ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

Joint Power Control and Resource Allocation for D2D Communications underlaying Cellular Networks

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Declaration

I hereby declare that this dissertation entitled **Joint Power Control and Resource Allocation for D2D Communications underlaying Cellular Networks** was carried out by me for the degree of **Masters of Science in Computer Science and Engineering**, MSc in CSE, under the guidance and supervision of Prof. Dr. Muhammad Mahbub Alam, Islamic University of Technology, Gazipur, Dhaka, Bangladesh.

The findings put forth in this work are based on my research and understanding of the original works and they are not published anywhere in the form of books, monographs or articles. The other books, articles and websites, which I have made use of are acknowledged at the respective place in this thesis.

For the present thesis, which I am submitting to the University, no degree or diploma or distinction has been conferred on me before, either in this or in any other University.

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Abstract

In order to improve the bandwidth utilization, Device to Device (D2D) communication underlaying cellular mode is coined in LTE and beyond. In this type of communication, the radio resources of primary users i.e. cellular User Equipment (UE) are shared by the secondary users i.e. D2D devices. This technology can achieve enhanced system capacity as well as spectrum efficiency if the secondary users share appropriate spectrum resources with primary users. Careful consideration should be taken while assigning resources, as inappropriate sharing of resources can instigate a substantial amount of co-channel interference in the cellular network, resulting in communication impairment to the primary users. Moreover, selecting a high transmission power to ensure data rate can affect corresponding users (primary or secondary) who are sharing the same RB(s) by introducing large interference. On the other hand, to mitigate the introduced interference, selecting a low transmission power may not ensure the expected data rate. Thus, an appropriate power control scheme will improve the co-channel interference as well as system capacity.

This dissertation addresses the challenges of allocating appropriate Resource Blocks (RBs) and selecting appropriate power levels for all primary and secondary users while maintaining individual demand data rates in polynomial time. Two objectives are addressed separately, namely: maximizing total system capacity and minimizing total system co-channel interference.

In this thesis, a joint power and resource allocation approach is proposed to maximize the system capacity or to minimize the system interference (specifically co-channel interference). First, the problem is converted into a bipartite graph where each node (cellular users and D2D users) is expanded into multiple instances according to the available power levels. The appropriate weight of the edges is selected for two different optimization problems. Then the proposed algorithm, the Multi-Value Bipartite Matching (MBM) Algorithm, is applied to the weighted bipartite graph problem. The numerical analyses demonstrate that the proposed techniques can determine the appropriate transmission power level for cellular users and D2D users for given constraints. In addition, their performance is superior to that of contemporary algorithms.

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Secondly, I would like to express my gratitude to my thesis supervisor, Prof. Dr. Muhammad Mahbub Alam, Professor, Department of Computer Science and Engineering, Islamic University of Technology (IUT), for his assistance and direction on this thesis. He taught me how to conduct research, think critically and become a graduate student successfully. His constant guidance, encouragement and continuous observation paved the way for a successful journey.

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Finally, I want to convey my gratitude to my loved ones. My parents, siblings and parents-in-law were always there to raise my spirits. My wife, Dr. Nusrat Jahan Arobi, was the one who really pushed me to get here. My daughter, Farisha Hussain Airha, brightened my days and made this journey more comfortable.

Faisal Hussain

May, 2022

Dedication

My respected parents

"Without whom none of my success would be possible"

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Chapter 1

Introduction

1.1 Overview

Over the last few decades, mobile traffic demand has been increased manifold due to rapid development as well as the ease of use of this technology. The number of mobile subscriptions will grow to around 6 billion (70 percent of the global population) by 2023 [1]. Conventional mobile communication, known as cellular communication, normally uses licensed spectrum under the supervision of a central base station, which is known as eNodeB (eNB) in LTE. In traditional cellular networks, transmitting and receiving nodes (known as cellular User Equipment (UE)) do not communicate directly, but rather pass data through eNB. Cellular UEs pass different control information to the eNB and vice-versa. The eNB assigns resources to the cellular UEs when they are required. It also sends Transmit Power Control (TPC) commands to cellular UEs to maintain a minimum signal to interference and noise ratio (SINR) [36]. Cellular UEs then start communication following the received TPC and resource assignment from eNB. However, transmitting and receiving devices using cellular communication through eNB in close proximity wastes valuable resources. These devices can communicate directly, offloading the data from eNB. This direct communication is known as Device to Device (D2D) communication. Although D2D communication in the unlicensed band is possible, the bandwidth of this category is decaying day by

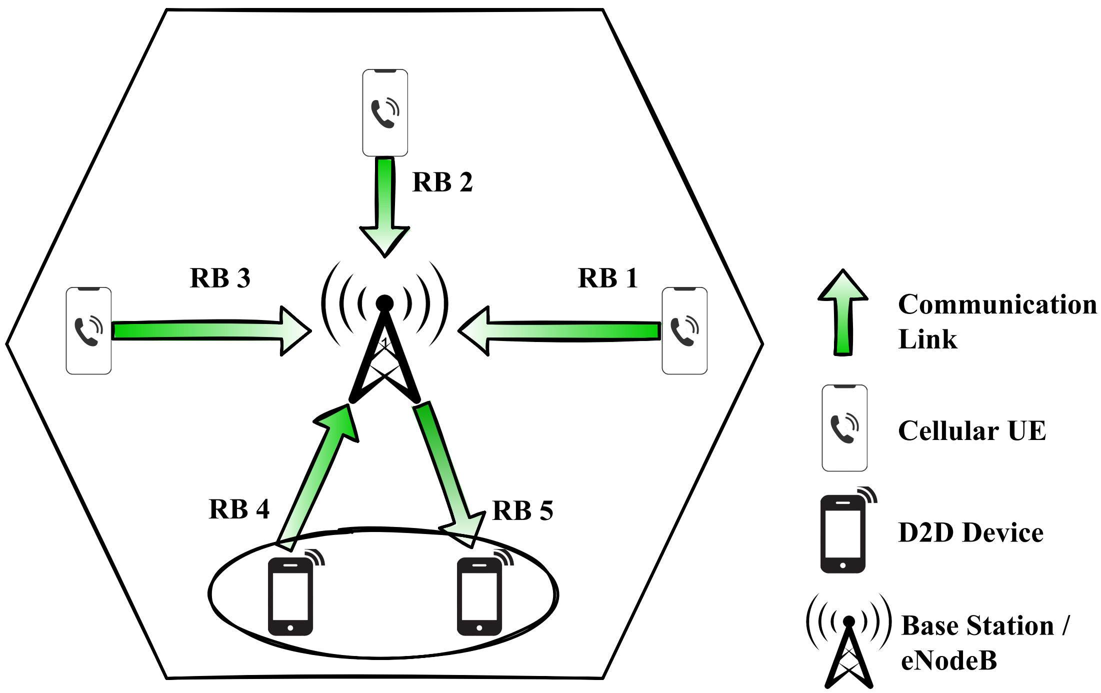


Figure 1.1: Traditional Cellular Communication

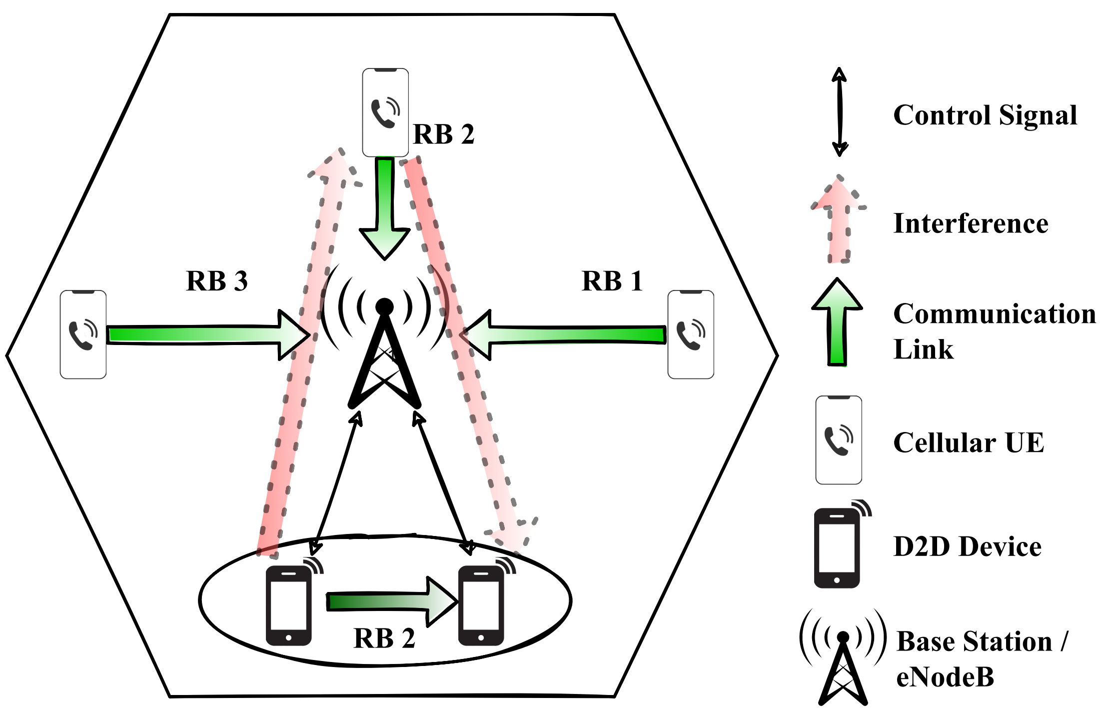


Figure 1.2: D2D Communication

day. Furthermore, the broad licensed spectrum will enable more D2D communication, which will be required in the future. Reusing the license spectrum is also possible as they are in close proximity to increase the spectrum efficiency. However, reusing license spectrum (also known as Resource Block (RB)) will introduce co-channel interference to the primary users of the cellular network. This interference level can be controlled to an acceptable value by intelligent resource sharing. Thus, an improved resource sharing mechanism will lead to maximizing the entire system sumrate (capacity) and reducing system interference. Figure 1.1 represents the traditional cellular communication. Figure 1.2 represents a scenario of D2D communication where the transmitting and receiving devices in close proximity reuse the RBs to communicate directly.

The rest of the chapter is organized as follows. Section 1.2 discusses the motivation for selecting this particular research topic. Section 1.3 presents specific problem statements for this dissertation. Section 1.4 outlines the contribution of the research work. Lastly, Section 1.5 presents the organization of the thesis.

1.2 Motivation

In the last decade, D2D communication has achieved immense appeal as a form of personal communication. With the popularity of smart hand-held devices, this means of communication is entering the corporate as well as private use as a technology. Numerous inter-device services, such as Vehicle to Vehicle (V2V) communication, interactive local guiding, social discovery, local gaming, content sharing in a gathering, and the downloading of media content in social events are significant sectors that might benefit from D2D communication [10]. Depending on the services, D2D devices may operate in different modes like multicast mode, relay mode etc. Figure 1.3 depicts the different types of services offered in the D2D communication paradigm.

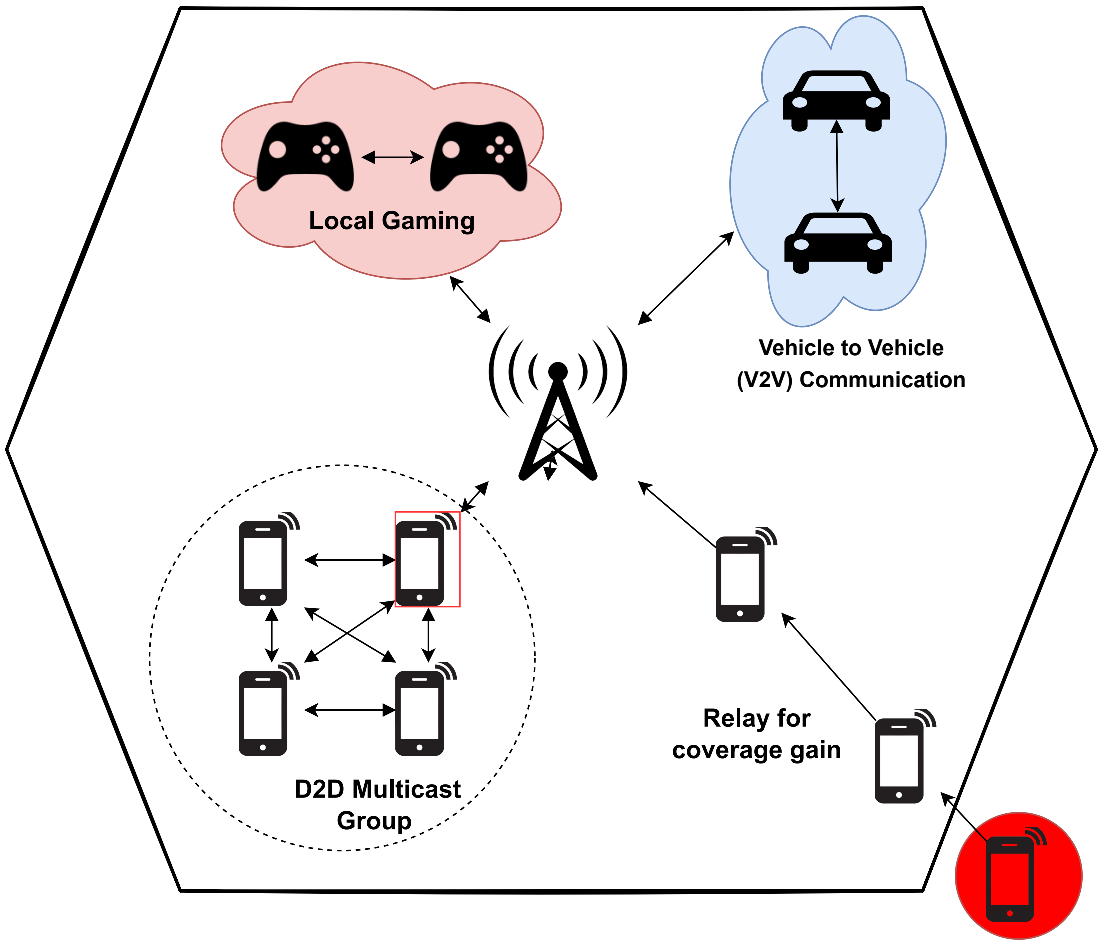


Figure 1.3: D2D Services

Outband and Inband are the two primary implementations of D2D communication based on the usage of spectral resources. Outband implementation uses unlicensed radio spectrum and Inband implementation uses licensed spectrum. Underlay and Overlay modes are two modes of implementation of Inband D2D communication. In case of Inband Underlay, both D2D and cellular devices reuse the same spectrum resources. On the other hand, in Inband Overlay, D2D and cellular devices use non-overlapping spectrum resources. According to a number of surveys [2, 3, 4] inband underlay is more practical and advantageous option when considering spectrum use and energy efficiency. This study focuses on inband underlay D2D communication, in which two user equipment (UEs) in close proximity communicate directly rather than via eNB [15, 39]. The benefits of using this technique include higher spectral efficiency, higher total system capacity, lower eNB traffic load, and lower device power consumption if the appropriate RBs from a traditional cellular network are reused [2, 39]. Inband underlay D2D communication was introduced with the commencement of fourth generation (4G) or Long Term Evolution (LTE), and since then, it has been one of the leading technologies in laying the groundwork for the fifth generation (5G) and beyond (5G+) [44]. Moreover, in future 6G, an effective implementation of intelligent D2D communication is necessary [49]. Apart from the aforementioned advantages, Inband Underlay D2D communication also provides increased bit-rate gain, spectral reuse gain, hop gain and coverage gain [11].

