ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

Capacity and Interference Aware Resource Allocations for Underlay Device-to-Device Communications

Author
Md. Sakhawat Hossen

Supervisor
Prof. Dr. Muhammad Mahbub Alam
Professor
Department of Computer Science and Engineering (CSE)
Islamic University of Technology

A thesis submitted to the Department of Computer Science and Engineering (CSE) in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) in CSE

Department of Computer Science and Engineering (CSE)
Islamic University of Technology (IUT)
A subsidiary organ of the Organization of Islamic Cooperation (OIC)
Gazipur 1704, Dhaka, Bangladesh

May, 2022

Declaration

I, hereby, declare that this dissertation entitled **Capacity and Interference Aware Resource Allocations for Underlay Device-to-Device Communications** was carried out by me for the degree of **Doctor of Philosophy in Computer Science and Engineering**, PhD in CSE, under the guidance and supervision of Prof. Dr. Muhammad Mahbub Alam, Islamic University of Technology (IUT), Gazipur, Dhaka, Bangladesh.

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

Author

____

Md. Sakhawat Hossen
Student ID: 134702

Date: ____________________

Abstract

Device-to-Device (D2D) communication in underlay in-band mode is the most beneficial among other modes of implementations as sharing the radio resources of existing cellular users with the D2D pairs increases the system capacity. The D2D pairs can communicate by reusing the appropriate resource blocks (RBs) of the existing cellular network which increases system capacity and spectral efficiency. However, due to an inefficient design, sharing resources with the D2D pairs may introduce potential co-channel interference in the cellular network which can affect the primary users. This mode of personal communication is attracting more researchers from academia, standardization bodies, and industry for further insight in developing efficient resource allocation schemes. In this dissertation, we work towards developing efficient resource allocation algorithms to minimize the system interference and maximize the system capacity to leverage the trade off between primary cellular user and the D2D user in terms of interference and capacity gain due to sharing.

Firstly, we address the research problem of minimizing interference while maintaining individual target sumrate. In One-to-One mode of sharing, it is assumed that one cellular user equipment (UE) is enough to meet the demand of a D2D. Our empirical studies show that in some scenarios, an individual cellular UE might not be enough to meet the individual target sumrate constraint. To tackle this issue, we have also considered One-to-Many and Many-to-Many mode of sharing which is a relatively unexplored research domain for centralized approach. Most of the existing research works in centralized approach addressed this problem from the One-to-One point of view for avoiding complexity. In distributed approach, there are some solutions that tackle this issue in both One-to-Many and Many-to-Many paradigms. However, distributed approach requires significantly higher number of message passing than centralized approach which in turn lead to inefficient usage of existing resources. In essence, we tackle the research problem of interference minimization while considering individual target sumrate for One-to-One as well as One-to-Many and Many-to-Many modes of sharing. We propose two separate algorithms for both One-to-One and One-to-Many sharing modes which are based on the Hungarian method and the stable marriage algorithm. For Many-to-Many sharing mode, we propose an algorithm inspired from the Kuhn-Munkres algorithm with backtracking process (KMB). We have modified the KMB algorithm to avoid some failed cases in our implementation setup. Moreover, we have designed an approximation algorithm to calculate the demand of a D2D pair and the capacity of

a cellular UE and incorporated that with the modified KMB algorithm to comply with the individual target sumrate demand in One-to-Many and Many-to-Many mode. Furthermore, the proposed algorithm improves the approximation process in run time. We have compared the proposed algorithms with state-of-the-art solutions and numerical evaluations find that our proposed algorithms outperform all of the existing algorithms in terms total system interference and return reasonable and competitive results in terms of total system sumrate.

Secondly, we address the research question of system sumrate maximization while maintaining the quality of service (QoS). This problem can be optimally solved in offline mode by using the weighted bipartite matching algorithm. However, in Long Term Evolution (LTE) and beyond (4G and 5G) systems, scheduling algorithms should be very efficient where the optimal algorithm is quite complex to implement. Hence, a low complexity algorithm which returns almost the optimal solution can be an alternative to this research problem. In this thesis, we propose two less complex stable matching based relax online algorithms which exhibit very close to the optimal solution. Our proposed solutions deal with fixed number of cellular UEs and a variable number of D2D pairs that arrive in the system online. Unlike online matching algorithms, we consider that an assignment can be revoked if it improves the objective function (total system sumrate). However, we want to minimize the number of revocation (i.e., the number of changes in the assignments) as a large number of changes in successive assignment can be expensive for the networks too. We consider various offline algorithms proposed for the same research problem as relaxed online algorithms. Through extensive numerical evaluations, we find that our proposed algorithms outperform all of the algorithms in terms of the number of changes in assignment between two successive allocations while maintaining the total system sumrate very close to the optimal algorithm.

Acknowledgements

It is an auspicious moment for me to submit my PhD's thesis work by which I am eventually going to end my PhD study. At the beginning, I want to express my heartfelt gratitude to Almighty Allah for bestowing his blessings upon me which have made it possible to complete this thesis research successfully. All thanks and praises be to Allah.

Secondly, I would like to thank my thesis supervisor, Prof. Dr. Muhammad Mahbub Alam, Professor, Department of CSE, IUT, for his support and guidance on this thesis. Dr. Alam has been instrumental in this work and for my career. He taught me the knowhow of research work, to think critically, the way of being a graduate student, and to teach effectively. His round the clock guidance, encouragement, and continuous observation have accelerated this thesis to be a successful one. Without his continuous support, this thesis would not see the daylight of a proper itinerary of the research world.

It was my pleasure to have received the cooperation and coordination of exemplary standard from the Head of the Department, Prof. Dr. Abu Raihan Mostafa Kamal, during various phases of my work. I am grateful to him for his constant and energetic guidance, constructive criticism, and valuable advice. The faculty members of the CSE department of IUT helped make my working environment a pleasant one, by providing a helpful set of eyes and ears when tackling different problems.

I would like to express my appreciation to my friend Dr. Salimur Choudhury for his insightful criticisms, comments, and suggestions regarding my works that led to substantial improvements in this dissertation.

I am indebted to my students Faisal Hussain and Md Yeakub Hassan who were always available for helping me in producing experimental results and writing in several stages. I am also indebted to Tasnim Ahmed for drawing figures and plotting graphs. Without their prompt support it would be impossible to complete this thesis work.

I would like to thank the jury members of my doctoral and examination committees for their insightful comments and constructive criticism which helped me to improve this dissertation.

My deepest gratitude goes to my family for their unconditional love and support throughout my life. I would like to acknowledge the sacrifice and love of my parents who always kept me motivated throughout my PhD journey, giving me every advantage they could and finally bestowing on me a love for learning. I would like to a thank my sister Saleha Jesmin Zeba and my brother Ahmed Kabir Suza who always stand as a constant source of encouragement and always pray for my success and happiness. I would love to thank my beloved wife Umma Tahomina for all the support, sacrifice and, care. Her patience and encouragement have upheld me and she had to endure most of the frustration related issues that a PhD students goes through and I cannot thank her enough for that. Finally, my son Umair Abdullah, with all his charm and innocence has always been inspiration to me to push myself further.

Last but not the least, I emotionally remember a fatherly character, Late Prof. Dr. M. A. Mottalib, former Head of the Department CSE, IUT who had been a continuous source of blessings, support, and encouragements.

Md. Sakhawat Hossen

May, 2022

Dedication

My respected parents

"Without whom, none of my success would be possible"

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Overview

The boom of communication networks in the last decade can be contributed to the tremendous advancement of mobile device technologies and the reduction in their production costs. This has allowed the infiltration of mobile communication devices into all spheres of our life. Usually, these devices use a dedicated licensed spectrum when communicating with cellular users. However, these devices have the capability to communicate amongst themselves directly using an unlicensed spectrum. If the devices use the licensed spectrum, the interference is kept at a very minimum state while the network resources are inefficiently utilized. However, this inefficient process can be improved if the devices share their valuable spectrum resources. In order to improve this resource sharing mechanism in Device-to-Device (D2D) communications, the most important aspects to consider are maximizing the total system sumrate (capacity) and minimizing the interference. Device-to-Device communication, or D2D communication, in cellular networks is described as communication that takes place directly between two mobile users and does not go via the Base Station (BS) or the core network. D2D communication is often invisible to the cellular network, and it can take place either on cellular frequency (also known as in-band) or on an unlicensed spectrum (i.e., out-band) [1]. There are several works regarding the maximization of system sumrate and minimizing the interference which is mostly offline algorithms [2] [3] [4]. Designing efficient online algorithms in D2D communication with a view to capacity maximization and interference minimization are the primary aims of this thesis.

Rest of the chapter is organized as follows. We have introduced D2D communication in Section 1.2. Section 1.3 represents the motivation of our research. We have presented the research challenges and research objectives in Section 1.4 and Section 1.5 respectively. Section 1.6 narrates the contributions of this dissertation. Finally, the overall structure of the dissertation is presented in Section 1.7.

1.2 Device-to-Device Communication

It is common knowledge that out-band technologies have been around for decades and run on unlicensed bands. In today's world, there are several distinct protocols and standards, some examples of which are Bluetooth, ZigBee, NFC, Wi-Fi Direct, and others. In certain pioneer literature research from a very long time ago, the possibility of D2D and cellular transmission coexistence was discussed. The latest research issue of integrating D2D in Long Term Evolution Advanced (LTE-Advanced) networks is one that has attracted a lot of attention from the industrial sector and is undergoing fast development in the third generation partnership project (3GPP) LTE standardization process [5]. The first effort to deploy D2D communication in a cellular network was undertaken by Qualcomm's FlashLinQ, which is a PHY/MAC network architecture for D2D communications that underlie cellular networks. This was the first time such an effort had been made. In order to provide an effective technique for timing synchronization, peer discovery, and link management in D2D-enabled cellular networks, FlashLinQ makes use of the orthogonal frequency division multiplexing (OFDM/OFDMA) technologies and distributed scheduling. In addition

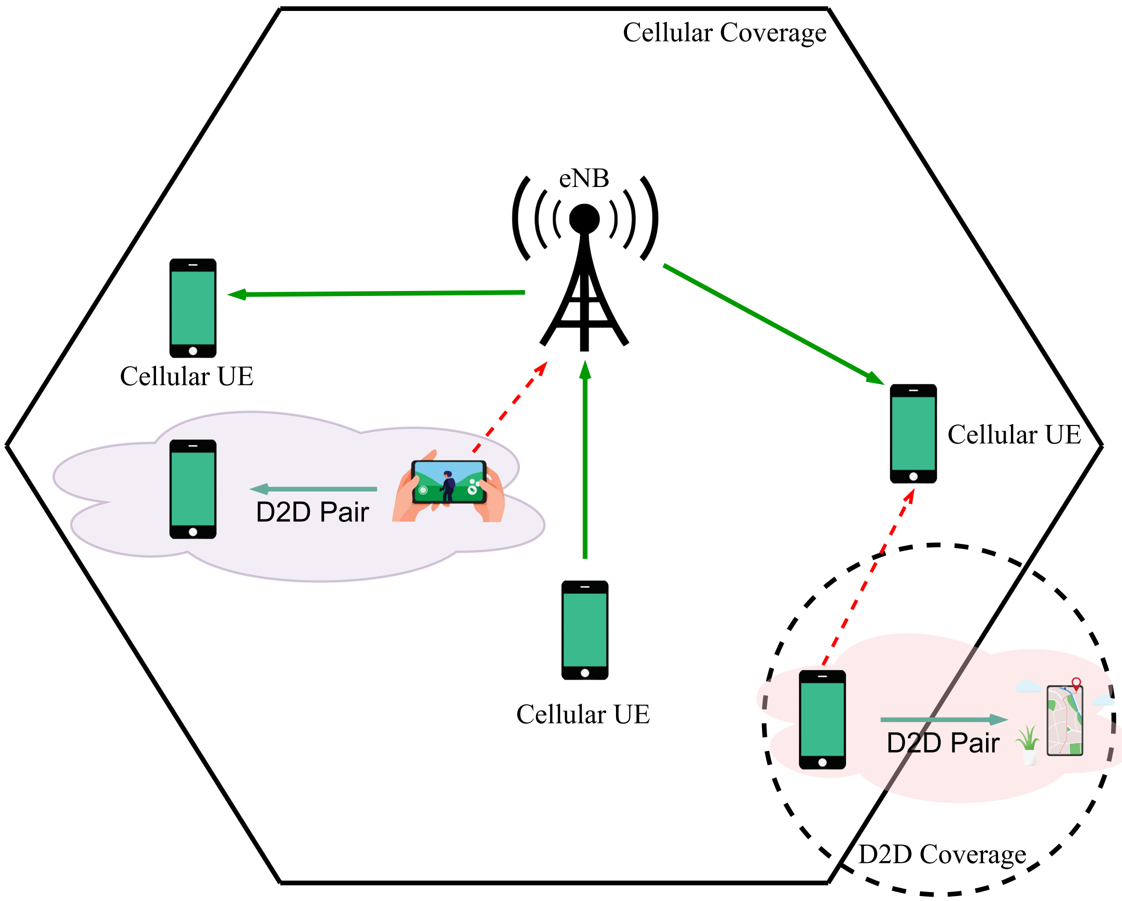


Figure 1.1: D2D communication

to research institutions and enterprises in the telecommunications industry, the 3GPP is looking into D2D communications as a kind of proximity service (ProSe) [1]. LTE D2D refers to a suite of technologies that have the capability of using ProSe. ProSe encompasses a variety of aspects, the most notable of which are discovery, communication, and ProSe-enabled UE. Using E-UTRA [6], the ProSe discovery method determines whether or not a cellular UE is in close proximity to another UE [7]. The communication that takes place between two cellular UEs that are in close proximity to one another and make use of an E-UTRAN [8] communication channel that has been created between the cellular UEs is referred to as ProSe communication. For instance, the communication link may be formed directly between the cellular UEs or it may be routed via the local eNB (eNodeB, base station in LTE).

In order to handle the prospective services such as commercial/social use and increased networking, LTE D2D has three primary roles- discovery, data communication, and relay. Using LTE radio technology, the D2D discovery method enables devices that are in close proximity to one another to discover and communicate with one another. This discovery is carried out inside the LTE network coverage and under the supervision of the operator (for example, using radio resources that have been allocated by the operator and allowed by the operator). However, it is also desirable that discovery be able to be accomplished with either partial or no network coverage (in which case one cellular UE of the D2D pair is under the network coverage and the other one is not). When compared to existing wireless technologies, such as Bluetooth and Wi-Fi Direct, it is possible that LTE D2D may allow a much wider discovery range. When compared to other technologies operating in the unlicensed ISM (industrial, scientific and medical) radio band, D2D communication which utilizes a licensed spectrum might potentially allow for more dependable discovery. The subscriber identity module (SIM) card may be used for authentication as well as holding discovery permissions, in particular, the permissions for third parties or merchants to find users. The D2D discovery that was designed for the LTE network has the potential to even replace Wi-Fi Direct when it comes to establishing a wireless local area network (WLAN) Wi-Fi connection between two Wi-Fi-enabled cellular UEs that are in close proximity to one another. The operator has the ability to manage proximity information (such as distance information, the area code of the network location, the status of radio coverage, user discovery capabilities, preferences, etc.), allowing its users and partners to use or build advanced proximity-based services.

The data connection between D2D users enables the data link to be immediately established between proximal D2D users rather than going via eNBs. By converting data traffic from a channel via infrastructure to a direct D2D path with service continuity, the operator might free up more bandwidth on its network for proximity-based service traffic without interrupting service. Secured D2D connections may be allowed by operator management, which will lead to an increase in usage. This is in contrast to the pending problems that are associated with the currently available out-band technologies regarding the security of data and traffic. Additionally, the operator's control makes it possible to provide a QoS framework that offers differentiated treatment according to D2D services, data traffic flows, subscribers, and other factors. In the event that network coverage is unavailable, the direct D2D communication is supposed to be able to operate independently using the pre-configured parameters. This is quite similar to the direct D2D discovery function.

A D2D relay makes it possible to construct multi-hop pathways between an infrastructure network (such as the Internet or a cellular network) and a cellular UE. D2D relay may be used to increase the data throughput of users who are located near the cell edge. It can also be utilized to share a connection with an endpoint UE that does not have direct access to the infrastructure networks. D2D relay may expand network coverage for both indoor and outdoor cellular UEs at a cheap cost, which complements the existing coverage extension methods in LTE that use heterogeneous networks (HetNet), such as Pico cells and Femtocells. A generic overview of the D2D communication is depicted in Fig. 1.1.

1.3 Motivation

With a tremendous spread and use of mobile hand-held devices in our daily life, D2D communication has become a buzzword in recent times. There is an urgent need to integrate the D2D communication mode into the next-generation cellular network in order to enable efficient discovery and communication between proximate users, and eventually provide ubiquitous connections and a rich range of services to mobile users. This is because of the popularity of smart devices, as well as the potentially huge market for proximity-based services and applications. Various inter-device-to-device communications like interactive local guidance, social discovery, local gaming, content sharing in a gathering, and downloading media content in concert are worth mentioning. This type of service can be offered by D2D communication underlay in traditional cellular network [9]. LTE and beyond (4G and 5G) offer such features where D2D communication is enabled by reusing conventional radio resources under the supervision of an eNB (eNodeB, base station in LTE). Figure 1.2 present such an motivating example scenario of D2D communication. The followings are some categories of services offered by D2D communication that may be used to classify the possible applications that could be based on the vicinity of a mobile user.

- Applications for commercial and social use such as local discovery and engagement with linked devices, objects, and people, and tailored services based around the contextual information collected.
- Improved connection (coverage, speed, cost, etc.) to network services by utilizing other local devices (also known as "enhanced networking").

Commercial and Social Use: proximity-based services may incorporate mobile as well as fixed equipment. For instance, private users may own smartphones or tablets; public sectors may possess sensors; advertising gadgets may be owned by retail outlets; etc. The following are some common instances of their application.

- Interactive local guidance: interactive guidance for customers, tourists, commuters, and users of commercial and public services, using smart beacons, sensors, and content servers embedded within objects in the environment. This type of guidance is provided by using smart beacons, sensors, and content servers embedded within objects in the environment.

- Connection to M2M and V2V Networks: Machine-to-Machine (M2M) and Vehicle-to-Vehicle (V2V) networks may both be controlled by devices that are equipped for D2D communication. In addition to this, they are able to provide M2M and V2V connections to cellular networks, acting in this capacity as gateways between M2M and cellular networks.

- Social discovery is the process of finding local people who are connected to one another via a social network (like Facebook or LinkedIn), who have similar interests (whether professional or personal), or who are going to the same event (like a party, concert, or sporting event), etc.

- Entertainment often incorporates a wide array of personal gadgets, such as mobile smart devices, gaming consoles, cameras, TVs, displays, and storage memory. Examples of this service include mobile smart devices engaged in online gaming with local multicasting, sharing music in a concert, sharing files in a conference, etc.

Enhanced Networking: D2D technology may be used to improve the connection of devices to an infrastructure network, often for the purpose of gaining access to the Internet or operator services. This can be accomplished via enhanced networking. This new mode of personal communication increases bit-rate gain (as the distance between the receiver and the sender is decreasing), reuse gain (as the D2D pairs and the cellular UEs simultaneously use the common radio resources), hop-gain (as D2D communication uses a single link rather than using uplink and downlink resources for sending and receiving) and coverage gain (as D2D communication can be possible at someplace where signal strength of the eNB is too low for cellular communication) [10]. Moreover, D2D communication is more power-efficient than the conventional cellular communication via the eNB [11].

The D2D pairs can communicate by reusing the appropriate resource blocks (RBs) of the existing cellular network which increases system capacity and spectral efficiency. To utilize this opportunity to greater extent, it is very much necessary to use an efficient resource (spectrum) allocation algorithm. The major challenges faced by a resource allocation algorithm include time, dynamic distribution of the cellular UEs as well as the D2D pairs, the Channel State Information (CSI) required for the optimal solution, and more importantly, interference. Though, Orthogonal Frequency Division Multiplexed (OFDM) radio resources are used to avoid inter-channel interference in LTE and beyond systems. However, due to a bad design, sharing resources with the D2D pairs may introduce potential co-channel interference in the cellular network which can affect the primary users [1], [12]. Hence, several research works in the area of resource allocation in D2D communication are focusing on different aspects including maximizing system sumrate, minimizing system interference, energy efficiency, improving spectrum usage, etc.

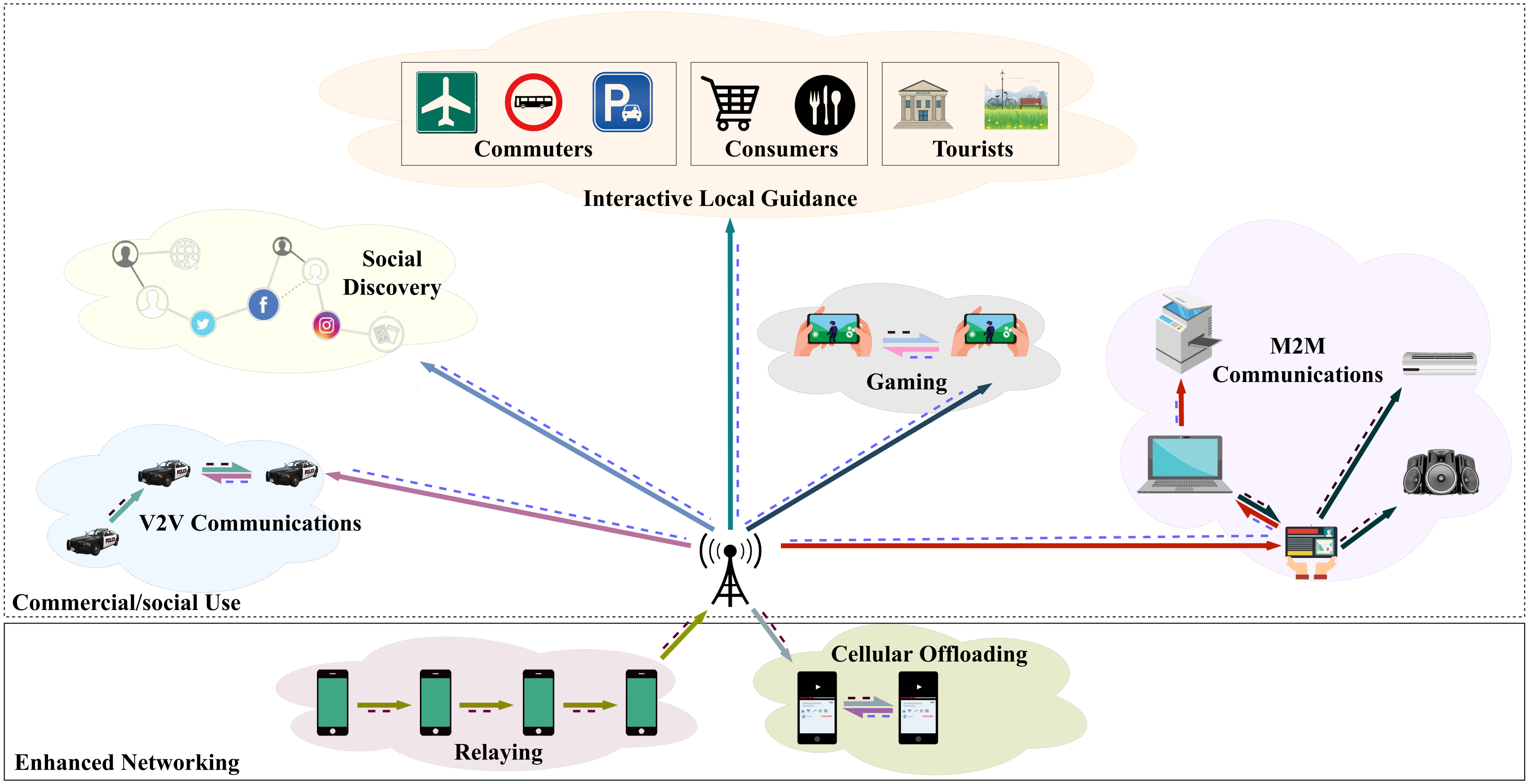


Figure 1.2: D2D Services

Depending on spectral utilization the D2D communication can be deployed in two major categories i.e., out-band[1, 13] and in-band [1, 13, 14, 15]. The out-band D2D communication utilizes the unlicensed spectrum band hence, there is no issue of interference among the cellular UEs and D2D pairs. The out-band D2D communication is divided into controlled and autonomous D2D communication. However, in out-band D2D communication, a mobile device requires two wireless interfaces, one for the cellular system and another (Wifi, Zigbee, Bluetooth) for the utilization of unlicensed spectrum hence it requires more energy to handle two wireless interfaces. The in-band D2D communication suffers from the issue of power control and the interference between the cellular UEs and D2D pairs as they share the radio resources in the licensed spectrum band. The in-band D2D communication can be deployed either underlay or overlay to the existing cellular network depending on the licensed spectrum dedication. In the case of underlay mode, each D2D pair can use the same radio resource that a cellular UE uses while in overlay mode, a dedicated portion of the cellular spectrum is used by the D2D pairs. Several surveys suggest that from the energy and spectrum utilization point of view, D2D communication is most convenient and beneficial in in-band underlay mode [14],[16],[1]. Survey in [1] is performed under the major topics of in-band (overlay and underlay) and out-band (autonomous and controlled) D2D communications. Survey in [14] is different from the work of Asadi et al [1] in the sense that it is not general but is a focused survey that provides a comprehensive and detailed overview of the mode selection, and interference management, power control, and spectrum allocation aspects of the underlay in-band D2D communication. Furthermore, by the year 2025, the Internet nodes will cover the majority of the day-to-day necessities, including food packages, furnishings, paper papers, and a great deal more, according to a research that was compiled by the National Intelligence Council (NIC) of the United States [17]. This mode of D2D communication is attracting more researchers from academia, standardization bodies, and industry for further insight and a lot more research is still necessary to achieve power and spectral efficiency by developing more efficient resource allocation schemes.

1.4 Research Challenges

In this dissertation, we focus on two major research challenges described in the following subsections.

1.4.1 Interference Minimization

Interference minimization while maintaining a target system sumrate by sharing radio resources among cellular user equipment (UEs) and Device-to-Device (D2D) pairs is an important research question in Long Term Evolution (LTE) and beyond (4G and 5G). Most of the existing solutions approach this research problem from the optimization point of view where the objective is to minimize interference while the total system sumrate is a constraint. However, the total system sumrate as a constraint ends up with insufficient data rates for some D2D pairs which might be unacceptable for some D2D services. The required system sumrate might be different for the individual user based on their respective task such as multiplayer gaming, content watching, document viewing, navigation, etc. Moreover, total system sumrate constraint might end up with some assigned D2D pairs having excessive bandwidth. This extra bandwidth leads to the wastage of scarce radio resources.
Different D2d users require different data rates depending on the availed D2D services. Although some D2D services requiring low data rates are satisfied with the RBs of one cellular UE, D2D pairs with data intensive D2D services might require the RBs of more than one cellular UE. Moreover, most existing centralized research works approached this subject from a One-to-One perspective in order to avoid complexity.

Some distributed methods address this issue in both One-to-Many and Many-to-Many paradigms. However, a distributed solution involves substantially more message passing than a centralized approach, resulting in inefficient resource utilization.

1.4.2 Sumrate Maximization

Maximizing the total system sumrate by sharing the RBs among the cellular UEs and the D2D pairs while maintaining the Quality of Service (QoS) in a D2D communication underlaying cellular networks. Existing research works related to this problem domain include solutions based on greedy heuristic [3], local search [4], stable matching [18], and graph algorithms [19], etc. Alongside the aforementioned solutions, an optimal algorithm based on a weighted bipartite matching algorithm is proposed in [20] to maximize the same objective function. All of the existing solutions are based on different offline algorithms and the research problem can be solved optimally in polynomial time using an offline weighted bipartite matching algorithm as shown in [20]. However, in the LTE system, the scheduling algorithm needs to be very efficient as the scheduling period is very short; preferably less than 1 ms [21]. The weighted bipartite matching algorithm (optimal) is quite complex to implement in such a short scheduling period.

So, to comply with the fast scheduling requirement, a possible remedy to the problem is to run the algorithms online. In an online implementation, an algorithm is run with a smaller instance of the problem specifically with the newly arrived nodes (D2D pairs or cellular UEs) with the available resource blocks (RBs) and the assignments among the nodes are irrevocable. However, in the current research problem, a strict online algorithm might leave some of the D2D pairs unassigned if none of the available cellular UEs can satisfy the constraints (SINR, QoS requirement, etc) which contradicts the research goal.

1.5 Research Objective

To address the major research challenges described in Section 1.4, this dissertation focuses on the following research objectives.

1.5.1 Interference Minimization Objective

Considering individual system sumrate as a constraint instead of total system sumrate in the addressed problem is more practical from the users' perspective. Due to the fact that different D2D pairs require different data rates based on the D2D services they are availing we address the topic of limiting interference while preserving individual target sumrate in this study. RBs of one cellular UE are presumed to be sufficient to meet the demand of a D2D in the One-to-One mode of sharing. However, according to our empirical tests, one cellular UE may not be enough to achieve the individual target sumrate constraint in some cases. The main reason is, that different D2D applications have high individual target sumrate like local gaming, video sharing, augmented reality advertisement, etc. To address this problem, we look into One-to-Many and Many-to-Many sharing modes, both of which are relatively untapped research topics for centralized approaches.

1.5.2 Capacity Maximization Objective

An optimal solution based on a weighted bipartite matching algorithm is found in the literature that can solve the problem in polynomial time. However, the weighted bipartite matching algorithm (optimal) is quite complex to implement in such a short scheduling period of LTE. To tackle this research challenge our objective is to design online algorithms that maximize the total system sumrate within reasonable execution time. However, a strict online algorithm does not allow revocation of assignments which might contradict the research goal. On the other hand, if we allow the revocation of an existing assignment, we could assign the new D2D pair (considering that, there exists at least one cellular UE that satisfies its QoS requirements and this assignment improves the overall system sumrate) to the revoked cellular UE and the revoked D2D pair to one of the available cellular UEs. In theory, if an online algorithm relaxes the irrevocable feature, it is called relax online algorithm [22]. Hence, a relaxed online algorithm that performs near to the optimal solution can be a potential alternative to the research problem. The revocation of assignments introduces a new research challenge that is the number of changes in resource allocation between two consecutive states of the system. Due to an inefficient design of an algorithm, the number of changes may increase which might be a potential reason for a significant system overhead [1], [23]. Though there exists a few online algorithms in D2D communication [24], [25], to the best of our knowledge, no other research works discuss an online/relax online algorithm for the same research problem that we consider for D2D communication in in-band underlay scenario.

1.6 Thesis Contributions

The maturity of D2D communication demands efficient resource allocation algorithms to allocate the radio resources of cellular UEs to the D2D pairs. The resource allocation (RA) algorithms are expected to allocate the radio resource in such a way that, the introduced interference due to sharing remains as minimum as possible so that the primary user (cellular UEs) are not adversely affected. Moreover, the RA algorithms are expected to maximize the system sumrate which is always a major concern of the network operators. We aim to design and develop efficient resource allocation algorithms that minimize system interference while satisfying individual sumrate demand targets. As the sumrate needed for each user is dependent on the corresponding network related job, ensuring the target sumrate for individual users optimizes the network usage experience from the user's perspective. Minimizing interference minimizes total necessary resources, which in turn optimizes the entire system from the operator's perspective. For the increasing sumrate demands due to the rapid technological advancements in cloud-based services, besides the One-to-One sharing method, we have formulated solutions for One-to-Many and Many-to-Many problem domains as well. In this research, we also provide online sub-optimal algorithms for maximizing the total system sumrate for various modes of sharing. The optimization problem can be expressed as either minimizing interference or maximizing the system sum rate. The followings are the major contributions of this dissertation:

- We provide near-optimal resource allocation algorithms based on the Hungarian method and the stable matching algorithm where the objective is to minimize system interference while maintaining individual target sumrate at the time of sharing radio sources of the cellular user to the D2D pairs. The majority of state-of-the-art algorithms ([26], [27], [28]) consider total system sumrate demand while minimizing the total system interference. In practice from the user's perspective, individual target sumrate demand is more interesting and appealing in this optimization problem because different users might need different data rates based on the service (i.e., online gaming, file transfer, local guidance, etc.) a D2D user is asking for. In Chapter 2, we have formulated the problem of interference minimization with individual sumrate demand as a weighted bipartite matching problem. We have also proposed RA algorithms to allocate the RBs of cellular UEs to the D2D devices to minimize the system interference while satisfying individual target sumrate.

- We solve the research question of minimizing interference due to D2D communication for both One-to-One, One-to-Many, and Many-to-Many sharing approaches. To meet up the individual demand of a D2D pair One-to-One mode of sharing might not be sufficient whereas a D2D might need the RBs of multiple cellular UEs and vice versa. In literature, there are some distributed algorithms addressing One-to-Many and Many-to-Many sharing. However, most of the state-of-the-art centralized algorithms only consider One-to-One sharing for the sake of simplicity. Our second contribution is to explore the One-to-Many and Many-to-Many sharing modes for the centralized algorithms in the addressed problem domain. In Chapter 2 and Chapter 3 we have proposed algorithms for One-to-One and One-to-Many sharing approach those are either Hungarian algorithm [29] or Stable marriage algorithm [30]. Chapter 2 also presents an algorithm for the Many-to-Many sharing approach which is inspired from [31] where they have employed backtracking with the Kuhn-Munkres (Hungarian) algorithm (KMB). One major contribution is that We have modified the KMB algorithm by introducing a new step. The existing KMB algorithm halts for some inputs and such examples are presented in the thesis with some counterexamples showing that the proposed algorithm can overcome the halting state. To comply with the individual target sumrate demand in One-to-Many and Many-to-Many modes, we have designed an approximation algorithm to calculate the demand of a D2D pair and the capacity of a cellular UE and incorporated that with the modified KMB algorithm which is another contribution to the proposes Many-to-Many algorithm. Furthermore, the proposed algorithm improves the approximation process in run time by excluding the extra demand as soon as the target sumrate constrained is satisfied.

- We provide stable matching based near-optimal relax online resource allocation algorithm where the objective is to maximize the total system sumrate for One-to-one as well as One-to-Many paradigms. To the best of our knowledge, this is the first-ever online algorithm in the addressed problem domain. In Chapter 3, we propose two relax online resource allocation algorithms for D2D communication in in-band underlay mode. The proposed algorithms consider two assignment schemes namely the restricted assignment scheme and the fair assignment scheme. The restricted assignment scheme provides a better system sumrate by avoiding the assignments that contribute to negative sumrate gain. On the other hand, the fair assignment scheme assigns more D2D pairs than the restricted assignment scheme by sacrificing some system sumrate gain. Network providers may choose any one of the schemes based on their needs. One of the major contributions of this chapter is to design the relax online algorithms in such a way that leads to a minimum number of changes in assignment between two successive allocations hence incurs minimal system overhead while maximizing the total system sumrate.

1.7 Dissertation Structure

The structure of the thesis is organized as follows. Chapter 2 represents the resource allocation algorithms for interference minimization in underly D2D communication. We have organized different proposed algorithms based on sharing mode (i.e., One-to-One, One-to-Many, and Many-to-Many). The main focus of this chapter is on the individual target sumrate of the D2D pairs and cellular UEs. The system model, problem formulation, description of the proposed algorithms, and numerical results are presented in the respective sections. Chapter 3 contains the resource allocation algorithms for capacity maximization. We have presented online and relax online algorithms for different sharing modes in different sections with a detailed description, analysis, and numerical results. Finally, Chapter 4 summarizes the research contributions and concludes the thesis with the directions for further investigations.

Chapter 2

Interference Minimization

2.1 Introduction

In the world of wireless and cellular communication, interference minimization is a well-established research subject. Due to the introduction of a new way of personal communication known as D2D communication underneath a cellular network in recent days, this field has received a lot of attention [5]. Instead of connecting over eNB (Base Station in LTE), two nearby cellulars UEs can interact directly via this form of communication. Different inter-device applications and services, such as sharing papers at a conference or downloading media content at a concert, are some of the driving instances where D2D communication may be a game-changer instead of a traditional cellular connection [9]. In wireless networks, cooperative communications based on relaying nodes show a lot of promise in terms of power efficiency, spectral efficiency, network coverage, and network capacity. High data rates and capacity are required for next-generation (5G) media-rich mobile apps, which are not viable in 4G networks. For a 5G cellular system, the necessity for high data rates and capacity necessitates complex reasoning. D2D communication is one of the emerging 5G architecture's technological components and it can help with vehicle-to-vehicle communication and cellular network offloading. D2D communication improves bit-rate gain (as the distance between the receiver and sender decreases), reuse gain (as both

D2D devices and cellular UEs use the same radio resources), hop-gain (as D2D communication uses a single link rather than uplink and downlink resources for sending and receiving), and coverage gain (as D2D communication can be used in places where the signal strength of eNB is too low for cellular communication) [10]. Furthermore, it uses less energy than communicating via eNB [11]. In the meanwhile, spectral demand is steadily expanding. Fortunately, D2D communication is made easier by LTE's inclusion of a feature that allows regular cellular networks' radio resources to be reused. As a result, permitting the reuse of licensed spectral bands meets the criteria. Reusing radio resources, on the other hand, may cause network interference. Even though LTE utilizes the Orthogonal Frequency Division Multiplexing (OFDM) approach to reduce interference, sharing resources with D2D devices may introduce possible co-channel interference in the cellular network, potentially affecting main users [1, 12].

