With Delay-Sensitive Traffic”. In: *IEEE Transactions on Vehicular Technology* 64.10 (2015), pp. 4551–4564. ISSN: 0018-9545. DOI: 10.1109/TVT.2014.2376038.

[Kal+15b] M. Kalil, A. Shami, and A. Al-Dweik. “QoS-Aware Power-Efficient Scheduler for LTE Uplink”. In: *IEEE Transactions on Mobile Computing* 14.8

(2015), pp. 1672–1685. ISSN: 1536-1233. DOI: 10.1109/TMC.2014.2363839.

[Kar72] R. M. Karp. "Reducibility among Combinatorial Problems". English. In: *Complexity of Computer Computations*. Ed. by R. E. Miller, J. W. Thatcher, and J. D. Bohlinger. The IBM Research Symposia Series. Springer US, 1972, pp. 85–103. ISBN: 978-1-4684-2003-6.

[KM78] Ravindran Kannan and ClydeL. Monma. "On the Computational Complexity of Integer Programming Problems". English. In: *Optimization and Operations Research*. Ed. by R. Henn, B. Korte, and W. Oettli. Vol. 157. Lecture Notes in Economics and Mathematical Systems. Springer Berlin Heidelberg, 1978, pp. 161–172. ISBN: 978-3-540-08842-4. DOI: 10.1007/978-3-642-95322-4_17. URL: http://dx.doi.org/10.1007/978-3-642-95322-4_17.

[Knu76] D. E. Knuth. *Mariages stables et leurs relations avec d'autres problèmes combinatoires: introduction à l'analyse mathématique des algorithmes*. Collection de la Chaire Aisenstadt. Presses de l'Université de Montréal, 1976.

[KT06] J. Kleinberg and E. Tardos. *Algorithm Design*. Pearson Education, 2006.

[Lee+14] D. H. Lee, K. W. Choi, W. S. Jeon, and D. G. Jeong. "Two-Stage Semi-Distributed Resource Management for Device-to-Device Communication in Cellular Networks". In: *IEEE Transactions on Wireless Communications* 13.4 (2014), pp. 1908–1920. ISSN: 1536-1276. DOI: 10.1109/TWC.2014.022014.130480.

[Lin+13] X. Lin, J. G. Andrews, and A. Ghosh. "A Comprehensive Framework for Device-to-Device Communications in Cellular Networks". In: *CoRR* abs/1305.4219 (2013). URL: http://arxiv.org/abs/1305.4219.

[Lin+14] X. Lin, J. Andrews, A. Ghosh, and R. Ratasuk. "An overview of 3GPP device-to-device proximity services". In: *IEEE Communications Magazine* 52.4 (2014), pp. 40–48. ISSN: 0163-6804. DOI: 10.1109/MCOM.2014.6807945.

[Mal+14] F. Malandrino, C. Casetti, C.-F. Chiasserini, and Z. Limani. "Fast resource scheduling in HetNets with D2D support". In: *2014 Proceedings IEEE INFOCOM*. 2014, pp. 1536–1544. DOI: 10.1109/INFOCOM.2014.6848089.

[Mir+14] M. Mirahmadi, A. Al-Dweik, and A. Shami. "Interference Modeling and Performance Evaluation of Heterogeneous Cellular Networks". In: *IEEE Transactions on Communications* 62.6 (2014), pp. 2132–2144. ISSN: 0090-6778. DOI: 10.1109/TCOMM.2014.2320719.

[Mou+14] X. Mou, L. Lei, and Z. Zhong. "Performance Analysis of Resource Allocation Schemes in Device-to-Device Communications with Bursty Traffic". In: *2014 International Conference on Information Science and Applications (ICISA).* 2014, pp. 1–4. DOI: 10.1109/ICISA.2014.6847444.

[Mou+15] A. Moubayed, A. Shami, and H. Lutfiyya. "Wireless Resource Virtualization With Device-to-Device Communication Underlaying LTE Network". In: *IEEE Transactions on Broadcasting* 61.4 (2015), pp. 734–740. ISSN: 0018-9316. DOI: 10.1109/TBC.2015.2492458.

[Mun57] J. Munkres. "Algorithms for the Assignment and Transportation Problems". In: *Journal of the Society of Industrial and Applied Mathematics* 5.1 (1957), pp. 32–38.

[MW70] D. G. McVitie and L. B. Wilson. "Stable marriage assignment for unequal sets". English. In: *BIT Numerical Mathematics* 10.3 (1970), pp. 295–309. ISSN: 0006-3835. DOI: 10.1007/BF01934199. URL: http://dx.doi.org/10.1007/BF01934199.

[NA14] N. Naderializadeh and A. S. Avestimehr. "ITLinQ: A New Approach for Spectrum Sharing in Device-to-Device Communication Systems". In: *IEEE Journal on Selected Areas in Communications* 32.6 (2014), pp. 1139–1151. ISSN: 0733-8716. DOI: 10.1109/JSAC.2014.2328102.

[Nic] *Six technologies with potential impacts on US interests out to 2025.* Conference Report CR 2008-07. National Intelligence Council, 2008.

[Nov+11] T. D. Novlan, R. K. Ganti, A. Ghosh, and J. G. Andrews. “Analytical Evaluation of Fractional Frequency Reuse for OFDMA Cellular Networks”. In: *IEEE Transactions on Wireless Communications* 10.12 (2011), pp. 4294–4305. ISSN: 1536-1276. DOI: 10.1109/TWC.2011.100611.110181.

[Ns3] *NS-3*. Retrieved on 10^{th}April, 2015. URL: http://www.nsnam.org/.