It is desirable to have an effective radio resource management and power allocation strategy in place in order to further the use of all of the advantages that were discussed earlier. The interference that is introduced into a resource allocation scheme as a result of the sharing of radio resources between cellular UEs and D2D pairs is a significant barrier to its effectiveness. In addition to this, when ill-fitting RBs are chosen, the total system interference in the already-existing cellular network reaches a level that is disastrous [35]. Moreover, the transmission power directly contributes to the level of introduced interference as well as system capacity. Selecting inappropriate power levels for transmitting devices either increases system interference or decreases the system capacity. It should be noted that the resource assignment problem and the power level selection problem are not disjoint problems, as the transmission power of devices reusing the same RB will affect the receive signal strength of those devices. So the resource assignment problem and the power level selection problem need to be considered as a single joint optimization problem. A significant number of academics are working on different resource allocation algorithms and power control mechanisms in D2D communication underlaying cellular networks with the aim of achieving different goals in different system model settings and this topic still needs more research.

1.3 Problem Statement

Most state-of-the-art existing solutions for capacity maximization and interference minimization algorithms consider the fixed power level of the devices and they ignore different power levels of devices at the time of resource allocation. However, controlling the power level of the cellular UEs and the D2D pairs is an effective way to minimize the interference. Moreover, selecting the appropriate power level of shared devices leads to better capacity gain. Transmission of data at an appropriate power level helps a device not introduce unwanted interference into the system. Hence, efficient RA algorithms to address the joint optimization problem of power control and resource allocation are very promising to fill up this research gap. In the literature, there are a few schemes that address this joint optimization problem and use meta-heuristic approaches like particle swarm optimization, genetic algorithms, etc. However, meta-heuristic approaches are non-deterministic, which may not return optimal solutions because of randomness. In this research, we aim to develop polynomial-time solvable deterministic algorithms to achieve theoretical maximum sumrate and minimum interference.

1.4 Thesis Contributions

In this thesis work, a joint optimization problem of resource allocation and power control is formulated. Two different objectives have already been addressed, namely capacity maximization and interference minimization. Our proposed approach performs competitively with the state-of-the-art approaches. The major contributions to this work are listed below.

- A modified bipartite matching algorithm is proposed to handle the problem scenario. This algorithm handles resource allocation as well as power level selection.

- An appropriate weight for the edge is proposed for both capacity maximization and interference minimization. An invalid assignment is marked so that our approach does not end up with an infeasible result.

- A polynomial time solution approach is proposed which supports the short scheduling time of the cellular network. The time complexity of the proposed approach is $O(n^3)$.

1.5 Organization of Thesis

The dissertation is organized in the following manner. Chapter 2 presents the literature review on different RA algorithms of D2D communication. Chapter 3 describes the system model and the problem formulation considered in this thesis work. Chapter 4 presents an analysis and description of the proposed approach along with the complexity analysis. Chapter 5 presents the numerical analysis and comparison of results of our proposed algorithm with existing algorithms. Finally, we conclude the dissertation in chapter 6 with a summary of contributions and future research directions.

Chapter 2

Literature Review

D2D communication can provide several benefits to devices in close proximity. Currently, wide research interest is growing around this topic. From 4G LTE and onwards, D2D communication underlaying traditional cellular networks is supported to achieve greater spectral efficiency. However, this mode of communication opens up different challenges [32] like resource allocation, power optimization, mode selection etc. in different kinds of system models. Recent studies have chosen these challenges in different combinations, like considering one or more challenges in their solution. In the following, some prominent studies are discussed in different categories.

2.1 Resource Allocation

Intra-cellular interference is absent in LTE and beyond, due to usage of the orthogonal resources by cellular UEs. However, D2D communication underlaying cellular networks shares the resources of cellular UEs in order to improve the spectral efficiency, resulting in intra-cellular interference. Thus, it is very important to use a resource allocation scheme that assigns proper resources to D2D devices. The researchers working on this problem are focusing on different goals while presenting their resource allocation scheme. The authors of [53, 31, 26, 24, 25] proposed resource allocation schemes with the aim of maximizing the system capacity. The optimal solution for this scenario is presented in [25] for different cardinality of D2D devices and cellular UEs. On the other hand, the authors of [29, 27, 17, 18] designed the resource allocation scheme with the aim of minimizing the interference provided that a certain level of system capacity will be attained. The authors of [19, 21] proposed online algorithm-based solutions to reduce the number of changes in resource assignment in each iteration. It should be noted that these strategies are deterministic approaches. Some meta-heuristic solutions are also available in the literature.

Yang et al. addresses the resource allocation and user matching (D2D users to cellular users) in D2D communication underlay cellular network using uplink resources [47]. They divide the process into two steps: in the first step, initial resource allocation to cellular users is done following a round-robin scheme, considering each cellular user with equal priority; in the second step, D2D pairs are matched with the cellular users to share the same resources as the cellular users assigned in the first step. They proposed a genetic algorithm based scheme to maximize the sumrate of each set of resource block, D2D pair and cellular user where the D2D pair and cellular user share the resource block. The breeding process of the proposed scheme is divided into six steps: selection (selecting parents from a generation based on the fit function), crossover (two offspring are produced from swapping some genes between two parents), self-adaptive mutation (mutation of any gene based on self-adaptive modulation probability), modification (to correct the gene to satisfy the constraint), elitism strategy prevention (best individual of the current generation is entered into the next generation without going through any breeding process to avoid randomness of GA), iteration (the number of genetic generations is selected based on the number of resources, cellular users and D2D pairs to reach a convergence state). It is noteworthy that they consider a D2D pair may share the resources of one cellular UE only and other D2D pairs in the system can not share the resources of that cellular UE. This is known as one to one sharing.

Ashtiani and Pierre addresses the problem of malicious eavesdroppers in the system along with cellular users and D2D pairs [5]. They formulate the problem to optimize the cell's secrecy capacity. The secrecy-capacity of the Gaussian wiretap channel in presence of eavesdropper is defined as the difference between actual receiver rate and overheard receiver rate by the eavesdropper. They proposed a solution Tabu Search for Resource Management - TSRM based on the meta-heuristic algorithm Tabu Search. They define three actions (Swap, Insertion and Reversion move) to find out the Neighborhood of a solution. When a best found solution is not improved for few iteration, perturbation is performed. It should be noted that authors assumed a system where one cellular user utilizes one subcarrier only and that sub-carrrier is not shared by any other cellular users; as well as a D2D pair share the resources of at most one cellular user and a sub-carrier resource can be shared by at most one D2D pair. This represent a one to one sharing paradigm.

These studies mainly focus on resource allocation strategies, assuming the mode of communication and transmission power are already selected. Besides these, there are several studies [6, 9, 40, 50, 22] based on distributed algorithms. However, a decentralized approach failed to perform well due to partial knowledge of the system configuration.

2.2 Power Control

The transmission power of sending nodes has a very large impact on system performance in D2D communication underlaying cellular network. Several studies focused on setting transmission power levels for all cellular UEs and D2D pairs to increase the system capacity or decrease the system interference.

Najla et al. address the problem of setting the transmission power of D2D users in the case when channel gains among D2D users are unknown [37]. The authors assume a system model where multiple BSs are present and multiple D2D users are present. However they did not assume any effect of cellular users in the system. They proposed a Deep Neural Network (DNN) based power control scheme where at first the relation between cellular users and D2D users channel gain is found out. Later this relation will be exploited to set the transmission power of D2D users. It should be noted that authors assumed that there are no known function to indicate the relation between cellular users channel gain and D2D users sum rate capacity. Therefore a supervised learning approach is applied to find out the transmission power of D2D users for maximizing the sumrate. Then the DNN is trained to build the mapping between cellular channel gains and targeted transmission power which results into final power setting of D2D transmitter.

Yu et al. addresses the power control problem in D2D communication [48]. The authors consider a system model where under an isolated BS, one cellular user and two devices combined to form a D2D pair are present. They analyze two cases. In the first case, both D2D and cellular users have the same priority. In this case, a greedy sum rate maximization is applied under a maximum transmission power constraint. In the second case, cellular users are prioritized, guaranteeing a minimum transmission rate. In addition, the authors put a constraint on the upper limit of transmission rate by modulation and coding scheme. The authors categorized three types of resource block - firstly, a non-orthogonal resource sharing scheme where cellular and D2D users share the same resources and BS coordinates the transmit power. Secondly, a separate resource sharing mode where D2D and cellular users use separate resource blocks, thus no co-channel interference. Therefore, maximum transmission power returns to maximum throughput. Thirdly, Cellular Mode, where D2D users communicate via BS like cellular systems. In this case, the maximum transmission power also returns the maximum throughput.

Gong and Wang address power allocation problem in D2D multicast communication underlaying cellular network [16]. The authors consider a multicast D2D receiver group getting transmission from a single D2D transmitter underlaying a traditional cellular network using uplink resources. They also consider two different cases for power allocation - in first case, a D2D transmitter is reusing one cellular user's resources and in second case, a D2D transmitter is reusing multiple cellular users' resources. They assumed that the D2D pairs are already assigned with the resources of cellular users to reuse, but the D2D transmission power is not fixed. Algorithms based on Particle Swarm Optimization for Power Allocation, namely - PPA-MTH and PPA-BTFH are proposed for solving the two cases. They did not mention which resource allocation algorithm should be used to assign the D2D pairs, which affects the maximization of the throughput.

In these studies, the authors focused on the power control scheme irrespective of resource allocation strategies. Morevere, few studies [8, 7, 46] focused on the minimization of total power consumption instead of the optimization of total system capacity or system inteference.

2.3 Resource Allocation and Power Control

Both resource allocation strategies and transmission power control are important for the system's performance. Many studies consider these two problems as a joint optimization problem instead of assuming they are separate problems.

Takshi et al. propose a genetic algorithm for joint optimization of resource allocation and power assignment to maximize the spectral efficiency of a overlay network [42]. Authors represent a resource block as a chromosome and the set of all chromosomes as a generation. In each chromosome, there might be multiple cellular users and D2D users with individual transmission power, representing that those devices are sharing the mentioned resource block. It should be noted that each chromosome needs to satisfy the constraints of the optimization problem. Following the traditional genetic algorithm, the authors designed a fitness function and then a selection probability based on that fitness value. Parent chromosomes are proportionally selected based on the selection probability. Then a crossover operation is applied to these parent chromosomes to generate a new generation following all constraints. The authors also mentioned a mutation process in 20% cases to avoid local optimum solutions.

Tan et al. formulates the problem statement to maximize the weighted-sum-rate (WSR) of the overlay D2D network, jointly optimizing the channel selection and the transmission power [43]. It should be noted that the authors identified the problem as non-convex and np hard. At first, they develop a Fractional Programming (FP) based centralized algorithm. It provides a near optimal solution based on the instantaneous global channel state information (CSI) and used it as benchmark algorithm. Later they propose a distributed Deep Reinforcement Learning (DRL) based algorithm with local information and some outdated local information. This reduces the signalling overhead compared to FP based scheme. As the transition probabilities are difficult to acquire, instead of the Markov Decision Process (MDP) model, the model-free RL Q-learning method is applied.

Gao et al. propose a Quantum Coral Reefs Optimization Algorithm (QCROA) [14] to optimize jointly the resource allocation and power control, maximizing the total throughput in cooperative D2D heterogeneous networks. They propose a novel Cooperative D2D Heterogeneous Network (CDHN) where D2D users share downlink resource blocks with cellular users and idle users in a cellular network as relay stations to complete transmission. The merits of the traditional coral reefs optimization algorithm and the quantum evolution algorithm are combined in QCROA.