Several research projects are now underway, with researchers focusing on various factors such as maximizing total rate, avoiding interference, and managing transmission power, among others [4], [3], [27]. Network providers may desire to prioritize primary users while supporting D2D communication by pooling resources to reach a specified system sumrate [27, 26]. To avoid the difficulty noted above, an effective resource allocation strategy can yield appropriate Resource Blocks (RBs) for the D2D pairs while maintaining a desirable system sumrate. The majority of state-of-the-art algorithms ([26], [27], [28]) consider total system sumrate demand while minimizing the total system interference. In practice, from the user's perspective, individual target sumrate demand is more interesting and appealing in this optimization problem because different users might need different data rates based on the service (i.e., Online gaming, file transfer, local guidance, etc.) a D2D user is asking for. So, the research problem of interference minimization while satisfying individual sumrate demand remains unaddressed in the research community. Moreover, to meet up the individual demand of a D2D pair One-to-One mode of sharing might not be sufficient where a D2D might need the RBs of multiple cellular UEs and vice versa. In literature, there are some distributed algorithms addressing One-to-Many and Many-to-Many sharing. However, most of the state-of-the-art centralized algorithms only consider One-to-One sharing for the sake of simplicity. In this chapter, we are addressing the optimization problem of resource allocation where the RBs of cellular UEs are shared with the D2D pairs with an aim to minimize the total system interference while maintaining the individual target sumrate.

The major contributions of this chapter are: we propose solutions for both One-to-One, One-to-Many, and Many-to-May sharing approaches that minimize the system interference while maintaining the individual target sumrate. We propose two algorithms for One-to-One sharing two algorithms for One-to-Many sharing and one algorithm for the Many-to-Many sharing approach. We translate the addressed resource allocation problem into a weighted bipartite matching problem. All of the proposed algorithms are based on either the Hungarian algorithm [29] or the Stable marriage algorithm [30] that return the solutions of the assignment problem in a Boolean matrix based on the mode of sharing. According to experimental results, the proposed resource allocation methods outperform a number of state-of-the-art techniques which ensures the effectiveness of the proposed algorithms.

The rest of the chapter is designed in the following manner. Section 2.2 canvasses prior works related to our topic of interest. Section 2.3 represents the system and channel model that we consider for the addressed problem. We formulate the problem for different modes of sharing in Section 2.4. Section 2.5 presents a detailed discussion of the proposed algorithm with working procedures. In Section 2.6, we calculate the run time complexity of the proposed algorithms. The experimental results are presented in Section 2.7. Finally, Section 2.8 draws the conclusion.

2.2 Related Work

In literature, we can find several studies reviewing different scopes of research e.g. on resource allocation, power control, admission control, massive multiple-input-multiple-output, time scheduling, network coding, designing protocol, etc. for D2D communication [32, 1]. Authors in [32] provided a thorough overview of the state-of-the-art focusing on D2D communication, especially within 3GPP LTE/LTE-A. First, it provides the in-depth classification of research looking at D2D from several perspectives. Numerous studies on various resource allocation problems of D2D communication underpinning cellular networks have been conducted, and they can be classified as follows:

The state-of-the-art research works focusing on resource allocation in D2D communication underlaying cellular networks choose different modes of resource sharing among the cellular UEs and the D2D pairs. We classify the degree of resource(i.e. RBs) sharing into three approaches (depicted in Fig. 2.1).

i. *One-to-One sharing* : One-to-One sharing implies that one D2D pair can share the RBs of only one cellular UE provided that no other D2D pairs share the RBs of that cellular UE.

ii. *One-to-Many sharing* : One-to-Many sharing implies that one D2D pair can share the RBs of multiple cellular UEs but multiple D2D pairs cannot share the RBs of a single cellular UE.

iii. *Many-to-Many sharing* : Many-to-Many sharing implies that one D2D pair can share the RBs of multiple cellular UEs, as well as multiple D2D pairs, can share the RBs of a single cellular UE.

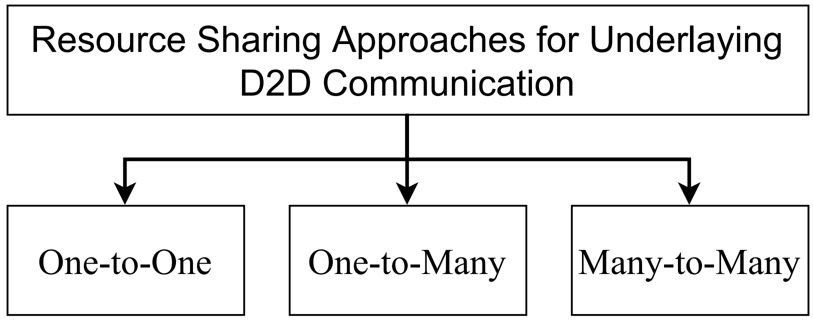


Figure 2.1: Sharing approaches of D2D communication underlaying cellular communication

2.2.1 One-to-One Sharing

The two-phase auction-based fair and interference aware resource allocation algorithm (TAFIRA) and minimum knapsack-based interference resource allocation algorithm are used in the article to mitigate system interference while maintaining a system sumrate in the context of D2D communication over LTE cellular networks (MIKIRA). TAFIRA and MIKIRA are two existing methods that address the same problem as we do. MIKIRA, a knapsack-based interference aware resource allocation system, is presented in [26]. The goal of MIKIRA is to decrease overall interference while keeping the system's total rate demand constant. They use a knapsack-based approximation strategy to solve the resource allocation problem. MIKIRA stops giving RBs to D2D couples once the demand for the targeted sumrate has been met. As a consequence, the resource allocation method is inequitable because some D2D pairs may not receive any resources from cellular UEs. When certain D2D pairs use multiple cellular UE resources and some cellular UEs share their resources with multiple D2D pairs, the approach does not yield a feasible solution, which violates the formulation of their optimization problem.

In [27], TAFIRA, a two-phase auction-based fair resource allocation method, is suggested, which additionally considers the challenge of minimizing system interference while maintaining a goal system total rate. However, it uses a greedy option to assign each D2D pair to at least one cellular UE and then seeks to minimize overall system interference. TAFIRA is divided into two phases: the first phase aims to assign resources in a way that causes the least amount of interference while assigning every D2D pair to a cellular UE in the system, and the second phase uses a local search algorithm to try to increase the sum rate by swapping allocated RBs with unallocated cellular UEs. In addition, TAFIRA is plagued with infeasible solutions. Furthermore, under the worst-case scenario, TAFIRA's performance ratio is unlimited.

The challenge of allocating D2D communication resources may be turned into a weighted bipartite matching problem. Interference reduction in D2D communication over a cellular network is discussed in [28], and two-phase resource allocation approaches for two types of assignment in D2D communication are provided. The Fair Assignment Resource Allocation (FARA) and Restricted Assignment Resource Allocation (RARA) approaches allow all D2D pairs to share RBs of exactly one cellular UE, whereas the Fair Assignment Resource Allocation (FARA) and Restricted Assignment Resource Allocation (RARA) approaches prevent D2D pairs from sharing RBs of any cellular UE if doing so reduces the sum rate.

In [33], a situation in which each sub-resource frame's block allocation for cellular users (CUs) has been investigated. The article only evaluates the uplink resource blocks for frequency-division duplex (FDD) based cellular networks since the downlink has more traffic. With adequate power management and scheduling of D2D users, utilizing these resource blocks for D2D communication without interfering with CU communication is proposed. Mondal et al. [33] have tackled the issue of D2D user resource allocation in a multipath time-varying propagation context. In order to achieve optimum proportional fairness among D2D users, a polynomial-time graph matching approach is suggested. The article estimated the excess SNR of CUs over their needed SNR threshold before giving resources to D2D users and used this gap to give power to D2D users.

The topic of correlating small cells (SCs) with network flying platforms (NFPs) was investigated in [34] while taking into account all relevant limitations (the number of NFPs), connections, maximum bandwidth of NFPs, maintaining a specific data rate, and so forth). AlSheyab *et al.* [34] presented two different approaches: firstly, associating SCs with other types of cells; secondly, associating SCs with other types of cells. NFPs are designed to reduce overall interference while taking into account a variety of factors. Each SC has a data rate that they want to achieve. The suggested HBIMTI method produces a solution that is close to optimum. SCs are connected to NFPs in the second form to lower the total number of NFPs. The system must be messed with while maintaining a desired total sum rate. In [35], the task of linking NFPs with SCs in a future cellular network is addressed in order to maximize the system sumrate while taking into consideration of each NFP bandwidth, the number of supported connections, and the minimum needed SINR. A centralized (HBCA) and a distributed (SMBDA) strategy are presented to find a sub-optimal link between the SCs and NFPs while minimizing computational cost. According to the numerical assessment of the case study, the performance of the suggested algorithms is better than that of the existing method in terms of the number of linked SCs and the total sum rate.

In D2D communication, a unique two-phase combinatorial method is suggested to find a resource allocation that reduces interference while maintaining a minimal goal sum rate [36]. Furthermore, when the interference created is uniform, the procedure requires polynomial time to find an optimum solution.

2.2.2 One-to-Many Sharing

Scholars have widely embraced graph theory as an efficient and effective approach for modeling and assessing the interference issue [37, 38, 39]. A novel greedy-based channel assignment mechanism is proposed in [40]. To begin, a new interference graph is constructed, which illustrates the interference that occurs when two communication lines utilize the same channel at the same time. Then, a new channel assignment approach that is simple and practical to apply is proposed to decrease system interference by allocating the optimal channel to each communication link in a greedy way. Furthermore, the channel assignment problem is translated into a robust graph coloring problem, and a near-optimal solution to limit system interference is sought. When compared to earlier techniques, the numerical results demonstrate that the suggested greedy-based strategy not only increases network capacity but also improves fairness among devices with relatively cheap processing costs.

Zhang *et al.* [41] propose a two-stage interference graph construction protocol for D2D communication underlaid by a cellular network, where the first stage is used to announce the existence of a D2D link to its neighboring area, and the second stage of the protocol is used to resolve any collisions that may occur during the announcement stage. Both steps are iterative, with the interference graph creation being treated as a link-level neighbor finding operation rather than a traditional device-level neighbor discovery technique. They do not, however, result in an increase in signal quality. An auction-based strategy is presented in [42], in which the whole resource is partitioned into homogeneous units and the value of each unit is estimated from channel capacity gain. [43] examines D2D communication on both the spectrum overlay and underlay of an existing cellular network with ad hoc networks. They use a technology known as Successive Interference Cancellation (SIC) to increase transmission capacity. Peng *et al.* [44] offers an interference tracing strategy to reduce interference from the cellular transmission to D2D communication, as well as an acceptable interference broadcasting approach to minimize interference created in the other direction. In [45], a Multiple Input Multiple Output (MIMO) transmission technique in the cellular downlink is presented to eliminate elaborated interference in D2D communication.

2.2.3 Many-to-Many Sharing

Game theory is widely utilized among all mathematical tools because, as a decision-making tool, it can quickly examine the complicated interplay of interdependent rational entities/players and forecast their set of strategies [46, 47]. It consists of seven elements: characters in the system, information system, strategy, action, income, sequence, and corresponding equilibrium. The three most significant aspects of the game theory system are characters, strategy, and income in the corresponding system. The Stackelberg game is a leader-follower design system. Cellular users are in charge, while D2D users lag behind. The leader takes action first, and the follower studies the leader's actions before deciding on their approach [48, 49]. The resources belong to the leader, who can charge him phony money to use them. It boosts both the leader's and follower's utility functions. The leader-follower pairing is determined by the network environment: one leader-one follower, multiple leaders-one follower, and one leader-many follower [48, 50]. This game theory technique has been utilized to determine the best strategy for users, the best pricing for leaders, and the best power for followers when it comes to resource distribution. Yin *et al.* [51] formulate the resource allocation problem into the Stackelberg game problem to derive distributed scheme. There has been an increasing tendency in recent years to apply game theory (GT) to many engineering domains in order to tackle optimization challenges involving several competing entities/contributors/players. Researchers in the fourth generation (4G) wireless network industry has also used this sophisticated theory to address long-term evolution (LTE) issues such as resource allocation, which is a major research area. In reality, the key to improved performance is the effective design of resource allocation algorithms. The dual problem of mode selection and optimal spectrum division is addressed using a Stackelberg game framework [52]. The distribution of UEs using different modes determines the best spectrum division. The spectrum divide, on the other hand, has an impact on UE distribution. The eNB assumes the role of a leader, while the UEs operate as followers, based on this cyclic dependency. To tackle the dynamic mode selection problem, an optimal control problem is given to the leader. The proposed approach can be employed as an incentive mechanism to drive the UE distribution closer to the optimal solution, according to the numerical analysis described in [52].

D2D communication was suggested in academia for the first time in [53] to allow multihop relays in cellular networks. Later studies [2, 54, 55, 56, 57] looked at the possibilities of D2D communications for increasing cellular network spectral efficiency. Multicasting [57, 58] peer-to-peer communication [59], video distribution [55, 60, 61, 62], machine-to-machine (M2M) communication [63], cellular offloading [64], and other possible D2D use-cases were quickly proposed in the literature. Qualcomm's FlashLinQ [65], which is a PHY/MAC network architecture for D2D communications underpinning cellular networks, was the first to try to integrate D2D communication in a cellular network. The vast majority of D2D communications literature recommends using the cellular spectrum for both D2D and cellular communications (i.e., underlay in-band D2D). The topic of interference mitigation between D2D and cellular communication is generally the focus of these studies [57, 66, 67, 68, 69, 70, 71, 72]. Some advocate allocating a portion of cellular capacity only to D2D communications in order to prevent the aforementioned interference problem (i.e., overlay in-band D2D). Resource allocation becomes critical in this situation to avoid wasting devoted cellular resources [73]. Other researchers recommend using out-band D2D communications in cellular networks rather than in-band D2D communications so that D2D communications do not interfere with the valuable cellular spectrum. The BS (i.e., controlled) or the users (i.e., uncontrolled) regulate the coordination across radio interfaces in out-band communications (i.e., autonomous). Because D2D communication frequently takes place over a second radio interface, out-band D2D communication faces several issues in terms of coordinating communication across two bands. Out-band D2D research looks on topics like power consumption [74, 75, 76, 77, 78] and architectural design for inter-technology.

The overlapping coalition formation game (OCFG) is a good technique to handle the challenge of D2D communications resource management. In [79], an OCFG was developed to consider interference management and resource allocation simultaneously, and a cooperative game was employed to maximize system utility. A Bayesian non-transferable utility OCFG was developed in [80] to tackle the spectrum sharing problem in D2D links and numerous co-located cellular networks, where D2D users either reuse cellular users' frequency resources or use an empty sub-band. An OCFG for resource allocation and relay selection in network coding aided D2D communications was presented in [81]. The coalition-building game was used in [82] to solve the resource allocation problem for the one-to-many reuse mode, in which one D2D user establishes a coalition. However, current OCFG research mainly considers whether to boost the coalition's usefulness by allowing people to join or depart at random. This strategy can assure the benefits of a single coalition, but ensuring the maximum use of the entire system produced by all coalitions is difficult. Interference sequences are utilized in [83] to lead the development of the initial coalition while splitting and merging sequences are employed to guide users to join or leave the coalition.

Table 2.1: Summary of Existing Resource Allocation Algorithms to Minimize the Interference for D2D Communication (One-to-One sharing)

One-to-One sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
TAFIRA [27]	Uplink	• Two phase auction based algorithm • Guarantees fairness of resource allocation	• Performance is unbounded in the worst case [84] • Does not return any solution in some cases though solution exists [84]	$O(n^2)$ for each phase
MIKIRA [26]	Uplink	• Knapsack based approximation algorithm	• Does not return optimal solution in most cases [84] • Does not return any solution in some cases though solution exists [28]	$O(n^2 log(n))$, n is the number of total cellular UEs

Table 2.1: Summary of Existing Resource Allocation Algorithms to Minimize the Interference for D2D Communication (One-to-One sharing)

One-to-One sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
RARA [85]	Uplink	• Two phase algorithm - Assignment Phase and Improvement Phase • Guaranteed solution if exists in the assignment phase • Returns highest system sum rate	• Unfair • Failure in first phase leads to deviation from optimal solution	$O(max(n^3, n*m*W))$, n is total cell, m is total D2D pairs, W is interference in Phase-I
FARA [85]	Uplink	• Fair • Weight matrix calculation is unlike RARA	• Failure in first phase leads to deviation from optimal solution	$O(max(n^3, n*m*W))$, n is cell, m is D2D pairs, W is interference in Phase-I

Table 2.2: Summary of Existing Resource Allocation Algorithms to Minimize the Interference for D2D Communication (One-to-Many sharing)

One-to-Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
HGA [85]	Downlink	• Based on Hungarian algorithm • Based on candidate set • Provide better sumrate	• Unfair • Greedy approach	$O(n^3)$

Table 2.3: Summary of Existing Resource Allocation Algorithms to Minimize the Interference for D2D Communication (Many-to-Many sharing)

Many-to-Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
OCFG [83]	Downlink	• Game theoretic approach • Splitting and merging sequence • Priority sequence for initial qualition	• Unfair • Overhead due to message passing	$O(M * L)$, M is Cell and L is RBs

2.3 System Model and Channel Model

The same system and channel models as in [27], [26], [86] are utilized here. LTE network consists of both uplink (UL) and downlink (DL) resources. In this work, we only consider the UL resources and Fig. 2.2 represents the system model. When using uplink resources, D2D receivers are subjected to interference from cellular UEs. The D2D transmitters, on the other hand, cause eNB to be disrupted [27]. In such an underlay system, D2D couples can interact directly with each other, but eNB [3] supervises connection establishment and resource allocation. Here, we consider a system with one eNB, n cellular UEs and m D2D pairs ($n >> m$) where the set of cellular UEs is represented as $C = \{c_1, c_2, c_3, ..., c_n\}$ and the set of D2D pairs is represented as $D = \{d_1, d_2, d_3, ..., d_m\}$. In the rest of the chapter, cellular UEs are denoted as c_i for each $1 \leq i \leq n$ and D2D pairs are denoted as d_j for each $1 \leq j \leq m$. Each D2D pair d_j, consists of a transmitting device d_j^t and a receiving device d_j^r. We consider our system as an Urban Micro System since it uses the Rayleigh fading path loss model with orthogonal channels and separate RBs for each cellular UE [27, 3]. Inter channel interference is therefore avoided, but co-channel interference may arise if any D2D pair utilizes the channel again. [3] is the recommended system's path loss (dB unit) model.

$$PL = 36.7 \log_{10}(dist) + 22.7 + 26 \log_{10}(f_c), \tag{2.1}$$

where, $dist$ (meter) is the distance between D2D transmitter and receiver and f_c (GHz) is the frequency of communication medium. The value of f_c is mentioned in the table 2.4. The channel gain between these two devices is [3]

$$G^{a,b} = 10^{-PL^{a,b}/10}, \tag{2.2}$$

where, a and b are the sending and receiving devices respectively. $PL^{a,b}$ is the distance dependent path loss between a and b.

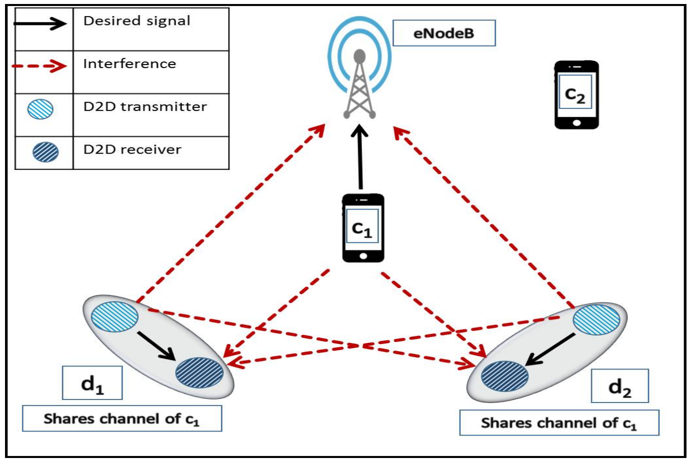


Figure 2.2: System model using uplink resources

2.4 Problem Formulation

This chapter deals with an assignment problem, where an assignment implies that a D2D pair is sharing the RBs of its assigned cellular UE. Based on the sharing approaches(One-to-One, One-to-Many, Many-to-Many), a D2D pair, d_j might be assigned to exactly one or multiple cellular UEs, and a cellular UE, c_i may share the RBs with exactly one or multiple D2D pairs in the system. Our goal is to find a set of assignments that incurs minimum interference due to resource sharing while maintaining an individual sumrate requirement for the D2D pairs as well as cellular UEs.

A number of necessary equations are presented in the followings which are necessary to formulate the addressed problem of interference minimization. Let us consider the transmission power 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 assume σ as the thermal noise at the receiver end, also known as the energy of Additive White Gaussian Noise (AWGN). Signal to Interference plus Noise Ratio (SINR) at the eNB in uplink phase while communicating with a cellular UE c_i (provided that one or more D2D pairs are reusing the same

RBs) is,

$$\gamma_{c_i}^{UL} = \frac{P^{c_i} G^{c_i,eNB}}{\sigma + \sum_{d_j} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,eNB}}, \tag{2.3}$$

where $x_{c_i}^{d_j}$ is a binary variable that indicates whether a D2D pair d_j shares the RBs of a cellular UE c_i or not. $G^{d_j^t,eNB}$ implies channel gain between the D2D transmitter d_j^t and the eNB, and $G^{c_i,eNB}$ implies the channel gain between the eNB and the cellular UE c_i [26]. If no D2D pair reuses the RBs of c_i, the Eq. (2.3) can be rewritten as,

$$\gamma_{c_i^0}^{UL} = \frac{P^{c_i} G^{c_i,eNB}}{\sigma}, \tag{2.4}$$

where, the co-channel interference is zero because no D2D pair is sharing the RBs of the cellular UE c_i. Similarly, the SINR at D2D receiver reusing uplink resources (provided that some other D2D pairs d_j is reusing the same RBs of c_i) is

$$\gamma_{d_j}^{UL} = \frac{P^{d_j^t} G^{d_j^t,d_j^r}}{\sigma + \sum_{c_i} x_{c_i}^{d_j} P^{c_i} G^{c_i,d_j^r} + \sum_{c_i} \sum_{d_{j'}(j \neq j')} x_{c_i}^{d_j} x_{c_i}^{d_{j'}} P^{d_{j'}^t} G^{d_{j'}^t,d_j^r}}, \tag{2.5}$$

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 and $G^{d_{j'}^t,d_j^r}$ denotes the channel gain between some other D2D transmitter $d_{j'}^t$ the D2D receiver d_j^r provided that $d_{j'}$ is also sharing the channel of cellular UE c_i. Hence the total interference is originated in the system due to sharing of resources by cellular UE c_i and D2D pair d_j is,

$$I_{c_i,d_j} = \sum_{d_j} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,eNB} + \sum_{c_i} x_{c_i}^{d_j} P^{c_i} G^{c_i,d_j^r} + \sum_{c_i} \sum_{d_{j'}(j \neq j')} x_{c_i}^{d_j} x_{c_i}^{d_{j'}} P^{d_{j'}^t} G^{d_{j'}^t,d_j^r}. \tag{2.6}$$

where, the first term indicates the interference experienced by the cellular UE c_i due to the D2D pairs who are sharing the channels, the second term indicated the introduced interference at the D2D receivers due to the cellular UEs, and the final and third term indicates the interference experienced by a D2D pair d_j due to some other D2D pairs($d_{j'}$) who are sharing the same channel.

According to Shannon's capacity formula [87], sum rate contribution of a cellular UE c_i using uplink resources can be represented as,

$$S_{c_i}^{UL} = B \log_2(1 + \gamma_{c_i}^{UL}), \tag{2.7}$$

where, $\gamma_{c_i}^{UL}$ indicates the SINR at eNB while communicating with cellular UE c_i and one or more D2D pairs. If no D2D pair reuses the RBs of cellular UE c_i, then the sum rate contribution of cellular UE c_i is,

$$S_{c_i^0}^{UL} = B \log_2(1 + \gamma_{c_i^0}^{UL}). \tag{2.8}$$

Similarly, the sumrate contribution of a D2D pair d_j using uplink resources can be presented as,

$$S_{d_j}^{UL} = B \log_2(1 + \gamma_{d_j}^{UL}), \tag{2.9}$$

where, $\gamma_{d_j}^{UL}$ 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.

Let the individual minimum sum rate requirement of any cellular UE c_i and D2D pair d_j be T_{c_i} and T_{d_j} respectively. Now, the problem of minimizing the total system interference while maintaining individual target sumrate can be formulated as the following mixed integer nonlinear programming (MINLP) problem:

$$\text{minimize} \sum_{i=1}^{n} \sum_{j=1}^{m} x_{c_i}^{d_j} I_{c_i,d_j} \tag{2.10}$$

subject to,

$$S_{d_j}^{UL} \geqslant T_{d_j} \tag{2.11}$$

$$S_{c_i}^{UL} \geqslant T_{c_i} \tag{2.12}$$

$$x_{c_i}^{d_j} \in \{0,1\} \, ; \quad \forall \, c_i \in C \text{ and } \forall \, d_j \in D \tag{2.13}$$

where, $S_{d_j}^{UL}$ of constraint (2.11) implies the sum rate of D2D pair d_j which needs to be higher or equal to the minimum sum rate requirement T_{d_j} and $S_{c_i}^{UL}$ of constraint (2.12) implies the sum rate of cellular UE c_i which needs to be higher or equal to the minimum sum rate requirement T_{c_i}. Here, S_{c_i} can have the following values

$$S_{c_i}^{UL} = \begin{cases} S_{c_i^A}^{UL} & \text{if a set of D2D pair A shares } c_i \text{ (using Eq. (2.7)),} \\ S_{c_i^0}^{UL} & \text{if no D2D pair shares } c_i \text{ (using Eq. (2.8))} \end{cases}$$

Constraint (2.13) confirms that the decision variable $x_{c_i}^{d_j}$ is a binary variable.
Based on the nature of the sharing approach(One-to-One, One-to-Many, and Many-to-Many) a number of constraints need to be satisfied. For One-to-One sharing, approach the objective function needs to satisfy the following two extra constraints.

$$\sum_{j=1}^{m} x_{c_i}^{d_j} \leqslant 1 \, ; \quad \forall \, c_i \in C \tag{2.14}$$

$$\sum_{i=1}^{n} x_{c_i}^{d_j} \leqslant 1 \, ; \quad \forall \, d_j \in D \tag{2.15}$$

Constraint (2.14) implies that a cellular UE might share the RBs with a maximum of one D2D pair and constraint (2.15) indicates that a D2D pair might share the

RBs of a maximum of one cellular UE. Both of the constraints (2.14) and (2.15) ensure the orthogonality among the cellular UEs and the D2D pairs while sharing the RBs. So, the stated optimization problem is to minimize the total system interference (Eqn. (2.10)) while satisfying the constraints (2.11) - (2.15) for One-to-One sharing approach.

In the case of the One-to-Many sharing approach, one D2D pair can share the RBs of multiple cellular UEs mutually exclusively. In this type of sharing approach, the objective function needs to satisfy constraint (2.14) of whereas constraint (2.15) can be relaxed as follows:

$$0 \leqslant \sum_{i=1}^{n} x_{c_i}^{d_j} \leqslant n \;, \quad \forall\, d_j \in D. \tag{2.16}$$

So, any solution to the interference minimization problem for One-to-Many sharing approach needs to satisfy the constraints (2.11), (2.12), (2.13), (2.14), and (2.16).

In the case of the Many-to-Many sharing approach, a D2D pair can share the RBs of multiple cellular UEs without holding the mutual exclusion property. In other words, we can say a D2D pair can share the RBs of multiple cellular UEs, and different D2D pairs can share the RBs of a particular cellular UE. In this case, both of the constraints (2.14) and (2.15) of One-to-One sharing can be relaxed. Constraint (2.14) can be relaxed as follows:

$$0 \leqslant \sum_{j=1}^{m} x_{c_i}^{d_j} \leqslant m \;, \quad \forall\, c_i \in C \tag{2.17}$$

So, any solution to the interference minimization problem for the Many-to-Many sharing approach needs to satisfy the constraints (2.11), (2.12), (2.13), (2.16), and (2.17).

2.5 Proposed Solutions

We propose solutions for both One-to-One, One-to-Many, and Many-to-May sharing approaches that minimize the system interference while maintaining the individual target sumrate. We propose two algorithms for One-to-One sharing. We name the first algorithm as Hungarian-based Interference Minimization Resource Allocation Algorithm (HIMRA) which is based on the optimal algorithm [29] to solve the bipartite matching problem. We name the second algorithm as Stable Marriage-based Interference Minimization Resource Allocation Algorithm (SMIMRA) which is based on the stable marriage algorithm [30]. Both algorithms are explained in Section 2.5.3.1 and Section 2.5.3.2 respectively. For One-to-Many sharing, we propose two algorithms that are variants of the One-to-One sharing approach. We name the first algorithm as Multiple Hungarian based Interference Minimization Resource Allocation Algorithm (M-HIMRA) whereas, we name the second algorithm of One-to-Many sharing as Multiple Stable Marriage based Interference Minimization Resource Allocation Algorithm (M-SMIMRA). Both algorithms are explained in Section 2.5.4.2 and Section 2.5.4.3 respectively. Finally, we propose one algorithm for the Many-to-Many sharing approach and we name the algorithm as Hungarian-based Many to Many Interference Minimization Resource Allocation Algorithm (HMM-IMRA). HMM-IMRA is inspired from [31] which uses backtracking along with the Hungarian algorithm [29] to solve the many to many assignment problems. HMM-IMRA is described in Section 2.5.5.

Resource allocation problem in D2D communication while minimizing the system interference is converted into a weighted bipartite matching problem. All of the proposed algorithms are either Hungarian[29] or Stable matching [30] based algorithms that use the weighted bipartite matching approach to allocate the RBs among the cellular UEs and the D2D pairs in in-band underlay mode with the intention of minimizing the system interference while maintaining individual target sumrate. Before describing the proposed algorithms we explain the formation of the bipartite graph and the weight calculation process used by both Hungarian and Stable matching-based approaches.

2.5.1 Formation of the Bipartite Graph

The bipartite graph is constituted of two disjoint sets, i) a set of existing cellular UEs C and ii) a set of D2D pairs D.

2.5.2 Weight Calculation

2.5.2.1 Weight calculation for the Hungarian method based Algorithms

We consider cellular UEs $C(c_1, c_2, \ldots, c_n)$ and D2D pairs $D(d_1, d_2, \ldots, d_m)$ as the two sets of vertices of the weighted bipartite matching problem where the edges between c_i and d_j represent the interference and sumrate introduced because of sharing of RBs between c_i and d_j. The weight of the edges is crucial for finding the best matching. The Hungarian-based algorithm runs weighted bipartite matching algorithm [29] to find the possible minimum system interference by sharing RBs among the set of cellular UEs and the set of D2D pairs.

We introduce an $n \times n$ matrix I as the weight matrix for the weighted bipartite matching algorithm (which represents the edges) where rows represent the cellular UEs and columns represent the D2D pairs. As the weighted bipartite matching algorithm deals with only square matrix, we add $(n - m)$ dummy D2D pairs in the weight matrix. At first, m columns of Y hold the interference caused by c_i and d_j using Eq. (2.6) and we assigned 0 to the remaining $(n - m)$ dummy D2D pairs as we do not want them to be matched in the final solution.

An $n \times n$ matrix S (similar to matrix I) is introduced to store a secondary weight of the edges between c_i and d_j for the matching algorithms. Here, the secondary weight matrix represents the system sumrate contributed by c_i and d_j using Eq. (2.7) and Eq. (2.9) respectively. This weight matrix is used to check the target sumrate demand. If $S_{i,j} \rightarrow Cell < T_{c_i}$ or $S_{i,j} \rightarrow D2D < T_{d_j}$, then, the the corresponding entry of the secondary weight matrix S will be infinite and Weight $infinity(\infty)$ is set to those edges which force the algorithm to avoid this type of sharing. However, for the remaining $(n - m)$ dummy D2D pairs, the weight is calculated by using (2.8), which ensures that dummy D2D pairs do not affect the selection of actual D2D pairs. the proposed Hungarian-based algorithm (HIMRA, M-HIMRA, and HMM-IMRA) use this weight calculation.

2.5.2.2 Weight calculation for Stable Matching based Algorithms

The stable matching-based algorithms for interference minimization use the introduced interference between a cellular UE and a D2D pair because of sharing as the weight value. This weight value is used to prepare the preference list of a node of a bipartite graph. We elaborated the weight-based preference list for capacity maximization in Section 3.5.1 that uses sumrate gain as the weight value. In this optimization problem, weight value (interference between a cellular UE and a D2D pair) is calculated by Eq. (2.6). We need to mention that if the individual target sumrate is not satisfied by any cellular UE c_i or by any D2D pair d_j, then, they should be removed from the preference list.

2.5.3 One-to-One Sharing Approach

2.5.3.1 Hungarian based Interference Minimization Resource Allocation Algorithm (HIMRA)

We translate the addressed resource allocation problem into a weighted bipartite matching problem. Here, each D2D pair needs to be assigned to at most one cellular

UE. The goal of the assignment is to attain minimum interference while maintaining the individual target system sum rate of the D2D pairs and cellular UEs. The input of HIMRA is a set of cellular UEs C, a set of D2D pairs D, and two sets of individual target system sumrate T_c and T_d for the cellular UEs and D2D pairs respectively. HIMRA invokes Hungarian minimization algorithm [29] (minimum weighted bipartite matching algorithm) to find the possible minimum total system interference by sharing RBs among a set of cellular UEs $C(c_1, c_2, \ldots, c_n)$ and a set of D2D pairs $D(d_1, d_2, \ldots, d_m)$. Flow chart of HIMRA and basic Hungarian algorithm is presented in Fig. 2.3 and Fig. 2.4. We consider C and D as the two sets of vertices of the matching problem where, the edges between $c_i \in C$ and $d_j \in D$ represent the interference, I_{c_i,d_j} introduced due to the sharing of RBs between c_i and d_j. We introduce two $n \times n$ matrix I and S in line 2 and 3 of algorithm 1 and the calculation of their value is discussed in subsection 2.5.2.1. The matrix I, is the interference weight matrix and the secondary matrix S, holds the sumrate contribution of the corresponding cellular UE and D2D pair. If any entry of the secondary weight matrix S is less than the corresponding individual target sumrate, this entry is set to infinity (∞). In line 6, the Hungarian algorithm is invoked which assigns cellular UEs to D2D pairs and returns the result to a Boolean matrix M (declared in line 5). Finally, the RBs are assigned in line 10 after checking the eligibility in line 8.