[Orl+04] J. B. Orlin, A. P. Punnen, and A. S. Schulz. “Approximate Local Search in Combinatorial Optimization”. In: *Proceedings of the Fifteenth Annual ACM-SIAM Symposium on Discrete Algorithms*. SODA ’04. New Orleans, Louisiana: Society for Industrial and Applied Mathematics, 2004, pp. 587–596. ISBN: 0-89871-558-X. URL: http://dl.acm.org/citation.cfm?id=982792.982880.

[Pen+09] T. Peng, Q. Lu, H. Wang, S. Xu, and W. Wang. “Interference avoidance mechanisms in the hybrid cellular and device-to-device systems”. In: *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*. 2009, pp. 617–621. DOI: 10.1109/PIMRC.2009.5449856.

[PF05] A. Petcu and B. Faltings. “A value ordering heuristic for local search in distributed resource allocation”. In: *Recent Advances in Constraints*. Springer, 2005, pp. 86–97.

[Phu+13] P. Phunchongharn, E. Hossain, and D. I. Kim. “Resource allocation for device-to-device communications underlaying LTE-advanced networks”.

In: *IEEE Wireless Communications* 20.4 (2013), pp. 91–100. ISSN: 1536-1284. DOI: 10.1109/MWC.2013.6590055.

[PS82] C. H. Papadimitriou and K. Steiglitz. *Combinatorial Optimization: Algorithms and Complexity*. Prentice-Hall, Englewood Cliffs, NJ, 1982.

[Saa+09] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar. "Coalitional Game Theory for Communication Networks: A Tutorial". In: *CoRR* abs/0905.4057 (2009). URL: http://arxiv.org/abs/0905.4057.

[Skl97] B. Sklar. "Rayleigh Fading Channels in Mobile Digital Communication Systems .I. Characterization". In: *IEEE Communication Magazine* 35.7 (1997), pp. 90–100. ISSN: 0163-6804. DOI: 10.1109/35.601747. URL: http://dx.doi.org/10.1109/35.601747.

[Sor15] S. Sorrell. *The Internet of Things: Consumer, Industrial & Public Services 2015-2020*. Retrieved on 16th December, 2015 from website. 2015. URL: http://www.juniperresearch.com/press/press-releases/iot-connected-devices-to-triple-to-38-bn-by-2020.

[Teh+14] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu. "Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions". In: *IEEE Communications Magazine* 52.5 (2014), pp. 86–92. DOI: 10.1109/MCOM.2014.6815897.

[Tio+00] S. R. Tiourine, A. J. Hurkens, and J. K. Lenstra. "Local search algorithms for the radio link frequency assignment problem". In: *Telecommunication systems* 13.2-4 (2000), pp. 293–314.

[Wan+15] F. Wang, Y. Li, Z. Wang, and Z. Yang. "Social Community Aware Resource Allocation for D2D Communications Underlaying Cellular Networks". In: *IEEE Transactions on Vehicular Technology* PP.99 (2015), pp. 1–1. ISSN: 0018-9545. DOI: 10.1109/TVT.2015.2450774.

[Xu+10] S. Xu, H. Wang, T. Chen, Q. Huang, and T. Peng. "Effective Interference Cancellation Scheme for Device-to-Device Communication Underlaying Cellular Networks". In: *2010 IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*. 2010, pp. 1–5. DOI: 10.1109/VETECF.2010.5594601.

[Xu+12a] C. Xu, L. Song, Z. Han, Q. Zhao, X. Wang, and B. Jiao. "Interference-aware resource allocation for device-to-device communications as an underlay using sequential second price auction". In: *2012 IEEE International Conference on Communications (ICC)*. 2012, pp. 445–449. DOI: 10.1109/ICC.2012.6364509.

[Xu+12b] C. Xu, L. Song, Z. Han, D. Li, and B. Jiao. "Resource allocation using a reverse iterative combinatorial auction for device-to-device underlay cellular networks". In: *2012 IEEE Global Communications Conference (GLOBECOM)*. 2012, pp. 4542–4547. DOI: 10.1109/GLOCOM.2012.6503834.

[Xu+13] C. Xu, L. Song, and Z. Han. "Resource Management for Device-to-Device Underlay Communication". In: *CoRR* abs/1311.1018 (2013). URL: http://arxiv.org/abs/1311.1018.

[YT12] C. H. Yu and O. Tirkkonen. "Device-to-Device underlay cellular network based on rate splitting". In: *2012 IEEE Wireless Communications and Networking Conference (WCNC)*. 2012, pp. 262–266. DOI: 10.1109/WCNC.2012.6214244.

[Zha+13a] H. Zhang, T. Wang, L. Song, and Z. Han. "Graph-based resource allocation for D2D communications underlaying cellular networks". In: *2013 IEEE/CIC International Conference on Communications in China - Workshops (CIC/ICCC)*. 2013, pp. 187–192. DOI: 10.1109/ICCChinaW.2013.6670591.

[Zha+13b] R. Zhang, L. Song, Z. Han, X. Cheng, and B. Jiao. "Distributed resource allocation for device-to-device communications underlaying cellular networks". In: *2013 IEEE International Conference on Communications (ICC)*. 2013, pp. 1889–1893. DOI: 10.1109/ICC.2013.6654797.

[Zha+13c] R. Zhang, X. Cheng, L. Yang, and B. Jiao. "Interference-aware graph based resource sharing for device-to-device communications underlaying cellular networks". In: *2013 IEEE Wireless Communications and Networking Conference (WCNC)*. 2013, pp. 140–145. DOI: 10.1109/WCNC.2013.6554553.

[Zul+10] M. Zulhasnine, C. Huang, and A. Srinivasan. "Efficient resource allocation for device-to-device communication underlaying LTE network". In: *2010 IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. 2010, pp. 368–375. DOI: 10.1109/WIMOB.2010.5645039.