Wang et al. works on a system model where D2D devices can reuse multiple channels [45]. Their aim is to maximize the total capacity of the cellular system. A joint channel selection and power control method is considered to achieve high quality communication for cellular users. Increasing reuse of D2D users will in turn increase the transmitting power of D2D devices, causing interference in cellular communication. Their model is designed to help a D2D pair learn power control and channel selection methods adaptively by interacting with the environment. They modeled the D2D interference problem as a Markov Decision Process (MDP). MDP is defined as a tuple (S_t,A_t,P,R) where S_t stands for a set of states, A_t stands for a set of actions,P stands for state transition probabilities and R stands for reward function. They used Deep Q-learning Network (DQN) for learning resource allocation and power selection policy. They used a Convolutional Neural Network (CNN) instead of a Q-table to derive the approximate Q-value.

These studies utilize non-deterministic approaches to solve the problem. Generally, any approach based on a meta-heuristic or machine learning solution may perform better in terms of execution time. However, they may be stuck in a local minima.

2.4 Other Approaches

Few studies consider other combinations of challenges like resource allocation and mode selection; resource allocation, mode selection and power control etc. It should be noted that, in the mode selection problem, the authors consider that the communicating devices will not decide whether they will establish a direct link (D2D Communication) or communicate via a base station (Cellular Communication), but rather the proposed approach will select the mode of communication.

Li et al. formulates a max-flow optimization problem with the aim of optimizing jointly the mode selection and the resource allocation for a large scale D2D communication underlaying cellular network. The authors assumed a system model where traditional cellular users are not present, but rather there are multiple BSs and under

each of the BSs there are several relay devices and several devices acting as senders and receivers instead of different cellular users and D2D pairs. These devices may act as either traditional cellular users or D2D pairs (may or may not use a relay device). They first model the D2D communication using a graph. They formulate the problem as a flow maximization problem using this graph. To emulate realistic behavior, they consider human mobility traces as proposed in Orlando [33] and Infocom06 [23].
Sun et al. proposed a hierarchical game theory based solution [41] to solve the problems of mode selection, spectrum allocation and power control, considering a sufficient amount of spectrum resources are available to the cellular network. A hedonic coalition game-based solution is proposed to solve the mode selection and resource allocation problems in the first step. After this, a non-cooperative game-based power control algorithm is applied to improve further performance.

Zhou et al. design a resource allocation scheme jointly considering mode selection, Modulation and Coding Scheme (MCS) assignment, resource allocation and power control [51]. Therefore they identified four variables (Mode Selection, MCS Selection, Resource Allocation, Power Control) which needs to be optimized. They simplify the complex constraint using lagrangian relaxation technique by adding the complex constraint in the objective function assigned with weight. The unsatisfied constraint add penalty in the solution represented by the weight. The authors' proposed sub-problems are - Resource Block Allocation Problem (RAP) and Model Selection and MCS Assignment sub-problem (MSMAP). A greedy algorithm is proposed to solve the RAP sub-problem. Tabu search-based meta-heuristic algorithm is proposed to solve the MSMAP sub-problem.

Researchers showed different scenarios where mode selection affects the system performance. However, this problem can be addressed separately.

2.5 Chapter Summary

The effectiveness of D2D communication underlaying cellular networks can be achieved by addressing the challenges of mode selection, resource allocation and power control etc. Existing studies offer solutions addressing different combinations of challenges presented in Section 2.1, 2.2, 2.3 and 2.4. Studies considering resource allocation and power control separately, discussed in Section 2.1 and 2.2 respectively. The transmission power of users can improve their own performance but impedes the performance of other users sharing the same resources. Thus, considering these two problems separately results in poor system performance. Studies addressing both the resource allocation and power control problems jointly are discussed in Section 2.3. Recent studies consider non-deterministic solutions to address this problem. Section 2.4 presents studies considering other combinations of challenges. The mode selection challenge mainly depends on the distance between the communicating devices, which can be resolved separately. However, the challenges of power control and resource allocation need to be addressed jointly to enhance the system performance.

Chapter 3

Problem Formulation

In this thesis, two different objective functions will be addressed separately. Thus, two separate problems are formulated. In order to understand the problem formulation, first the system model and channel model are laid down in the following sections.

3.1 System Model

This thesis examines the same system and channel models as in [27], [26]. Though LTE network resources include both uplink (UL) and downlink (DL) components, the UL resources are considered here, and Figure 3.1 depicts the system model. D2D receivers are susceptible to interference from cellular UE when using uplink resources. On the other hand, D2D transmitters introduce interference at eNB [28]. D2D pairs can interact directly in such an underlay system, but the eNB monitors power level allocation, connection formation and resource distribution [53].

In the experimental setup, it is considered that an omni-directional antenna is present in eNB, cellular UEs and D2D pairs. The eNB communicates through control signals with cellular UEs and D2D pairs to share important information. The eNB informs the cellular UEs and D2D pairs about the transmission power and the RBs to use for transmission using this control signal. This thesis examines a single cell area with one eNB, m D2D pairs and n cellular UEs. The set of D2D pairs is denoted as

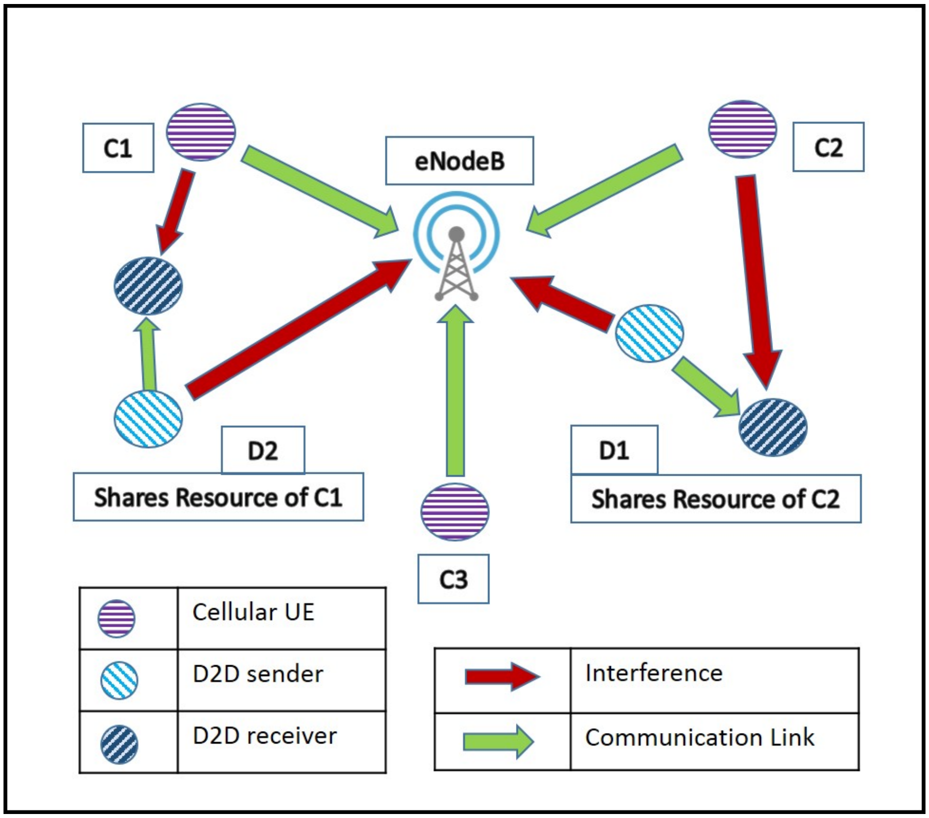


Figure 3.1: System Model Using Uplink Resources

$D = \{d_1, d_2, d_3, ..., d_m\}$. The set of cellular UEs is denoted as $C = \{c_1, c_2, c_3, ..., c_n\}$. Each D2D pair d_j, is composed of a transmitting device d_j^t and a receiving device d_j^r.

3.2 Channel Model

An Urban Micro System is considered, which uses the Rayleigh fading path loss model with orthogonal channels and separate RBs for each cellular UE [28, 53]. No co-channel interference is present in the case of cellular communications. However, D2D communication will introduce co-channel interference in the channel when it shares the RB. The path loss (dB unit) model considers the recommendations in [53] . The path loss model is

$$PL = 36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c), \tag{3.1}$$

here the distance between the transmitter and the receiver is d (meter) and the frequency of the medium is f_c (GHz).

Now, the channel gain between the receiver p and transmitter q is

$$G^{p,q} = 10^{-PL^{p,q}/10}, \tag{3.2}$$

here $PL^{p,q}$ is the distance-dependent path loss between p and q.

3.3 Problem Formulation

This research deals with resource assignment and power allocation problems simultaneously. The D2D pair shares the resources of existing cellular UEs in the inband mode of D2D communication. The term assignment of D2D pair d_j to cellular UE c_i or vice-versa implies that both d_j and c_i share the same resource blocks. Power allocation denotes the setting of transmission power to a cellular UE c_i or D2D pair d_j.

Two optimization objectives are addressed in this thesis work. It should be noted that these two objectives are not considered in the same problem statement. Two different problem statements are proposed. The aim is to find a set of allocations of transmission power and RBs to cellular UEs and D2D pairs that give a good solution to the individual optimization problem.

Before stating the problem statement, in the following, a number of equations are stated which are necessary for the addressed research problem. Assume that the transmission powers of a cellular UE c_i, D2D transmitter d_j^t and eNB are p_{c_i}, $p_{d_j^t}$ and p_{eNB} respectively. We also consider σ as the thermal noise at the receiver end, also known as the energy of Additive White Gaussian Noise (AWGN). It is noted that a maximum of one D2D pair can reuse the RBs of a cellular UE. Signal to Interference plus Noise Ratio (SINR) at the eNB in the uplink phase while communicating with a cellular UE c_i (provided that D2D pair d_j is reusing the same RBs) is

$$\gamma_{eNB,c_i,d_j} = \frac{p_{c_i} G^{c_i,eNB}}{\sigma + p_{d_j^t} G^{d_j^t,eNB}}, \tag{3.3}$$

where, $G^{d_j^t,eNB}$ implies channel gain between the D2D transmitter d_j^t of D2D pair d_j and the eNB, and $G^{c_i,eNB}$ implies the channel gain between the eNB and the cellular UE c_i [30]. The equation (3.3) can be rewritten if no D2D pair reuses the RBs of c_i, as

$$\gamma_{eNB,c_i,0} = \frac{p_{c_i} G^{c_i,eNB}}{\sigma}, \tag{3.4}$$

here, the term denoting the co-channel interference present in the denominator of equation (3.3) is zero as no D2D pair is reusing the RBs of c_i. Similarly, if the D2D pair d_j is reusing the same RBs as c_i, then SINR at the D2D receiver is

$$\gamma_{d_j,c_i} = \frac{p_{d_j^t} G^{d_j^t,d_j^r}}{\sigma + p_{c_i} G^{c_i,d_j^r}}, \tag{3.5}$$

where, $G^{d_j^t,d_j^r}$ denotes the channel gain between the D2D transmitter d_j^t and the D2D receiver d_j^r. Thus, the total system interference introduced is

$$I_{c_i,d_j} = p_{d_j^t} G^{d_j^t,eNB} + p_{c_i} G^{c_i,d_j^r}. \tag{3.6}$$

According to Shannon's capacity formula [12], sumrate contribution of a cellular UE c_i (provided that D2D pair d_j is sharing the resources) can be represented as

$$S_{c_i,d_j} = B\log_2(1+\gamma_{eNB,c_i,d_j}) + B\log_2(1+\gamma_{d_j,c_i}), \tag{3.7}$$

where, γ_{c_i,d_j} indicates the SINR at eNB while communicating with cellular UE c_i and γ_{d_j,c_i} indicates the SINR at D2D receiver d_j^r while communicating with D2D transmitter d_j^t and B is the bandwidth of the channel. If a cellular UE c_i uses dedicated RB (no D2D pair is sharing the RB), then the sum rate offering of cellular UE c_i is

$$S_{c_i,0} = B \log_2(1 + \gamma_{c_i,0}). \tag{3.8}$$

Now, based on the above equations, we formulate two separate problems of capacity maximization and interference minimization as follows.

3.3.1 Capacity Maximization

The system sumrate is based on the equation (3.7) and equation (3.8). There are some QoS requirements that need to be considered as well. Therefore, the optimization problem of maximizing the total system sumrate can be formulated as

$$\begin{aligned}
\underset{x,y_c,y_d}{\arg\ \max} & \Big(\sum_{i=1}^{n}(1-\sum_{j=1}^{m} x_{c_i}^{d_j})S_{c_i,0}N_{c_i} + \sum_{i=1}^{n}\sum_{j=1}^{m} x_{c_i}^{d_j} S_{c_i,d_j} N_{c_i} \Big) \\
&= \sum_{i=1}^{n}(1-\sum_{j=1}^{m} x_{c_i}^{d_j})B\log_2(1+\gamma_{c_i,0})N_{c_i} \\
&+ \sum_{i=1}^{n}\sum_{j=1}^{m} \Big(x_{c_i}^{d_j} B\log_2(1+\gamma_{eNB,c_i,d_j}) + B\log_2(1+\gamma_{d_j,c_i}) \Big) N_{c_i} \\
&= \sum_{i=1}^{n}(1-\sum_{j=1}^{m} x_{c_i}^{d_j})B\log_2(1+\frac{(\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} p_{c_i}^{w})G^{c_i,eNB}}{\sigma})N_{c_i} \\
&+ \sum_{i=1}^{n}\sum_{j=1}^{m} \Big(x_{c_i}^{d_j} B\log_2(1+\frac{(\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} p_{c_i}^{w})G^{c_i,eNB}}{\sigma + (\sum_{z=1}^{k_{d_j}} y_{d_j}^{z} p_{d_j}^{z})G^{d_j^t,eNB}}) \\
&+ B\log_2(1+\frac{(\sum_{z=1}^{k_{d_j}} y_{d_j}^{z} p_{d_j}^{z})G^{d_j^t,d_j^r}}{\sigma + (\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} p_{c_i}^{w})G^{c_i,d_j^r}}) \Big) N_{c_i}
\end{aligned} \tag{3.9}$$

subject to,

$$S_{c_i} \geqslant S_{c_i}^{demand},\ \forall\, c_i \in C \tag{3.10}$$

$$S_{d_j} \geqslant S_{d_j}^{demand},\ \forall\, d_j \in D \tag{3.11}$$

$$p_{c_i} = \{p_{c_i}^1, p_{c_i}^2, \ldots, p_{c_i}^{l_{c_i}}\}, \quad \forall\, c_i \in C \tag{3.12}$$

$$p_{d_j} = \{p_{d_j}^1, p_{d_j}^2, \ldots, p_{d_j}^{k_{d_j}}\}, \quad \forall\, d_j \in D \tag{3.13}$$

$$x_{c_i}^{d_j} = \{0,1\}\ , \quad \forall\, c_i \in C \quad \text{and} \quad \forall\, d_j \in D, \tag{3.14}$$

$$y_{c_i}^{w} = \{0,1\}\ , \quad \forall\, c_i \in C \quad \text{and} \quad 1 \leqslant w \leqslant l_{c_i}, \tag{3.15}$$

$$y_{d_j}^{z} = \{0,1\}\ , \quad \forall\, d_j \in D \quad \text{and} \quad 1 \leqslant z \leqslant k_{d_j}, \tag{3.16}$$

$$\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} = 1, \quad \forall\, c_i \in C \tag{3.17}$$

$$\sum_{z=1}^{k_{d_j}} y_{d_j}^{z} = 1, \quad \forall\, d_j \in D \tag{3.18}$$

$$\sum_{j=1}^{m} x_{c_i}^{d_j} \leqslant 1\ , \quad \forall\, c_i \in C \tag{3.19}$$

$$\sum_{i=1}^{n} x_{c_i}^{d_j} \leqslant 1\ , \quad \forall\, d_j \in D \tag{3.20}$$

The joint optimization problem presented here, considers three decision variables - shared status x, power level selection status of cellular UE y_c and power level selection status of D2D pair y_d.