Algorithm 1 Hungarian based Interference Minimization Resource Allocation Algorithm (HIMRA) - One-to-One Sharing

1: **procedure** HIMRA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n), T_c, T_d$)
2:     Let $I[1 \ldots n][1 \ldots m]$ be a new matrix to hold interference
3:     Let $S[1 \ldots n][1 \ldots m]$ be a new matrix to hold sumrate
4:     Assign weight in I and secondary weight S, as described in Section 2.5.2.1
5:     Let $M[1 \ldots n][1 \ldots n]$ be a Boolean matrix to store result
6:     M = HungarianMinimization(I)
7:     **for** $i = 1$ to n and $j = 1$ to m **do**
8:         **if** $M_{i,j} = TRUE$ and $I_{i,j} \neq \infty$ **then**
9:             Assign RBs of c_i to d_j
10:         **end if**
11:     **end for**
12: **end procedure**

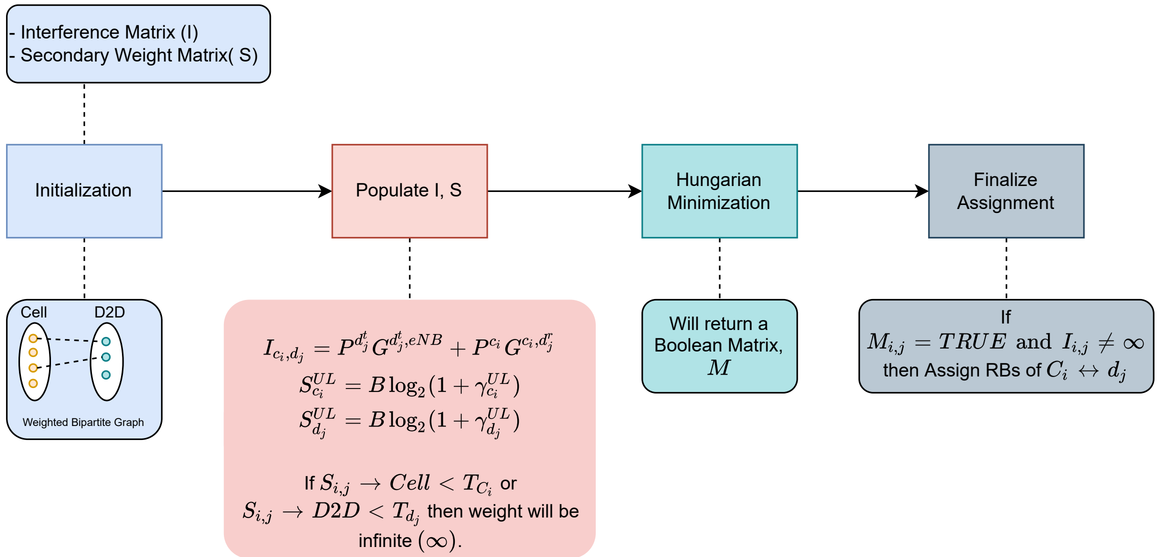


Figure 2.3: Flow chart of HIMRA

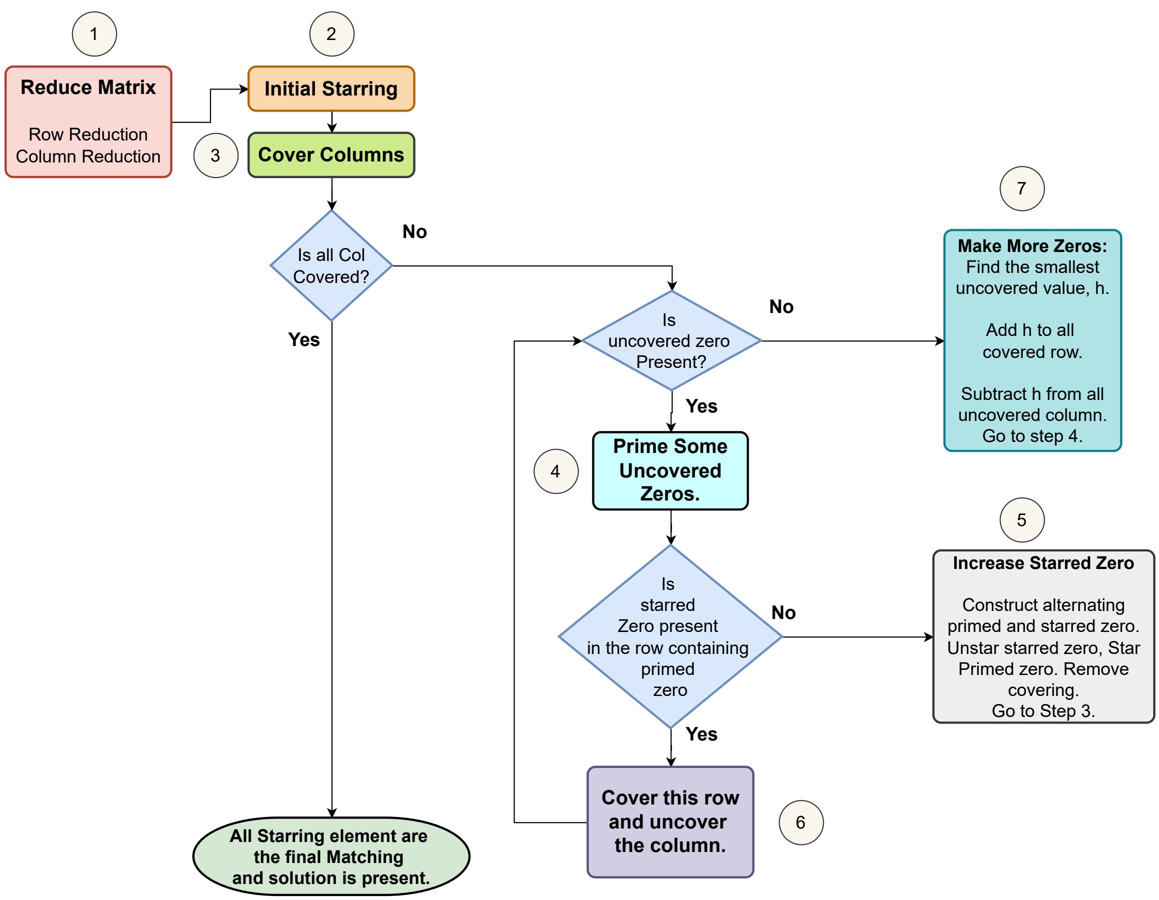


Figure 2.4: Flow chart of the Hungarian algorithm

2.5.3.2 Stable Marriage based Interference Minimization Resource Allocation Algorithm (SMIMRA)

The second proposed algorithm SMIMRA (Algorithm 2) for the One-to-One sharing approach is based on the stable matching algorithm [30]. Flow chart of SMIMRA and basic stable matching algorithm is presented in Fig. 2.5 and Fig. 2.6 respectively. In Algorithm 2, we consider the resource allocation problem as a bipartite graph with n cellular UEs in one set and m D2D pairs in another set. SMIMRA calculates the preference lists for both of the cellular UEs and the D2D pairs based on Eq. (2.6) (Line 2, Algorithm 2). In SMIMRA, the D2D pairs act as the proposer of the stable marriage algorithm (Line 3 Algorithm 2). SMIMRA (Algorithm 2) assigns a cellular UE and a D2D pair together such that there are no other cellular UEs and D2D pairs that would provide lower interference than their current assignment (Line $3-6$ Algorithm 2). If there are no such cellular UE or D2D pairs, all of the assignments are stable. If such assignments occur (Line 9 Algorithm 2) then, SMIMRA revokes those assignments and reassigns them to the highly preferred nodes. When all of the D2D pairs are assigned to the cellular UEs, SMIMRA stops its execution and returns the allocation as the final result.

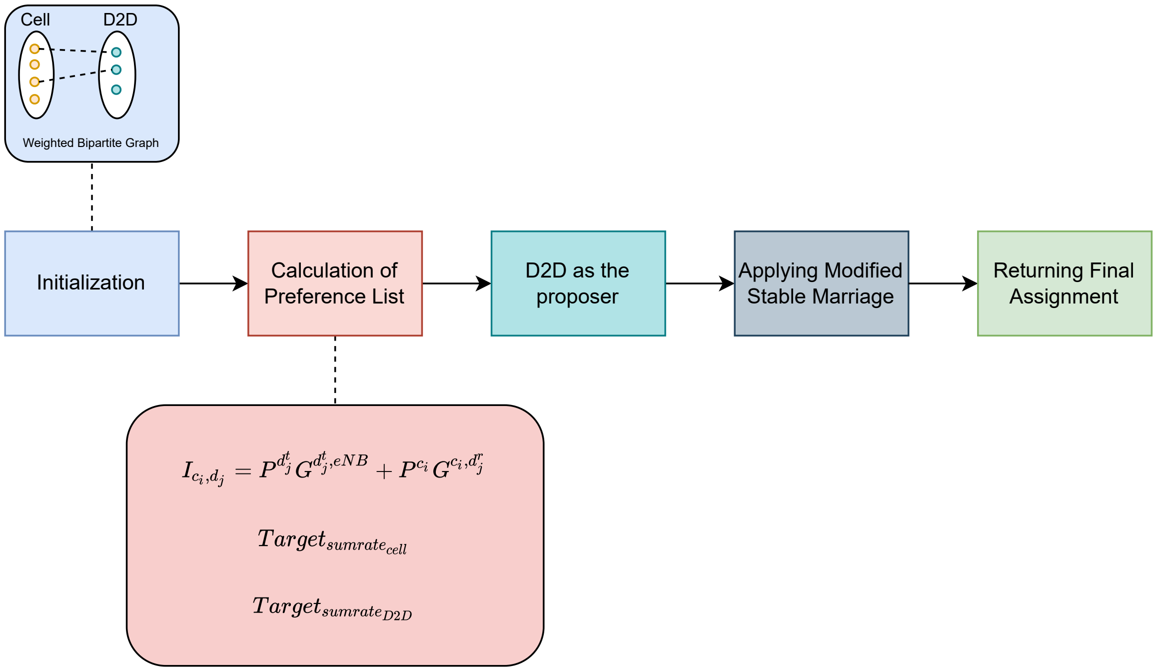


Figure 2.5: Flow chart of SMIMRA

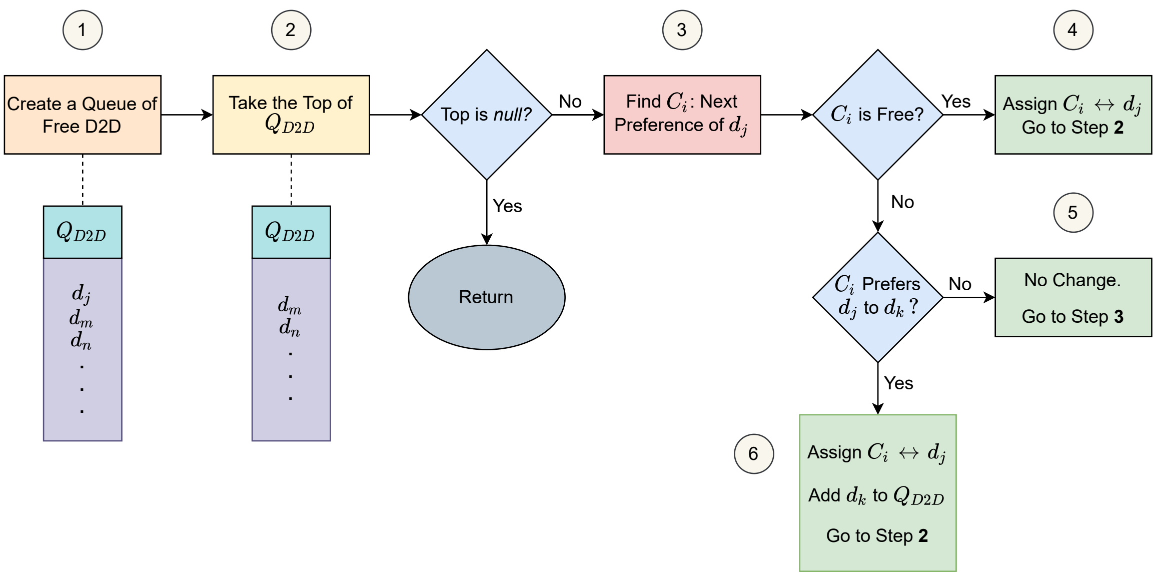


Figure 2.6: Flow chart of basic stable matching algorithm

Algorithm 2 Stable Marriage based Interference Minimization Resource Allocation Algorithm (SMIMRA) - One-to-One Sharing

procedure SMIMRA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n), T_c, T_d$)
    Calculate the preference lists using Eq. (2.6) described in Section 2.5.2.2
    while $\exists$ D2D pair $d_j \in D$ who still has a cellular user $c_i \in C$ to request to **do**
        c_i = Most preferred and non-attempted cellular UE on d_j's preference list
        if c_i is free **then**
            (c_i, d_j) become assigned
        else
            For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
            if c_i prefers d_j to d_k **then**
                (c_i, d_j) become assigned
                Add d_k to the list of free D2D pairs.
            else
                (c_i, d_k) remain assigned
            end if
        end if
    end while
end procedure

2.5.4 One-to-Many Sharing Approach

2.5.4.1 Relaxation of Individual Target Sumrate Constraint

For One-to-Many and Many-to-Many sharing approaches, a relaxed problem statement is used. Instead of using the constraint of individual target sumrate, cell capacity ($c_i^{capacity}$) and D2D requirements (d_j^{req}) is used. Out of many possibilities, we approximate cell capacity ($c_i^{capacity}$) and D2D requirements (d_j^{req}) in the following manner:

- **Cell Capacity ($c_i^{capacity}$) :** The highest number of D2D pairs which can share the RBs of cellular UE c_i and still satisfy the individual target sumrate constraint (according to Eq. (2.12)) of c_i.

$$\sum_{j=1}^{m} x_{c_i}^{d_j} \leq c_i^{capacity} \tag{2.18}$$

Only for the Many-to-Many sharing approach, constraint (2.18) will be used instead of constraint (2.12).

- **D2D Requirement (d_j^{req}) :** RBs of the minimum number of cellular UEs which is required to be shared by the D2D pairs d_j to satisfy the individual target sumrate constraint (according to Eq. (2.11)) of d_j.

$$\sum_{i=1}^{n} x_{c_i}^{d_j} = d_j^{req} \tag{2.19}$$

For One-to-Many and Many-to-Many sharing approach, constraint (2.19) will be used instead of constraint (2.11).

In this thesis, an approximation algorithm is used to calculate the cell capacity ($c_i^{capacity}$) and the D2D requirement (d_j^{req}).

Approximation Algorithm for Cell Capacity ($c_i^{capacity}$): When a D2D pair d_j shares the RBs of a cellular UE c_i, d_j introduces interference to c_i. The more the number of D2D pairs shares, the more the interference will be at c_i. As the interference increases, the sumrate of cellular UE reduces. Thus, there is a maximum number of y D2D pairs that can share the RBs of c_i without reducing the $S_{c_i}^{UL}$ less than T_{c_i}. In the followings, we provide the derivation of y where I_d^{max} is the interference introduced by a D2D pair d_j while sharing the RBs of c_i which is the maximum among all D2D pairs and B represents the bandwidth of the channel.

$$
\begin{aligned}
T_{c_i} &= B * log_2(1 + SINR) \\
&= B * log_2(1 + \frac{Signal}{Interference}) \\
&= B * log_2(1 + \frac{Signal}{y * I_d^{max}}) \\
y &= \frac{Signal}{(2^{\frac{T_{c_i}}{B}} - 1) * I_d^{max}}
\end{aligned}
$$

It is noteworthy that, if $y > m$, where m is the number of D2D pairs, then $y = m$ is set as this is the maximum number of D2D pairs available in the system. Finally, y is set as the value for $c_i^{capacity}$.

Approximation Algorithm for D2D pairs Requirement (d_j^{req}): For any D2D pair d_j, we first create a list of all cellular UEs in ascending order based on the sumrate of D2D pair d_j while, sharing each c_i. Then, we find a number y where summation of the first y number is greater than the T_{d_j}. Finally, y is set as the value for D2D pair requirement d_j^{req}.

2.5.4.2 Multiple Hungarian based Interference Minimization Resource Allocation Algorithm (M-HIMRA)

This algorithm is a One-to-Many approach adoption of algorithm 1. Instead of the individual target sumrate constraint of the D2D pair, the D2D requirement is used. The main adoption is to expand the weight matrix S and I to d_j^{req} numbers according to constraint (2.19) in line 5 of algorithm 3. Thus, the Hungarian Algorithm will return d_j^{req} number of matching for d_j which satisfies the constraint (2.19). The flow chart of M-HIMRA is presented in Fig. 2.7.

Algorithm 3 Multiple Hungarian based Interference Minimization Resource Allocation Algorithm (M-HIMRA) - One-to-Many Sharing

procedure M-HIMRA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
  Let $I[1 \ldots n][1 \ldots m]$ be a new matrix to hold interference
  Let $S[1 \ldots n][1 \ldots m]$ be a new matrix to hold sumrate
  Assign weight in I and secondary weight S, as described in Section 2.5.2.1
  Expand columns of S and I such that for each d_i there will be x duplicate columns in the weight matrices.
  Let $M_{Expanded}[1 \ldots n][1 \ldots \sum_{d_i \in D} d_i.x]$ be a new matrix
  $M = \textsc{HungarianMinimization}(I)$
  Let $M[1 \ldots n][1 \ldots m]$ be a new Boolean matrix to hold result
  Reduce the expanded matrix $M_{Expanded}$ from $d_i.x$ column to one column
  for $i = 1$ to n and $j = 1$ to m **do**
    if $M_{i,j} = TRUE$ **then**
      Assign RBs of c_i to d_j
    end if
  end for
end procedure

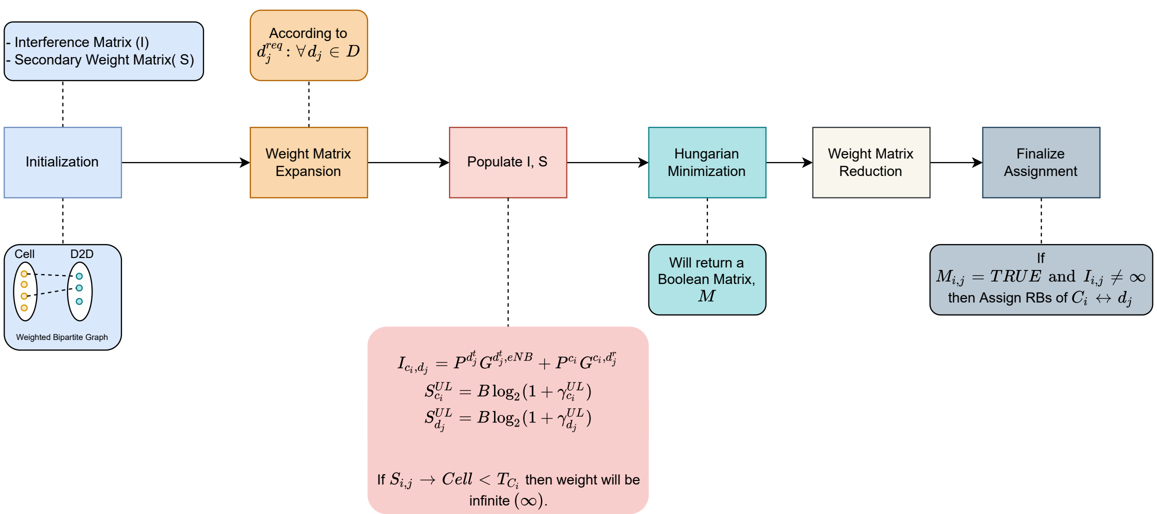


Figure 2.7: Flow chart of M-HIMRA

2.5.4.3 Multiple Stable Marriage based Interference Minimization Resource Allocation Algorithm (M-SMIMRA)

This algorithm is a One-to-Many adoption of algorithm 2. Instead of the individual target sumrate constraint of the D2D pair, the D2D pair requirement is used. The main adoption is changing the action when a D2D pair d_j is assigned to c_i. For

One-to-Many approach - after assignment, the constraint (2.19) is checked and d_j is removed from Q_d^{free} only if the constraint is satisfied in. Flow diagram of M-SMIMRA and modified stable marriage algorithm used in M-SMIMRA is presented in Fig. 2.8 and Fig. 2.9 respectively.

Algorithm 4 Stable Marriage based Interference Minimization Resource Allocation Algorithm (M-SMIMRA) - One-to-Many Sharing

procedure M-SMIMRA($D(d_1, d_2, \dots, d_m), C(c_1, c_2, \dots, c_n)$)
  Calculate the preference lists using Eq. (2.6) described in Section 2.5.2.2
  Create a queue of free D2D pairs Q_d^{free} by inserting all D2D pairs
  while $\exists$ D2D pair $d_j \in Q_d^{free}$ still has a cellular user $c_i \in C$ to request to **do**
    c_i = Most preferred and non-attempted cellular UE on d_j's preference list
    if c_i is free **then**
      (c_i, d_j) become assigned
      if d_j satisfies Eq. (2.19) **then**
        remove d_j from the Q_d^{free}
      end if
    else
      For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
      if c_i prefers d_j to d_k **then**
        (c_i, d_j) become assigned
        if d_j satisfies Eq. (2.19) **then**
          remove d_j from the Q_d^{free}
        end if
        Add d_k to the list of free D2D pairs.
      else
        (c_i, d_k) remain assigned
      end if
    end if
  end while
end procedure

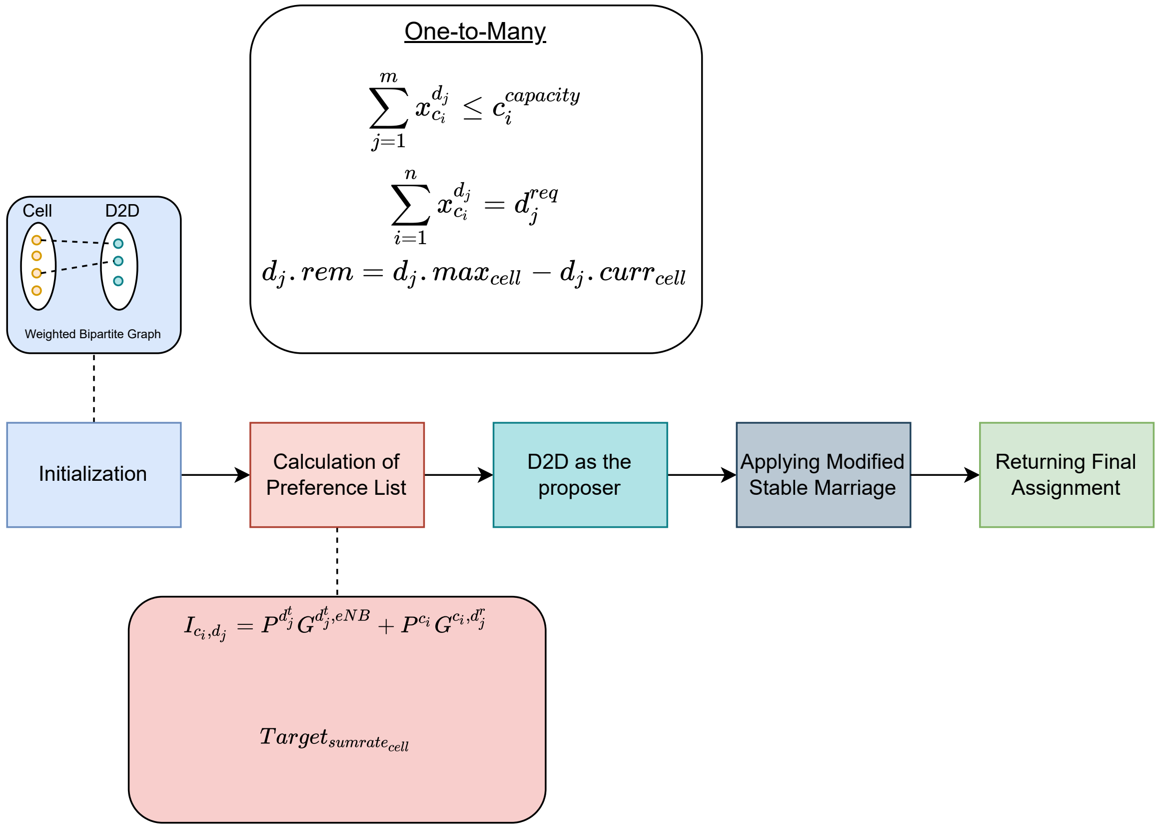


Figure 2.8: Flow chart of M-SMIMRA

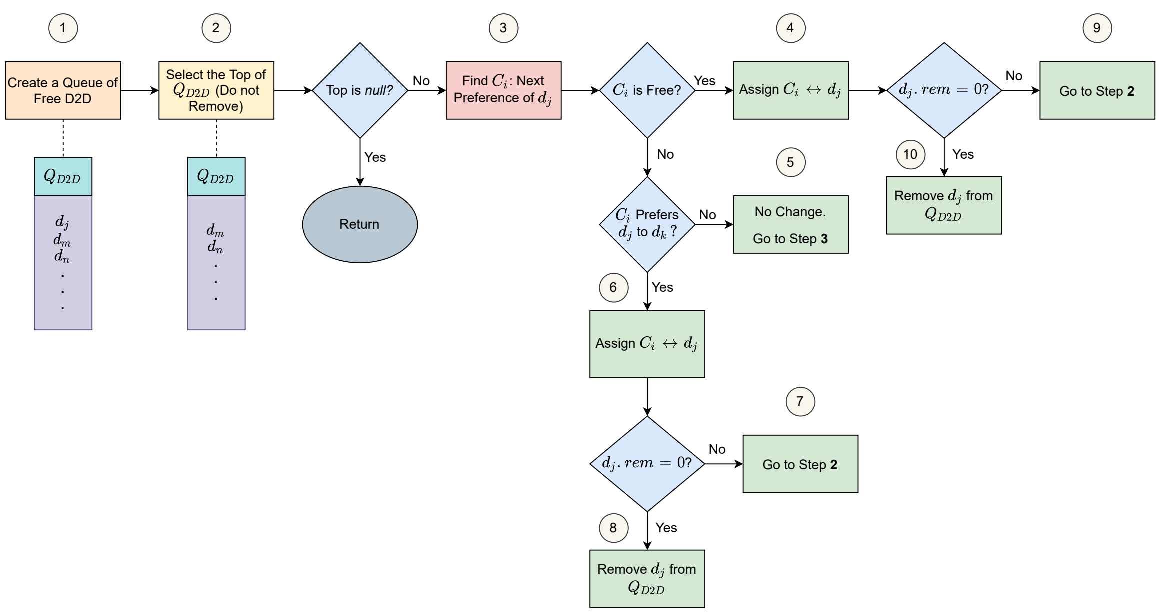


Figure 2.9: Modified stable matching algorithm for M-SMIMRA

2.5.5 Many-to-Many Sharing Approach

2.5.5.1 Hungarian based Many to Many Interference Minimization Resource Allocation Algorithm (HMM-IMRA)

Hungarian-based Many to Many Interference Minimization Resource Allocation Algorithm (HMM-IMRA) is inspired by KMB [31] algorithm. HMM-IMRA is presented in two phases. In the first phase (HMM-IMRA-PREPARATION), the weight matrix is prepared and in the second phase (HMM-IMRA-PROCESSING), the weight matrix is processed to find the bipartite matching. The flow chart of HMM-IMRA is presented in Fig. 2.10.

HMM-IMRA-PREPARATION: At first, an $n \times m$ interference weight matrix Q is created where, Q_{ij} represents one to one interference if d_j shares the RBs of c_i. After that in line (3), the capacity list is populated where each cellular UE's capacity is stored. Similarly, in line (4), D2D pairs' requirement lists *Requirement* store each D2D pair's demand. In line (5), the total cell capacity is compared to the total D2D demand. If D2D demand is higher, no solution is possible. After that, Q matrix is expanded to a $k \times k$ matrix, M according to cell capacity and D2D requirement in line (11). Now, we populate the dummy rows with infinity (∞) in M matrix.

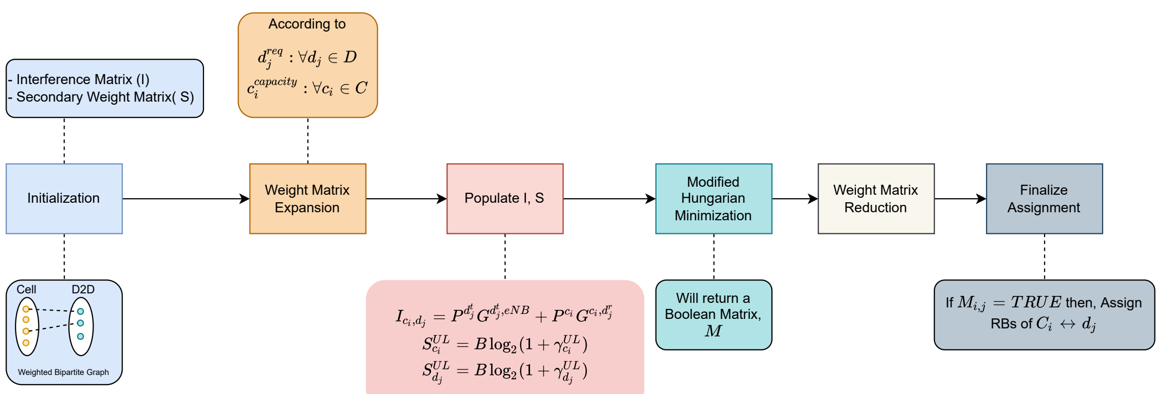


Figure 2.10: Flow chart of HMM-IMRA

HMM-IMRA-PROCESSING: Like the KMB algorithm (for One-to-One approach), the proposed algorithm has the following steps

- Step 1: Row Column Minimization in line 2
- Step 2: Initial Starring in line 5
- Step 3: Covering Column in line 8
- Step 4: Prime Some Uncovered Zero in line 15
- Step 5: Increasing Starred Zero in line 23
- Step 6: Increasing Zeros in line 28
- Step 7: Next Starring in line 31
- Step 8: Solution in line 35

In the proposed algorithm, we have introduced a new step (Step 7: Next Starring). The important change with the One-to-One Hungarian algorithm approach is making zeros to unavailable between the same Cell and the same D2D which represent invalid association while Starring or Priming a zero. These unavailable zeros can not be considered while performing any operation. These unavailable zeros will be available when Starring or Priming is removed. In the **Step 7: Next Starring**, all stars, primes, and coverings are removed and after that, starring is done following the rules of Step 1: Initial Starring. After that, it will go to step 3. This new starring removes a halting case which is discussed with an example in Section 2.5.5.2. Flow chart of the KMB algorithm and modified KMB used in HMM-IMRA is presented in Fig. 2.11 and Fig. 2.12 respectively.

Algorithm 5 Preparation Stage - Hungarian based Many to Many Interference Minimization Resource Allocation Algorithm (HMM-IMRA) - Many-to-Many Sharing

procedure HMM-HIMRA-PREPARATION($L(l_1, l_2, \ldots, l_n)$)
  Create $n \times m$ interference matrix
  Create a cell capacity list, *Capacity* according to constraint (2.18).
  Create a requirement list *Requirement* according to constraint (2.19).
  if $\sum_{i=0}^{n-1} Capacity[c_i] \geq \sum_{j=0}^{m-1} Requirement[d_j]$ **then**
    Continue
  else
    return "Solution is not present."
  end if
  $K \leftarrow \sum_{i=0}^{n-1} Capacity[c_i]$
  Expand the $n \times m$ matrix Q into $K \times K$ matrix M according to the capacity list *Capacity* and requirement list *Requirement*, where cellular c_i has $Capacity[c_i]$ rows in M and D2D d_j has $Requirement[d_j]$ columns in M.
  Assign the uninitialized columns with ∞.
end procedure

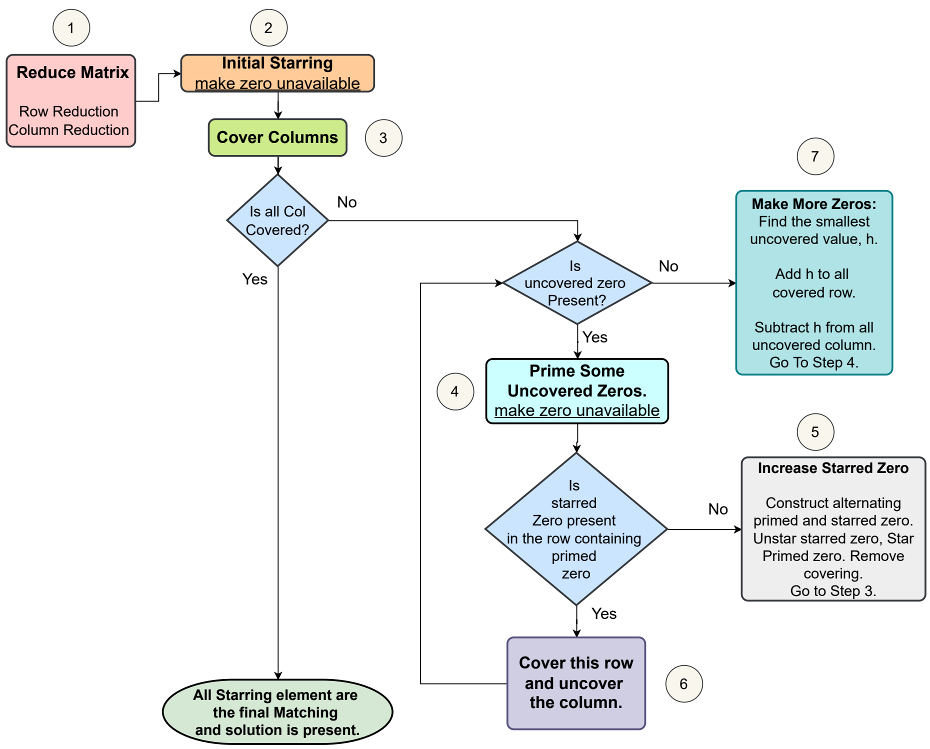


Figure 2.11: Flow chart of original KMB

Algorithm 6 Processing Stage - Hungarian based Many to Many Interference Minimization Resource Allocation Algorithm (HMM-IMRA) - Many-to-Many Sharing

procedure HMM-IMRA-PROCESSING(M)
  Step 1: (Reduce Matrix)
  Subtract each element of a row with the minimum value of the row.
  Subtract each element of a column with the minimum value of the column.
  Step 2: (Initial Starring)
  Find a zero value which does not have any starred zero in its row and column.
  Make all other zeros to be unavailable for the sub-matrix.
  Step 3: (Covering Column)
  Cover each column with starred zero.
  if The number of covered columns are equal to K **then**
    go to Step 8
  else
    Go to Step 4.
  end if
  Step 4: (Prime Some Uncovered Zero)
  Find an uncovered zero and prime it.
  Make all other zeros to be unavailable for same sub-matrix.
  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 follows:

- z_0 : Uncovered primed zero found in step 4.
- z_1 : The starred zero in the column of z_0 (if any)
- z_2 : The primed zero in the row of z_1 (if there is z_1, there will always be z_2)

  Continue until the series terminates at a primed zero that has no starred zero in its column.
  Unstar each starred zero, star each primed zero, erase all primes and, uncover every row and column.
  Backtracking: Make all unavailable element of the sub-matrix of erased starred zero to available.
  Step 6: (Make More Zeros)
  Add the smallest uncovered zero to each element of covered row and subtract from each element of uncovered column.
  Go to step 7 removing all star, prime and covering.

```
        Step 7: (Next Starring)
        Find all zeroes which does not have any starred zero in its row or column and
    star them.
        Make all other zeros to be unavailable for same sub-matrix.
        Go to step 4.
        Step 8: (Solution)
        If M[i, j] is starred, then assign ith cellular UE to jth D2D pair
    end procedure
```

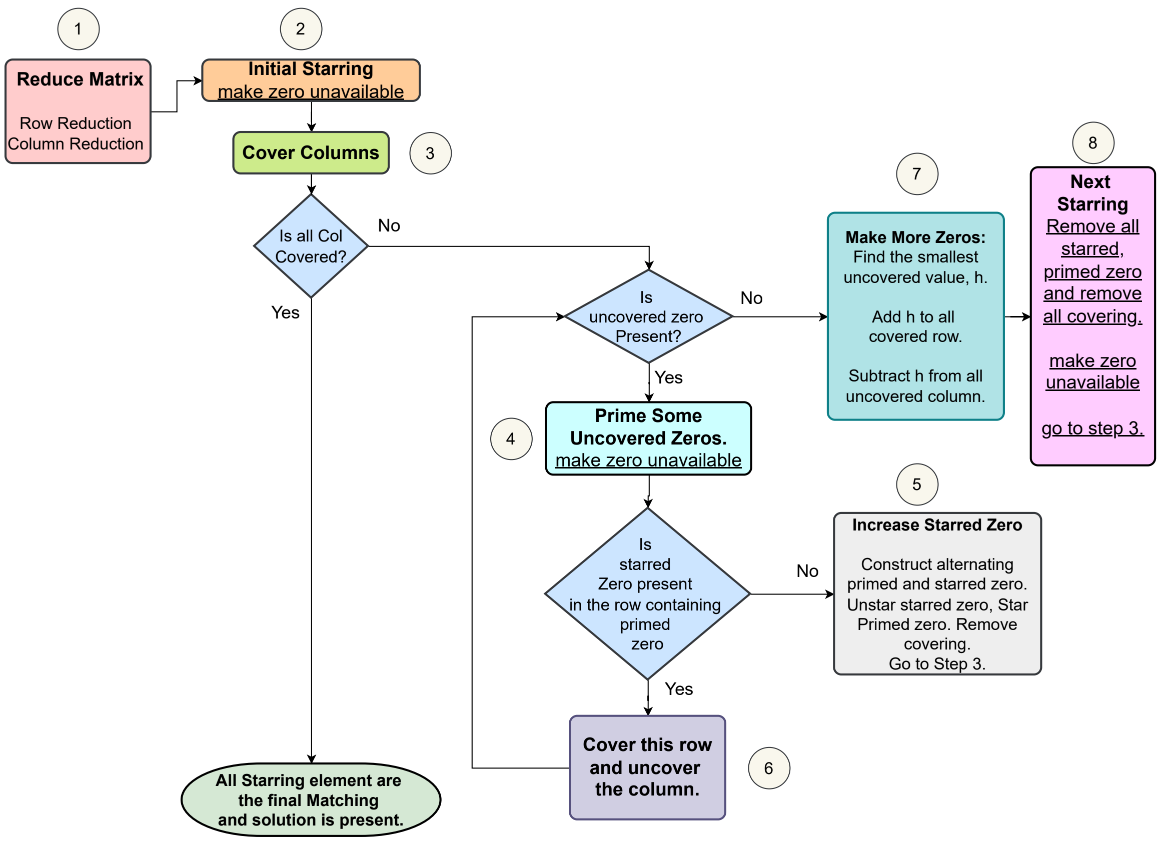


Figure 2.12: Flow chart of modified KMB used in HMM-IMRA

2.5.5.2 An example of KMB's failed case and our approach towards solution

In this subsection, we illustrate an example scenario where the KMB algorithm fails to return a solution although a solution exists. We also illustrate a step-by-step walk-through of the modified KMB algorithm used in HMM-IMRA that returns a solution in the same example scenario. Figure 2.13 and 2.14 represents the different states of execution of the KMB and modified KMB algorithm respectively. In Fig. 2.13, we have considered two cellular UEs and two D2D pairs where each D2D pair requires two cellular UEs to fulfill the sumrate demand and every cellular user has a capacity of sharing a maximum of two D2D pairs. KMB starts with the cost matrix shown in state 1 (Numeric characters inside each circle over the rectangular box represent state number). State 2 represents the expanded cost matrix after the preparation stage. In state 1 and state 2 with different colors, the expansion of the cost matrix is shown. Then, KMB starts the processing stage by reducing the cost matrix. State 3 and 4 represent the state of the cost matrix after row reduction and column reduction respectively. State 5 and 6 represent the state of the cost matrix after initial starring and column covering, respectively. We need to mention that, whenever there is a starred/primed element (0) in the weight matrix, the remaining entries of the sub-matrix with a value 0 becomes unavailable and we mark the unavailable entries in grey color in Fig. 2.13 and Fig. 2.14. These elements cannot be considered for calculation when they are marked as unavailable. For example, the entry at (c11, d21) is starred and the corresponding entries (c11, d22) (c12, d21) and (c12, d22) of the sub-matrix are marked as unavailable. After state 6, as all the columns are not covered, the solution assignment is not reached yet. Then, KMB looks for uncovered 0 to prime in state 7. However, there is no uncovered 0 to prime. In state 8, KMB makes some more 0s by subtracting the minimum uncovered element, $h = 2$ from all the uncovered columns and add to the covered rows. In state 9, KMB primes the uncovered 0 (c11, d12 entry of the cost matrix), and as there's a starred 0 (c11, d21) in the same row, uncovers the column (d21) and covers the row (c11). After state 9, KMB looks for more uncovered 0s to prime since all the columns are not covered yet and try to make more 0s. However, there is no non-zero uncovered element and KMB fails to make more 0s, thus, can not reach a solution. State 10 in Fig. 2.13 represents the halting state of KMB in our example scenario.

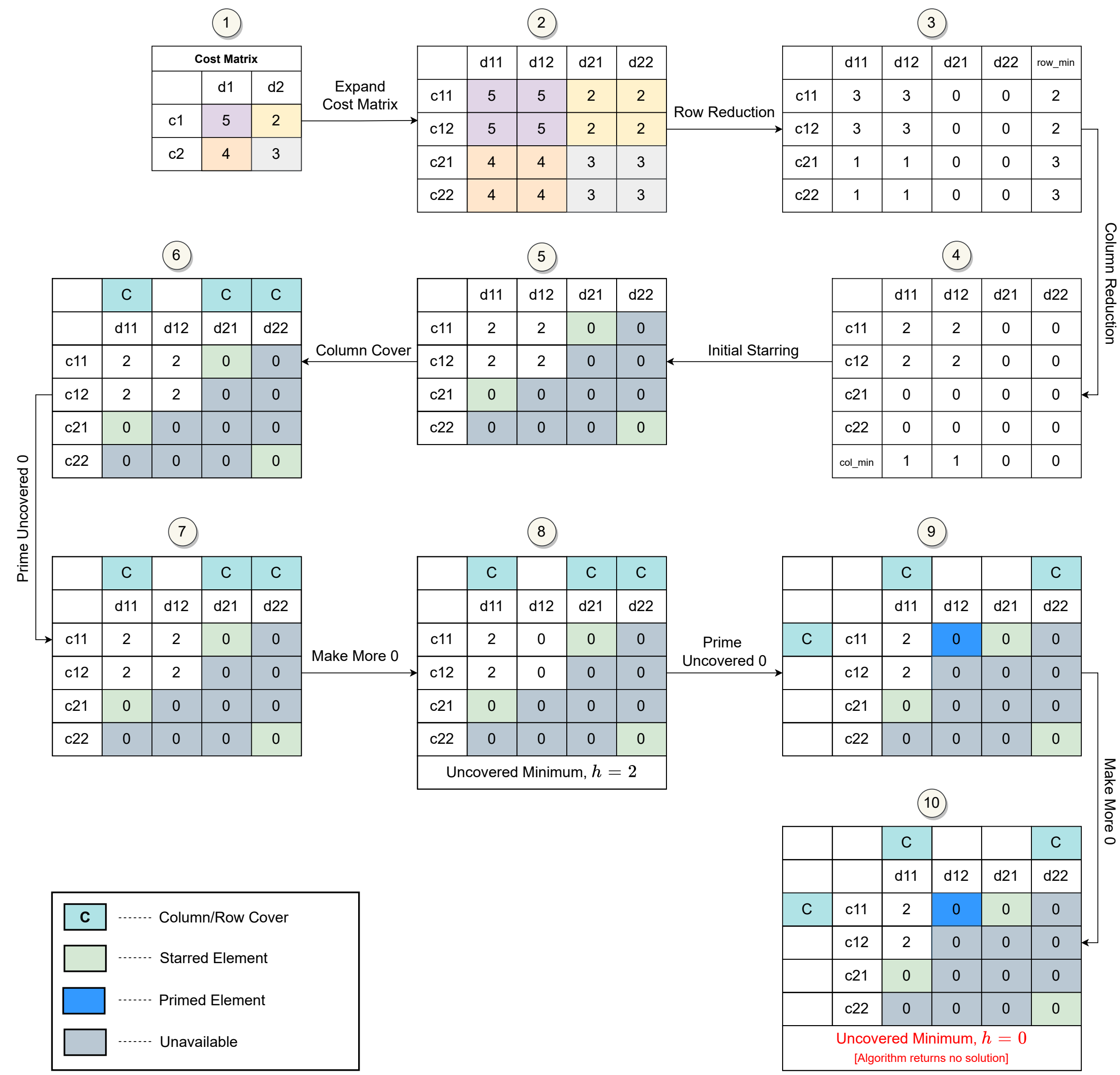


Figure 2.13: An example of KMB's failed case

In Fig. 2.14, we illustrate our solution approach in the aforementioned scenario by modifying the existing KMB algorithm. The modified states are presented in the dotted rectangle in Fig. 2.14. In the modified approach, after state 8 (Make more 0s), instead of priming uncovered 0s, we go to the next starring state where we uncover all rows and columns as well as adjust all unavailable elements. Like the initial starring, we perform starring on the current cost matrix again which is presented in state 9. After column covering, it can be observed from state 10 of Fig. 2.14 that all columns are covered, thus, obtaining a solution.

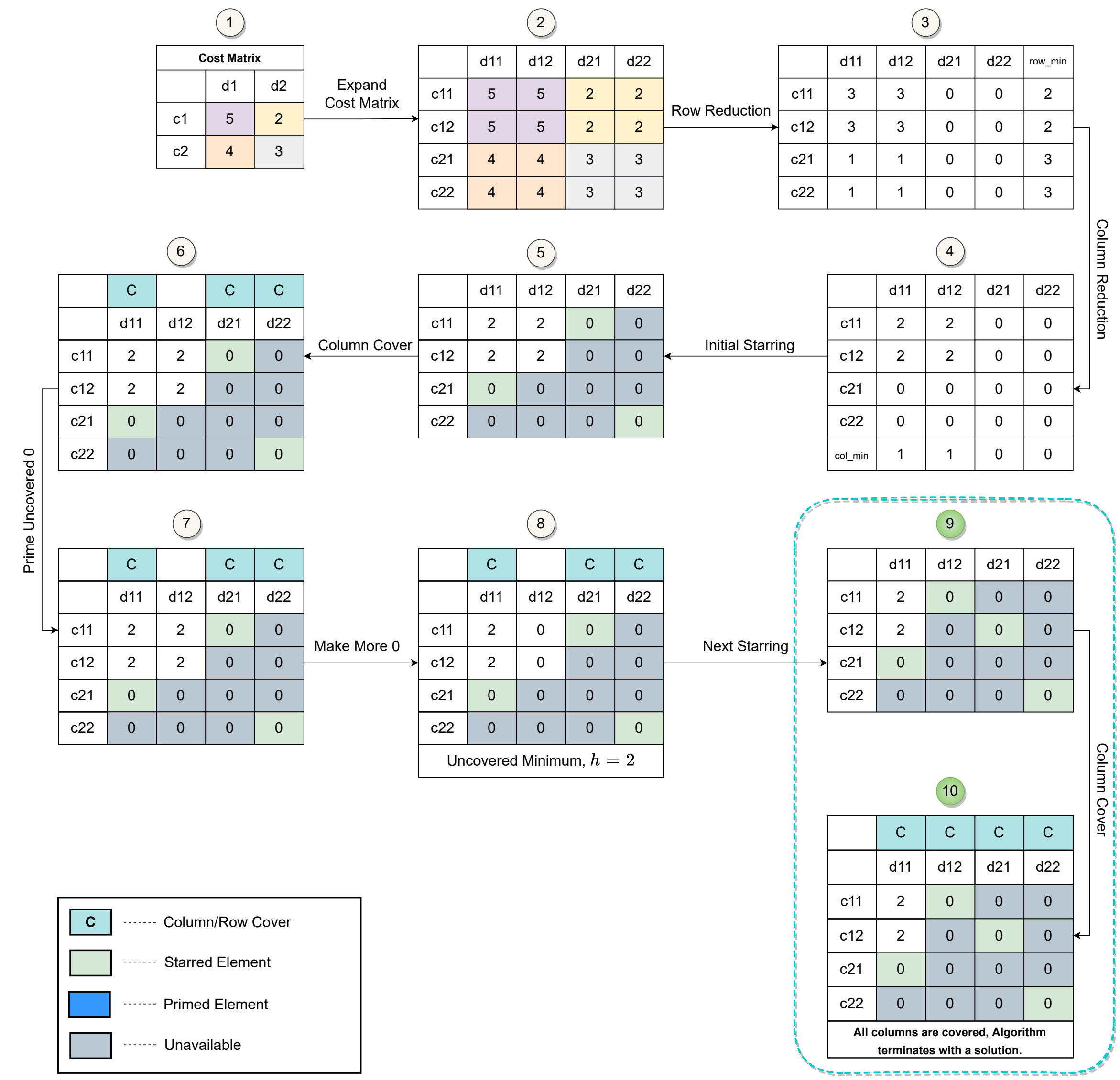


Figure 2.14: Modified KMB towards solution

2.6 Complexity Analysis

Three of the proposed algorithms (HIMRA, M-HIMRA, and HMM-IMRA) for interference minimization are based on the Hungarian algorithm. The running time of these three algorithms is dominated by the execution of the Hungarian algorithm which is $O(n^3)$ (n is the total cellular UEs) [29]. For the One-to-One variant, HIMRA (Algorithm 1), Hungarian Minimization is invoked in line 6 that requires n^3 iterations. Other operations like populating the weight matrices (Line 2), finalizing the assignments (Line 8) requires n^2 iterations. So, the overall run time of HIMRA is $O(n^3)$. For the One-to-Many variant, M-HIMRA (Algorithm 3), the individual sum-rate constraint is relaxed as demand (number of cellular UEs required by a D2D pair (k:=$\sum \mathrm{d}_j^{req}$)). In the case of M-HIMRA, Hungarian invocation (Line 7) needs k^3 iterations. Other operations like weight matrices population (Line 8) requires $n * m$ iterations, weight matrix expansion and reduction (Line 5 and line 9) requires $k * n$ iterations for each of the operations, and finalizing the assignments (Line 11) requires n^2 iterations. The overall run time complexity of the M-HIMRA is $O(k^3)$ where k:=$\sum \mathrm{d}_j^{req}$.

The Many-to-Many variant, HMM-IMRA is a two-stage algorithm. The preparation stage (Algorithm 5) defines a new variable c_i^{cap} to represent the capacity of a cellular UE (Maximum number of D2D pairs that can be shared with) along with the demand of D2D a pair d_j^{req}. The running time is dominated by the weight matrix expansion (Line 11, Algorithm 5) which is $O(K^2)$ where, $K := \sum \mathrm{c}_i^{cap}$. The processing stage of HMM-IMRA (Algorithm 6) is inspired by KM_B [31] that uses backtracking for the many-to-many assignment that has the worst time complexity of $O(K^3)$ where, $K := \sum \mathrm{c}_i^{cap}$ (total capacity of all cellular UEs).

SMIMRA (Algorithm 2) is a stable marriage-based algorithm and it requires $n*m$ number of iterations for preference calculation and $n * m$ number of iterations for applying the stable marriage algorithm. So, SMIMRA has a run time complexity of $O(n*m)$. If the number of D2D pairs and cellular UEs are the same in number, the run time complexity is $O(n^2)$. M-SMIMRA (Algorithm 4) is also a stable marriage-based algorithm where the individual sumrate constraint is relaxed as demand (number of cellular UEs required by a D2D pair (d_j^{req})). For preference calculation, M-SMIMRA requires $n * m$ iterations and for the matching operation, it requires $\sum d_j^{req} * n$ iterations. We can say the run time complexity of M-SMIMRA is $O(\sum \mathrm{d}_j^{req} * \mathrm{n})$.

2.7 Numerical Results

2.7.1 Experimental Environment

We simulate different scenarios to evaluate the efficiency of the proposed algorithms (HIMRA, SMIMRA, M-HIMRA, M-SMIMRA, and HMM-IMRA). We use the C++ programming language for the numerical analysis that supports the LTE system. The research problem we consider is a type of assignment problem which is one of the fundamental combinatorial optimization problems in the branch of optimization. In the experiment, our main objective is to find the assignments of the D2D pairs with the cellular UEs. Based on the assignments, we need to calculate SINR, interference, and system sumrate from their respective equations. We need to mention that as we do not need to implement the PHY, MAC, and network layer to implement the proposed resource allocation algorithms, a networking simulator is not essential for the numerical analysis. We use the same experimental parameters as [27], [26] (Table 2.4) and tweak some of the parameters to examine the variability of our findings, and we discover that our suggested algorithm performs consistently. A single cell network is used in the experimental setup. Because some researchers believe the D2D pair is in the same room [88], the maximum distance allowed between the transmitter and receiver of a D2D pair is 15 meters, and a wider distance eliminates the benefits received through D2D communication. The cell radius is set to 1000 m since the macro cell radius normally starts at 1000 m [89]. The individual target sumrate for a D2D pair T_{D2D} is set to a random value between 10 and 15 and for a cellular UE, the target sumrate T_{cell} is set to a random value between 1 and 3. The total number of cellular UEs is fixed at 100, and the number of D2D pairs is varied from 10 to the total number of cellular UEs. Each of the offered numerical results is an average of

Table 2.4: Experimental Parameters

Parameter	Value
Cell Radius	1000 meters
Cellular Users	250
D2D pairs	10 to 250 (increments of 10)
Maximum D2D pair distance	15 meters
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Base Station transmit power	46 dBm
Noise power (AWGN)	-174 dBm
Carrier Frequency	1.7 GHz for LTE
Bandwidth, B	180 kHz [3]
D2D target T_{D2D}	Random value ($1 \sim 3$)
Cell target T_{cell}	Random value ($10 \sim 15$)

20 separate runs for a certain scenario. Note that, we also replicate the method with different numbers of cellular UEs, and the results are similar in every situation.

2.7.2 Result Comparisons

2.7.2.1 Result comparison for One-to-One algorithms

Different Algorithms for Performance Comparisons: To the best of our knowledge, there is no existing algorithm that addresses the same research problem of considering the individual target sumrate demand. We compare the proposed algorithms with some state-of-the-art algorithms (TAFIRA and FARA) that consider the total system sumrate demand. We discuss the key points of all of the algorithms in the next subsection. Then, we discuss how the proposed algorithm performs compared to the existing algorithm with the experimental result in the following subsections.

Two phase auction-based fair resource allocation algorithm (TAFIRA): TAFIRA [27] considers the same problem of interference minimization we are considering. However, TAFIRA minimizes the interference while achieving the system sumrate demand by allocating all D2D pairs to the available cellular UEs. In Phase-I, TAFIRA creates a bidding pool with all cellular UEs and a set of bidders with all D2D pairs. Each bidder has a greedy choice to bid for the cellular UE that produces minimum interference. Once all D2D pairs are allocated to cellular UEs, the algorithm calculates the total system sumrate according to the allocation. If the calculated system sumrate satisfies the sum rate demand, TAFIRA terminates and reports the allocation as the final result. But if the demand is not satisfied in Phase-I, TAFIRA goes to Phase-II with the result provided in Phase-I where it releases a D2D pair and allocates it to any of the unallocated cellular UEs only if it improves the system sum rate.

Fair Assignment Resource Allocation (FARA) FARA [28] is the two-phased algorithm for fair assignment. In the phase-I FARA, a weighted bipartite matching approach is used to solve the interference minimization problem and in the phase-II, local search techniques are used to improve the solution of phase-I.

Experimental results

In this subsection, we represent a performance analysis for different resource allocation algorithms with a fixed number of UE = 100 and compare HIMRA and SMIMRA with the existing ones. The following experimental results depict the optimization capability according to our problem formulation for interference minimization.

Total system interference for different RA algorithms is illustrated in Fig. 2.15. It is observed that HIMRA and SMIMRA obtained lower total system interference compared to other RA algorithms, namely, Random, FARA, and TAFIRA. The performance was consistent throughout the experiment for the number of D2Ds ranging from 10 to 60. Between HIMRA and SMIMRA, SMIMRA achieved comparatively lower interference. SMIMRA obtained the lowest total system interference of -88.47 dBm and TAFIRA obtained the highest total system interference of -78.365 dBm for 60 D2D pairs.

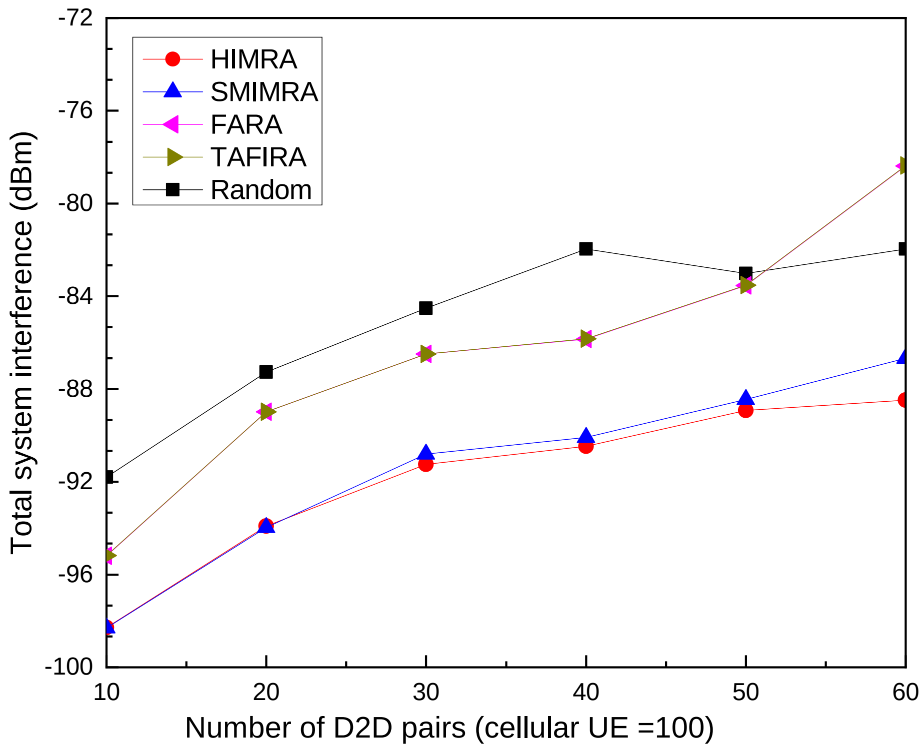


Figure 2.15: Total system interference for different RA algorithms (cellular UEs = 100)

Figure 2.16 represents per D2D interference obtained by our proposed HIMRA and SMIMRA concerning existing RA algorithms. Our proposed algorithms obtained the lowest interference for each D2D pair compared to other algorithms.

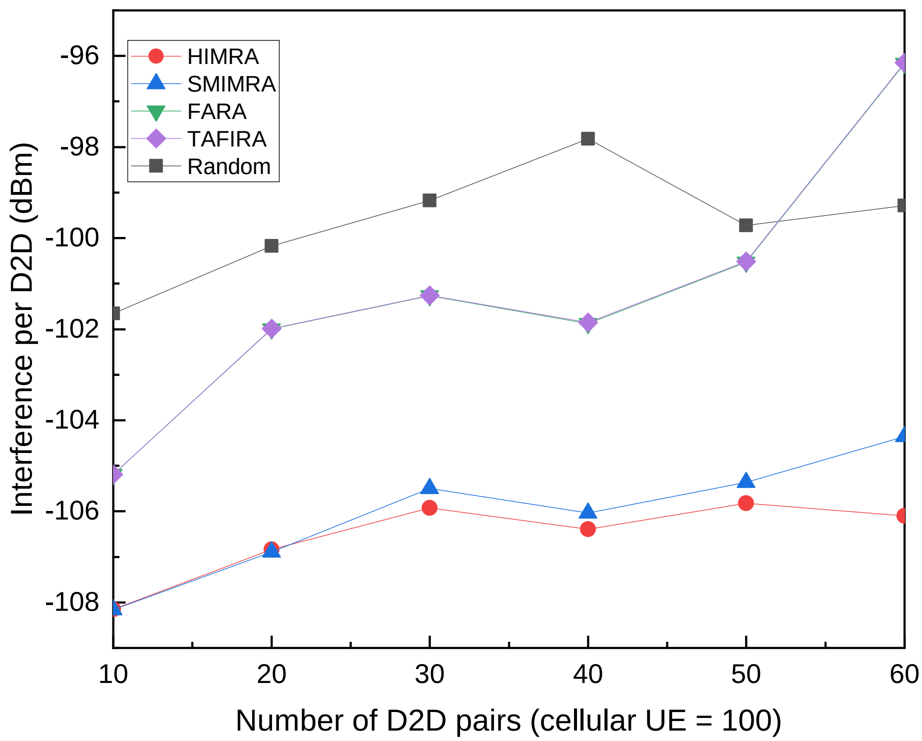


Figure 2.16: Interferences per D2D for different RA algorithms

The corresponding system sumrate is depicted in Fig. 2.17 and FARA and TAFIRA obtained the highest total system sumrate and the Random algorithm achieves the lowest total system sumrate. The performance of the two proposed algorithms is somewhere in the middle of the two extremes. HIMRA and SMIMRA's total system capacity is higher than Randoms' but lower than that of TAFIRA and FARA. Even though HIMRA and SMIMRA have slightly lower total system capacity than TAFIRA and FARA, the proposed algorithms are better suited for an environment where lower interference is given higher priority and notice that the proposed algorithm did so while maintaining a reasonable total system sumrate. For several D2Ds ranging from 10 to 60, SMIMRA obtained a slightly higher total system capacity than HIMRA with a minimum value of 2165 bps/Hz and a maximum value of 2415 bps/Hz.

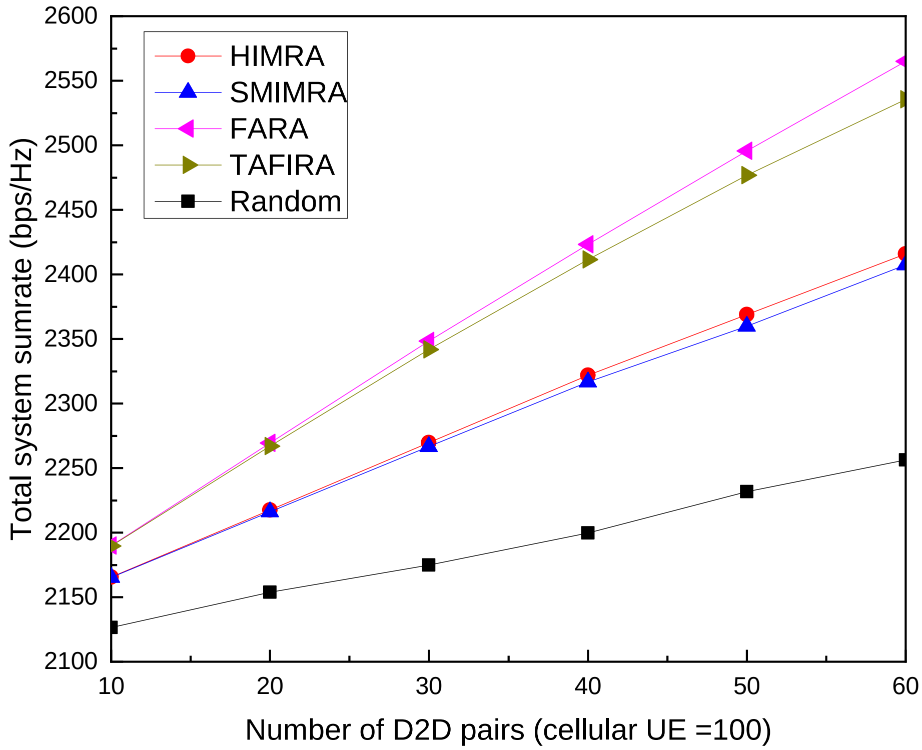


Figure 2.17: Total system sumrate for different RA algorithms (cellular UEs = 100)

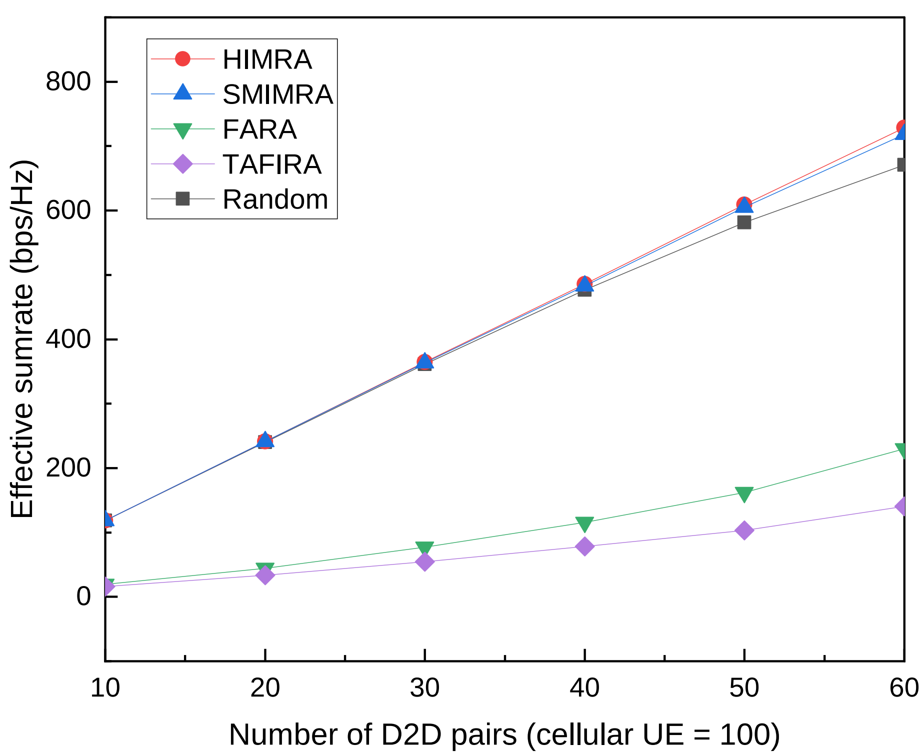


Figure 2.18: Effective sumrate for different RA algorithms (cellular UEs = 100)

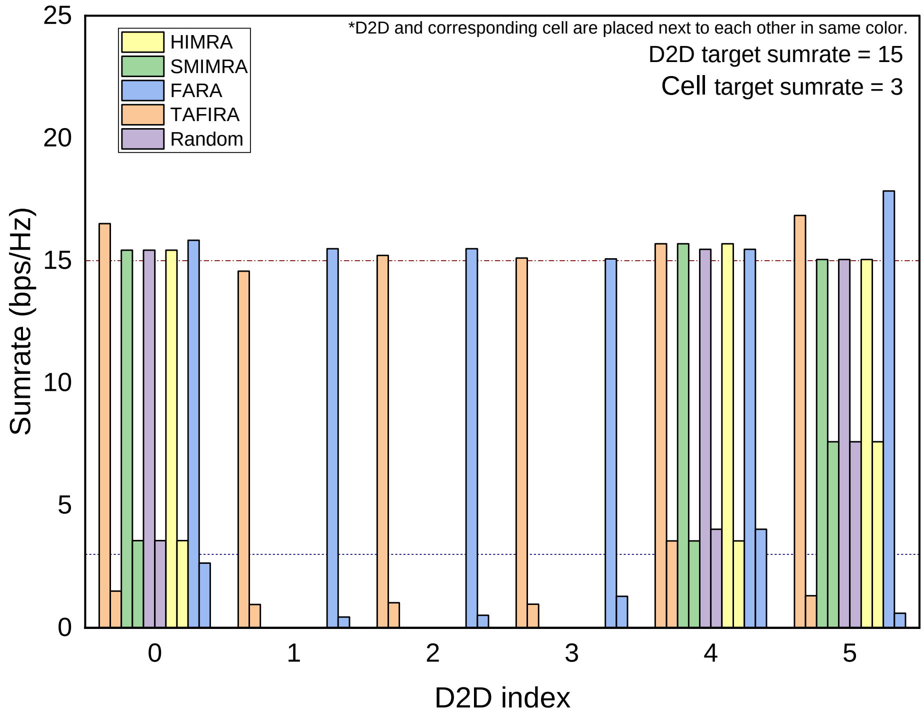


Figure 2.19: D2D vs assigned cell sumrate for different RA algorithms

Figure 2.20 represents the effective sumrate per D2D for different RA algorithms and our proposed algorithms obtained the highest effective sumrate for D2D pairs. Effective sumrate is formulated as the cumulative target D2D sum if both the cellular and D2D pair have a capacity equal to or more than their corresponding target capacity. If any of these two targets are not met, no value is added to the cumulative effective D2D sumrate, thus lower performance.

While having the lowest total system interference, the proposed algorithms admitted a satisfactory number of D2D pairs as shown in Fig. 2.21. Throughout the experiment for varying number of D2D pairs, the number of admitted D2D pairs are almost equal to the total number of D2D pairs. Since the objective of HIMRA and SMIMRA is to minimize interference, it sometimes leads to the admission of fewer D2Ds than TAFIRA and FARA. Since the Jain fairness index [90] is closely related to the ratio of the number of admitted D2D pairs and the number of total D2D pairs, the Random algorithm obtained the lowest Jain fairness index score for both admitted

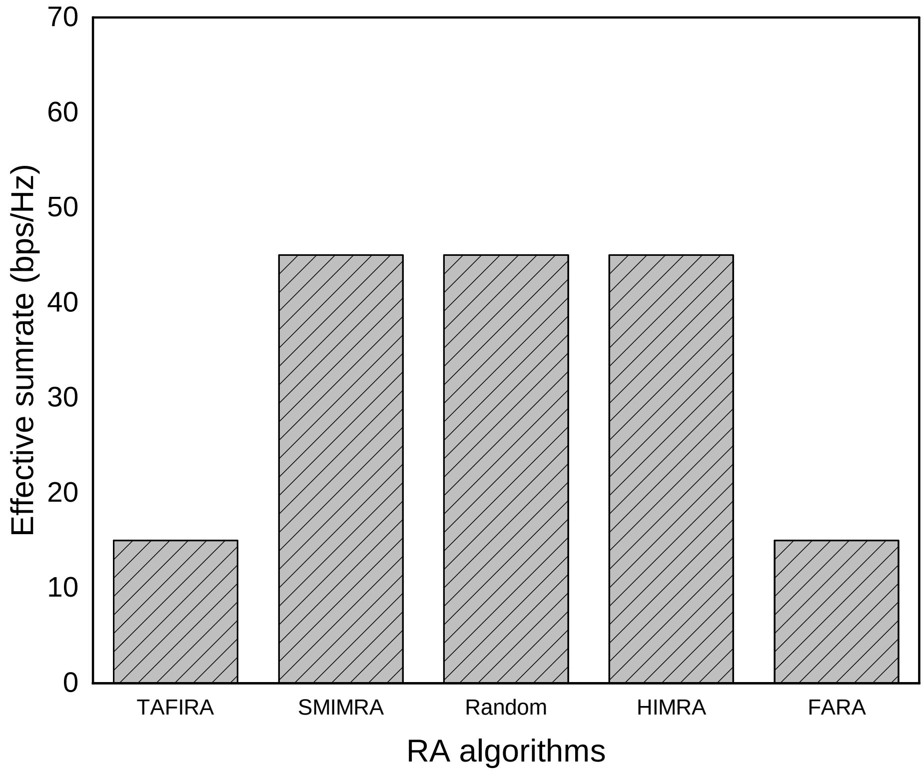


Figure 2.20: Effective sumrate for different RA algorithms

and all D2D pairs. The D2D admission rate of the proposed algorithms is very similar to TAFIRA and FARA which leads to a very similar Jain fairness index score in both cases as illustrated in Fig. 2.22 and 2.23. For admitted D2Ds, the Jain fairness index score for the proposed two algorithms was between 0.96 and 0.97 while SMIMRA's performance was negligibly better than HIMRA's. To minimize interference, HIMRA and SMIMRA did not admit all D2Ds which resulted in an approximate drop of 0.02 for the Jain fairness index score based on all D2D pairs and the performance of TAFIRA and FARA remained almost consistent.

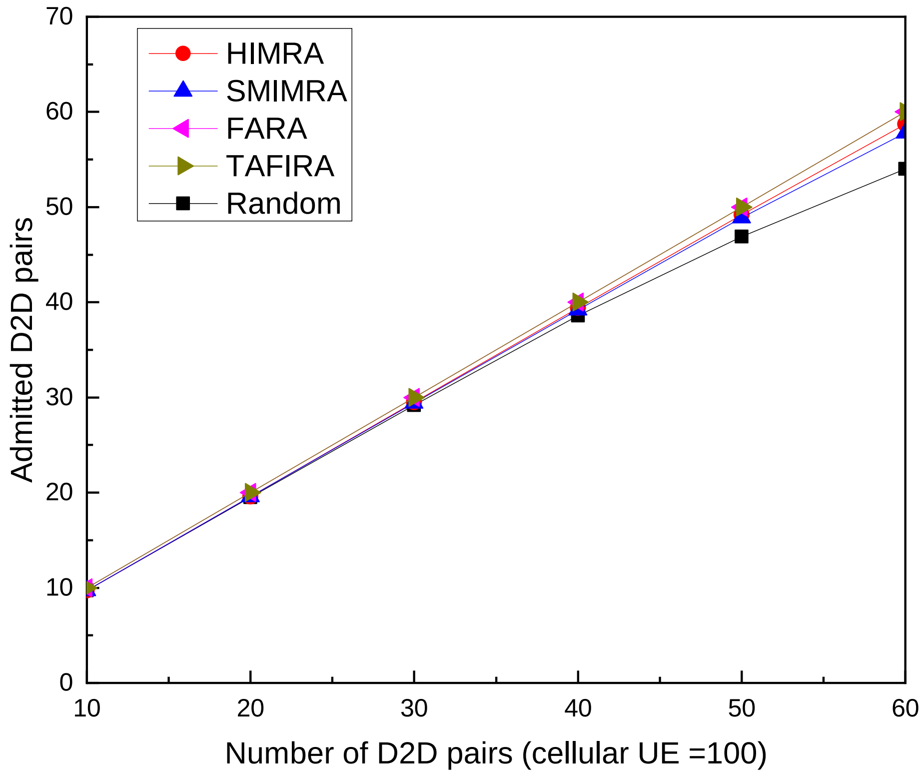


Figure 2.21: Number of admitted D2D pairs for different RA algorithms (cellular UEs = 100)

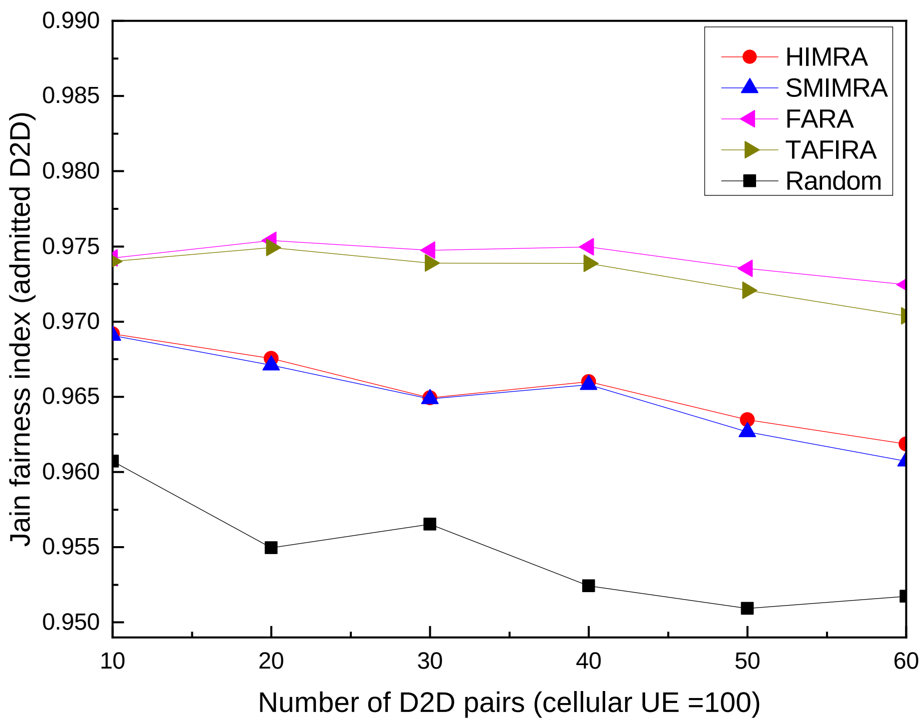


Figure 2.22: Jain fairness index of the admitted D2D pairs for different RA algorithms (cellular UEs = 100)

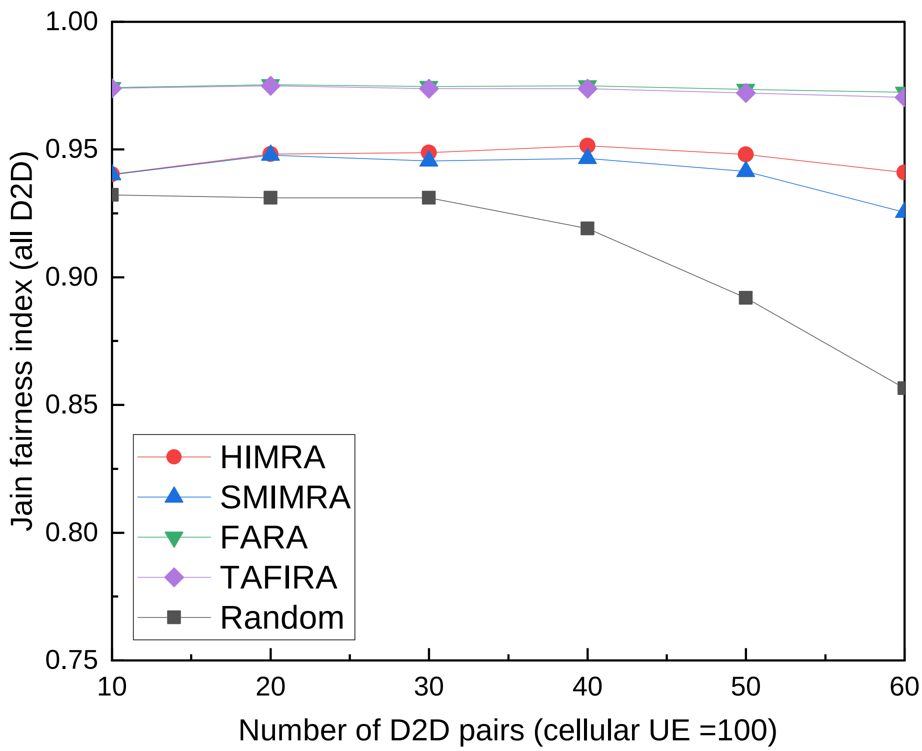


Figure 2.23: Jain fairness index of all D2D pairs for different RA algorithms (cellular UEs = 100)

Figures 2.24 and 2.25 illustrate the average sumrate for the first five cellular UEs and D2D pairs respectively along with their minimum and maximum sumrate. Notice that, the total system sumrate obtained by TAFIRA and FARA was more than the proposed algorithms because they admitted more number of D2D pairs whereas, the proposed algorithms did not allow the D2D pairs failing to satisfy the sumrate demand which resulted in less total system capacity. But, for individual system sumrate for cell and D2D illustrates that in most of the scenarios, the proposed algorithm provides a better sumrate than TAFIRA and FARA which is on par with the Random algorithm.