The first part of the objective function is total sumrate contribution of the unassigned cellular UEs (no D2D pairs shares these cellular UEs), where $S_{c_i,0}$ represents the sumrate contribution of an unassigned cellular UE c_i. The second part of this equation represents the total sum rate contribution of the assigned cellular UEs with the D2D pairs where S_{c_i,d_j} represents the sumrate contribution of a cellular UE c_i and a D2D pair d_j when d_j reuses the RBs of c_i. Using equation (3.7) and equation (3.8) the objective function is expanded. Moreover using equation (3.3), (3.4) and (3.5), the objective function is further expanded. Here N_{c_i} in the objective function (3.9) implies the number of RBs allocated to a cellular UE c_i. If a D2D pair is assigned to cellular UE c_i, then N_{c_i} number of RBs will be allocated to D2D pair d_j also.

In this objective function, the transmission power of cellular UE and D2D pair is controlled by the decision variables y_c and y_d respectively. Additionally the shared status of any cellular UE and D2D pair is controlled by the decision variable x.

Constraint (3.14) denotes that, $x_{c_i}^{d_j}$ is a binary variable that indicates whether a D2D pair d_j shares the RBs of a cellular UE c_i or not.

Constraint (3.15) denotes that, $y_{c_i}^{w}$ is a binary variable that indicates whether a cellular UE c_i will set the transmission power to $p_{c_i}^{w}$. Here p_{c_i} is a set of discrete transmission power level available for cellular UE c_i mentioned in the constraint (3.12) and $p_{c_i}^{w}$ is the w^{th} element in the set. It should be noted that the number of power level available for each cellular UE c_i might be different due to difference in capacity of devices, in terms of transmission power. The size of the set p_{c_i} is l_{c_i}.

Similarly constraint (3.16) denotes that, $y_{d_j}^{z}$ is a binary variable that indicates whether the transmitting device of a D2D pair d_j will set the transmission power to $p_{d_j}^{z}$. Here p_{d_j} is a set of discrete transmission power level available for transmitting device of

D2D pair d_j mentioned in the constraint (3.13) and $p_{d_j}^z$ is the z^{th} element in the set. It should be noted that the number of power level available for each transmitting device of a D2D pair d_j might be different due to difference in capacity of devices, in terms of transmission power. The size of the set p_{d_j} is k_{d_j}.

Constraint (3.10) and constraint (3.11) denotes the individual demand sumrate constraint for cellular UE c_i and D2D pair d_j.

Constraint (3.17) denotes that only one power level can be selected for any cellular UE. Moreover, constraint (3.18) denotes that only one power level can be selected for any D2D pair.

Constraint (3.19) and constraint (3.20) represent the one to one allocation - the first constraint is one cellular UE c_i cannot be assigned to multiple D2D pairs and second one is a D2D pair d_j can be assigned to at-most one cellular UE.

3.3.2 Interference Minimization

The total system interference is based on the equation 3.6. Therefore, the optimization problem of minimizing the total system interference is

$$\begin{aligned}&\underset{x,y_c,y_d}{\arg}\ \min \sum_{i=1}^{n}\sum_{j=1}^{m} x_{i,j} I_{c_i,d_j}\\ &= \sum_{i=1}^{n}\sum_{j=1}^{m}\Big(x_{i,j}(\sum_{z=1}^{k_{d_j}} y_{d_j}^{z} p_{d_j}^{z}) G^{d_j^t,eNB} + (\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} p_{c_i}^{w}) G^{c_i,d_j^r}\Big)\end{aligned} \tag{3.21}$$

subject to,

$$S_{c_i} \geqslant S_{c_i}^{demand},\ \forall\, c_i \in C \tag{3.22}$$

$$S_{d_j} \geqslant S_{d_j}^{demand},\ \forall\, d_j \in D \tag{3.23}$$

$$p_{c_i} = \{p_{c_i}^1, p_{c_i}^2, \ldots, p_{c_i}^{l_{c_i}}\}, \quad \forall\, c_i \in C \tag{3.24}$$

$$p_{d_j} = \{p_{d_j}^1, p_{d_j}^2, \ldots, p_{d_j}^{k_{d_j}}\}, \quad \forall\, d_j \in D \tag{3.25}$$

$$x_{c_i}^{d_j} = \{0,1\}\ , \quad \forall\, c_i \in C \quad \text{and} \quad \forall\, d_j \in D, \tag{3.26}$$

$$y_{c_i}^{w} = \{0,1\}\ , \quad \forall\, c_i \in C \quad \text{and} \quad 1 \leqslant w \leqslant l_{c_i}, \tag{3.27}$$

$$y_{d_j}^{z} = \{0,1\}\ , \quad \forall\, d_j \in D \quad \text{and} \quad 1 \leqslant z \leqslant k_{d_j}, \tag{3.28}$$

$$\sum_{w=1}^{l_{c_i}} y_{c_i}^{w} = 1, \quad \forall\, c_i \in C \tag{3.29}$$

$$\sum_{z=1}^{k_{d_j}} y_{d_j}^{z} = 1, \quad \forall\, d_j \in D \tag{3.30}$$

$$\sum_{j=1}^{m} x_{c_i}^{d_j} \leqslant 1\ , \quad \forall\, c_i \in C \tag{3.31}$$

$$\sum_{i=1}^{n} x_{c_i}^{d_j} \leqslant 1\ , \quad \forall\, d_j \in D \tag{3.32}$$

where the optimization problem mentioned here is to minimize the total system interference. I_{c_i,d_j} represents interference introduced at eNB and D2D pair when a cellular UE c_i shares RBs with a D2D pair d_j. Like the optimization problem of capacity maximization discussed in subsection 3.3.1 this optimization problem has three decision variables - x, y_c and y_d. The representation of this variable is same as discussed in previous subsection.

The individual target sumrate constraint is presented in (3.22) and in (3.23) for cellular UE c_i and D2D pair d_j. Individual power level availability constraints are given in (3.24) and (3.25). Constraint (3.29) and (3.30) represent that a cellular UE and a D2D pair will transmit using only one of the available transmission power levels. Constraint (3.31) and (3.32) represent the one to one allocation of RBs to cellular UEs and D2D pairs. The details of the constraints are not reiterated as they have similar meaning to the first optimization problem presented in subsection 3.3.1.

3.4 Chapter Summary

In this chapter, the system model is explained in section 3.1. In this system model, D2D pairs reuse the uplink resources of cellular UEs. The channel model is explained in section 3.2, where the channel model of the Urban Micro System is considered. Section 3.3 started with the formulation of SINR, sumrate and interference. Based on these equations, two separate objective functions are presented in subsection 3.3.1 and 3.3.2.

Chapter 4

Solution Approach

This thesis proposes a solution approach by formulating the problem into a bipartite graph problem. Both the transmission power assignment and resource assignment of cellular UEs and D2D pairs will be handled simultaneously with this approach. The principle of the proposed solution approach can be explained with an exhaustive search approach of the problem. First the exhaustive search approach will be discussed in section 4.1, then the proposed solution approach will be discussed in section 4.2. Later, the complexity analysis is shown in section 4.3 and concluded with the chapter summary in section 4.4.

4.1 Exhaustive Search

Assume that there are two cellular UEs c_1 and c_2 and two D2D pairs d_1 and d_2. Two transmission power levels, p_1 and p_2 available for c_1, c_2, d_1 and d_2. Figure 4.1 shows all possible combinations of assignment with all possible power levels.

Figure 4.1 (a), $c_1^{p_1}$ row indicates c_1 with transmission power p_1, $c_2^{p_1}$ row indicates c_2 with transmission power p_1, $d_1^{p_1}$ column indicates d_1 with transmission power p_1 and lastly, $d_2^{p_1}$ column indicates d_2 with transmission power p_1. If the power level is fixed, then only one combination is possible. The Hungarian bipartite matching algorithm can solve that in polynomial time with a complexity of $O(n^3)$.

For the given condition, there are 16 different possible combinations as shown in Figure 4.1 (a)-(p). Assuming a minimization problem, first the bipartite matching needs to be applied and the minimum matching weight value has to be calculated for each combination. Then, the minimum among these 16 combinations will be selected. The assignment of power levels and resources of the selected combination will be the optimal solution. In the given scenario, combination (a) of Figure 4.1 returns the lowest value . Moreover, the assignment returned from the hungarian algorithm for Figure 4.1 (a) is $c_1^{p_1}$ with $d_1^{p_1}$ and $c_2^{p_1}$ with $d_2^{p_1}$. So, the power level of c_1, c_2, d_1 and d_2 will be p_1 and c_1 share RBs with d_1 and c_2 share RBs with d_2.

Assume that the number of cellular UE is n, number of D2D pairs is m and $n > m$. Moreover, the number of power levels of cellular UE c_i, is represented by l_{c_i} and that of D2D pair d_j is represented by k_{d_j}. Let $U = \prod_{i=1}^{n} l_{c_i}$ and $V = \prod_{j=1}^{m} k_{d_j}$. So, there will be a maximum of $U \times V$ combinations. So the complexity of the exhaustive approach will be $O(U \times V \times n^3)$.

4.2 Proposed Solution Approach

The proposed solution addresses both the two optimization problems, i.e. the maximization of the system capacity and the minimization of the system interference, while maintaining some constraint. The solution approach is divided into two steps, namely - Step 1: Preparation Stage and Step 2: Execution Stage. The Preparation Stage is subdivided into two steps : 1. Formation of the bipartite graph, and 2. Assignment of weight. Similarly, the execution stage is subdivided into two steps: 1. Multi-value bipartite matching algorithm, and 2. Final assignment of power level and resources.

Figure 4.2 represents the flow diagram of the solution approach. The proposed solution starts with the preparation stage. First, a weight matrix is initialized according to

	$d_1^{p_1}$	$d_2^{p_1}$
$c_1^{p_1}$	2	3
$c_2^{p_1}$	4	5

(a)

	$d_1^{p_2}$	$d_2^{p_1}$
$c_1^{p_1}$	3	3
$c_2^{p_1}$	6	5

(b)

	$d_1^{p_1}$	$d_2^{p_2}$
$c_1^{p_1}$	2	5
$c_2^{p_1}$	4	6

(c)

	$d_1^{p_2}$	$d_2^{p_2}$
$c_1^{p_1}$	3	5
$c_2^{p_1}$	6	6

(d)

	$d_1^{p_1}$	$d_2^{p_1}$
$c_1^{p_2}$	3	5
$c_2^{p_1}$	4	5

(e)

	$d_1^{p_2}$	$d_2^{p_1}$
$c_1^{p_2}$	5	5
$c_2^{p_1}$	6	5

(f)

	$d_1^{p_1}$	$d_2^{p_2}$
$c_1^{p_2}$	3	7
$c_2^{p_1}$	4	6

(g)

	$d_1^{p_2}$	$d_2^{p_2}$
$c_1^{p_2}$	5	7
$c_2^{p_1}$	6	6

(h)

	$d_1^{p_1}$	$d_2^{p_1}$
$c_1^{p_1}$	2	3
$c_2^{p_2}$	5	7

(i)

	$d_1^{p_2}$	$d_2^{p_1}$
$c_1^{p_1}$	3	3
$c_2^{p_2}$	7	7

(j)

	$d_1^{p_1}$	$d_2^{p_2}$
$c_1^{p_1}$	2	5
$c_2^{p_2}$	5	8

(k)

	$d_1^{p_2}$	$d_2^{p_2}$
$c_1^{p_1}$	3	5
$c_2^{p_2}$	7	8

(l)

	$d_1^{p_1}$	$d_2^{p_1}$
$c_1^{p_2}$	3	5
$c_2^{p_2}$	5	7

(m)

	$d_1^{p_2}$	$d_2^{p_1}$
$c_1^{p_2}$	5	5
$c_2^{p_2}$	7	7

(n)