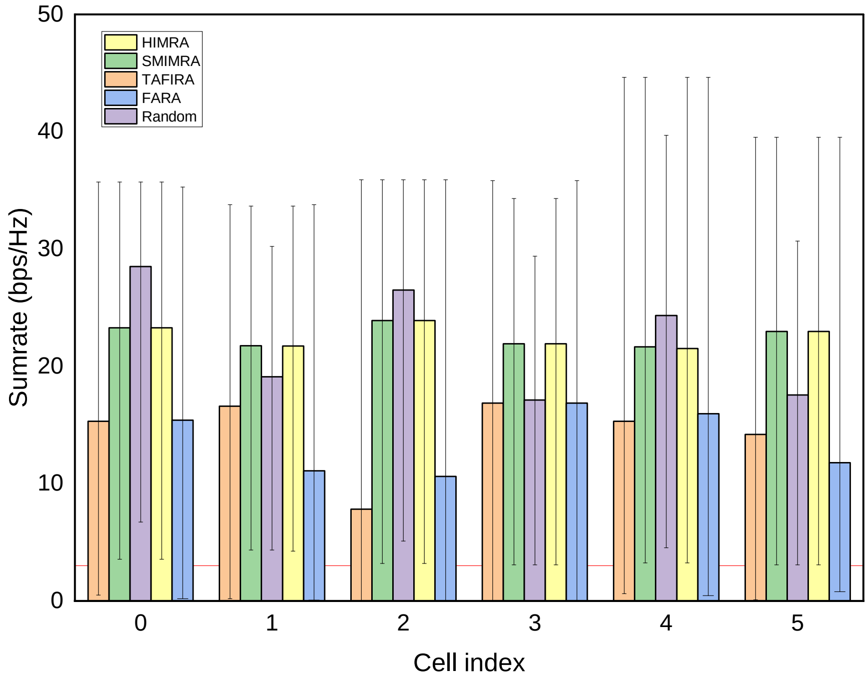


Figure 2.24: Average, minimum, and maximum sumrate of the cellular UEs for different RA algorithms

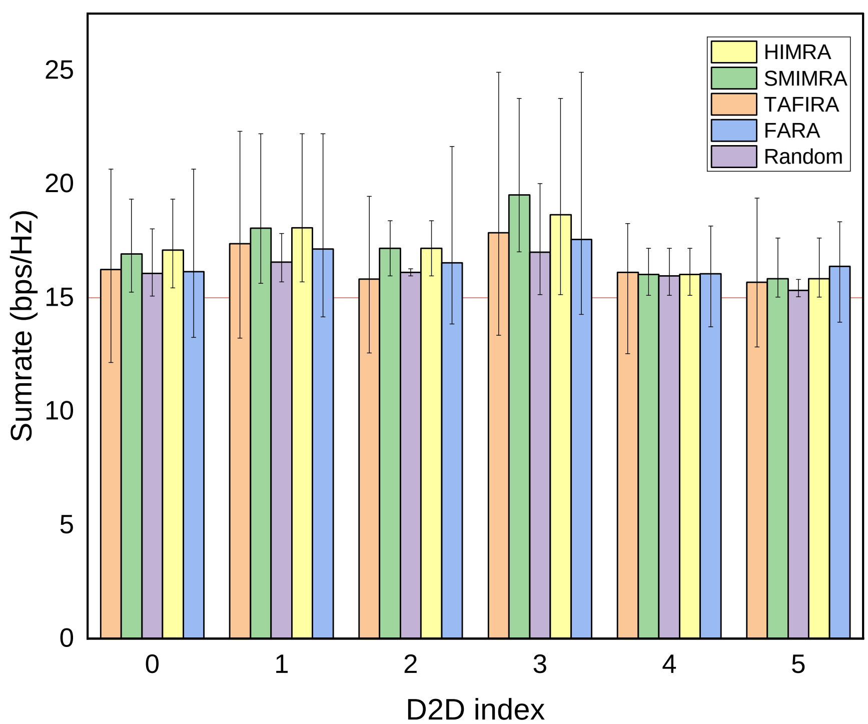


Figure 2.25: Average, minimum, and maximum sumrate of the D2D pairs for different RA algorithms

To illustrate the assignment strategy of the RA algorithms, Fig. 2.19 demonstrates the sumrate obtained by individual D2D pairs for different RA algorithms. The adjacent bar represents the cell sumrate of the cell that is connected to the corresponding D2D for the same algorithm which is shown in Fig. **??**. Effective sumrate is considered a metric to show the effectiveness of different RA algorithms. If the D2D sumrate and the corresponding cell sumrate exceed the respective target sumrate, then the D2D target sumrate of that D2D pair contributes to the effective sumrate. The total effective sumrate for an RA algorithm is calculated cumulatively for all D2D pairs. From the illustration, it can be observed that the effective sumrate of the proposed algorithm is significantly higher than TAFIRA and FARA.

2.7.2.2 Result Comparison for One-to-Many sharing algorithms

Different Algorithms for Performance Comparison: To the best of our knowledge, there is no existing algorithm that addresses the same research problem of considering the individual target sumrate demand for One-to-Many sharing. We compare the proposed algorithms with a greedy solution (RGA) for capacity maximization. We discuss the key points of all of the algorithms in the next subsection.

Restricted Greedy Algorithm(RGA) RGA [85] is based on the concept of the candidate set. A candidate set represents the feasible cellular UEs, that which a D2D pair might share the RBs with. The eligibility to enter the candidate set is governed by the fact that a cellular UE can be a member of the candidate set of a D2D device only if they both produce positive sumrate gain. RGA algorithm follows an approach where a single D2D pair can share the RBs of multiple cellular UEs and the highest weight needs to be selected for sharing each time and it does not care about the number of D2D pairs assigned in the medium. If the RBs of a cellular UE are shared then that cellular UE is removed from the candidate sets of all other

D2D pairs. Hence, several D2D devices with a non-empty candidate set may remain unassigned.

Experimental results

Our proposed algorithms also showed satisfactory performance in One-To-Many paradigm which is also on par with the performance results described in Subsection 2.7.2.1. Figure 2.26 illustrates the total system interference for increasing number of D2D pairs. Proposed algorithms perform consistently in comparison to each other whereas, the total system interference is higher than the Restricted Greedy Algorithm (RGA). Our problem formulation is based on interference minimization and to the best of our knowledge, this is the only existing algorithm in this problem objective domain. On the other hand, RGA is a greedy-based solution that does not consider the target sumrate that we have to fulfill in case of assignment thus, the higher system interference in our case. It is also observed that, for an increasing number of D2D pairs, the total system interference of the proposed algorithms is decreasing and for 60 D2D pairs, M-SMIMRA achieves less interference than RGA. In our experiments, M-SMIMRA achieved the lowest total system interference of -94.43dBm whereas, RGA and M-HIMRA achieved the lowest of -93.79dBm and -91.24dBm respectively.

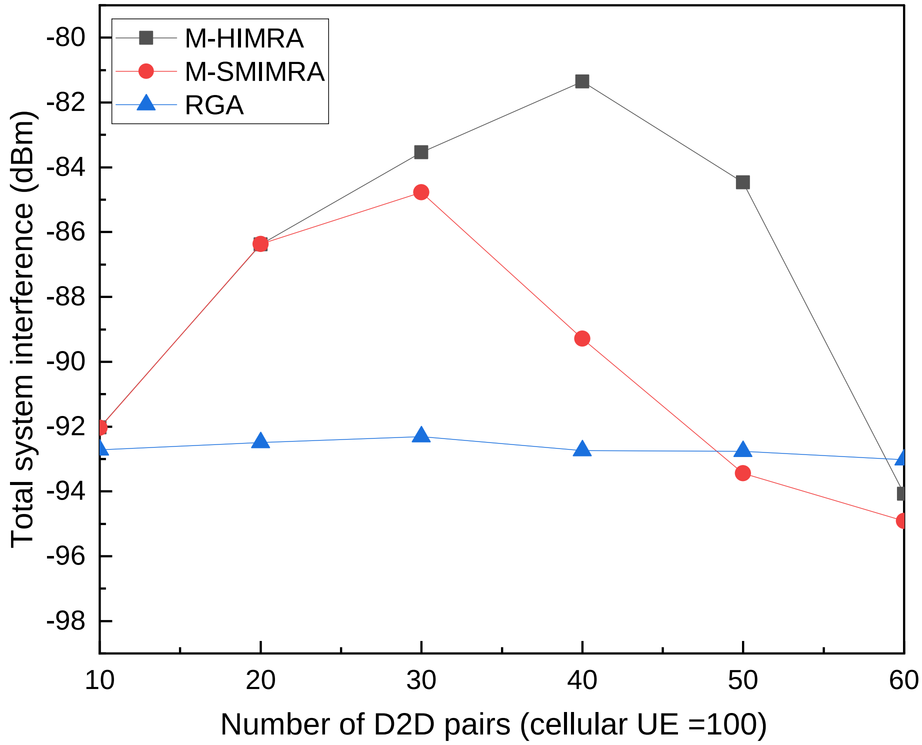


Figure 2.26: Total system interference for different RA algorithms (cellular UEs = 100)

Figure 2.27 represents interference per D2D for One-to-Many mode of sharing and our proposed M-HIMRA and M-SMIMRA obtained the least interference per D2D whereas, stable matching based M-SMIMRA performed slightly better than M-HIMRA.

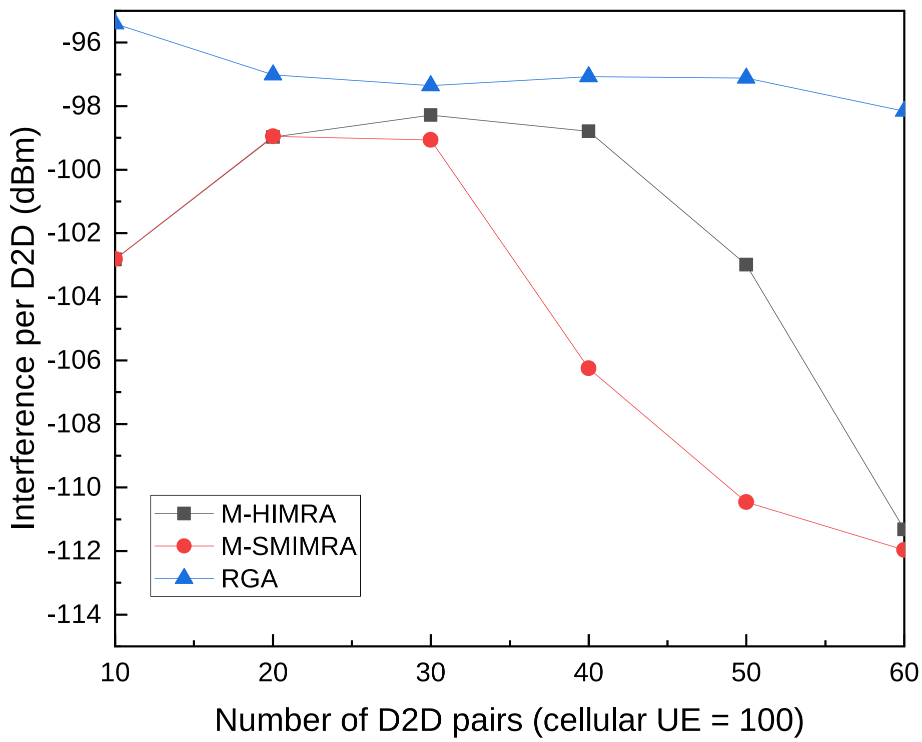


Figure 2.27: Interferences per D2D for different RA algorithms (cellular UEs = 100)

In case of the total system sumrate, the performance of M-HIMRA and M-SMIMRA is close to each other which is lower than RGA as shown in Fig. 2.28.

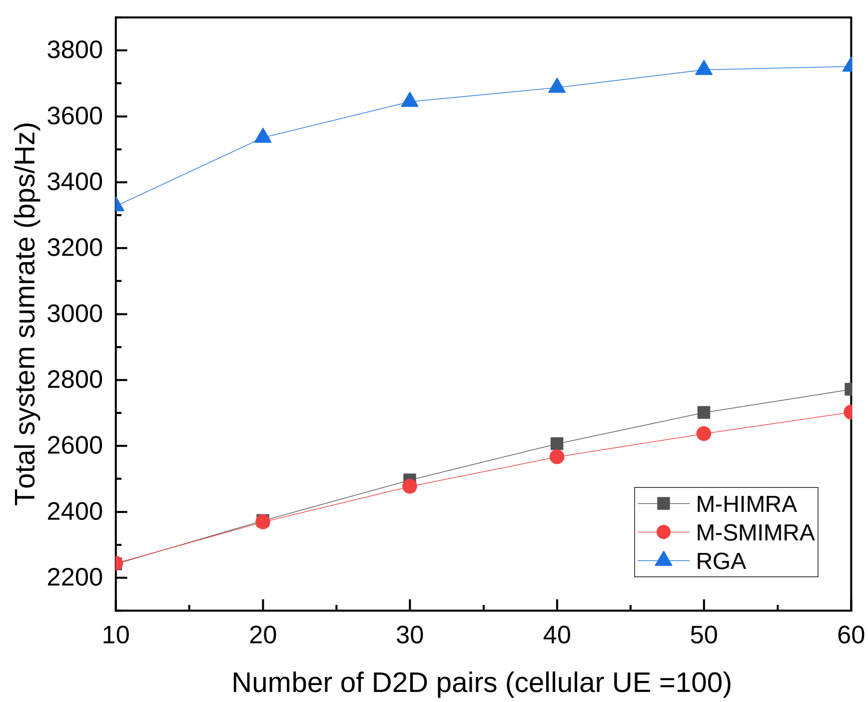


Figure 2.28: Total system sumrate for different RA algorithms (cellular UEs = 100)

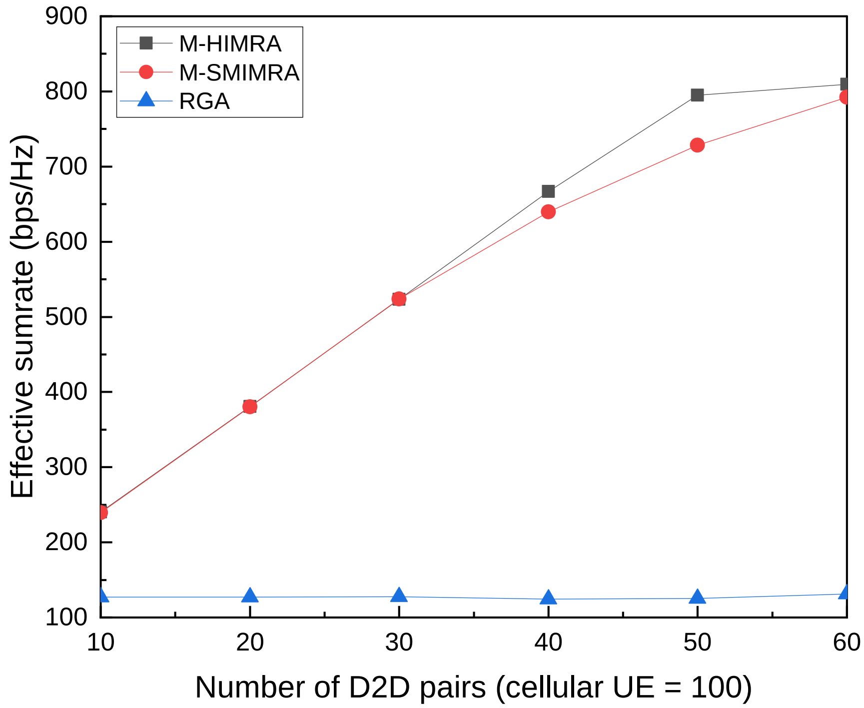


Figure 2.29: Effective sumrate for different RA algorithms (cellular UEs = 100)

Since RGA is a capacity maximization algorithm, it assigns all cells to a minimal number of D2Ds. As a result, a few D2Ds contain most of the cells whereas other D2Ds remain unassigned, thus, resulting in an unfair scenario and the same phenomenon is shown in Fig. 2.30, which depicts the number of the shared cell as well as shared D2D count for individual RA algorithms. It can also be observed that being a greedy-based algorithm, the shared cell count for RGA is always equal to the number of cellular UE. The same circumstance is responsible for the proposed algorithms to have a significantly higher Jain fairness index score than RGA as illustrated in Fig. 2.31. On admitted cellular UEs, the Jain fairness index score of the proposed algorithms is close to 0.9 whereas, RGA achieved around 0.7 on average for varying numbers of D2D pairs. On the other hand, the Jain fairness index score for the proposed algorithms is consistent in both admitted D2D pairs and all D2D pairs which is not the case for RGA. The Jain fairness index score significantly dropped to a minimum of 0.03 for 60 D2D pairs in the case of RGA.

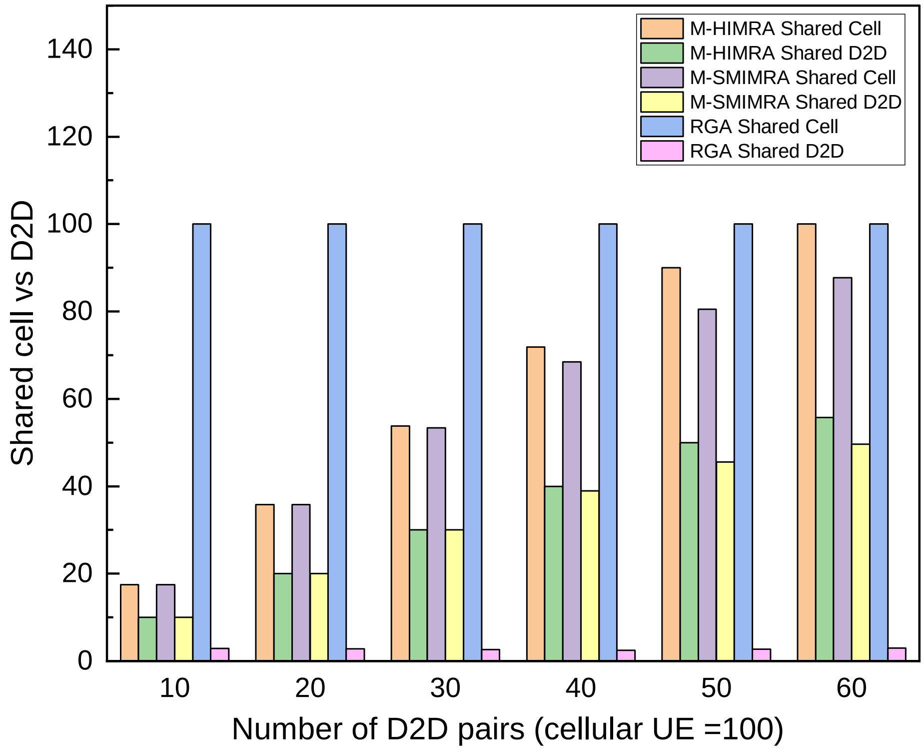


Figure 2.30: Number of assigned D2D pairs vs cellular UEs for different RA algorithms (cellular UEs = 100)

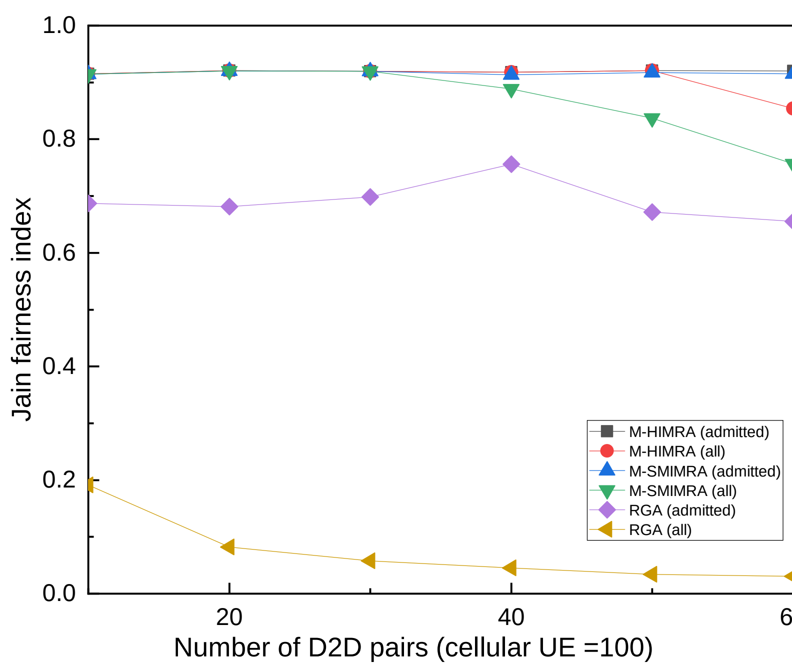


Figure 2.31: Jain fairness index for different RA algorithms (cellular UEs = 100)

Individual cell and D2D sumrate for different RA algorithms in case of One-to-Many paradigm is depicted in Fig. 2.32 and Fig. 2.33.

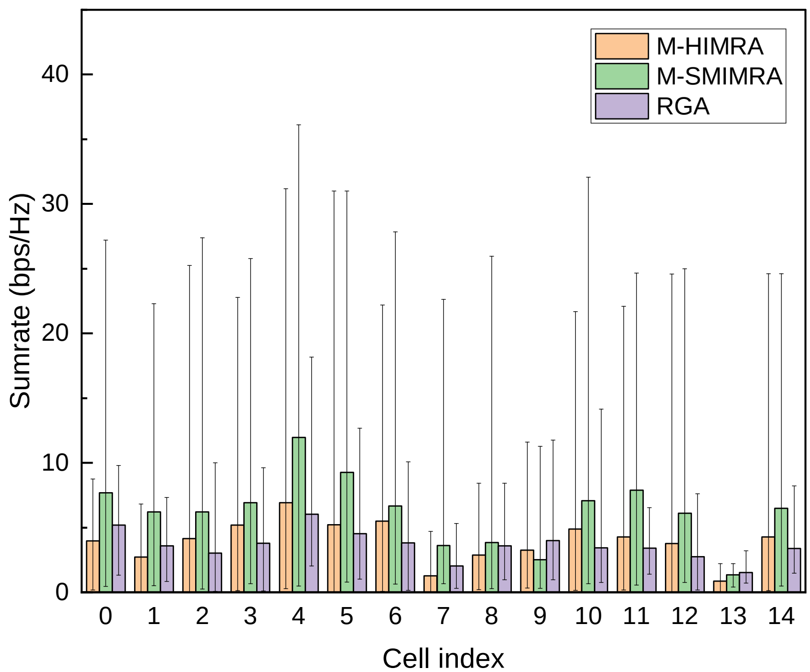


Figure 2.32: Average, minimum, and maximum sumrate of the Cellular UEs for different RA algorithms

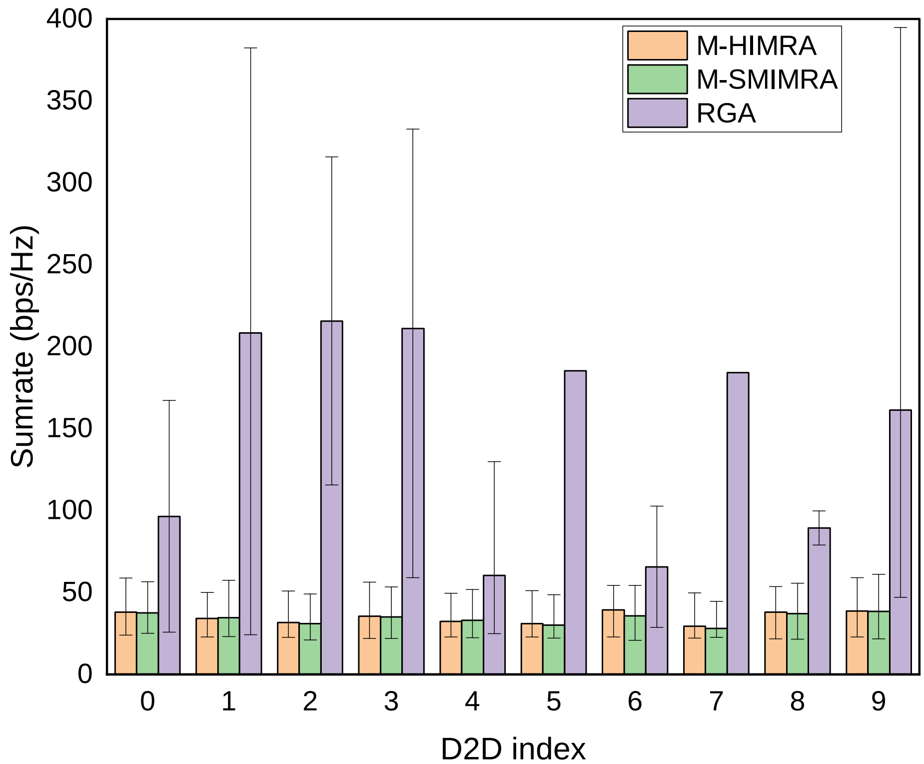


Figure 2.33: Average, minimum, and maximum sumrate of the D2D pairs for different RA algorithms

2.7.2.3 Result Comparison for Many-to-Many sharing algorithms

Different Algorithms for Performance Comparisons: To the best of our knowledge, there is no existing algorithm that addresses the same research problem of considering the individual target sumrate demand for Many-to-Many sharing. We compare the proposed algorithms with We have compared the proposed RA algorithm for Many-to-Many problem domain with two algorithms (KMB, and OCFG). We discuss the key points of all of the algorithms in the next subsection.

Kuhn-Munkres algorithm with backtracking (KMB): KMB [31] solves the Many-to-Many assignment problem by introducing backtrack processes.

Overlapping coalition formation game (OCFG): OCFG [79] is a game-theoretic technique to handle the challenge of D2D communications resource management. OCFG considers interference management and resource allocation simultaneously for the capacity maximization of the D2D pairs. OCFG is a cooperative game with merging and splitting sequences to form a coalition. The initial coalition formation is guided by the priority sequence.

Experimental results

Our experimental results show that the proposed algorithm provided results that are aligned with our research objective; interference minimization while achieving individual target sumrate. It can be observed from Fig. 2.34 that for a varying number of D2D pairs, the proposed algorithm achieved the lowest total system interference for almost all scenarios and KMB achieved the highest total system interference. The performance of OCFG slightly deteriorated from the proposed HMM-IMRA. Since our objective is to minimize total system interference, the total system sumrate obtained by the proposed HMM-IMRA lag behind the other two algorithms illustrated in Fig. 2.36. The sumrate obtained by OCFG is close to our proposed algorithm.

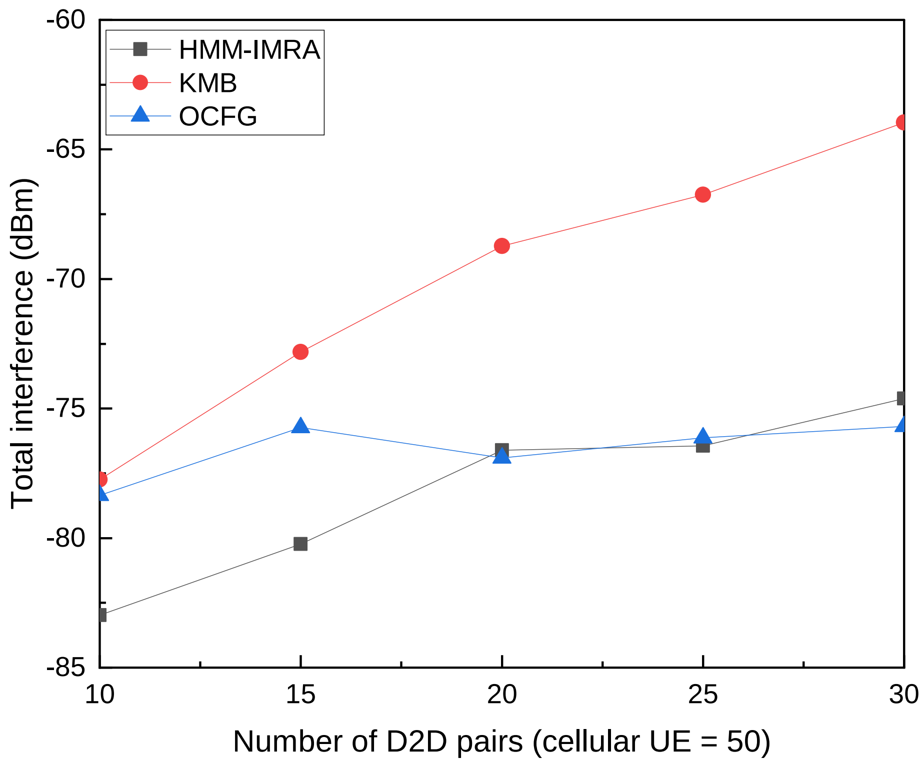


Figure 2.34: Total system interference for different RA algorithms (cellular UEs = 50)

Figure 2.35 represents interference per D2D for Many-to-Many mode of sharing and our proposed HMM-IMRA obtained the least interference per D2D for 50 cellular UEs.

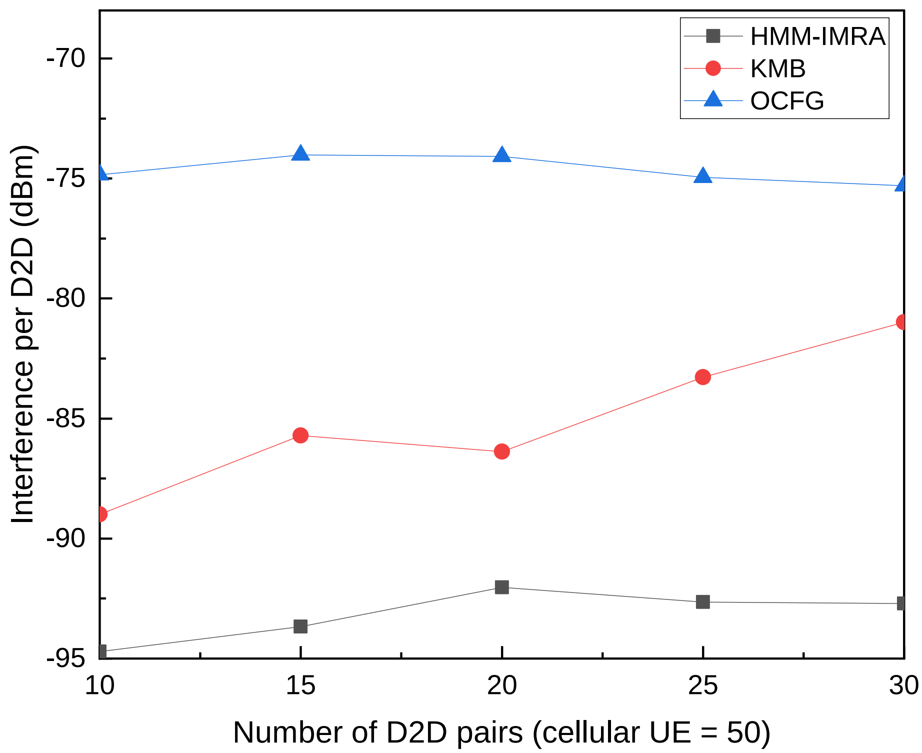


Figure 2.35: Interference per D2D for different RA algorithms (cellular UEs = 50)

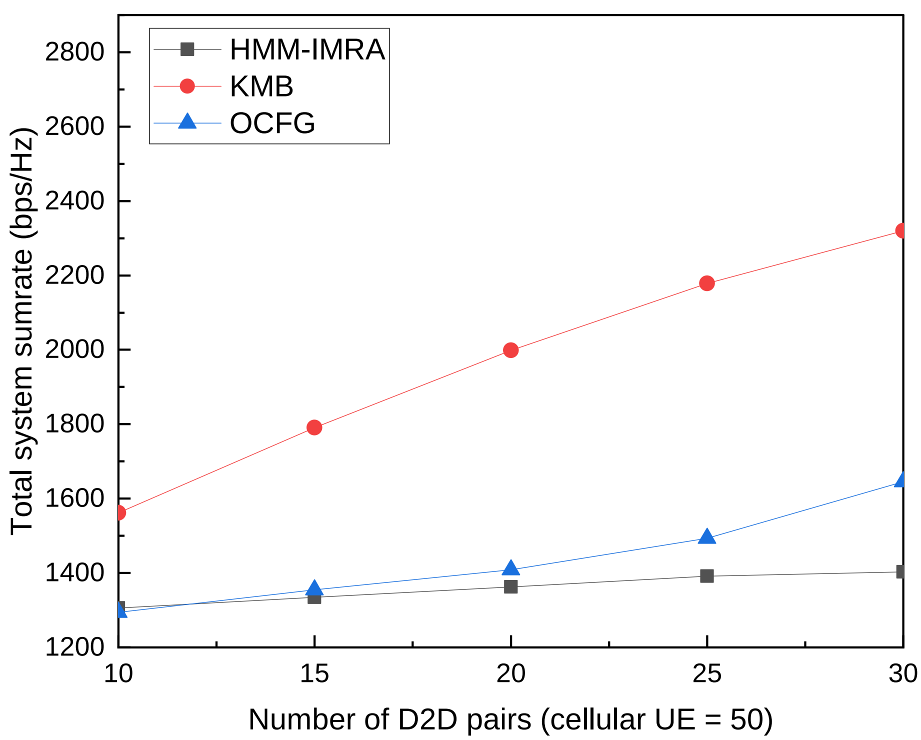


Figure 2.36: Total system sumrate for different RA algorithms (cellular UEs = 50)

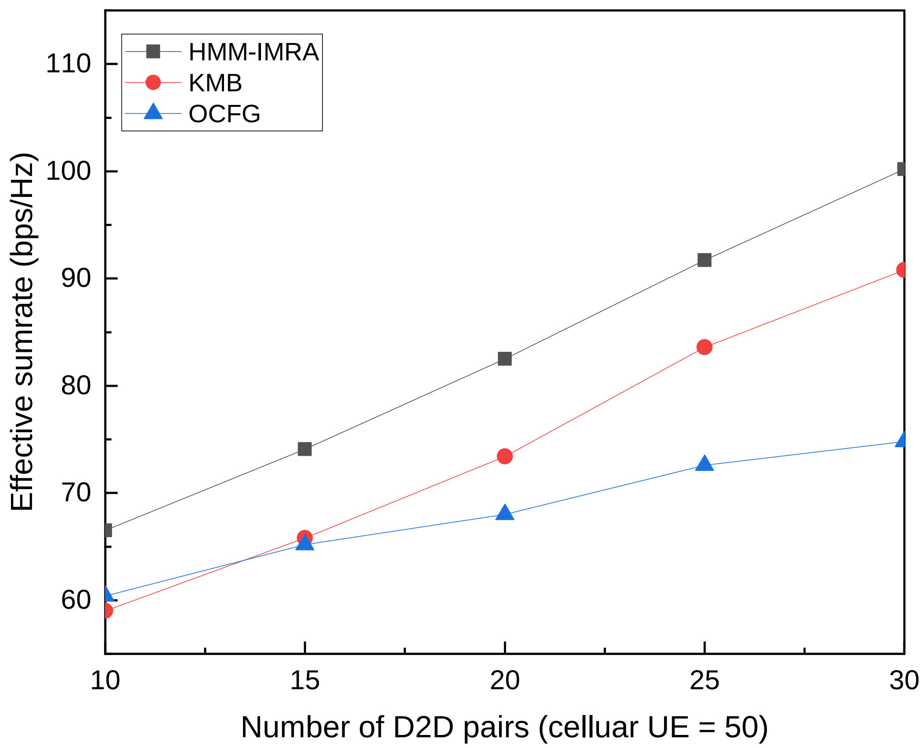


Figure 2.37: Effective sumrate for different RA algorithms (cellular UEs = 50)

As demonstrated in Fig. 2.38, our suggested methods accepted a sufficient number of D2D pairs while having the lowest total system interference. Throughout the trial, the number of admitted D2D pairs is nearly equal to the total number of D2D pairs, regardless of the number of D2D pairings. As the goal of HMM-IMRA is to reduce interference, it occasionally results in fewer D2D pairs being admitted than OCFG and KMB. Owing to fact that the Jain fairness index is strongly connected to the ratio of admitted and total D2D pairs, the OCFG method achieved the lowest Jain fairness index score for both admitted and all D2D pairs which are shown in Fig. 2.40. The proposed methods have a D2D admission rate that is extremely comparable to KMB, resulting in a very similar Jain fairness index score in both circumstances, as shown in Fig. 2.38. Our suggested approach scored between 0.96 and 0.97 on the Jain fairness measure for admitted D2D pairs. HMM-IMRA and KMB did not admit all D2Ds to reduce overall system interference, resulting in a 0.02 decline in the Jain fairness index score based on all D2D pairings.

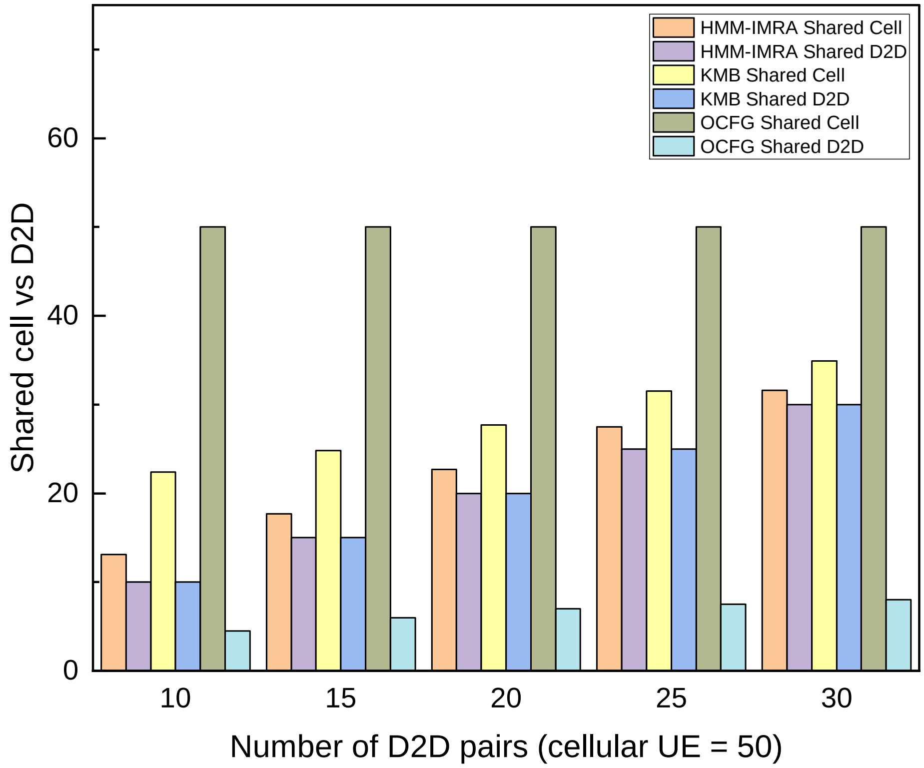


Figure 2.38: Number of assigned D2D pairs vs cellular UEs for different RA algorithms (cellular UEs = 50)

In Fig. 2.39, the straight line represents the required number of cellular UEs to admit per D2D. It is evident from the figure that the allocation scheme of OCFG is irrational since it admitted most of the cellular UEs to only a few D2D pairs to gain maximum sumrate. Another algorithm KMB where the assignment is done without approximation and failed to meet the D2D demand thus resulting in less sumrate and more interference. On the other hand, our proposed algorithm, HMM-IMRA which assigns cells to D2D pairs based on an approximation has successfully met individual D2D demands. So, it is evident from the figure that approximation is important in D2D communication for interference minimization as well as capacity maximization.

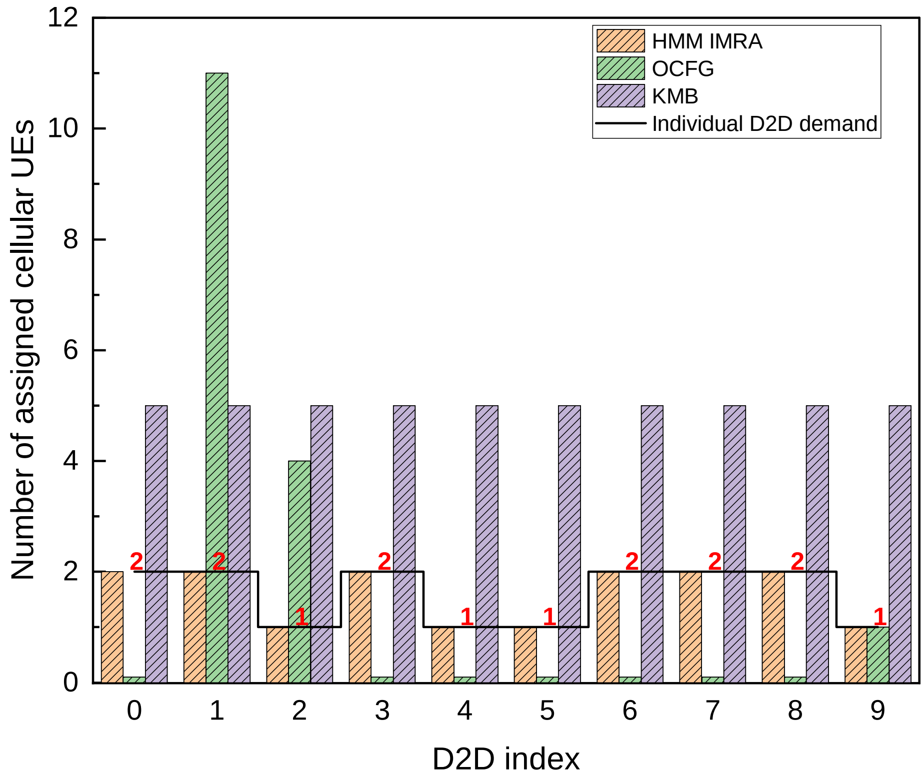


Figure 2.39: Number of assigned D2D pairs vs cellular UEs for different RA algorithms (cellular UEs = 50)

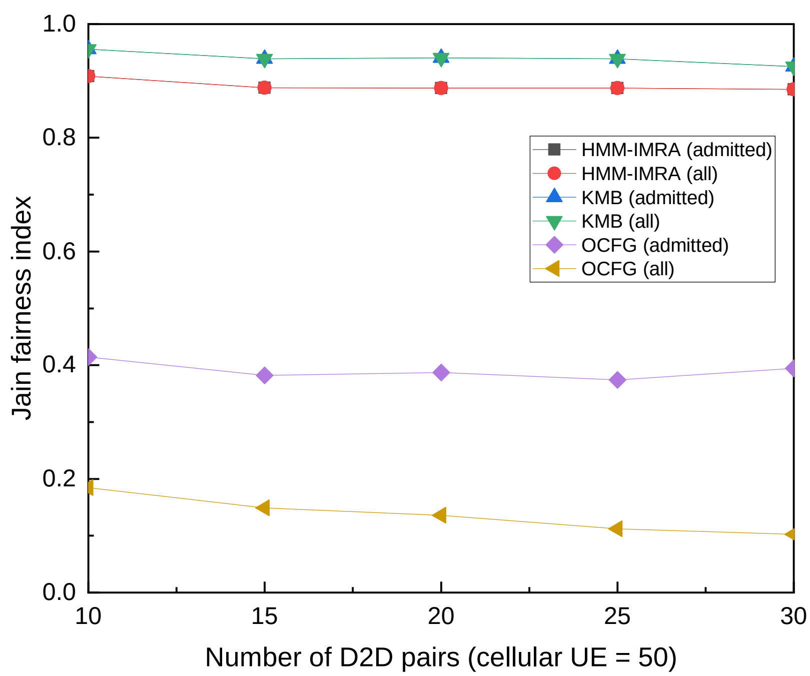


Figure 2.40: Jain fairness index for different RA algorithms (cellular UEs = 50)

Figures 2.41 and 2.42 show individual cell and D2D sumrate for several RA methods in the Many-to-Many paradigm.

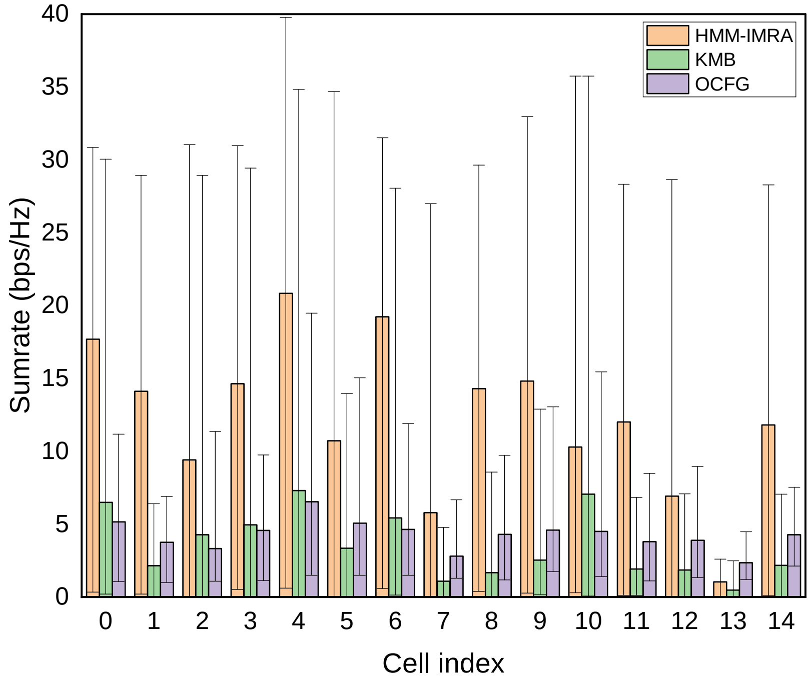


Figure 2.41: Average, minimum, and maximum sumrate of the cellular UEs for different RA algorithms

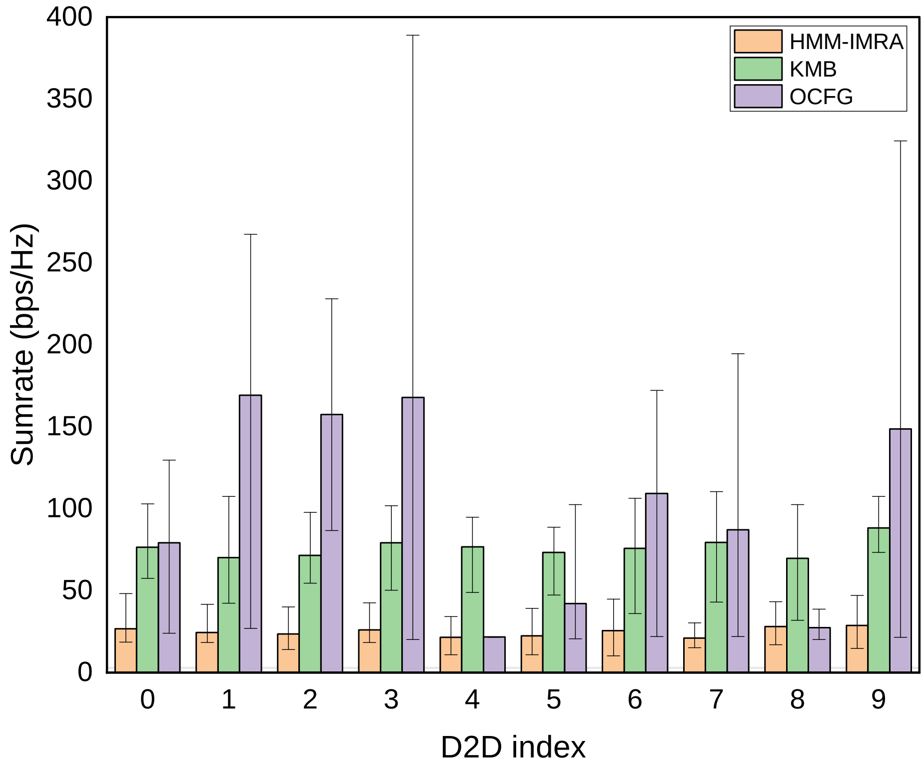


Figure 2.42: Average, minimum, and maximum sumrate of the D2D pairs for different RA algorithms

2.8 Summary

This chapter looks at how to reduce interference in D2D communication over a cellular network. In D2D communication, we offer resource allocation techniques for three types of sharing approaches (One-to-One, One-to-Many, and Many-to-Many). We construct the problem of interference minimization as a weighted bipartite matching problem and apply the proposed algorithms to allocate RBs to the D2D devices while minimizing the system interference. Proposed algorithms HIMRA (One-to-One), M-HIMRA (One-to-Many), and HMM-IMRA (Many-to-Many) algorithms apply the Hungarian method to minimize interference whereas SMIMRA (One-to-One) and M-SMIMRA(One-to-Many) apply stable marriage algorithm to solve the assignment problem. Our proposed Many-to-Many algorithm HMM-IMRA is inspired from [31] where they have employed backtracking with the Kuhn-Munkres (Hungarian) algorithm to allow many to many sharing. However, We find that the existing KMB algorithm does not provide any solution for some input set where a solution exists. We have modified their algorithm and used that in HMM-IMRA. We discovered that our suggested method always guarantees solutions when they are available. Experimental results show that the proposed approaches outperform existing algorithms in terms of interference, admission rate, Jain fairness index, and effective bandwidth.

Chapter 3

Capacity Maximization

3.1 Introduction

This chapter addresses the research question of maximizing the total system sumrate by sharing the RBs among the cellular UEs and the D2D pairs while maintaining the Quality of Service (QoS) in a D2D communication underlaying cellular networks. The research problem is initially addressed by Zulhasnine et al. [3]. They propose a greedy heuristic-based resource allocation algorithm as a solution to the problem. A local search technique is applied to solve the same research problem in [4] which uses the result of the greedy heuristic [3] as the initial feasible solution. A stable matching algorithm [91] based solution is proposed in [18] to solve the sumrate maximization problem where the preference list is calculated based on the proximity of the cellular UEs and the D2D pairs. A graph-based solution is proposed in [19] where the resource allocation problem is formulated as a maximum weight problem. An optimal algorithm based on a weighted bipartite matching algorithm is proposed in [20] to maximize the same objective function. All of the existing solutions are based on different offline algorithms and the research problem can be solved optimally in polynomial time using an offline weighted bipartite matching algorithm as shown in [20]. However, in an LTE system, the scheduling algorithm needs to be very efficient as the scheduling period is very short; preferably less than 1 *ms*. The weighted bipartite matching algorithm (optimal) is quite complex to implement in such a short scheduling period. So, to comply with the fast scheduling requirement, a possible remedy is to run the algorithms online. In an online implementation, an algorithm is run with a smaller instance of the problem specifically with the newly arrived nodes (D2D pairs or cellular UEs) with the available resources (RBs) and the assignments among the nodes irrevocable. However, in the current research problem, a strict online algorithm might leave some of the D2D pairs unassigned if none of the available cellular UEs can satisfy the constraints (SINR, QoS requirement, etc) which contradicts the research goal. On the other hand, if we allow the revocation of an existing assignment, we could assign the new D2D pair (considering that, there exists at least one cellular UE that satisfies its QoS requirements and this assignment improves the overall system sumrate) to the revoked cellular UE and the revoked D2D pair to one of the available cellular UEs. In theory, if an online algorithm relaxes the irrevocable feature, it is called relax online algorithm [22]. Hence, a relaxed online algorithm that performs near to the optimal solution can be a potential alternative to the research problem. The revocation of assignments introduces a new research challenge which is the number of changes in resource allocation between two consecutive states of the system. Due to a bad design of an algorithm, the number of changes may increase which might be a potential reason for a significant system overhead [1], [23]. Though in the literature, there exist few online algorithms in D2D communication [24], [25]. To the best of our knowledge, no other research work discusses an online or relax online algorithm for the same research problem that we consider in this thesis for D2D communication in an in-band underlay scenario.

In the proposed solutions, we present two different assignment schemes i.e., the restricted assignment scheme and the fair assignment scheme. The restricted assignment scheme avoids a sharing that decreases the total system sumrate whereas there is no such restriction on the fair assignment scheme. One of the major contributions of this research work is to design the relax online algorithms in such a way that leads to a minimum number of changes in assignment between two successive allocations hence, incurs minimal system overhead while maximizing the total system sumrate. Numerical results suggest that proposed algorithms outperform the existing offline algorithms in terms of both total system sumrate and the number of changes in successive allocations for both of the assignment schemes. Moreover, the proposed algorithms perform very close to the optimal algorithm [29] in terms of total system sumrate with less number of changes in successive allocations.

The remaining part of the chapter is organized as follows: Section 3.2 presents the background and some notable related works. Section 3.3 discusses the system model and channel model of D2D communication underlay to a cellular network. Section 3.4 contains the problem formulation. Section 3.5 presents the proposed algorithms with analysis. Section 3.7 presents the experimental results, input data model, experimental environment, and performance evaluation. The run time complexity and trace analysis of the proposed algorithms are presented in Section 3.6. Finally, Section 3.8 concludes the chapter with remarks.

3.2 Related Work

To avail the utmost benefits of D2D communication, several research works are ongoing where researchers are deploying different schemes like interference control [92, 44, 93, 94, 95, 96, 97], mode selection [1] [98, 99, 100, 101], power control [102, 103, 101, 104], and spectral resource allocation [105, 106, 107, 108] to exploit the diversity of the communication links. This is achieved by adaptively allocating network resources to optimize some network performance metrics like throughput, delay, interference, etc. A number of surveys have been conducted on different aspects of D2D communication [13, 109, 110, 15, 14, 16, 111, 1, 112, 113, 114, 115, 116]. The authors in [109, 32, 110, 15] have presented the survey on general D2D communication, but there is no survey on mode selection, interference management, and resource alloca-

[1] In general, mode selection involves choosing between cellular mode (i.e., the BS is used as a relay) and D2D mode (i.e., the traffic is directly transmitted to the receiver)

tion. A survey in [1] provides the role of D2D communication in 4G cellular network areas. The survey provided the taxonomy of D2D communication, and then the taxonomy-based detailed survey was presented. This survey also discusses the weakness of D2D communication architecture in cellular networks, enlightening issues such as interference management and power control. The survey work presented in [111] provides a summary of the outcomes for D2D communication in a cellular network. A detailed survey on D2D communication is provided according to the main research areas ranging from peer discovery and link setup to D2D services and applications. The prototypes and the experiments of D2D communication namely, Data Spotting, Relay-by-Smart phone, and Flash LinQ, are reviewed, and their architectural features are discussed. In [110] the authors studied the general D2D communication concept that can involve any D2D links, for example, vehicle-to-vehicle, human-to-human, machine-to-machine, and vehicle-to-human. This is because, from the channel modeling and channel measurements perspective, different types of D2D links will lead to different communication scenarios and thus result in different D2D communication channel models. Another survey [16] discusses cooperative communication and issues degrading the performance of the network such as power consumption, multicasting, and relay selection. Moreover, design challenges and different techniques to handle these limitations are discussed. Authors in [14] present a detailed and systematic survey of D2D communication on the aspect of mode selection, interference management, and resource allocation. They also point out some open research problems in D2D communication.

There are mainly two types of resource allocation schemes in the D2D communication namely, centralized scheme and distributed scheme. Although both schemes have their relative advantages and disadvantages, distributed schemes are more complex and inefficient from the signal processing point of view [1]. Moreover, in distributed schemes, multiple nodes take decisions independently so the joint decision might not comply with the system goal. Numerous research works have been conducted on various resource allocation problems recently that follow the centralized scheme as this research work deals with. Apart from very few works, most of the existing centralized algorithms are offline. Now we discuss some of the related offline algorithms (summarized in Table 3.1) those address the same research problem we are considering in this chapter.

In [3], a greedy heuristic is proposed to select the D2D pairs based on channel quality information to reduce the interference of the cellular network. A D2D pair with the lowest channel gain which is not yet assigned is selected for a cellular UE that has a higher Channel Quality Information (CQI) given that the QoS constraints are maintained. However, this process may not terminate in the worst case. Moreover, some of the D2D pairs might be missed out to be allocated or some of the D2D pairs selected earlier for some of the cellular UEs might give a better sumrate to some other cellular UEs chosen later on.

A local search algorithm in [4] is designed to solve the same resource allocation problem where the target is to maximize the system sumrate while maintaining some QoS constraints. The result of the greedy heuristic [3] is considered the initial feasible solution of this algorithm. Since the final result of a greedy heuristic might miss out on some assignments of D2D pairs which is considered the optimal solution, these D2D pairs can also be missed out in the final assignments returned by this local search algorithm. In practice, the local optima of the algorithm can be far away from the global solution too. Moreover, as local search is an iterative improvement technique, it might take much more time to reach the final solution and may not be very useful in LTE and beyond networks.

A deferred acceptance-based algorithm is proposed in [18] to solve the same problem where the D2D pairs and the cellular UEs maintain a preference list of nodes (D2D pairs or cellular UEs) wish to share with. The preference list is calculated based on the increasing order of the proximity which is not the best approach for this optimization problem. Moreover, the preference matrix does not consider the QoS requirements. Examples can be shown easily where an assignment is possible using this algorithm where QoS requirements are not met.

A graph-based algorithm in [19] is proposed to solve the resource allocation problem in the uplink channel which is similar to the problem we are considering. They formulate the allocation of the channel to the D2D pairs to obtain the maximum system capacity as a maximum weight matching problem. However, they do not consider QoS requirements as well as allow some D2D pairs to share which may incur a lower sumrate.

Hussain *et al.* [20] propose an optimal resource allocation algorithm for maximizing the system sumrate. It is found that some sharing can also decrease the system sumrate. Considering this observation, they design an optimal algorithm based on weighted bipartite matching which avoids such sharing and maximizes the total system sumrate. Consider that, we have a set of already known cellular users and D2D pairs are coming online and once a D2D pair arrives, we assign it to one of the available cellular users. However, if none of the available cellular users can satisfy its QoS, we can not assign it. On the other side, if we could break an existing assignment, we could assign this new D2D pair (considering there exists at least one cellular user that satisfies its QoS requirements and this assignment improves the overall system sumrate). In addition, the revoked D2D pair can also be assigned to any of the available channels (if QoS requirements are met). We summarize all of the discussed algorithms in Table 3.1, 3.2 and 3.3 respectively.

Table 3.1: Summary of Existing Resource Allocation Algorithms to Maximize the System Capacity for D2D Communication (One-to-One sharing)

One-to-One sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
Greedy Heuristic [3]	Uplink/ Downlink	• Greedy approach. • Uses CQI (Channel Quality Identifier) as evaluation weight. • QoS is maintained.	• Might not terminate in some cases • Resources are allocated only based on QoS constraints	$O(n^2)$ for each phase
LORA [4]	Downlink	• Local search technique. • Uses [3] as the initial feasible solution. • QoS is considered.	• Performance depends on the initial feasible solution. • Might be stuck in local optima.	$O(n^2S)$, S is total system sum rate and n is the number of total cellular UEs
DARA [18]	Downlink	• Stable matching algorithm. • Uses proximity for preference calculation.	• Proximity is not an appropriate choice of preference for the application. • Ultimate result differs from theory. • QoS is not considered	$O(n^2)$, n is the number of cellular UEs.

Table 3.1: Summary of Existing Resource Allocation Algorithms to Maximize the System Capacity for D2D Communication (One-to-One sharing)

One-to-One sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
Graph-Based [19]	Downlink	• Maximum weight matching algorithm. • Uses sum rate as evaluation weight.	QoS is not considered	$O(mn)$, m is the number of D2D pairs and n is the number of cellular UEs.

Table 3.2: Summary of Existing Resource Allocation Algorithms to Maximize the System Capacity for D2D Communication (One-to-Many sharing)

One-to-Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
CORAL [117]	Downlink	• Better sumrate • Unfair due to core region	• consider channel gain solely • Greedy approach and • Might be stuck in local optima	$O(mn^2)$, m is D2D pairs and n is cell
RGA [85]	Downlink	• Strict candidate set	• Unfair • Greedy approach	$O(n^2)$

Table 3.2: Summary of Existing Resource Allocation Algorithms to Maximize the System Capacity for D2D Communication (One-to-Many sharing)

One-to-Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
OGA [85]	Downlink	• Flexible candidate set	• Unfair • Greedy approach	$O(n^2)$
HGA [85]	Downlink	• Hungarian algorithm based • Fair	• High complexity	$O(n^3)$

Table 3.3: Summary of Existing Resource Allocation Algorithms to Maximize the System Capacity for D2D Communication (Many-to-Many sharing)

Many-to-Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
GOAL [118]	Downlink	• Graph coloring based approach.	Produces low sum rate in critical scenario	$O(nm^2)$, m is D2D pairs, n is cell
MAD [85]	Downlink	• Graph coloring based approach • Better result than GOAL • No issue of critical scenario	Complex weight and color assignment	$O(nm^2)$, m is D2D pairs, n is cell

Cai *et al.* [118] propose a graph coloring-based heuristic algorithm (GOAL) where the D2D pairs are represented as vertices and the RBs of the cellular UEs are represented as a set of colors. They formulate the research problem as a mixed-integer nonlinear programming problem (MINLP) with the objective to maximize the system capacity. However, they consider an unrealistic scenario where the total number of the D2D pairs is larger than that of the cellular UEs. To justify this scenario, they consider many to many relationships among the D2D pairs and cellular UEs which means one D2D pair can share the resources of multiple cellular UEs, as well as multiple D2D pairs, can share the resource of a single cellular UE. Such a scenario is not found in any other resource allocation problem for D2D communication and the model is very complex. In [85], another many-to-many sharing algorithm is proposed named Multiple allocations in D2D (MAD) is also a graph coloring-based algorithm and outperforms GOAL in case of some critical scenarios. A number of research works [84], [27], [26] address the research problem of interference minimization while maintaining a target sumrate by sharing the radio resources among the cellular UEs and the D2D pairs. In [26], a knapsack-based approximation algorithm is proposed to solve the resource allocation problem. In [27], a bi-phase resource allocation algorithm is proposed where an auction-based fair algorithm is used in the first phase to allocate the resources and in the second phase, a local search technique is used to improve the solution of the first phase. A similar algorithm is proposed in [84] where a weighted bipartite matching algorithm is used in the first phase to minimize the system interference at the time of allocating the resources among the cellular UEs and the D2D pairs. Janis *et al.* [119] introduce an interference aware resource allocation scheme that utilizes the uplink radio resources. This approach works in a coordinated fashion where the D2D pairs sense the radio environment and send it to the base station. Then the base station creates the local awareness of the radio environment among the D2D pairs and the cellular UEs and exploits the multi-user diversity of the cellular network to minimize the interference. A similar work is presented in [97] that suggests an interference-limited area for the cellular UEs where the D2D pairs share the uplink resources. Similarly, a restricted zone is also modeled for the downlink medium. In both of the cases, a candidate set of D2D pairs is selected for the allocation. However, the allocation of a candidate D2D pair may not be the optimal one.

Feng *et al.* [120] propose a three-step scheme that performs admission control of the D2D pairs initially to check whether the QoS requirement for both a D2D pair and a cellular UE is met or not and then performs an optimal power control scheme to maximize the overall throughput of the system and finally, a maximum weighted bipartite matching is used for the final allocation. The admissibility of a D2D pair is calculated depending on the transmission range of the D2D pair and a cellular UE. They also formulate an estimation process of required power and adopt the maximum weighted bipartite matching algorithm to calculate the feasible solution. However, some of the D2D pairs might be considered in the admissible set which reduces the system capacity. Huang et al. [121] propose a game theory-based resource allocation algorithm for the multi-cell environment that utilizes uplink resources. They have characterized each base station (BS) as a player competing for the RBs where the utility of each player is defined as the revenue collected from both the cellular UEs and the D2D pairs by using the RBs. They claim that each player is blind to their peers' payoff information which means the information about the peers' transmission parameter may be incomplete. In this approach, a player uses some probabilistic methods to determine the strategy of other players.

An analysis of the D2D communication on both spectrum overlay and underlay to the existing cellular network with ad-hoc networks is discussed in [43]. They present the major implications of the coexistence of cellular and ad-hoc networks. They also apply a technique called successive interference cancellation to generate a good transmission capacity. A similar research problem is addressed by Huang *et al.* in [122] where they propose that frequency separation of a cellular network from an ad hoc network overlaying the cellular network would give maximum transmission capacity rather than spatial diversity, i.e. disjoint sets of sub-carriers are used by the ad hoc network. The performance of D2D communication underlay to cellular communication is analyzed in [123] which reduces the performance degradation of the existing cellular network by controlling the transmitting power of the D2D pairs.

A position-based mode selection and resource allocation are addressed by X. Liu *et al.* in their work [124]. In this position information, at first, they introduced an offline channel state information. Then they divided the geographical region into some grids of equal size. Within the same grid area, each of the mobile stations feed-backs the signal strength along with the location information previously obtained. The eNB averages the collected signal strengths and further retrieves CSI which is later on used to estimate SINR in that grid. Then an optimization problem is formulated to maximize the sum rate of all the users. They proposed a differential evolution algorithm to solve the optimization problem to find the optimum mode and resource allocation. Therefore, in their work, at first, an offline channel state information model is used to estimate the SINR at each location. Then the optimization problem is formulated to maximize the sum rate of all users subject to the constraints of the minimum data rate for the links.

A number of game-theoretic solutions have been proposed for the resource allocation problem of D2D communication. In [83], an overlapping coalition formation game (OCFG) has been proposed to maximize the sumrate of all D2D pairs.

The contribution and differences of various surveys have been presented in Table 3.4.

Table 3.4: Summary of Contributions and Differences of Various Surveys

References	In-band	Out-band	Centralized	Distributed	Power control	Spectrum allocation
[1]	✓	✓			✓	
[16]					✓	
[110]	✓		✓	✓	✓	
[14]	✓		✓	✓	✓	✓
[109]	✓					
[124]	✓		✓	✓		✓
[112]	✓	✓		✓		✓
[113]	✓	✓	✓	✓	✓	✓
[114]	✓			✓		✓
[115]	✓		✓			✓

3.3 System Model and Channel Model

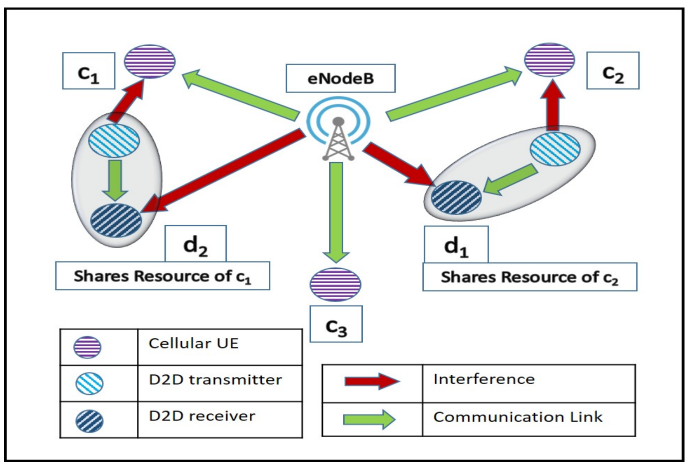


Figure 3.1: System model using downlink resources

This thesis considers a system with a single cell area consisting of a single eNB, some D2D pairs, and some cellular UEs. In a normal scenario, the total number of the cellular UEs is much higher than the total number of the D2D pairs. We consider a similar scenario used in [4],[3],[18] with n cellular UEs and m D2D pairs ($n>>m$) and a cellular UE can share the RBs with a single D2D pair. The set of the cellular UEs is represented as, $C = \{c_1, c_2, c_3, ..., c_n\}$, whereas the set of the D2D pairs is represented as, $D = \{d_1, d_2, d_3, ..., d_m\}$. A D2D pair $d_j \in D$ contains a receiving device d_j^r and a transmitting device d_j^t. Though the D2D pairs directly communicate with each other, the connection establishment and the resource allocation is handled by the eNB [18].

LTE network consists of both uplink (UL) and downlink (DL) resources. In our work, we only consider the DL resources, and Fig. 3.1 represents the system model we consider. The eNB transmits a signal to the cellular UEs using DL resources, so the cellular UEs only experience interference from their shared D2D transmitters (c_1 is affected by d_2 and c_2 is affected by d_1) whereas, D2D receivers encounter interference from the eNB (both d_1 and d_2 are affected by the eNB). As c_3 does not share the RBs with any of the D2D pairs, c_3 experiences no interference.

We consider an Urban Micro System, which follows Rayleigh fading path loss model [4],[3],[18]. As the channels are assumed to be orthogonal, only intra channel interference is present. The path loss (db unit) equation is,

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

where, $dist$ (meter) is the distance between a D2D transmitter and a receiver and f_c (GHz) is the medium frequency. Now the channel gain between these two devices is,

$$G^{x,y} = 10^{-PL^{x,y}/10}, \tag{3.2}$$

where, x and y are the two devices and $PL^{x,y}$ is the distance dependent path loss between x and y.

We consider the total number and the relative position of the cellular UEs and the D2D pairs in the system at any moment as a state of the system. The state of such a dynamic system might change over time due to the following events.

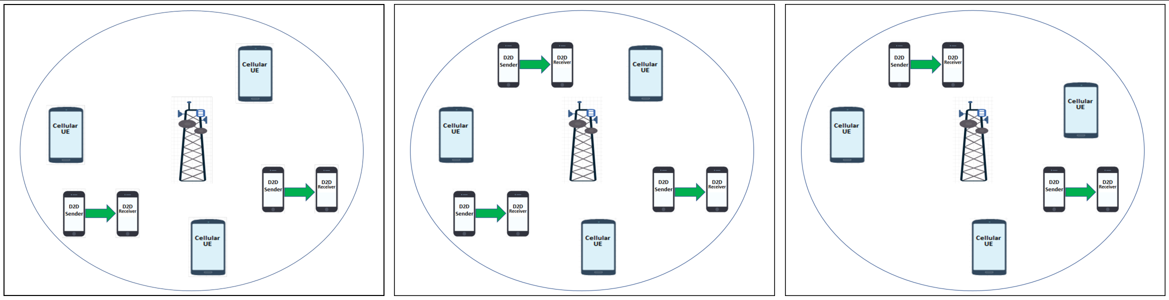
- **D2D Arrival:** New D2D pair comes into the cell. Resource Blocks need to be allocated to the newcomer. So this event changes the state of the system.

- **Cellular Arrival:** A new cellular UE comes into the cell making the previous sharing a sub-optimal solution. There is a chance that sharing may change to attain a higher sumrate which subsequently changes the state of the system.

- **D2D Departure:** A D2D pair leaves the system making the previous sharing a sub-optimal solution. There is a possibility that the existing D2D pair can share with the newly freed cellular UE to attain a higher system sumrate.

- **Cellular Departure:** If a shared cellular UE leaves the system, the shared D2D pair will be out of resource blocks. Thus the system state is changed.

In this thesis, we consider that the state of the system changes over time due to the arrival or departure of the D2D pairs into the system as well as due to the mobility of both the cellular UEs and the D2D pairs. Figure 3.2 depicts different states of the system with the arrival and departure of the D2D pairs. We consider the D2D arrival/departure as a system event that triggers the resource allocation process to allocate the RBs for the new state of the system. In other words, we can say that when a new D2D pair arrives in the system, the necessary RBs for communication needs to be allocated to the newcomer as this event changes the state of the system. We also accommodate user mobility in our model by defining some decision points where we trigger the proposed resource allocation schemes with the new location of the devices (cellular UEs and D2D pairs). Every decision point is considered a system event because it represents a new state of the system as the location of the devices is changed. However, we impose restrictions on the minimal interval between two decision points. We limit this just to keep the model simple, otherwise, implementation of user mobility in our system would be impractical.



(a) Initial state (b) D2D arrival (c) D2D departure

Figure 3.2: Different states of the system

3.4 Problem Formulation

The SINR of a receiver is the ratio between the received signal power and the interference with the noise power. In a downlink interference model, the SINR value of a cellular UE depends on the transmitting power of the eNB, channel gain between the eNB, and the cellular UE as well as the intra channel interference. Let us consider the individual transmitting power of the eNB, a cellular UE c_i, and a D2D transmitter d_j^t are P^{eNB}, P^{c_i}, and $P^{d_j^t}$ respectively. The thermal noise which is also known as the energy of Additive White Gaussian Noise introduced at the receiver end is denoted by σ. So the SINR of a cellular UE c_i in DL phase [3] can be represented as,

$$\gamma_{c_i}^{DL} = \frac{P^{eNB} G^{eNB,c_i}}{\sigma + \sum_{d_j} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,c_i}}, \tag{3.3}$$

where, $G^{d_j^t,c_i}$ implies the channel gain between a D2D transmitter d_j^t and a cellular UE c_i. A binary variable, $x_{c_i}^{d_j}$ indicates whether the D2D pair, d_j shares the RBs of the cellular UE, c_i or not. In the denominator, summation refers to the total interference of all the D2D pairs sharing the RBs of the cellular UE c. If none of the D2D pairs share the RBs of the cellular UE c_i, no intra cell interference is incurred. So the SINR of such the cellular UE using DL resources can be represented as,

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

Similarly, the SINR at the receiving end of a D2D pair d_j using DL resources [3] can be presented as,

$$\gamma_{d_j}^{DL} = \frac{\sum_{c_i} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,d_j^r}}{\sigma + P^{eNB} G^{eNB,d_j^r} + \sum\limits_{c_i \epsilon C} \sum\limits_{\substack{d_j' \epsilon D, \\ d_j' \neq d_j}} x_{d_j}^{c_i} x_{d_j'}^{c_i} P^{d_j^{t'}} G^{d_j^{t'},d_j^r}}, \tag{3.5}$$

where, $G^{d_j^t,d_j^r}$ implies the channel gain between the transmitting end d_j^t and the receiving end d_j^r of the D2D pair d_j. Summation on the numerator indicates the total signals incurred from a D2D pair d_j for different cellular UEs sharing the same D2D pair d_j. Double summation in the third term of the denominator indicates the total interference from other D2D devices $d_j' \epsilon D$ which are using the same RBs as the D2D pair d_j. This type of interference is present in a many-to-one or many-to-many sharing approach where multiple D2D pairs can share the RBs of a single cellular UE.