	$d_1^{p_1}$	$d_2^{p_2}$
$c_1^{p_2}$	3	7
$c_2^{p_2}$	5	8

(o)

	$d_1^{p_2}$	$d_2^{p_2}$
$c_1^{p_2}$	5	7
$c_2^{p_2}$	7	8

(p)

Figure 4.1: All possible combination of the matrix

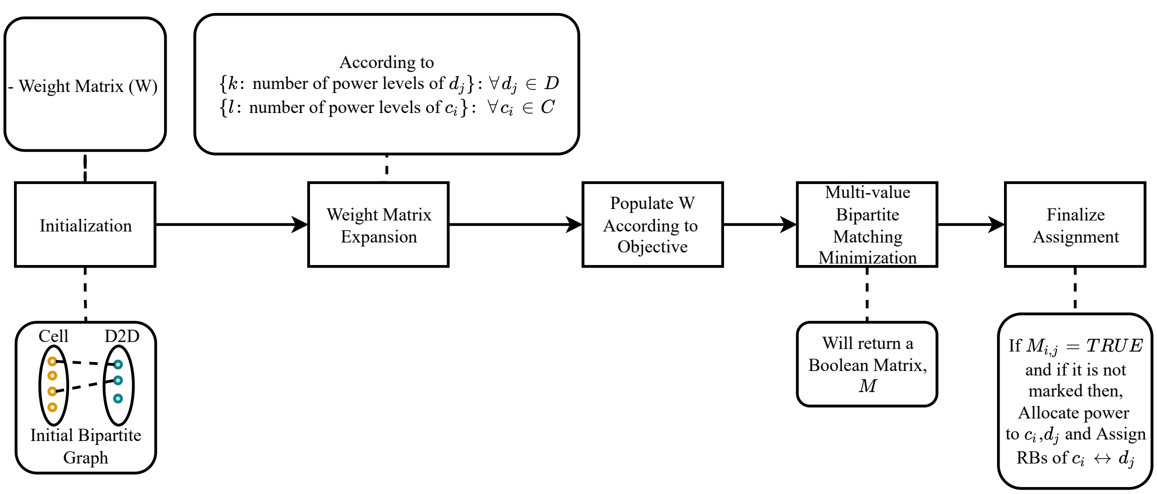


Figure 4.2: Flow chart of the solution approach

the number of cellular UEs and D2D pairs. This initialized matrix is then expanded according to the available transmission power levels for each cellular UE and each D2D pair. Following the objective function of the problem, the weight matrix will then be populated. The Multi-value Bipartite Matching Minimization Algorithm will be applied to the weight matrix which returns a boolean matrix containing the initial assignment of resources and transmission power levels of cellular UEs and D2D pairs. This initial assignment undergoes a finalization stage which ensures the satisfaction of constraints.

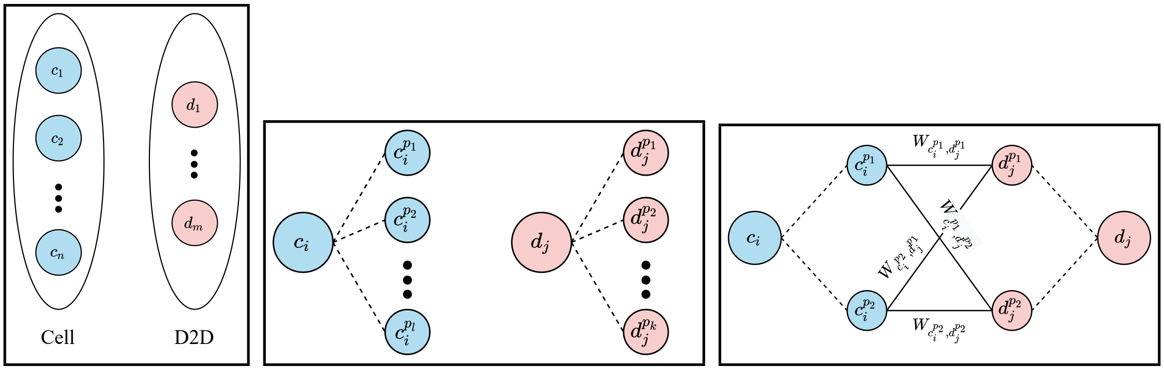
In the subsequent subsections these approaches are discussed.

4.2.1 Step 1 : Preparation Stage

In the preparation stage, the problem is formulated into a bipartite graph. After that, the weight of the edge is assigned. In the following, the working procedures for the sub-tasks of the preparation stage are described.

4.2.1.1 Formation of the bipartite graph

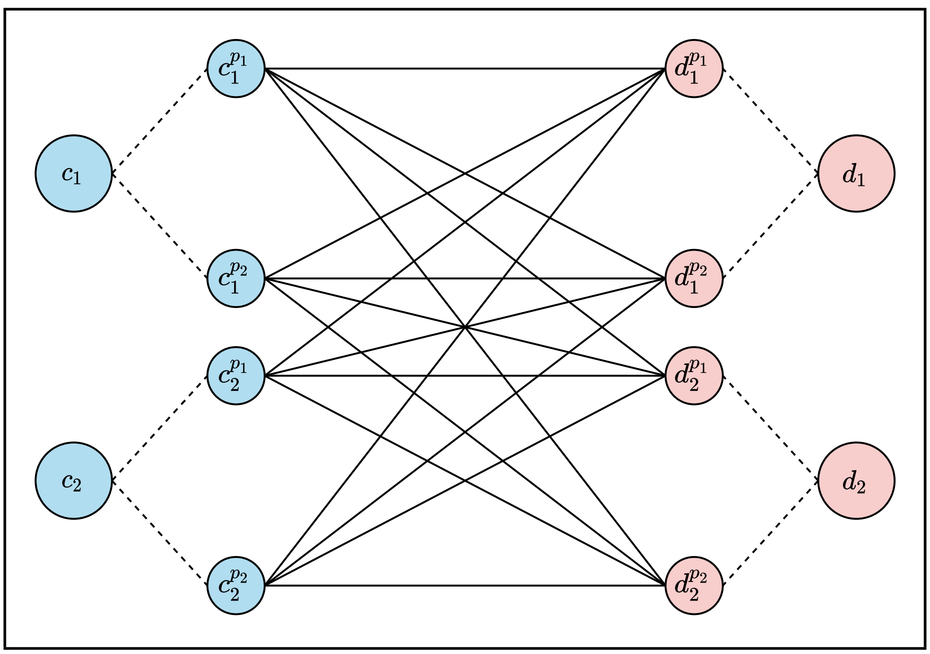
Figure 4.3 shows the step-by-step formulation of the bipartite graph. Firstly, the system has a set of D2D pairs D and a set of cellular UEs C. These two sets conform to the *initial bipartite graph* shown in Figure 4.3 (a). After that, each node of the two sets will be expanded according to the number of power levels available according to the constraints (3.24) and (3.25). Therefore, each cellular UE c_i will be expanded to a l_{c_i} number of instances and each D2D pair d_j to a k_{d_j} number of instances. Figure 4.3 (b) shows the expansion of instances for one arbitrary cellular UE c_i and one arbitrary D2D pair d_j. Figure 4.3 (d) depicts the bipartite graph with the expanded instances of all cellular UEs and all D2D pairs, defined as *expanded bipartite graph.* A node, $c_i^{p_l}$ of the expanded bipartite graph, represents the cellular UE c_i with power level p_l. Similarly, $d_j^{p_k}$ represents the D2D pair d_j with power level p_k. It should



(a) Initial bipartite graph

(b) Expansion of instances

(c) Weight Assignment of expanded instance



(d) Final bipartite graph

Figure 4.3: Formulation of the Multi-value Bipartite Graph

be noted that, at the same moment, any cellular UE/D2D pair cannot be assigned multiple power levels. So, selecting one power level will make the other power levels invalid (if there are any). It necessarily means that after the final match, only one of the expanded nodes of all the initial nodes will be present in the solution.

4.2.1.2 Assignment of weight

The selection of weight for an edge is crucial to getting a global optimum result. For two different objectives, two different appropriate weights should be calculated. Figure 4.3 (c) depicts the weight assignment between any two nodes c_i and d_j, of the initial bipartite graph. Here it is assumed that, the cellular UE c_i has two power levels available p_1 and p_2 and the D2D pair d_j has two power levels available p_1 and p_2. The weight between $c_i^{p_l}$ and $d_j^{p_k}$ is denoted by $W_{c_i^{p_l},d_j^{p_k}}$.

Algorithm 1 Weight of Capacity Maximization Problem

procedure WEIGHTSUMRATE($c_i^{p_l}$,$d_j^{p_k}$)
    c_i's transmission power $= p_l$
    d_j's transmission power $= p_k$
    if $S_{eNB,c_i,d_j} + S_{d_j,c_i} \geq S_{eNB,c_i,0}$ **then**
        if $S_{d_j} \geq S_{d_j}^{demand}$ and $S_{c_i} \geq S_{c_i}^{demand}$ **then**
            $W_{c_i^{p_l},d_j^{p_k}} = S_{eNB,c_i,d_j} + S_{d_j,c_i}$
▷ According to [24] the weight is chosen
        else if $S_{c_i} \geq S_{c_i}^{demand}$ **then**
            $W_{c_i^{p_l},d_j^{p_k}} = S_{eNB,c_i,0}$ and MARK it.
▷ sumrate demand of D2D pair is not satisfied, but cellular UE is satisfied.
        else
            $W_{c_i^{p_l},d_j^{p_k}} = -\infty$ and MARK it.
        end if
    else
        if $S_{c_i} \geq S_{c_i}^{demand}$ **then**
            $W_{c_i^{p_l},d_j^{p_k}} = S_{eNB,c_i,0}$ and MARK it.
            ▷ sumrate demand of D2D pair is not satisfied.
        else
            $W_{c_i^{p_l},d_j^{p_k}} = -\infty$ and MARK it.
        end if
    end if
end procedure

4.2.1.2.1 Capacity Maximization The weight matrix calculation for the capacity maximization problem is presented in Algorithm 1. Sumrate of cellular UE c_i (if shared with D2D pair d_j) is S_{eNB,c_i,d_j} using equation (3.7) and if not shared by any D2D pairs $d_j \in D$ is $S_{eNB,c_i,0}$ using equation (3.8). On the other hand, if d_j shared the RBs of c_i the sumrate is S_{c_i,d_j}. If the RBs of a cellular UEs are shared with a D2D pair, it is not certain that the total sumrate contribution after sharing will be greater than before sharing [24]. In some cases, the sumrate contribution after sharing may decrease. Thus, in line 4, the gain of the sumrate contribution is checked. The proposed algorithm should select the assignments earlier that have a positive sumrate contribution. After that, the individual demand rate of cellular UE will be checked. In any case, if the individual demand rate of cellular UE is not met, the proposed approach should avoid selecting it earlier. Thus, the weight is $-\infty$ in line 10 and 17. Moreover, if a D2D pair d_j does not reuse the RB of a cellular UE c_i then the sumrate of cellular UE becomes the sumrate contribution. Thus, in line 5, if the sumrate demand $S_{d_j}^{demand}$ is not satisfied by a D2D pair d_j, then the weight $S_{eNB,c_i,0}$ is selected. It should be noted that if any sharing is not possible in this step, we mark them in lines 10 and 17. This mark will be necessary in the Execution Stage.

Algorithm 2 Weight of Interference Minimization

```
procedure WEIGHTINTERFERENCE(c_i^{p_l}, d_j^{p_k})
    c_i's transmission power = p_l
    d_j's transmission power = p_k
    if S_{d_j} ≥ S_{d_j}^{demand} and S_{c_i} ≥ S_{c_i}^{demand} then
        W_{c_i^{p_l}, d_j^{p_k}} = I_{c_i,d_j}
                                   ▷ According to [17] the weight is chosen
    else
        W_{c_i^{p_l}, d_j^{p_k}} = ∞ and MARK it.
    end if
end procedure
```

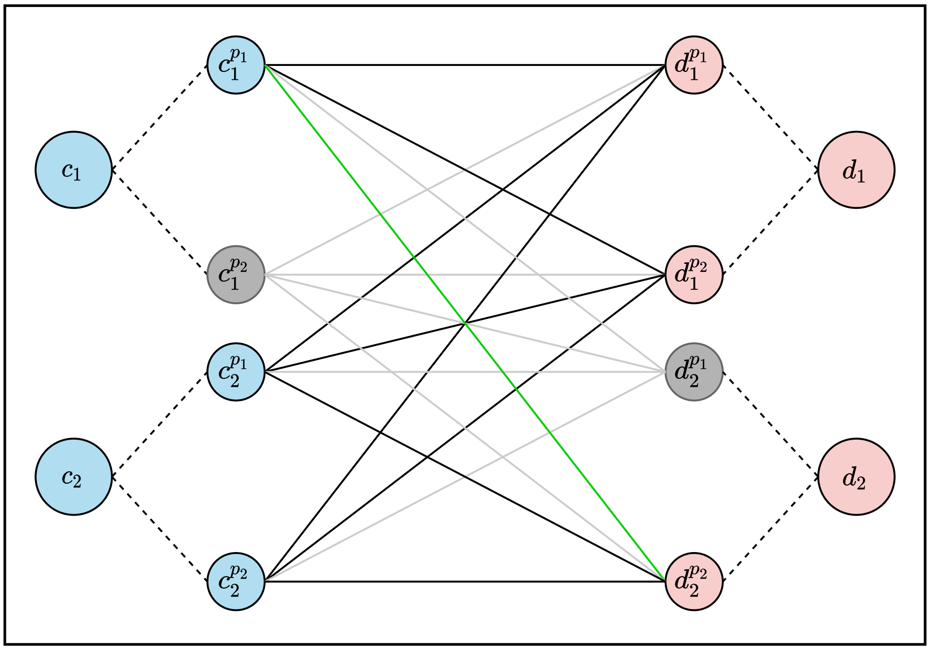
	$d_1^{p_1}$	$d_1^{p_2}$	$d_2^{p_1}$	$d_2^{p_2}$
$c_1^{p_1}$	2	3	3	5
$c_1^{p_2}$	3	5	5	7
$c_2^{p_1}$	4	6	5	6
$c_2^{p_2}$	5	7	7	8