If B is the channel bandwidth, according to the Shannon's Capacity formula, the sumrate contribution of a cellular UE c_i, using down link resources can be presented as,

$$R_{c_i}^{DL} = B \log_2(1 + \gamma_{c_i}^{DL}). \tag{3.6}$$

If none of the D2D pairs share the RBs of the cellular UE c_i, then the sumrate contribution of c_i can be presented as,

$$R_{c_i^0}^{DL} = B \log_2(1 + \gamma_{c_i^0}^{DL}). \tag{3.7}$$

Similarly, the sumrate contribution of the D2D pair d_j, using DL resources can be presented as,

$$R_{d_j}^{DL} = B \log_2(1 + \gamma_{d_j}^{DL}). \tag{3.8}$$

Now, based on Eqn. (3.6), Eqn. (3.7), and Eqn. (3.8), the optimization problem of maximizing the total system sumrate while satisfying the QoS requirements can be formulated as,

$$\max \Big(\sum_{c_i}^{C} (1 - \sum_{d_j}^{D} x_{c_i}^{d_j}) R_{c_i^0}^{DL} N_{c_i} + \sum_{c_i}^{C} \sum_{d_j}^{D} x_{c_i}^{d_j} (R_{c_i}^{DL} + R_{d_j}^{DL}) N_{c_i} \Big) \tag{3.9}$$

subject to,

$$\gamma_{c_i}^{DL} \geqslant \gamma_{c_i,target}^{DL}, \ \forall \, c_i \in C \tag{3.10}$$

$$\gamma_{d_j}^{DL} \geqslant \gamma_{d_j,target}^{DL}, \ \forall \, d_j \in D \tag{3.11}$$

$$x_{c_i}^{d_j} = \{0, 1\} \ , \quad \forall \, c_i \in C \quad \text{and} \quad \forall \, d_j \in D, \tag{3.12}$$

where, $x_{c_i}^{d_j}$ is a decision variable which indicates whether a D2D pair, d_j shares the RBs of a cellular UE, c_i or not and N_{c_i} implies the number of RBs allocated to a cellular UE c_i. The first part of the objective function (Eqn. 3.9) maximizes the total sumrate contribution of the unassigned cellular UEs where the optimization variable, $R_{c_i^0}^{DL}$ represents the sumrate contribution of an unassigned cellular UE, c_i^0. The second part of the objective function maximizes the total summrate contribution of the assigned cellular UEs with the D2D pairs where the optimization variables, $R_{c_i}^{DL}$ and $R_{d_j}^{DL}$ represent the individual sumrate contributions of a cellular UE, c_i and a D2D pair, d_j respectively when d_j reuses the RBs of c_i. $\gamma_{c_i,target}^{DL}$ and $\gamma_{d_j,target}^{DL}$ represent the SINR thresholds for a cellular UE, c_i and a D2D pair, d_j respectively. Constraints (3.10) and (3.11) ensure the QoS requirements by maintaining a minimum required

SINR value for normal transmission rate where as constraint (3.12) confirms that the decision variable, $x_{c_i}^{d_j}$ is a binary variable.

Based on the nature of the sharing approach (One-to-One, One-to-Many, and Many-to-Many), a number of constraints need to be satisfied. For One-to-One sharing approach, the objective function needs to satisfy the following two extra constraints.

$$\sum_{d_j} x_{c_i}^{d_j} \leqslant 1 \,, \quad \forall\, c_i \in C \tag{3.13}$$

$$\sum_{c_i} x_{c_i}^{d_j} \leqslant 1 \,, \quad \forall\, d_j \in D \tag{3.14}$$

Constraint (3.13) implies that a cellular UE might share the RBs with a maximum of one D2D pair and constraint (3.14) indicates that a D2D pair might share the RBs of a maximum of one cellular UE. Both of the constraints (3.13) and (3.14) ensure the orthogonality among the cellular UEs and the D2D pairs while sharing the RBs. So, the stated optimization problem is to maximize the total system sumrate (Eqn. (3.9)) while satisfying the constraints (3.10) - (3.14) for One-to-One sharing approach.

In case of One-to-Many sharing approach, one D2D pair can share the RBs of multiple cellular UEs mutually exclusively. In this type of sharing approach, the objective function need to satisfy constraint (3.13) of whereas, constraint (3.14) can be relaxed as follows:

$$0 \leqslant \sum_{c_i} x_{c_i}^{d_j} \leqslant n \,, \quad \forall\, d_j \in D. \tag{3.15}$$

So, any solution to the maximization problem for One-to-Many sharing approach need to satisfy the constrains (3.10), (3.11), (3.12), (3.13), and (3.15).

In the case of Many-to-Many sharing approach, a D2D pair can share the RBs of multiple cellular UEs without holding the mutual exclusion property. In other words, we can say a D2D pair can share the RBs of multiple cellular UEs, and different D2D pairs can share the RBs of a particular cellular UE. In this case, both constraints (3.13) and (3.14) of One-to-One sharing can be relaxed. Constrain (3.13) can be relaxed as follows:

$$0 \leqslant \sum_{d_j} x_{c_i}^{d_j} \leqslant m \;, \quad \forall \, c_i \in C \tag{3.16}$$

So, any solution to the maximization problem for Many-to-Many sharing approach need to satisfy the constrains (3.10), (3.11), (3.12), (3.15), and (3.16).
Although Eqn. (3.3) and Eqn. (3.5) suggest the concept of multiple sharing among the D2D pairs and the cellular UEs, proposed algorithms One-to-One sharing approach avoid multiple sharing among them. Sharing the RBs of a single cellular UE with multiple D2D pairs generate higher interference to the existing cellular network which might not be acceptable and sharing the RBs of multiple cellular UEs by a single D2D pair produces a complex model.

We define two types of assignment schemes i.e., the restricted assignment scheme and the fair assignment scheme of the proposed solution for One-to-One sharing approach. In the restricted assignment scheme, if an assignment returns a negative sumrate gain for a particular cellular UE and a D2D pair, that particular sharing is avoided. More specifically, for a cellular UE, $c_i \in C$ and a D2D pair, $d_j \in D$; if the value of ($R_{c_i}^{DL}$ + $R_{d_j}^{DL}$ - $R_{c_i^0}^{DL}$) is negative, the restricted assignment scheme does not assign the RBs of c_i to d_j. However, there is no such restriction on the fair assignment scheme which means every D2D pair gets a fair chance of sharing the RBs of a cellular UE given that constraints (3.10) and (3.11)) are satisfied. This thesis aims to maximize the total system sumrate contributed by all of the individual cellular UEs and the D2D pairs in a particular allocation in both the fair and the restricted assignment schemes for

One-to-One sharing approach. Moreover, special attention is given to maintaining a minimal number of changes in assignment between two successive states of the system for this approach.

3.5 Proposed Solutions

We propose solutions for both One-to-One and One-to-Many sharing approaches which maximize the system's capacity to address the research problem. We propose two relax online algorithms for One-to-One sharing. We name our first algorithm as Relax Online Resource Allocation Algorithm (RORA). Our second algorithm is a variant of our first algorithm and we name our second algorithm as Conservatively Relax Online Resource Allocation Algorithm (CRORA). Both of the algorithms are explained in Section 3.5.3.1 and Section 3.5.3.2 respectively. For One-to-Many sharing, we propose two online algorithms. We name the first proposed algorithm as Fair Multiple Online Resource Allocation Algorithm (F-MORA), and we name the second algorithm of One-to-Many sharing as Restricted Multiple Online Resource Allocation Algorithm (R-MORA). Both of the algorithms are explained in Section 3.5.4.1 and Section 3.5.4.2 respectively. All of the four proposed algorithms are stable matching [30] based algorithms to allocate the RBs among the cellular UEs and the D2D pairs in in-band underlay mode while maximizing the total sumrate of a system. A stable matching algorithm is applied on a bipartite graph of two disjoint sets where all of the members of each set prepare a list that represents their degree of preference for all of the members of another set. To prepare the preference list, every member of a set ranks all of the members of another set based on some criteria. The stable matching algorithm finds a matching between two members from two disjoint sets based on the preference list. In other words, we can say a stable matching algorithm maps the elements from one set to the elements of another set. We treat the resource allocation problem as a bipartite matching problem and apply the proposed algorithms to find a stable matching or an assignment between a D2D pair and a cellular UE. The performance of a stable matching algorithm depends on the different criteria based on which preference list is calculated. So, before describing the proposed algorithms, we shed some light on the calculation of the preference list of any node (D2D pair or cellular UE) in the following subsection.

3.5.1 Weight based Preference List

The preference list of a node of a bipartite graph is the main element of a stable matching algorithm. The existing stable matching-based algorithm [18] for resource allocation in D2D communication uses proximity, as the basis of preference list calculation where a node with a lower distance is preferred over a node with a higher distance. In the proposed algorithms, instead of using proximity, we use sumrate gain as a weight value to generate the preference list of a node. As the prime goal is to maximize the total system sumrate, in preference calculation, sumrate gain is the weight value.

Assume that, $R_{c_i}^{d_j}$ is the sumrate contribution when a cellular UE, c_i shares the RBs with a D2D pair, d_j and $R_{c_i}^{0}$ is the sumrate contribution when the cellular UE, c_i does not share the RBs with any of the D2D pairs. So,

$$\triangle R = R_{c_i}^{d_j} - R_{c_i}^{0} \tag{3.17}$$

implies the gain in total system sumrate when a cellular UE, c_i shares the RBs with a D2D pair, d_j. So if the value of $\triangle R$ is non-negative, that particular sharing does not reduce the total system capacity. So, $\triangle R$ is the weight based on which the preference lists of all of the nodes are calculated. In the proposed algorithms, a D2D pair, d_j prefers a cellular UE, c_i over another cellular UE, c_i' if (c_i,d_j) provides better sum rate gain than (c_i',d_j) and same thing is true for a cellular UE. The sumrate gain can be either positive or negative which means the total system sumrate can either increase or decrease if a D2D pair shares the RBs of a cellular UE. We define a binary variable, $p^R_{c_i,d_j}$ to indicate the presence of a node (cellular UE or D2D pair) in the preference list of another node for the restricted scheme as,

$$p^R_{c_i,d_j} = \begin{cases} 1, & \text{if } \triangle R \text{ is non-negative and constraints (3.10) and (3.11) are satisfied,} \\ 0, & \text{otherwise.} \end{cases}$$

which indicates that in the case of the restricted assignment scheme if a D2D pair, d_j and cellular UE, c_i return non-negative sumrate gain and satisfy constraints (3.10) and (3.11) then only d_j is kept in the preference list of c_i and vice-versa. In the case of the fair assignment scheme, all of the nodes are always kept in the preference list whether they are providing positive or negative sumrate gain given that constraints (3.10) and (3.11) are satisfied. Similarly for the fair assignment scheme we define a binary variable, $p^F_{c_i,d_j}$ as,

$$p^F_{c_i,d_j} = \begin{cases} 1, & \text{if constraints (3.10) and (3.11) are satisfied,} \\ 0, & \text{otherwise.} \end{cases}$$

3.5.2 Algorithm Scheduler

Algorithm 7 is a scheduler that triggers the proposed algorithms RORA (Algorithm 8) and CRORA (Algorithm 9) based on two system events namely, arrival event and mobility event. We define the arrival of a D2D pair in the system as an arrival event and the movement of the cellular UEs and the D2D pairs as a mobility event. The occurrence of any one or both of the events trigger the proposed algorithms

(RORA and CRORA) to give a new assignment for the new state. To accommodate, the mobility of the nodes in the proposed solutions, we define some decision points where we calculate the location of the devices (cellular UEs and D2D pairs). In every decision point, a mobility event triggers both of the proposed algorithms because every decision points represent the new state of the system as the location of the devices is changed. In the current implementation, we do not consider the departure event of the D2D pairs to keep the model simple. Although departure event would make the system more realistic; its exclusion does not add any demerit point to the proposed algorithms as any of the arrival and departure events would trigger the proposed algorithms (RORA and CRORA) with a new set of cellular UEs and D2D pairs.

3.5.3 Algorithms for One-to-One Sharing Approach

We propose two relax online resource allocation algorithms for One-to-One sharing approach in the in-band underlay D2D communication. Both RORA and CRORA are based on a stable matching algorithm [30]. In the existing online weighted bipartite algorithm [125] and stable matching algorithm [126], an assignment is irrevocable. However, in the proposed solution, we allow revocation of an assignment to meet our research goal of maximization of the total system sumrate. Our proposed relax online algorithms assume the cellular UEs as a fixed set and the D2D pairs as an adversary set which means the total number of D2D pairs varies in different states of the system as they arrive in the system online. The proposed algorithms run when a new D2D pair arrives into the system and we define the arrival of a D2D pair as a system event. An occurrence of such a system event leads to a change in the state of the system and it triggers the proposed algorithms to change the current resource allocation.

3.5.3.1 Relax Online Resource Allocation Algorithm (RORA)

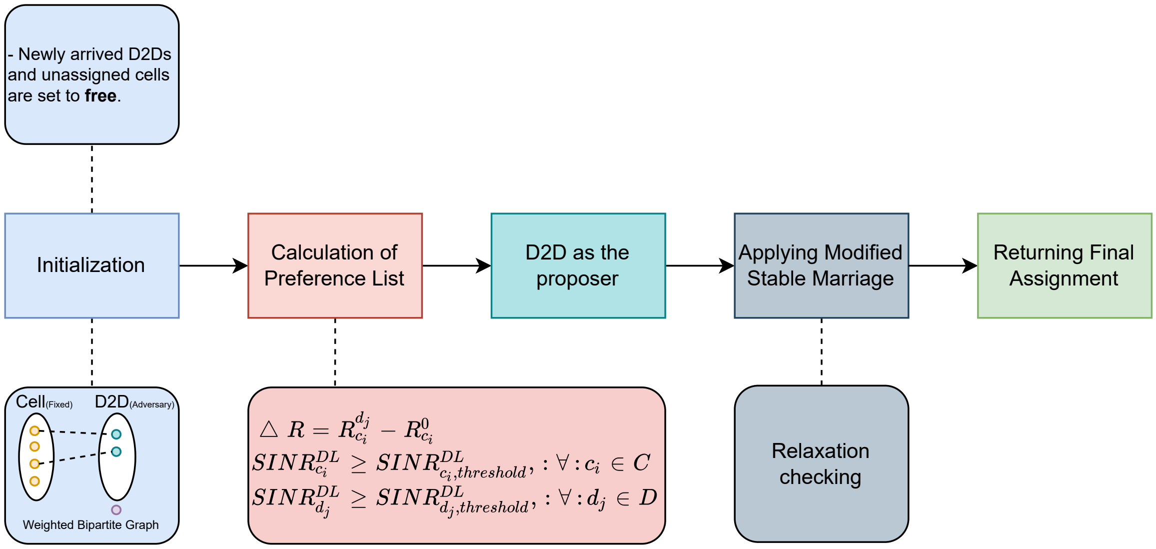


Figure 3.3: Flow chart of RORA/CRORA

Our first proposed algorithm RORA (Algorithm 8) for One-to-One sharing approach is based on the stable matching algorithm [30] which assumes the cellular UEs as a fixed set and the D2D pairs as an adversary set meaning the total number of the D2D pairs varies in the system in course of time. The flow chart of RORA is presented in Fig. 3.3. In Algorithm 8, we consider the resource allocation problem as a bipartite graph with n cellular UEs in one set and m D2D pairs in another set. In the beginning, we initialize the newly arrived D2D pairs and the unassigned cellular UEs as free (Line 2 Algorithm 8). Then, we calculate the preference lists for both of the cellular UEs and the D2D pairs based on Eqn. (3.17) and the binary variables, $p^{R}_{c_i,d_j}$ and $p^{F}_{c_i,d_j}$ as described in subsection 3.5.1 (Line 3 Algorithm 8). In RORA, the D2D pairs facilitate the proposal part of the stable matching algorithm (Line 5 Algorithm 8). RORA (Algorithm 8) assigns a cellular UE and a D2D pair together in such a way that there are no other cellular UEs and D2D pairs that would provide a better sumrate than their current assignment (Line $4-7$ Algorithm 8). If there are no such cellular UE or D2D pairs, all of the assignments are stable. If such assignments occur

(Line 10 Algorithm 8), then RORA revokes those assignments. Line number 10 of Algorithm 8 facilitates the relaxation property of RORA which allows the revocation of an existing assignment. The RBs of the revoked cellular UEs are assigned to the newly arrived D2D pairs and the revoked D2D pairs are added to the list of free D2D pairs. When all of the D2D pairs are assigned to the cellular UEs, RORA stops its execution and returns the allocation as the final result.

3.5.3.2 Conservatively Relax Online Resource Allocation Algorithm (CRORA)

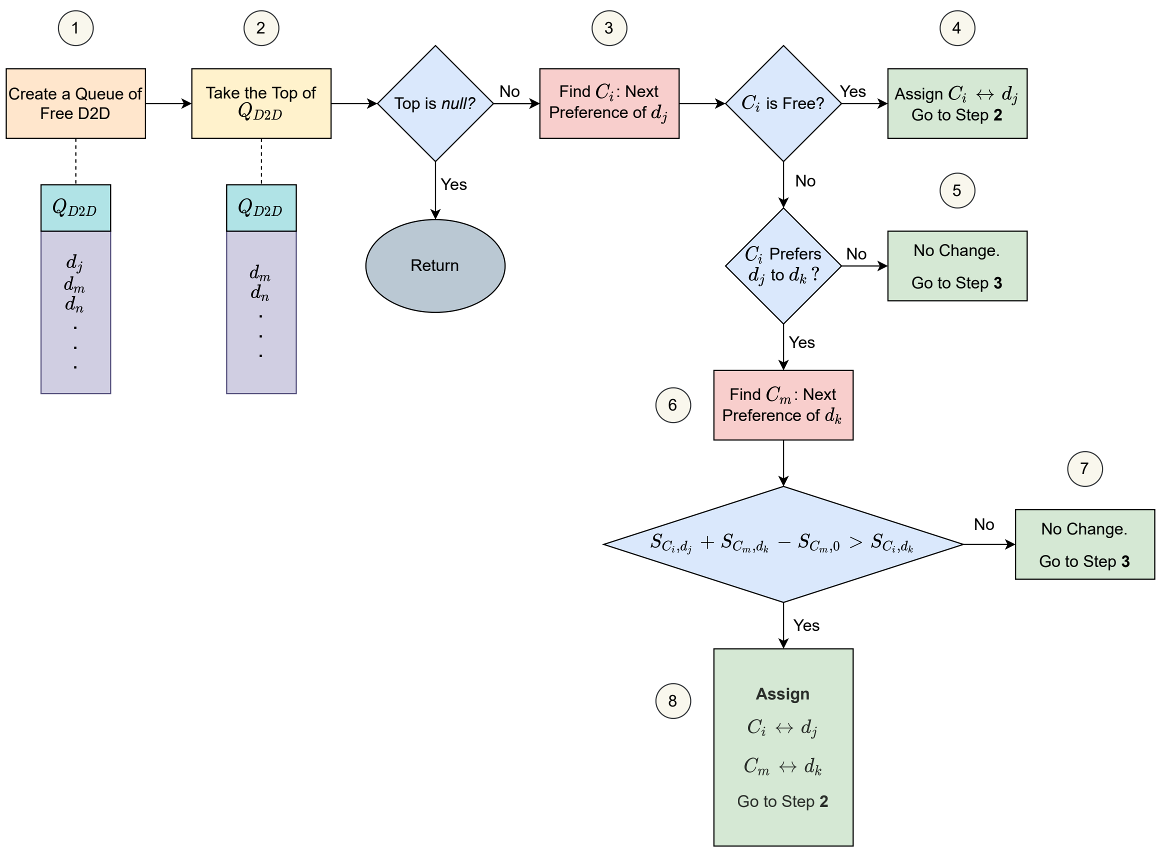


Figure 3.4: Modified stable matching algorithm for CRORA

Our second algorithm CRORA (Algorithm 9) for One-to-One sharing approach is a variant of the first proposed algorithm RORA and works similarly as RORA works with some extra carefulness. To leverage the extra system overhead due to the relaxation property (revocation of assignment), we design CRORA in a conservative way. Up to line number 10 of CRORA is similar to that of RORA where CRORA calculates the preference lists of both of the cellular UEs and the D2D pairs and considers the D2D pairs as the proposer of the stable matching algorithm. CRORA is a conservative variation of RORA as an extra condition is checked (Line 11 Algorithm 9) at the time of assignment where there is a necessity of revocation. This new condition ensures that if the revoked D2D pair would contribute negative system sumrate gain along with its new partner, this revocation is not allowed. Hence, the number of changes is reduced and at the same time, the objective of sumrate maximization is achieved. The flow chart for the modified stable matching algorithm is presented in Fig. 3.4. The new condition (Line 11 Algorithm 9) considers, $c_m \in C$ as the next available preferred cellular UE for the associated D2D pair, d_k. If c_m is empty, i.e. there is no such free cellular UE for d_k, then there is no sumrate contribution ($S_{c_m,d_j} = 0$). As c_m is free, so $S_{c_m,0}$ represents the sumrate contribution, c_m when it does not share the RBs with any of the D2D pairs. In other words, we can say if there is a necessity for revocation (Line 10 Algorithm 9) right away, CRORA will not revoke the assignment, rather it will check the new condition (Line 11 Algorithm 9). If the new condition is satisfied, only then does it revokes the assignment otherwise CRORA goes with the existing assignment and hence reduces the number of changes in assignment between two successive allocations.

3.5.4 Algorithms for One-to-Many Sharing Approach

Two online algorithms are proposed for One-to-Many sharing approach to maximize the system capacity. In this sharing approach, one D2D pair can share the RBs of one or more cellular UE, but no two D2D pairs are allowed to share the same cellular UE. It should be noted that to maximize the system capacity, it is possible that a D2D pair

Algorithm 7 Algorithm Scheduler

procedure SCHEDULER($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
  Call $RAAlgorithm1(D, C)$ for RORA or $RAAlgorithm2(D, C)$ for CRORA
  while $TRUE$ **do**
    if $Event_{Arrial} \mid\mid Event_{Mobility}$ **then**
      Call $RAAlgorithm1(D, C)$ for RORA or $RAAlgorithm2(D, C)$ for CRORA
    end if
  end while
end procedure

Algorithm 8 Relax Online Resource Allocation Algorithm (RORA)

procedure RORA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
  Newly arrived D2D pairs and unassigned cellular UEs are initialized as free.
  Calculate the preference lists using Eqn. (3.17)
  while $\exists$ free D2D pair $d_j \in D$ still has a cell $c_i \in C$ to request to **do**
    c_i = Most preferred and non-attempted cellular UE on d_j's preference list
    if c_i is free **then**
      (c_i, d_j) become assigned
    else
      For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
      if c_i prefers d_j to d_k **then**
        (c_i, d_j) become assigned
        Add d_k to the list of free D2D pairs.
      else
        (c_i, d_k) remain assigned
      end if
    end if
  end while
end procedure

Algorithm 9 Conservatively Relax Online Resource Allocation Algorithm (CRORA)

procedure CRORA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
    Newly arrived D2D pairs and unassigned cellular UEs are initialized as free.
    Calculate the preference lists using Eqn. (3.17)
    while $\exists$ free D2D pair $d_j \in D$ still has a cell $c_i \in C$ to request to **do**
        c_i = Most preferred and non-attempted cellular UE on d_j's preference list
        if c_i is free **then**
            (c_i, d_j) become assigned
        else
            For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
            if c_i prefers d_j to d_k **then**
                if $S_{c_i,d_j} + S_{c_m,d_k}$ - $S_{c_m,0} > S_{c_i,d_k}$ **then**
                    (c_i, d_j) become assigned
                    (c_m, d_k) become assigned
                else
                    (c_i, d_k) remain assigned
                end if
            else
                (c_i, d_k) remain assigned
            end if
        end if
    end while
end procedure

can share RBs of many cellular UE such that, other D2D pairs will not be assigned to any RBs. Thus, with the viewpoint of fairness, we proposed two algorithms. One is Fair Multiple Online Resource Allocation Algorithm "F-MORA" and the other is Restricted Multiple Online Resource Allocation Algorithm "R-MORA". The details of the algorithms are discussed in the following subsections.

3.5.4.1 Fair Multiple Online Resource Allocation Algorithm (F-MORA)

The F-MORA (Algorithm 10) assigns RBs to D2D pairs of multiple cellular UEs with fairness. The flow chart of F-MORA is presented in Fig. 3.5 along with the maximization of the capacity of overall system. F-MORA also try to assign RBs to all D2D pairs so that no D2D pairs face starvation. For proper functioning of F-MORA, we have introduced four variables max_no_cell (d_j), cur_no_cell(d_j), c_i.pref(d_j), and tempAssoc $[c_i]$. $max\_no\_cell(d_j)$ denotes that the maximum number of cellular UEs that a D2D pair, d_j can share RBs with. It is assumed that a D2D pair, d_j can not effectively use RBs of higher than this number. cur_no_cell(d_j) denotes the number of cellular UEs that a D2D pair d_j is currently associated with. c_i.pref(d_j) represents cellular UE c_i's preference value for a D2D pair d_j and c_i.pref(d_j) represents A D2D pair temporarily assigned to a cellular UE c_i (initial value is NULL).

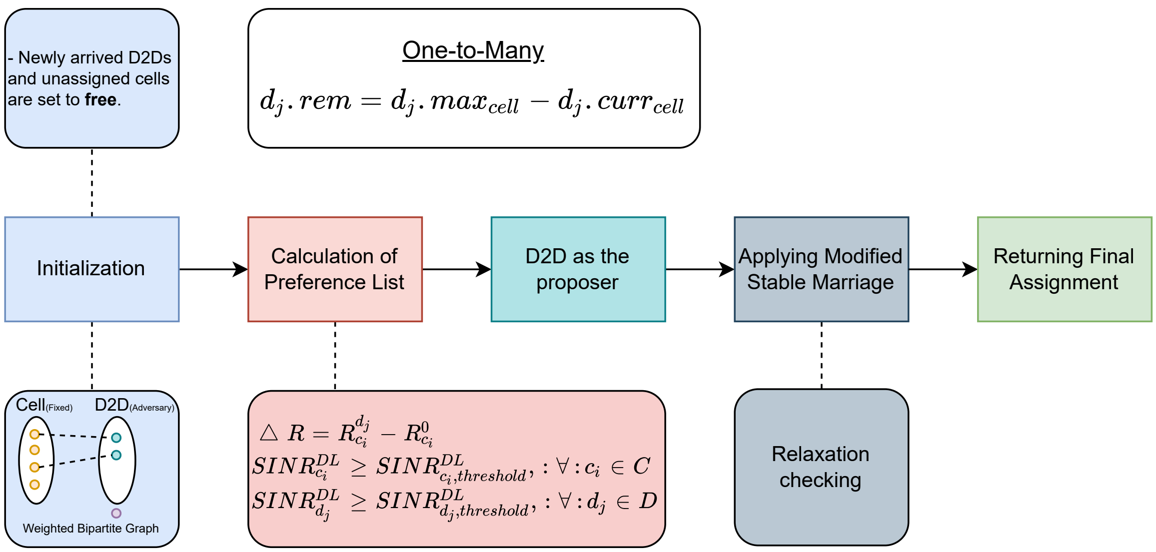


Figure 3.5: Flow chart of F-MORA/R-MORA

Due to its online nature, in each iteration of the algorithm, there will be some free cellular UEs (RBs associated with these cellular UEs are not shared by any D2D pairs yet) and some used cellular UEs (RBs associated with these cellular UEs are shared by some other D2D pairs already). At the beginning of the procedure, the preference list of free cellular UEs and the new D2D pair in the system is calculated using the Eq. (3.17). Thus, each free cellular UE, c_i will have a sequence of new D2D pairs (will be termed as a preference list of c_i) that it can share RBs with, and similarly, each D2D pair, d_j will have a sequence of free cellular UEs (will be termed as preference list of d_j) that it can share RBs with.

In line 5, a queue of D2D pairs, Q_{D2D} is generated made of D2D pairs that can still share more cellular UEs. After that in line [7 - 21], the temporary association of free cellular UEs and D2D pairs in Q_{D2D} undergoes. For each D2D pair, d_j in Q_{D2D}, a free cellular UE, c_i from the preference list of the D2D pair, d_j is selected in an orderly fashion. This cellular UE, c_i is temporarily assigned to the D2D pair, d_j if the c_i is not associated with any other D2D pair (d_{prev}). On the contrary, if the preference of the D2D pair, d_j is more than the D2D pair, d_{prev} to the cellular UE c_i, the cellular UE c_i will be temporarily assigned to the D2D pair, d_j. Moreover, D2D pair, d_{prev} will be inserted to Q_{D2D}. The D2D pair, d_j is popped from Q_{D2D} if temporarily assigned. As all D2D pairs are getting chances of sharing RBs with some cellular UEs, this algorithm is termed fair.

In line 24, all the temporary assignment in the previous block is finalized. If no assignment is done in this block for some iteration, the algorithm reaches an end. Flow chart of modified stable marriage algorithm for F-MORA is presented in Fig. 3.6

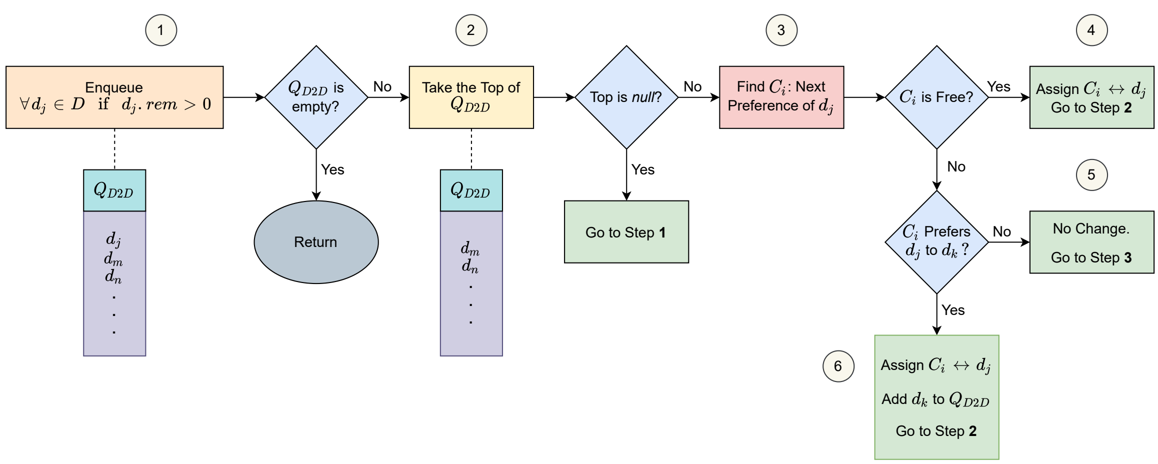


Figure 3.6: Modified stable matching algorithm for F-MORA

3.5.4.2 Restricted Multiple Online Resource Allocation Algorithm (R-MORA)

The R-MORA (Algorithm 11) assigns RBs to D2D pairs of multiple cellular UEs without fairness. Thus a number of D2D pairs may face starvation where other D2D pairs shared RBs with multiple cellular UE. Like F-MORA, we have introduced three variables tempD2DAssign(c_i), numCellAssocTemp(d_j), and max_no_cell (d_j). Newly introduced variable tempD2DAssign(c_i) denotes the D2D pair assigned to a cellular UE c_i temporarily, numCellAssocTemp(d_j) represents the number of cellular UEs assigned to a D2D pair d_j temporarily and max_no_cell (d_j) indicates the maximum number of cellular UEs that can be assigned to a D2D pair d_j. Like F-MORA, at the beginning of the algorithm, the preference list for all free cellular UEs and new D2D pairs are calculated. After that a queue, Q_{D2D} is created which is composed of the new D2D pairs. Unlike F-MORA, a D2D pair will only be popped from the queue if it is assigned to $max\_no\_cell(d_j)$ number of cellular UEs. Thus, it is possible to assign some D2D pairs to all free cellular UEs which will not be fair for some D2D pairs who will not be assigned to any cellular UE.

The main part of R-MORA is presented in line [4 - 23], where the new D2D pairs are assigned to free cellular UEs. At the beginning, a D2D pair, d_j from Q_{D2D} is taken and $max\_no\_cell(d_j)$ number of cellular UEs are temporarily assigned in line [6 - 21]. After assigning $max\_no\_cell(d_j)$ number of cellular UEs for one D2D pair temporarily it is popped from Q_{D2D} in line 20. A temporarily assigned D2D pair to a cellular UE will only be unassigned if another D2D pair also choose that cellular UE and also the cellular UE prefers the new D2D pair over the previous D2D pair (in line 13). The unassigned D2D pair will be inserted to Q_{D2D} again to get temporary association.

After completing the temporary assignment, the final assignment is done in line 22. Flow chart of modified stable marriage algorithm for F-MORA is presented in Fig. 3.7.