Figure 4.4: Single matrix combining all possible combination

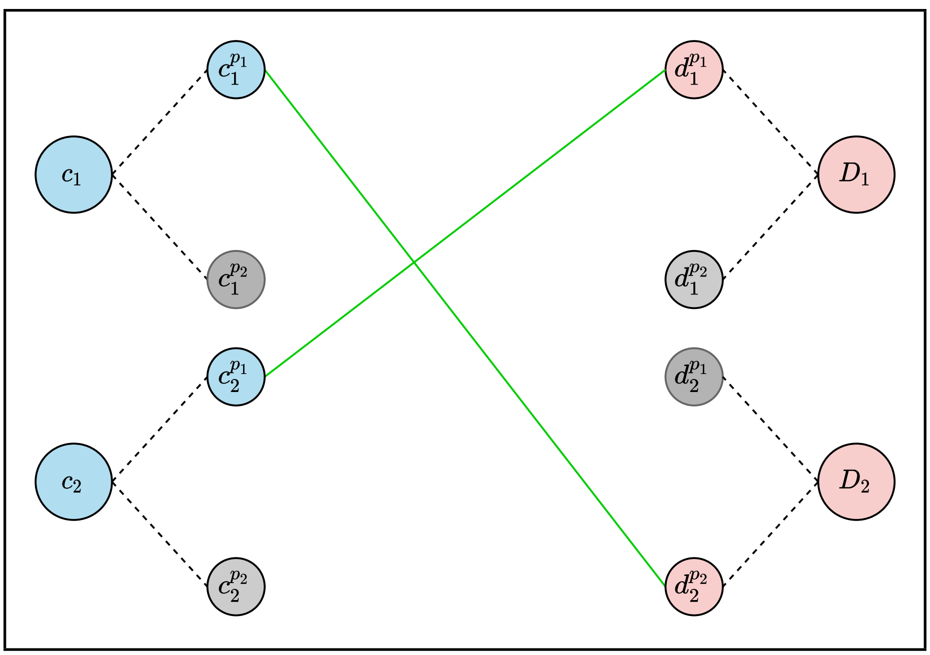
4.2.1.2.2 Interference Minimization The weight matrix calculation for the interference minimization problem is presented in Algorithm 2. The problem formulation considers only co-channel interference. If there is no sharing, then the interference is zero. If d_j shares the RBs of c_i, then interference is denoted by I_{c_i,d_j}. The sumrate demand of cell c_i and D2D pair d_j is checked in line 4. If the sumrate demand of a cellular UE or a D2D pair is not satisfied due to any assignment, then the weight ∞ is selected in line 7 and these assignments are marked for the Execution Stage.

4.2.2 Step 2: Execution Stage

In this step, the multi-value bipartite matching (MBM) algorithm is applied to the expanded matrix. After step 1, a single matrix with $\sum_{i=1}^{n} l_{c_i}$ number of rows and $\sum_{j=1}^{m} k_{d_j}$ number of columns will be prepared. Figure 4.4 denotes a single matrix containing all possible combinations. This matrix will be used in step 2.



(a) Selecting an edge for candidate solution - an intermediate step



(b) Final Assignment

Figure 4.5: Assignment in Multi-value Bipartite Graph

4.2.2.1 Multi-Value Bipartite Matching (MBM) Algorithm

A multi-value bipartite matching algorithm is shown in Algorithm 3. This algorithm is designed with inspiration from the many-to-many Khun Munkres algorithm with backtracking (KMB) [52]. This algorithm has a halting state. To avoid the halting state, authors in [20] provided a modified version of the KMB algorithm. MBM adapts the modified KMB algorithm. Only the adaptation is discussed in the following. It should be noted that Algorithm 3 has similar steps to the original Khun Munkres algorithm.

4.2.2.1.1 Adaptation of MBM Algorithm As any D2D pair or cellular UE can adopt only one power level it will be invalid to have assignment of two different power levels by a particular cellular UE and D2D pairs. At any step of the algorithm if an expanded instance is selected as a candidate solution then all other instances associated to that cellular UE and D2D pair will be invalid. Figure 4.5 (a) shows that edge between $c_1^{p_1}$ and $d_2^{p_2}$ is selected in an intermediate step and $c_1^{p_2}$ and $d_2^{p_1}$ is needed to be made unavailable. So that MBM algorithm do not assign an invalid match. In the line 7 and 13 of Algorithm 3, **make other row column unavailable** is performing same operation shown in Fig. 4.5 (a). This operation takes place when a starring operation is done. Starring a cell in $c_i^{p_l}$ row and $d_j^{p_k}$ column of the matrix implies, a candidate solution is chosen where RBs of c_i will be shared with d_j. Moreover, in the candidate solution, the power level of c_i is p_l and power level of d_j is p_k. As one candidate solution selected p_l power level for c_i, all other power levels of c_i (in other words all other rows) must be made unavailable for further consideration as they may produce invalid solution. Similarly all other power levels of d_j (in other words all other columns) must be made unavailable. Therefore, MBM algorithm avoids assigning invalid matching with **make other row column unavailable** operation.

Algorithm 3 Multi Value Bi-partite Matching Algorithm

```
procedure MBM(M)
    Step 1: (Row Column Minimization)
    Subtract the minimum value of a row from each element of that row.
                              ▷ Each row will contain at least one zero value now.
    Subtract the minimum value of a column from each element of that column.
                              ▷ Each column will contain at least one zero value now.
    Step 2: (Initial Starring)
    Find a zero value which does not have any starred zero in its row and column.
    Make other row column unavailable.
          ▷ Unavailable the instance of any expanded node other than the selected
  instance as in Fig. 4.5 (a)
    Step 3: (Covering Column)
    Cover each column with starred zero.
    If the number of covered columns are equal to available columns go to Step 8
  else go to Step 4.
    Step 4: (Prime Some Uncovered Zero)
    Find an uncovered zero and prime it.
    Make other row column unavailable.
          ▷ Unavailable the instance of any expanded node other than the selected
  instance as in figure 4.5a
    if There exists a starred zero in the row containing primed zero. then
        Cover this row and uncover the column
    else
        Go to step 5
    end if
    Repeat Step 4 until there is no uncovered zero left.
    Step 5: (Increasing Starred Zero)
    Construct a series of alternating prime and starred zero as following:
      • z0 : Uncovered primed zero found in step 4.
      • z1 : The starred zero in the column of z0 (if any)
      • z2 : The primed zero in the row of z1 (if there is z1, there will always be z2)
    Continue until the series terminates at a primed zero that has no starred zero
  in its column.
    Unstar each starred zero and Star each primed zero. Erase all primes and
  uncover every row and column.
    Backtracking: Make available all unavailable row columns of same cellular
  and same D2D pair of erased Starred zero.
    Step 6: (Increasing Zeros)
    Add the smallest uncovered zero to each element of the covered row and
  subtract from each element of the uncovered column.
    Go to step 7 removing all stars, prime and covering.
```

28: **Step 7**: (Next Starring)
29: Find all zeroes which do not have any starred zeros present in their row or column and star them.
30: <u>*Make other row column unavailable.*</u>
▷ Unavailable the instance of any expanded node other than the selected instance as in figure 4.5a
31: Go to Step 4.
32: **Step 8**: (Solution)
33: return the solution M
34: **end procedure**

Like the operation of KMB and modified KMB, in line 24 backtracking is executed. In this case the unavailable rows and columns of the matrix will be available again. This operation takes place when a starred element is un-starred, which represents a matching is deselected. Assume a cell in $c_i^{p_l}$ row and $d_j^{p_k}$ column of the matrix is un-starred. In this step no power level of c_i and d_j is invalid as the said matching is not present in the candidate solution after un-starring. Hence, all other unavailable power levels of c_i and d_j can be considered. Therefore, backtracking operation allows the MBM algorithm to search for matching with different power levels which was unavailable.

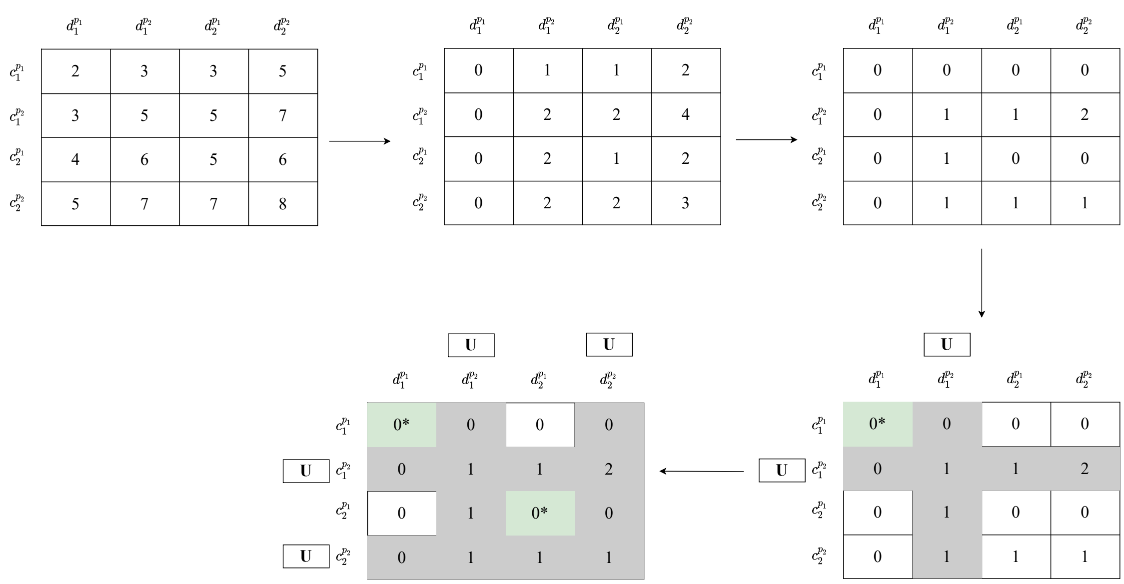


Figure 4.6: Step-by-Step iterations of the MBM Algorithm

4.2.2.1.2 A simple run of MBM In Fig. 4.6, we have demonstrated the step-by-step working mechanism of our proposed algorithm for a given arbitrary weight matrix. Note that this example does not require all the steps of MBM algorithm to reach the solution. At first *row reduction* is done. Later *column reduction* takes place to reduce the matrix. The next step is initial starring step. In this particular bipartite matching if one element is starred then the other rows and columns of that starred element needs to be made unavailable. In fourth state of the diagram, first element $(c_1^{p_1}, d_1^{p_1})$ becomes green as it is starred and other associated columns and rows of that cellular UE d_1 and c_1, respectively, is made unavailable with grey color. U represents that particular row/column is unavailable. In fifth state, initial starring is continued and $(c_2^{p_1}, d_2^{p_1})$ is starred and associated rows and column is made unavailable. No starring is possible after that. Now in the column cover step $d_1^{p_1}$ and $d_2^{p_1}$ is covered. The number of column covered is two which is equal to number of available columns. So this is the final match returned by the MBM algorithm.

4.2.2.2 Final Assignment of power level and resources

This step is after the assignment returned from the MBM algorithm. MBM algorithm will return a solution of the expanded bipartite graph. It will only return the available nodes of the expanded graph which indicates that for one cellular UE or one D2D pair only one level will be selected. While assigning a weight in subsection 4.2.1.2, some edges were marked as they do not maintain the individual constraint. There may be some cases even after a correct weight this type of marked edges may be selected by the algorithm. So in this step of post processing, these marked edges will not be assigned which ensures that the correctness of the algorithm.

4.3 Complexity Analysis

Assume the number of power level of cellular UE c_i, is represented by l_{c_i} and that of D2D pair d_j is represented by l_{d_j}. Let $u = \sum_{i=1}^{n} l_{c_i}$ and $v = \sum_{j=1}^{m} l_{d_j}$. Assume $Y = max(u, v)$ In step 1, first a bipartite graph is created which is equivalent prepare a matrix which is constant time. Next the assignment of weight the sumrate contribution needs to be calculated which is $O(Y^2)$. The complexity of the MBM algorithm is $O(Y^3)$. Analyzing each step of MBM algorithm 3, it is seen that each step of the algorithm is not more than $O(Y^3)$. In the post processing step the complexity is $O(n^2)$. Thus the complexity of the total approach is $O(Y^3)$.

4.4 Chapter Summary

In chapter 4, first an exhaustive search approach is presented. Later proposed solution approach is discussed. Proposed solution approach is divided into two steps. In the first first step the bipartite graph is formed and appropriate weight is assigned. Note that, based on two objective functions the weight is calculated. Later multi-value bipartite matching algorithm is applied on the graph to get the intermediate solution. This solution is filtered by the post-processing approach to avoid assignments or power allocation which may lead to failure in meeting the individual demand sumrate.

Chapter 5

Result Analysis

5.1 Simulation Environment

A C++ program is used to write the code for the numerical simulation. Our research problem is a type of assignment problem. The main goal of the simulations is to find out how the D2D pairs are connected to the cellular UEs and choose the right power level. Based on this assignment, and using necessary equations mentioned in section3.3 the numerical values of SINR, sumrate and interference are calculated.

The same simulation parameters as [28], [30] (Table 5.1) and moderate a few parameters. Our proposed algorithm performs consistently in this environment. The environment considers a single eNB which can be extended. The maximum distance allowed between the transmitter and receiver of a D2D pair is 15 meters as many consider that D2D communication takes place within close proximity [38]. Generally, the macro-cell radius is 1000 m [13]. The individual sumrate demand of a Cellular UE, S_d^{demand} is selected randomly from a range of $1 \sim 3bps/Hz$ and the individual sumrate demand of a D2D pair, S_d^{demand} is selected randomly from a range of $1 \sim 15bps/Hz$. For analysis, the number of D2D pairs is varied from 10 to 90 where the number of cellular UE is kept fixed at 100. Each simulation result is an average of 20 separate run for a certain scenario.

Table 5.1: Simulation Parameters

Parameter	Value
Cell Radius	1000 meters
Cellular Users	100
D2D pairs	10 $\sim$ 90 (increments of 10)
Maximum D2D pair distance	15 meters
Cellular user transmit power	18 $\sim$ 20 dBm
D2D transmit power	17 $\sim$ 20 dBm
Noise power (AWGN)	-174 dBm
Carrier Frequency	1.7 GHz for LTE
Sumrate Demand of cell, S_c^{demand}	Random value (1 $\sim$ 3 bps/Hz)
Sumrate Demand of D2D pairs, S_d^{demand}	Random value (1 $\sim$ 15 bps/Hz)

In the next subsection, the description and the performance of different other resource allocation (RA) algorithms compared to our algorithm are explained.

5.2 Result Analysis

In this section, we compare our proposed algorithms with existing capacity maximization and interference minimization algorithms and assess the effectiveness of our work.

5.2.1 Maximization of Total System Capacity

For the numerical study, several existing algorithms are compared with the proposed solution. For the system capacity maximization problem, the proposed algorithm is compared with ccnc [24], genetic [42] and a random algorithm.

Figure 5.1 illustrates the comparison of total system capacity obtained by our proposed algorithm with the existing algorithms and it is noticed that our proposed algorithm obtains a substantial advantage in total system capacity over the other algorithms. Among these algorithms, the random algorithm obtained the lowest system capacity compared to others, which is almost 400 bps/Hz less than our algorithm on average. It can also be observed from Figure 5.1 that the genetic algorithm performed better at first and the overall performance of the genetic algorithm deteriorated gradually. For a genetic algorithm to perform at its peak, the population needs to be increased exponentially, assuming an increasing number of D2D pairs, which increases the required computation power. Since increasing the required computation power exponentially with respect to the number of D2D pairs is not feasible for real-life applications, we used a fixed population size of 50 in our implementation. While the fixed population value exceeded the required population for peak performance of the genetic algorithm, its performance started to deteriorate.

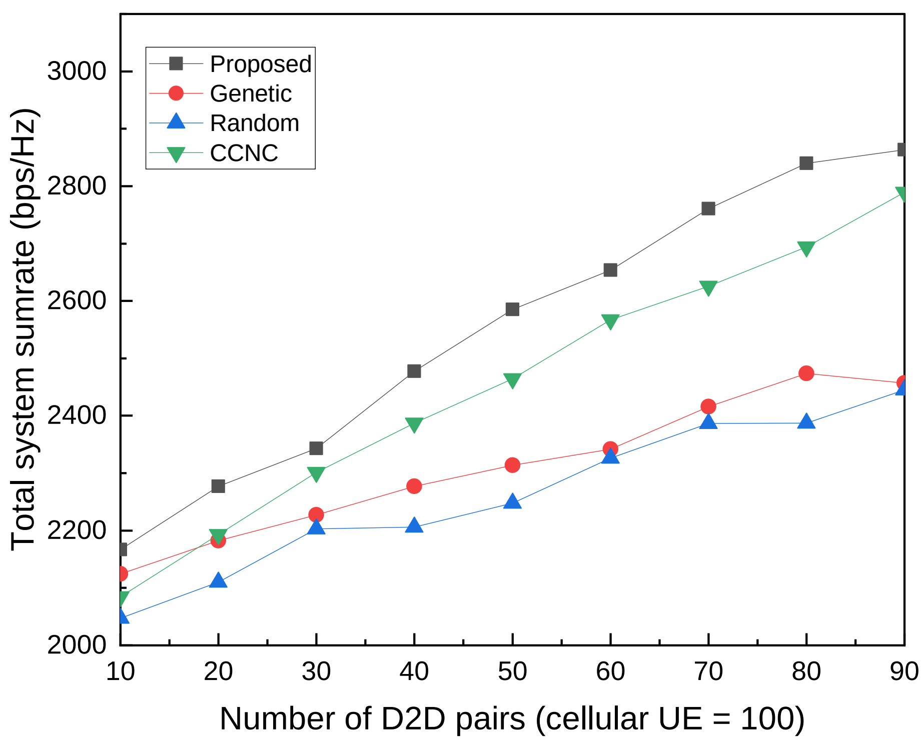


Figure 5.1: Comparison of Total System Capacity in Sumrate Maximization (number of cellular UE = 100)

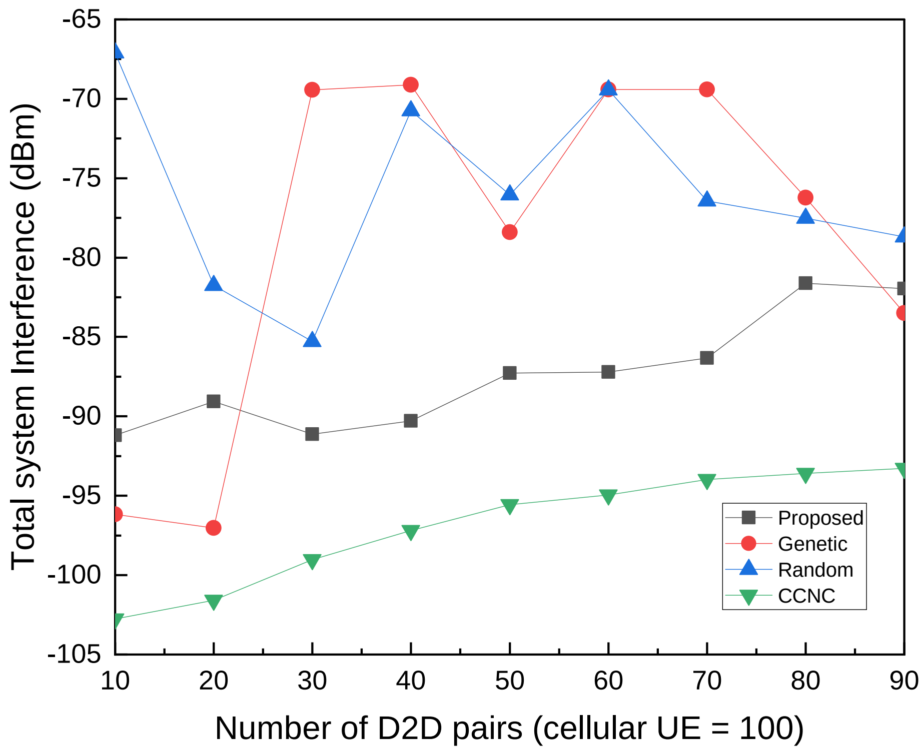


Figure 5.2: Comparison of Total System Interference in Sumrate Maximization (number of cellular UE = 100)

Though our objective is to maximize sumrate, it is also important to maintain a certain quality of service to the end users with respect to the other performance metrics, such as interference, admission rate, fairness, etc. While achieving the maximum total system sumrate, our proposed algorithm achieved a comparable total system interference, which is on par with the existing prominent algorithms as depicted in Figure 5.2. Our proposed algorithm performed better than both CCNC with and without constraint in terms of total system interference as well as provided more stable performance than genetic and random algorithms for various numbers of D2D pairs.

The admission rate is a vital metric in terms of performance for a resource allocation algorithm. As observed from the figure 5.3, the proposed algorithm performs better than the genetic, random and CCNC in most of the scenarios, which makes our

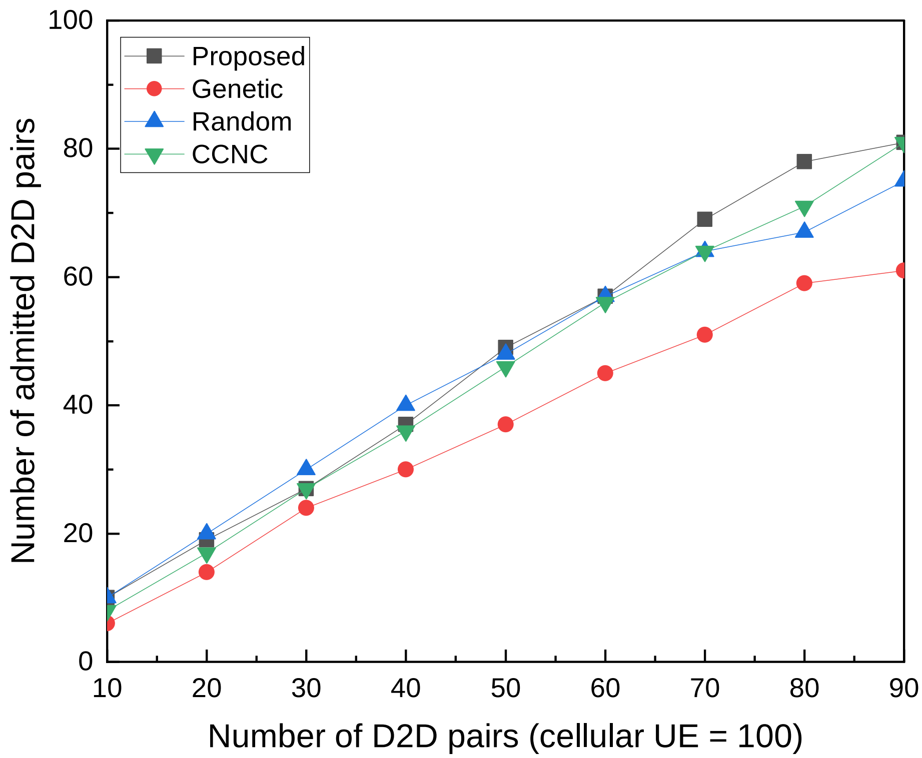


Figure 5.3: Comparison of admission rate of D2D in Sumrate Maximization (number of cellular UE = 100)

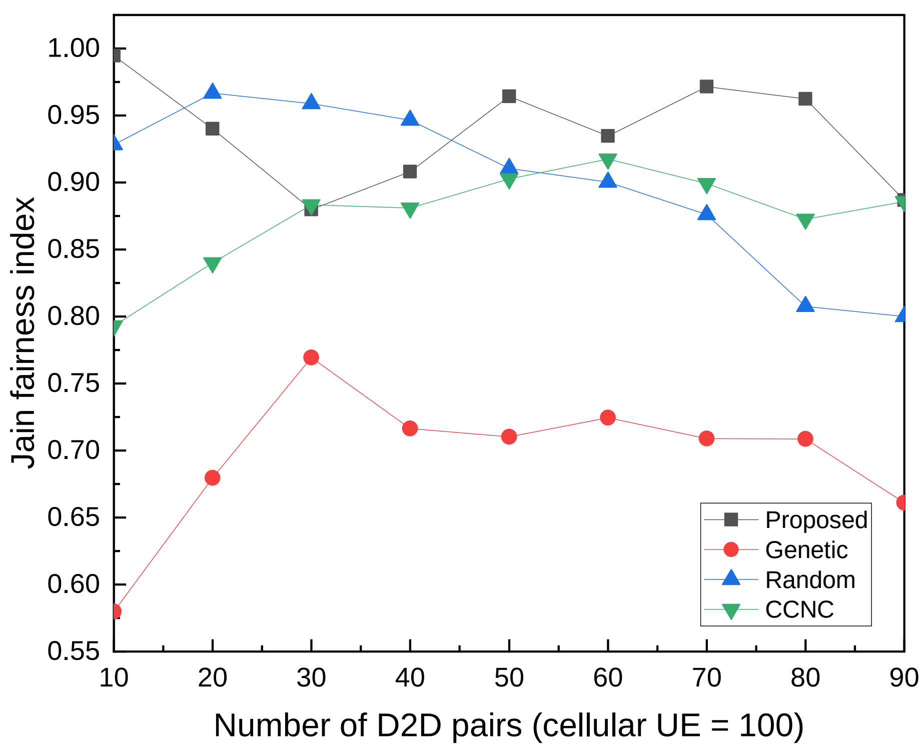


Figure 5.4: Comparison of Jain Fairness in Sumrate Maximization (number of cellular UE = 100)

algorithm give a higher fairness score than these algorithms for various numbers of D2D pairs as depicted in Figure 5.4.

5.2.2 Minimization of Total System Interference

In this subsection, we compare the performance of our proposed algorithm, which was developed considering interference minimization as an objective, with other interference minimization resource allocation algorithms, namely, HIMRA[20], RARA[17], and Random.

Figure 5.5 shows the total system interference obtained by our algorithm as well as other interference minimization resource allocation algorithms and it is observed that our proposed algorithm obtains the lowest interference for various number of D2D pairs. The Hungarian algorithm-based solution, HIMRA performed the closest to our proposed algorithm in terms of total system interference and the random algorithm

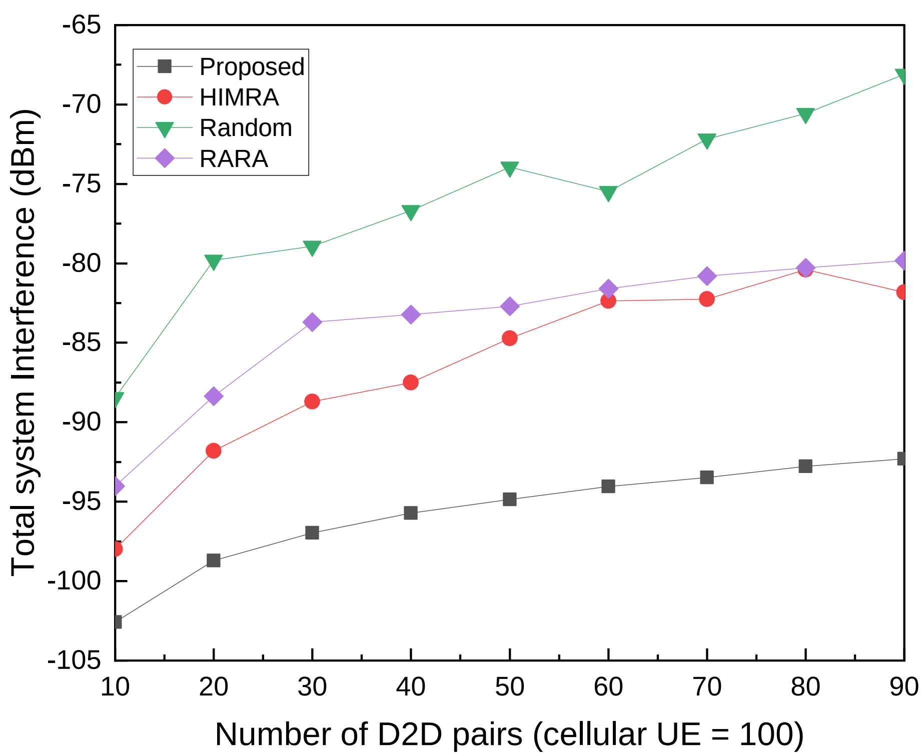


Figure 5.5: Comparison of Total System Interference in Interference Minimization (number of cellular UE = 100)

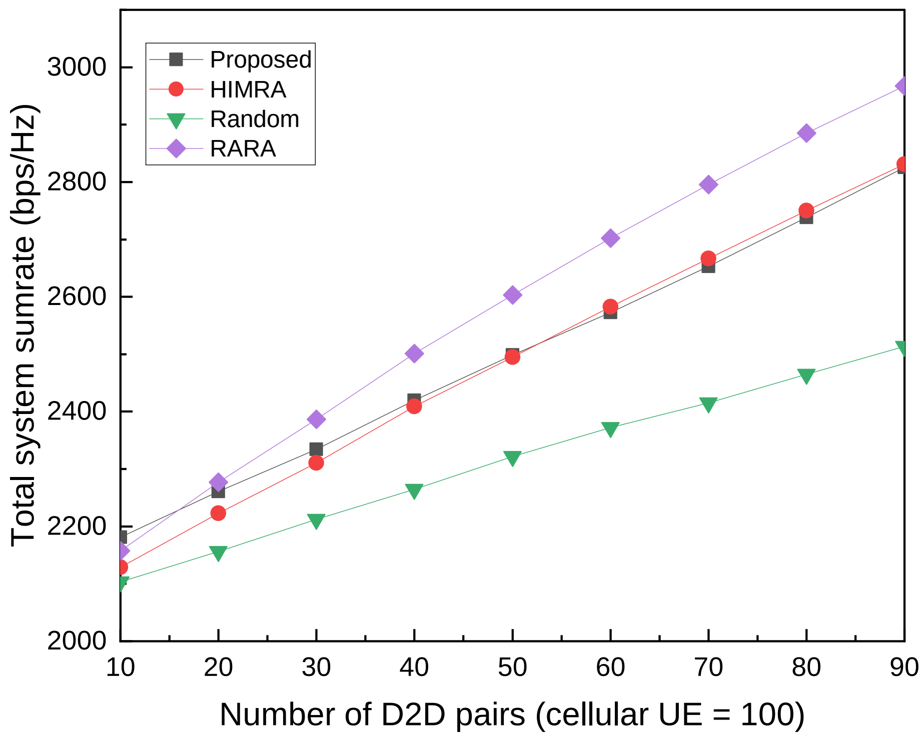


Figure 5.6: Comparison of Total System Capacity in Interference Minimization (number of cellular UE = 100)

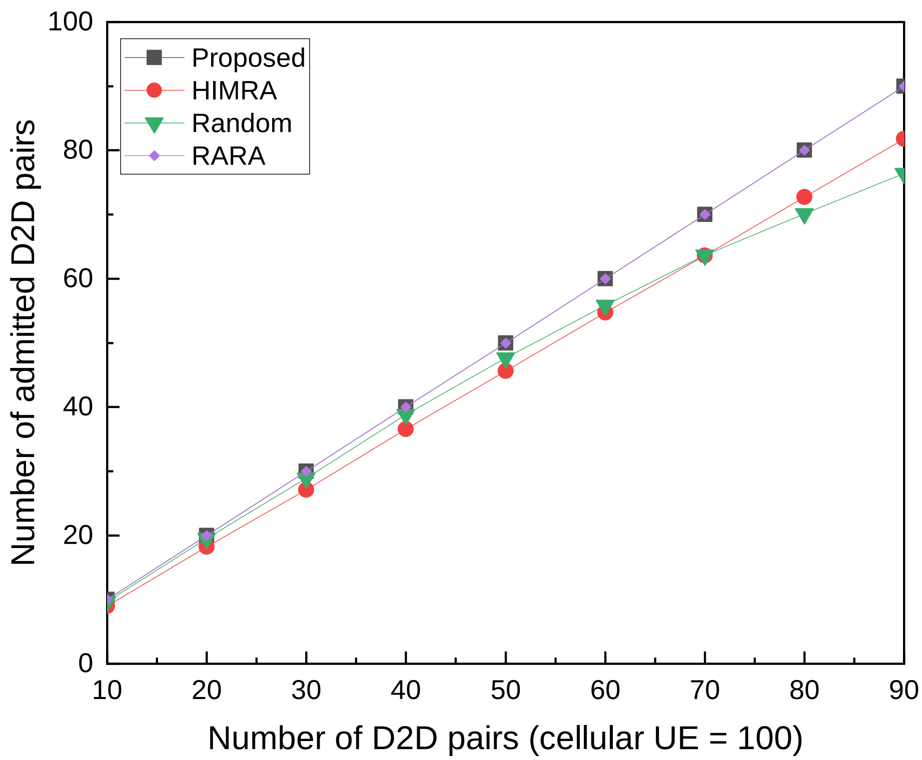


Figure 5.7: Comparison of admission rate of D2D in Interference Minimization (number of cellular UE = 100)

performed the worst. Our algorithm achieved almost 20 dBm less interference on average than the random algorithm.

While achieving the lowest system interference, our proposed algorithm was able to achieve comparable performance in terms of total system capacity as well as shown in Figure 5.6. It achieved better system capacity than the random algorithm and almost similar total system capacity to the HIMRA algorithm.

Our algorithm also admits a higher number of D2D pairs than other interference minimization algorithms, as depicted in Figure 5.7 which is on par with the RARA algorithm.

5.3 Chapter Summary

Chapter 5 presents the performance of the proposed algorithm. Before discussing the performance, the simulation environment is laid down in Section 5.1. The range of numeric values for different variables is listed in this section. The numerical simulation is completed by following these ranges in a C++ program. Later, the results collected from this program are compared with the relevant existing algorithm in Section 5.2. Different performance matrices are considered in the comparison, namely - total system capacity, total system interference, admission rate, jain fairness. The analysis shows that, proposed algorithm performs reasonably better compared to the existing algorithms.

Chapter 6

Conclusion

Over the last decade, device-to-device (D2D) communication has exploded in popularity as a means of personal communication. With the popularity of smart hand-held devices, this style of communication is entering the industry as well as private use. D2D communication may be used for a variety of inter-device services, including file sharing, media content downloading, and so on. We focused on inband underlay D2D communication in this study, where two user equipment (UEs) in close proximity interface directly rather than via eNodeB. If the appropriate Resource Blocks (RBs) from a traditional cellular network are reused, the benefits of utilizing this technology include enhanced spectrum efficiency, greater overall system capacity, reduced traffic load on the eNB, and lower power consumption of the cellular UEs. In addition to the benefits listed above, inband underlay D2D communication offers higher bit-rate gain, spectrum reuse gain, hop gain, and coverage gain. D2D communication is enabled by reusing conventional radio resources under the supervision of an eNB, which is available in LTE and later generations (4G and 5G) (eNodeB, base station in LTE). Furthermore, in the future, 6G will require a good implementation of intelligent D2D communication. The added interference caused by radio resource sharing across cellular UEs and D2D pairs severely hampers a resource allocation mechanism. Furthermore, when ill-fitting RBs are used, total system interference in the current cellular network increases to a catastrophic level citemin. As a result, a lot of academics are working on resource allocation algorithms to reduce system interference while preserving the goal sum rate, and this topic still needs to be explored further.

6.1 Summary

This thesis deals with two optimization problems. Researchers in this area provide a number of RA algorithms. However, there are less number of deterministic solutions. A hungarian-based polynomial-time solvable deterministic algorithm is used to achieve the theoretical maximum sumrate and minimum interference, a. When compared to existing algorithms in their respective fields, the proposed approach achieved remarkable performance in terms of total system interference, total system sumrate and admission rate.

6.2 Future Work

This thesis does not consider one to many and many to many sharing approaches. Therefore, in the future, those variants could be analysed. It could be difficult to identify an optimal solution for many to many sharing approach. However, a Hungarian-based solution could be modified to address the same problem for many to many sharing approach as well on an approximate weight matrix. Study of a system model with different categories of D2D services is also required. As there are different RA algorithms available aiming at different scenarios and different goals, it is essential to combine this solution to suggest which algorithm should be deployed by an operator in different user demography with different demand rates.

List of Acronyms

4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AWGN	Additive White Gaussian Noise
BS	Base Station
CDHN	Cooperative D2D Heterogeneous Network
CNN	Convolutional Neural Network
CSI	Channel State Information
CU	Cellular User
D2D	Device to Device
DARA	Deferred Acceptance based Resource Allocation
DL	Downlink
DNN	Deep Neural Network
DQN	Deep Q-learning Network
DRL	Deep Reinforcement Learning
eNB	evolved Node B
FP	Fractional Programming
KMB	Kuhn-Munkres Algorithm with Backtracking
LTE	Long Term Evolution
MBM	Multi-Value Bipartite Matching Algorithm
MDP	Markov Decision Process

MSMAP	Model Selection and MCS Assignment sub-Problem
QCROA	Quantum Coral Reefs Optimization Algorithm
QoS	Quality of Service
RA	Resource Allocation
RAP	Resource Block Allocation Problem
RB	Resource Block
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference and Noise Ratio
TPC	Transmit Power Control
UE	User Equipment
UL	Uplink
V2V	Vehicle to Vehicle
WSR	Weighted-Sum-Rate

List of Notations

B	Bandwidth of the channel
c_i	i^{th} Cellular UE
C	Set of Cellular UEs
d_j	j^{th} D2D pair
d_j^r	Receiving device of j^{th} D2D pair
d_j^t	Transmitting device of j^{th} D2D pair
D	Set of D2D pairs
$G^{p,q}$	Channel gain between p and q
$G^{c_i,eNB}$	Channel gain between cellular UE c_i and the eNB
$G^{d_j^t,eNB}$	Channel gain between D2D transmitter d_j^t and the eNB
$G^{d_j^t,d_j^r}$	Channel gain between the D2D transmitter d_j^t and the D2D receiver d_j^r
I_{c_i,d_j}	Interference introduced to the system due to the sharing of resources by cellular UE c_i and D2D pair d_j
k_{d_j}	Size of the set p_{d_j}
l_{c_i}	Size of the set p_{c_i}
N_{c_i}	Number of RBs allocated to cellular UE c_i
p_{c_i}	Set of discrete transmission power levels available for cellular UE c_i
$p_{c_i}^w$	w^{th} element in the set p_{c_i}
p_{d_j}	Set of discrete transmission power level available for transmitting device of D2D pair d_j
$p_{d_j}^z$	z^{th} element in the set p_{d_j}

$PL^{p,q}$	Distance dependent path loss between p and q
S_{c_i}	Sumrate of cellular UE c_i
S_{d_j}	Sumrate of D2D pair d_j
S_{c_i,d_j}	Sumrate contribution to the system due to sharing of resources by cellular UE c_i and D2D pair d_j
$S_{c_i,0}$	Sumrate contribution to the system by cellular UE c_i if no D2D pair shares the resources of c_i
$S_{c_i}^{demand}$	Sumrate demand of cellular UE c_i
S_{d_j}	Sumrate contribution of a D2D pair d_j
$S_{d_j}^{demand}$	Sumrate demand of D2D pair d_j
$x_{c_i}^{d_j}$	Binary variable that indicates whether a D2D pair d_j shares the RBs of a cellular UE c_i or not
$y_{c_i}^{w}$	Binary variable that indicates whether a cellular UE c_i will set the transmission power to $p_{c_i}^{w}$
$y_{d_j}^{z}$	Binary variable that indicates whether the transmitting device of a D2D pair d_j will set the transmission power to $p_{d_j}^{z}$
γ_{eNB,c_i,d_j}	SINR at the eNB when c_i shares the channel with D2D pair d_j
$\gamma_{eNB,c_i,0}$	SINR at the eNB when the c_i does not share the channel with any D2D pair
γ_{d_j,c_i}	SINR at the receiver of the D2D pair d_j when it shares the channel with c_i
σ	Thermal noise at the receiver end

List of Publications

1. **F. Hussain,** M.Y. Hassan, M.S. Hossen and S. Choudhury, "System capacity maximization with efficient resource allocation algorithms in D2D communication." *IEEE Access*, 6, pp.32409-32424, 2018.

2. M.S. Hossen, M.Y. Hassan, **F. Hussain**, S. Choudhury, and M.M. Alam, "Relax online resource allocation algorithms for D2D communication", *International Journal of Communication Systems, Wiley*, 31(10), p.e3555, 2018.

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