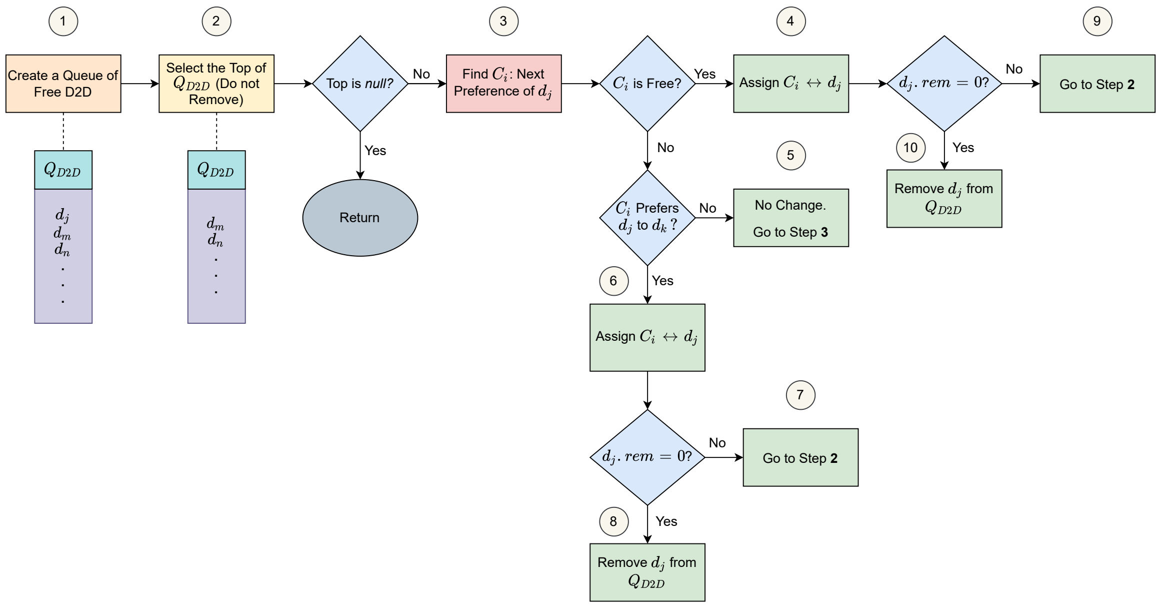


Figure 3.7: Modified stable matching algorithm for R-MORA

3.6 Trace Analysis and Run-Time Complexity

3.6.1 Trace Analysis on Assignment Strategy:

In this subsection, we focus on the the assignment strategy of the optimal Hungarian and the proposed algorithms. Here, we present a simple example (Figure 3.8) that explains why the proposed algorithms in general needs less number of changes in assignment between two successive allocations compared to the Hungarian algorithm which provides the optimal result in terms of total system sumrate [20]. Let us consider the state of Fig. 3.8a with two cellular users, c_1, c_2 and one D2D pair, d_1. The sumrate contributions of d_1 are, S_{c_1,d_1} and $(S_{c_1,d_1} - \epsilon)$ when it shares the RBs of c_1 and c_2 respectively where ϵ is a very small real number. According to both optimal

Algorithm 10 Fair Multiple Online Resource Allocation Algorithm (F-MORA)

procedure F-MORA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
    Calculate the preference lists using Eqn. (3.17)
    while no new assignment is occurred **do**
        if max_no_cell(d_j) > cur_no_cell (d_j) **then**
            Enque $d_j \in D2D$ in Q_{D2D}
        end if
        while Q_{D2D} is empty **do**
            d_{front}=Q_{D2D}.top()
            c_i = first non-attempted Cell in d_{front}'s preference list
            if tempAssoc[c_i]=NULL **then**
                tempAssoc[c_i]=d_{front}
                Q_{D2D}.pop(d_{front})
            else
                d_k=tempAssoc[c_i]
                if c_i.pref(d_k) < c_i.pref(d_{front}) **then**
                    tempAssoc[c_i]=d_{front}
                    Q_{D2D}.pop(d_{front})
                    Q_{D2D}.push(d_k)
                end if
            end if
        end while
        for $C_i \in cell$ **do**
            if tempAssoc[c_i] $\neq$ NULL **then**
                assign (c_i, tempAssoc[c_i])
                new assignment occurs
            end if
            .
        end for
    end while
end procedure

Algorithm 11 Restricted Multiple Online Resource Allocation Algorithm (R-MORA)

procedure R-MORA($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$)
  Calculate the preference lists using Eqn. (3.17)
  Enqueue $\forall$ d$_j \in D$ in Q_{D2D}
  while Q_{D2D} is not empty **do**
    d_{front}=Q_{D2D}.top()
    while d_{front}'s pref is not traverse completely **do**
      c_i=next preferred cell of d_{front}'s preference
      if tempD2DAssign(c_i) is free **then**
        temporarily assign c_i to d_{front}
      else
        d_k=tempD2DAssign[c_i]
      end if
      if pref(d_k) $<$ pref(d_{front}) **then**
        Temporarily assign c_i to d_{front}
        Temporarily unassign d_k from c_i
        if numCellAssocTemp(d_{front})=max_no_of(d_{front}) **then**
          Q_{D2D}.pop(d_{front})
        end if
      end if
      Q_{D2D}.pop(d_{front})
    end while
    Convert all temporary assignment (c_i to d_j) into permanent assignment
  end while
end procedure

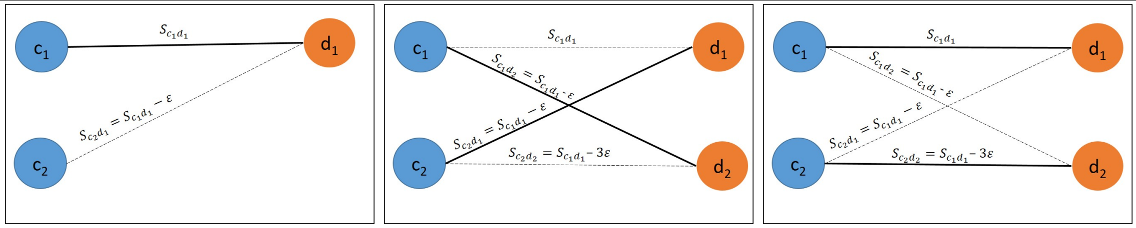
and the proposed algorithms, d_1 would share the RBs of c_1 (solid lines represent a valid assignment). Suppose, in the next state a new D2D pair, d_2 enters into the system. The sumrate contributions of d_2 are, $(S_{c_1,d_1} - \epsilon)$ and $(S_{c_1,d_1} - 3\epsilon)$ when it shares the RBs of c_1 and c_2 respectively. Now, according to the Hungarian algorithm (Figure 3.8b), new associations would be c_1d_2 and c_2d_1 with a total sumrate contribution of $2(S_{c_1,d_1} - \epsilon)$ and it encounters one change in resource allocation (d_1 is revoked from c_1 and d_2 is assigned to c_1). However, according to the proposed algorithms (Figure 3.8c) the new associations would be c_1d_1 and c_2d_2 with a total sumrate contribution of $(2S_{c_1,d_1} - 3\epsilon)$. It is noted that proposed algorithms do not encounter any change in resource allocation, hence less system overhead contribution.

Now, we present a small example in Fig. 3.9 that shows the output traces of the optimal Hungarian algorithm, RORA, and CRORA. We generate the output traces for a simple scenario with a fixed number of 5 cellular UEs and a variable number of D2D pairs. We start with a single D2D pair and in course of time, more D2D pairs arrive in the system online, and finally, there are 5 D2D pairs in the system (all of the algorithms terminate when the total number of D2D pairs exceeds the total number of cellular UEs in the system). Figure 3.9a, 3.9b, and 3.9c represent the output trace of the optimal algorithm (Hungarian), RORA, and CRORA respectively where individual row represents a state of the system with different number of D2D pairs. For all of the algorithms, total system sumrate and number of changes (revocations) in different states of the system are presented in respective columns of Fig. 3.9a, 3.9b, and 3.9c. The column index of a D2D pair represents the cellular UE to which it is currently assigned. In every row, the green color represents the newly arrived D2D pair and the red color represents the revoked D2D pairs from the previous state. For example, in Fig. 3.9a, row number 3 represents the state of the system with 5 cellular UEs and 3 D2D pairs where d_3 is the newly arrived D2D pair. For this state, the Hungarian algorithm returns a total sumrate of 157.935 with a single change in the assignment where d_2 is revoked from c_5 and assigned to c_4. By analyzing the output traces of Fig. 3.9a, 3.9b, and 3.9c, we can see that the optimal Hungarian algorithm returns a total sumrate of 152.61 and performs a total of 4 revocations whereas, RORA returns a total sumrate of 149.567 and perform a total of 3 revocations. On the other hand, CRORA returns a total sumrate of 149.345 with only one revocation. Both RORA and CRORA return close to the Hungarian algorithm (optimal) total system sumrate with less number of changes in allocation (revocation). We need to mention that although RORA and CRORA return similar total system sumrate, CRORA returns a remarkably less number of changes in successive allocation. This is due to the extra carefulness (Line 11 Algorithm 9) at the time of revocation. This observation will be more vivid when we present the experimental data in Section 3.7 with a bigger instance of the system.

We observe that, although the Hungarian algorithm is optimal in terms of total system sumrate which ensures the highest achievable system sumrate it might assign less number of D2D pairs than the other algorithms. To prove this observation, let us consider the similar scenario of Fig. 3.8 where the sumrate contributions of d_1 are 10 and 5 when it shares the RBs of c_1 and c_2 respectively. According to both Hungarian and proposed algorithms, d_1 would share the RBs of c_1. Suppose in the next state a new D2D pair, d_2 enters into the system and the sumrate contribution of d_2 is 4 when it shares the RBs of c_1. However, d_2 does not meet the QoS constraints when it shares the RBs of c_2. In this state of the system, the Hungarian algorithm returns a total sumrate of 10 with c_1 assigned to d_1 and leaves d_2 unassigned. However, proposed algorithms return a total sumrate of 9 with the associations c_1d_2 and c_2d_1.

3.6.2 Run-Time Complexity

We design stable matching-based relax online algorithms (RORA and CRORA) and online algorithms (F-MORA and R-MORA) for One-to-One and One-to-Many sharing respectively which in practice give a very close to the optimal solution. Stable matching-based algorithms converge (become stable) after $O(n^2)$ [91] steps where n represents the total number of elements in both sets of the bipartite graph. So, both RORA and CRORA have a complexity of $O(n*m)$ in the worst case and $O(nlogn)$ in the average case where n is the total number of cellular UEs and m is the number of total D2D pairs while $m << n$. We can easily prove that both RORA and CRORA terminate after at most $m*n$ number of iterations. In the case of RORA and CRORA, in each iteration (Line 4 of Algorithm 8 and Algorithm 9), an unassigned D2D pair proposes (for the only time) to a cellular UE it has never proposed to before. Let us consider $\rho(t)$ as the set of pairs (d_j, c_i) such that a D2D pair, d_j proposes to a



(a) Initial state (b) Hungarian algorithm (c) RORA and CRORA

Figure 3.8: Trace analysis on assignment strategy (Hungarian vs proposed algorithms)

cellular UE, c_i by the end of the iteration t. We can easily observe that for all of the iterations, the size of $\rho(t+1)$ is necessarily greater than the size of $\rho(t)$. However, there are only $m*n$ number of possible pairs of a cellular UE and a D2D pair in total in the system, the value $\rho(\cdot)$ can increase at most $m*n$ in course of time with the progress of both RORA and CRORA. It proves that both proposed algorithms terminate within a maximum of $m*n$ number of iterations. It is to be noted that, CRORA is conservatively designed and due to the extra condition checking (Line 11 Algorithm 9), the number of revocations is less than RORA. So, the run time complexity of CRORA is normally less than RORA. In the worst case, CRORA requires a $m*n$ number of iterations to terminate whereas in the average case, it requires less number of iterations than RORA to terminate. In the case of F-MORA and R-MORA, we use a new variable, $k := \sum \text{max\_no\_cell}\ (\text{d}_j)$ which denotes the maximum number of cellular UEs that a D2D pair, d_j can share with. For F-MORA, and R-MORA, it requires $m*n$ number of iterations for preference calculation and $k*n$ number of iterations for applying the stable marriage algorithm. So, both of the algorithms have a run time complexity of $O(k*n)$.

The running time of RORA and CRORA are the same as DARA [18] and better than LORA [4] and the Hungarian algorithm [29]. LORA has a complexity of $O(n^2S)$ where S is the total sumrate of the system with n cellular users. For the Hungarian algorithm, the run time complexity is $O(n^3)$.

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_1	d_2	d_3	1	157.935
4	d_3		d_1	d_4	d_2	2	159.211
5	d_3	d_4	d_1	d_5	d_2	1	152.61

(a) Hungarian algorithm

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_2	d_1	d_3	2	156.716
4	d_1		d_2	d_4	d_3	1	157.621
5	d_1	d_5	d_2	d_4	d_3	0	149.567

(b) RORA

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_1	d_2	d_3	1	157.935
4		d_4	d_1	d_2	d_3	0	158.02
5	d_5	d_4	d_1	d_2	d_3	0	149.345

(c) CRORA

Figure 3.9: Trace analysis (Hungarian [optimal] algorithm vs proposed algorithms)

3.7 Experimental Results

3.7.1 Experimental Environment

We simulate different scenarios to evaluate the efficiency of the proposed algorithms (RORA, CRORA, F-MORA, and R-MORA). We use the C++ programming language for the numerical experiment that supports the LTE system. The research problem we consider is a type of assignment problem which is one of the fundamental combinatorial optimization problems. In the experiments, our main objective is to find the assignments of the D2D pairs with the cellular UEs. Based on the assignments, we need to calculate SINR, interference, and system sumrate from their respective equations. We use the same experimental parameters (Table 3.5) as in [4],[3],[18] and some other variants of these parameters for the performance evaluation of the proposed algorithms. A single cell network is considered in the experimental analysis. We consider that the cellular UEs and the D2D pairs are uniformly distributed in the cell area where D2D pairs (D2D transmitters and D2D receivers) are uniformly distributed in a random cluster with a maximum radius of 15 meters. All the experimental results presented in this research are an average of 50 different runs for a particular scenario.

Table 3.5: Experimental Parameters

Parameter	Value
Cell Radius	1000 meters
Maximum D2D pair distance	15 meters
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Base Station transmit power	46 dBm
Noise power (AWGN)	-174 dBm
Carrier Frequency	1.7 GHz for LTE
$\gamma^{DL}_{c_i,target}$	Random
$\gamma^{DL}_{d_j,target}$	Random

3.7.2 Input Data Model

For all of the experimental results presented in this research, we start with 300 cellular UEs and a single D2D pair. Based on the system events, the number of D2D pairs in the system varies over time whereas the number of cellular UEs is fixed. We stop the experiment when the number of D2D pairs in the system becomes 225 (75% of the number of the cellular UEs as we are considering a system where the number of the cellular UEs is much greater than the number of the D2D pairs). However, based on the mobility system events, the relative positions of both the D2D pairs and the cellular UEs change over time. We use Markov Modulated Poisson Process (MMPP)[127] to model the arrival and mobility event. MMPP arrival/mobility event rate, λ_s is determined by the phase, s of the Markov chain [128], where the total number of states is, S (i.e., s = 1,2,. . . ,S). In the numerical experiment, we consider only two states of the Markov chain working in a discrete-time where λ_1 is the rate of state 1 and λ_2 is the rate of state 2. So, we can say that both arrival event (D2D pairs) and mobility event (both D2D pairs and cellular UEs) are modeled using discrete-time Markov Modulated Poisson Process (dMMPP). At the time of an arrival event, we consider any random number of D2D pairs between 1 and 9. However, proposed algorithms can handle any number of D2D pairs at a single arrival event. Moreover, we perform an extensive numerical experiment with a different number of cellular users and a different number of initial D2D pairs with different arrival rates and we find that all of the experimental results are almost identical to the result we present here in terms of performance.

3.7.3 Result Comparison

3.7.3.1 Result comparison for One-to-One sharing approach

Different Algorithms for Performance Comparisons We consider different resource allocation algorithms to compare the performance of proposed algorithms (RORA and CRORA) in terms of total system sumrate and the number of changes in assignment between two consecutive states of the system. Each of the algorithms is briefly explained here with its key points.

Deferred Acceptance Based Algorithm for Resource Allocation (DARA): DARA [18] also follows the stable matching algorithm presented in [129]. However, preferences for both the cellular UEs and the D2D pairs are calculated depending on their locations. A device in close proximity is preferred over the far one. Depending on the given preference, a D2D pair selects a cellular UE to share the RBs. But distance is not the only factor behind a better sumrate. It is assumed that a lower distance is preferred over a higher distance. However, a cellular UE experiences more interference from a nearby assigned D2D pair and we encounter such observations in the numerical experiments. Moreover, in some cases, this algorithm allows a cellular UE and a D2D pair to share the RBs even though QoS is not satisfied.

Local Search Based Resource Allocation Algorithm (LORA): A local search algorithm LORA [4] uses the allocation given by the greedy algorithm [3] as the initial feasible solution. Then it swaps assignment between a D2D pair and a cellular UE only if the swapping improves the objective function, as well as if the constraints, are satisfied. LORA can also face a similar problem encountered by the greedy algorithm [3]. The final result of the greedy heuristic might miss out on some of the D2D pairs for assignments that are considered the optimal solution. These D2D pairs can also be missed out in the final assignments returned by the local search algorithm and in practice, the local optima of this algorithm can be far away from the global solution.

Hungarian (Optimal) Algorithm: Hungarian algorithm [29] is a weighted bipartite matching based algorithm used in [19],[120],[20] for similar resource allocation problems in D2D communications. The Hungarian algorithm is an optimal algorithm that outperforms other heuristic algorithms. In the numerical analysis, we also consider a similar algorithm [29].

In simulation graphs, proposed algorithms are named RORA and CRORA and the optimal Hungarian algorithm is named "optimal".

- **Experiment-1**

  We compare the proposed algorithms (RORA and CRORA) with the existing offline algorithms for both the fair assignment scheme and the restricted assignment scheme. For both of the assignment schemes, we compare the algorithms with respect to the total system sumrate and the number of changes in assignment between two successive allocations. Figure 3.10 represents the comparison of the total system sumrate returned by the algorithms in different states of the system for the fair assignment scheme. From the graph presented in Fig. 3.10, we can observe that both RORA and CRORA perform very close to the optimal algorithm and LORA performs next to the proposed algorithms whereas DARA performs the worst. The reason for DARA's poor performance is that the preference list of DARA is based on the increasing order of the proximity which is not the best approach for this optimization problem. For clarity, we present the normalized system sumrate returned by different algorithms in Fig. 3.11, where the graph is normalized with respect to the optimal algorithm. From Fig. 3.11, we can observe that in the fair allocation scheme, both RORA and CRORA perform almost 99.95% of the optimal algorithm and by a very narrow margin, CRORA outperforms RORA in terms of total system sumrate. Figure 3.13 represents the comparison of different algorithms in terms of the number of changes in successive allocation. We exclude DARA from this comparison as it performs remarkably poorly in terms of system sumrate. Figure 3.13 suggests that both RORA and CRORA outperform LORA and the optimal algorithm where the individual line represents a cumulative number of changes for different algorithms in discrete-time event. RORA performs approximately 55% less number of changes than LORA and 5% less number of changes than the optimal algorithm whereas CRORA performs remarkably approximately 92% less number of changes than LORA and 75% less number of changes than the optimal algorithm. In terms of the number of changes, CRORA outperforms RORA by performing approximately 70% less number of changes in assignment between two successive states.

For the restricted assignment scheme, we compare RORA and CRORA with the optimal Hungarian algorithm only as there is no existing variant of the restricted version. Figure 3.14 shows the comparison of the algorithms in terms of the total system sumrate where an individual line represents the increase of the total system sumrate returned by the algorithms with respect to time. Like the fair assignment scheme in the restricted assignment scheme, RORA and CRORA perform very near to the optimal (Hungarian) algorithm. For better visualization, we present the normalized system sumrate returned by different algorithms in the restricted assignment scheme in Fig. 3.15 where the graph is

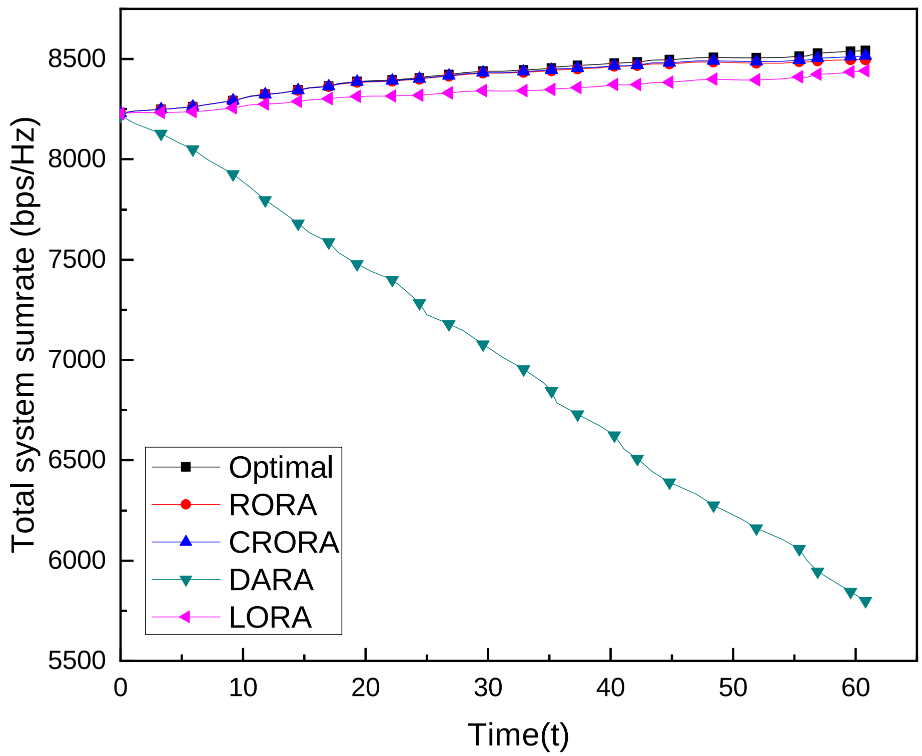


Figure 3.10: Total system sumrate in each state of the system for the fair assignment scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

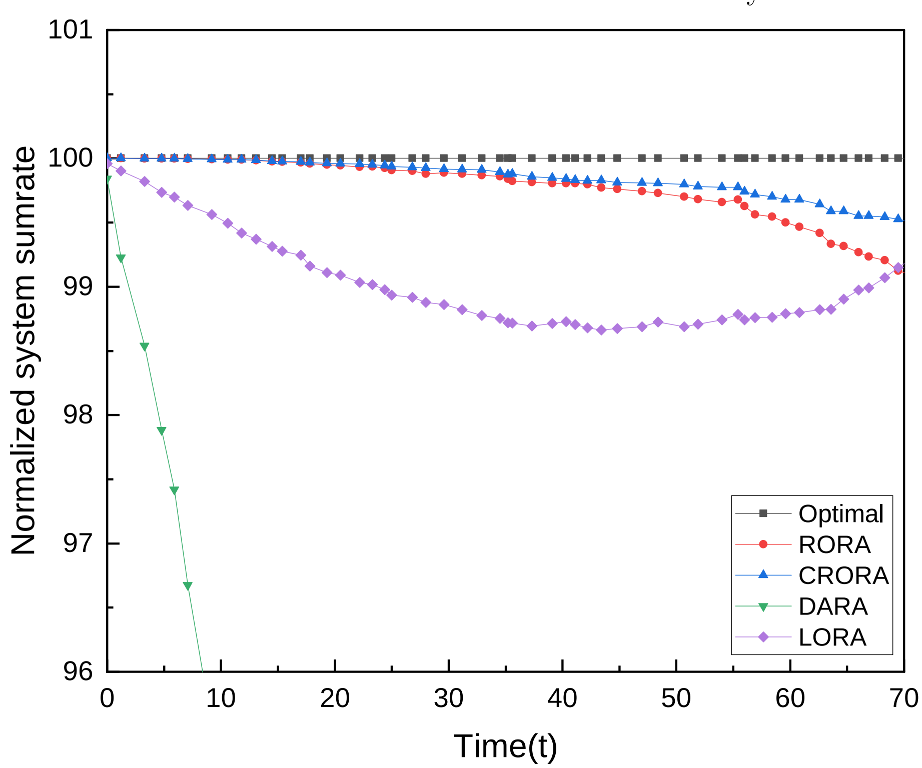


Figure 3.11: Normalized system sumrate in each state of the system for the fair assignment scheme (Normalized with respect to the optimal Hungarian algorithm)(cellular UEs = 300 and maximum number of D2D entry at a time=10)

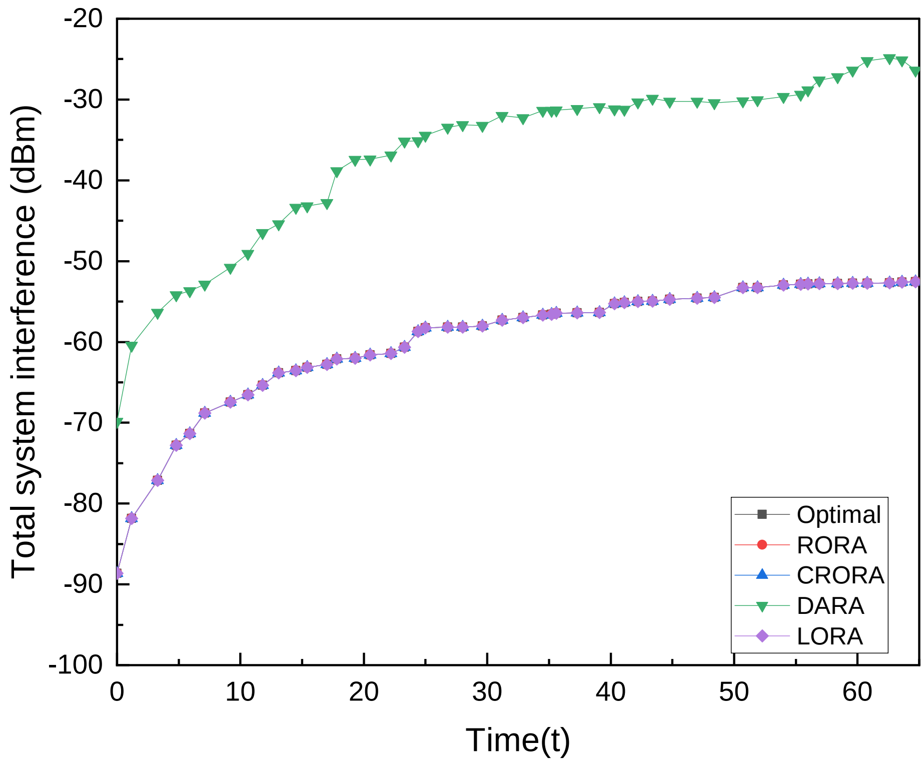


Figure 3.12: Total system interference in each state of the system for the fair assignment scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

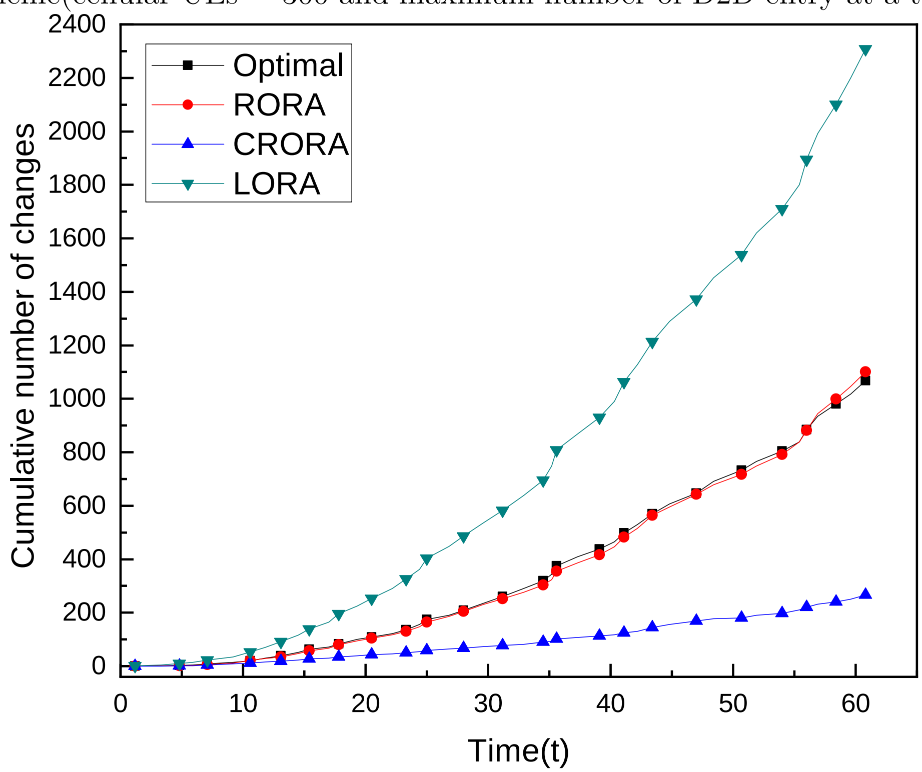


Figure 3.13: Cumulative number of changes in each state of the system for the fair assignment scheme (cellular UEs = 300 and maximum number of D2D entry at a time=10)

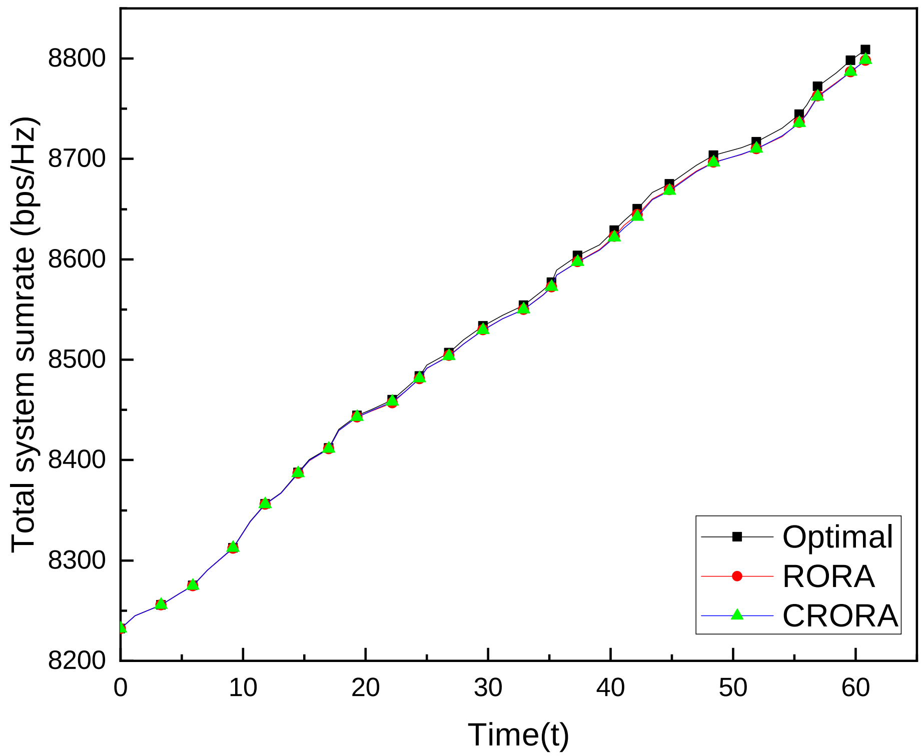


Figure 3.14: Total system sumrate in each state of the system for the restricted assignment scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

normalized with respect to the optimal algorithm. From Fig. 3.15, we can easily observe that in the restricted assignment scheme, the performance of RORA and CRORA is almost similar which is approximately 99.97% of the optimal Hungarian algorithm. Figure 3.17 represents the comparison of the algorithms in the restricted assignment scheme in terms of the number of changes in assignment between two successive states. In the restricted assignment scheme, RORA outperforms the optimal algorithm by performing approximately 20% less number of changes in assignment between two successive allocations. On the other hand, CRORA outperforms both RORA and the optimal algorithm where CRORA performs approximately 60% less number of changes than CRORA and approximately 68% less number of changes than the optimal algorithm. We need to mention that, in the restricted assignment scheme, presumably, some D2D pairs cannot be assigned because they provide negative sumrate gain. The number of

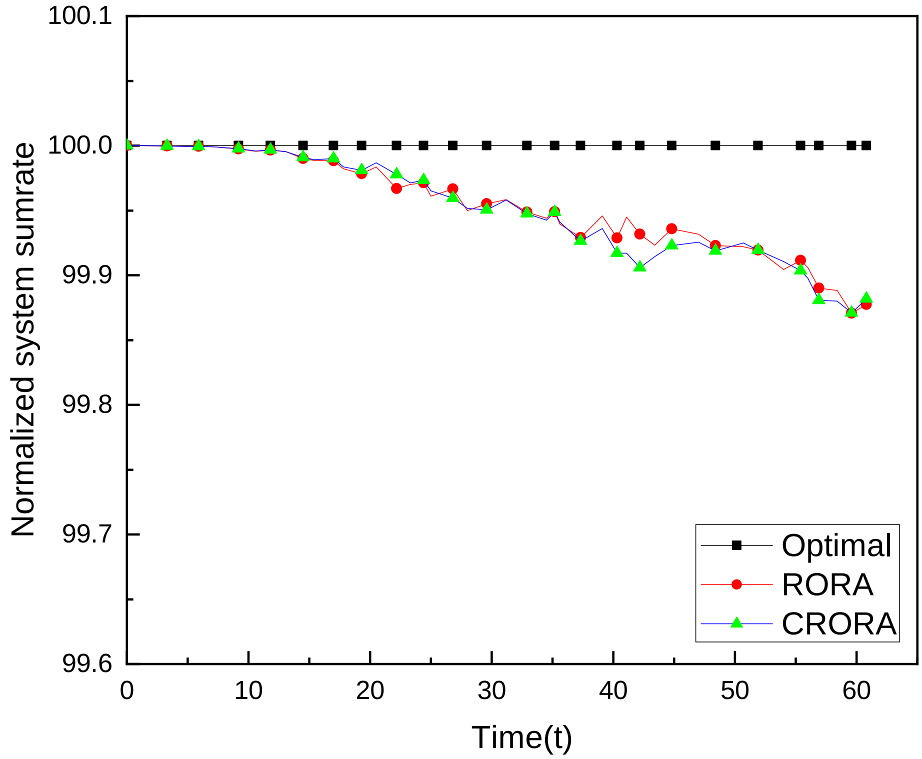


Figure 3.15: Normalized system sumrate in each state of the system for the restricted assignment scheme (Normalized with respect to the optimal Hungarian algorithm)(cellular UEs = 300 and maximum number of D2D entry at a time=10)

assigned D2D pairs by the optimal algorithm is 153 out of a total of 225 D2D pairs whereas, RORA assigns 150 D2D pairs, and CRORA assigns 155 D2D pairs out of 225 D2D pairs finally present in the system. Although our target is to maximize total system sumrate, we have also compared total system interference with the existing algorithms in both fair and restricted modes. Besides giving a satisfactory performance in terms of total system sumrate, our proposed RORA and CRORA provided very less interference compared to the existing LARA and DARA and the performance is very close to an optimal algorithm. Similar performance in terms of total system interference is achieved in both fair and restricted mode which is depicted in Fig. 3.12 and 3.16 respectively.

Based on all of the numerical results, we can say that in both of the assignment schemes, the proposed algorithms (RORA and CRORA) return a total system

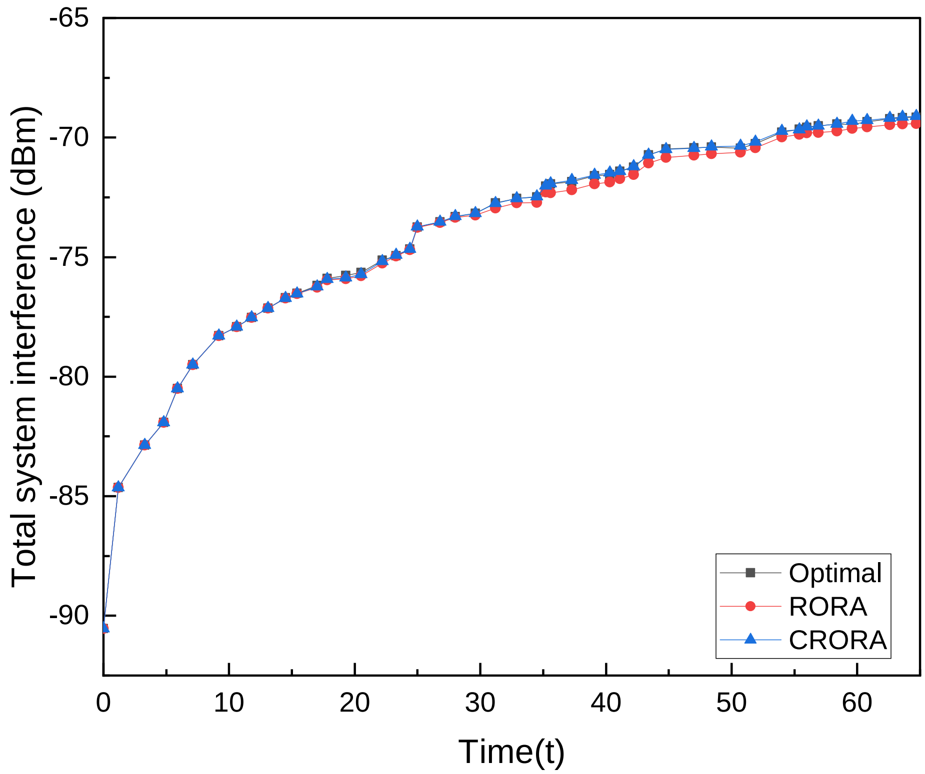


Figure 3.16: Total system interference in each state of the system for the restricted assignment scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

sumrate that is very close to the total system sumrate returned by the optimal algorithm. Moreover, in the fair assignment scheme, RORA and CRORA outperform LORA and DARA in terms of total system sumrate. On the other hand, in terms of the number of changes, both RORA and CRORA outperform all of the algorithms in both of the assignment schemes.

- **Experiment-2**

  We further extend our experimental analysis by comparing two proposed algorithms RORA and CRORA in both fair and restricted assignment schemes with a varying number of fixed cellular UE counts and the maximum number of D2D entries at a certain time.

  Figure 3.18 depicts the performance comparison of the proposed algorithm with the optimal algorithm as well as DARA and LORA using a fixed number of cel-

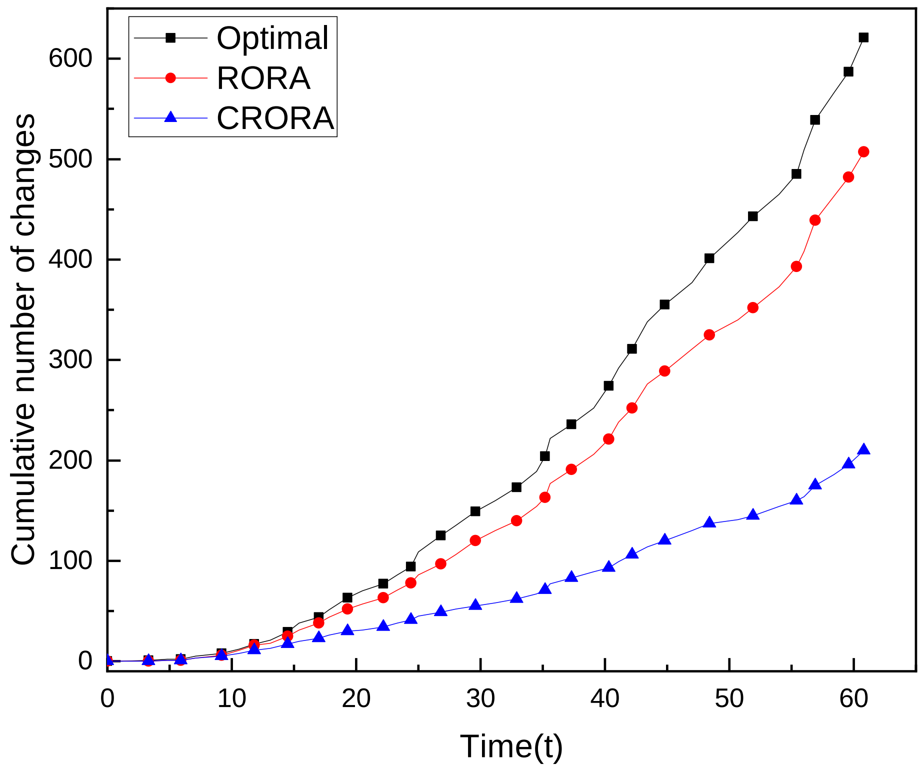
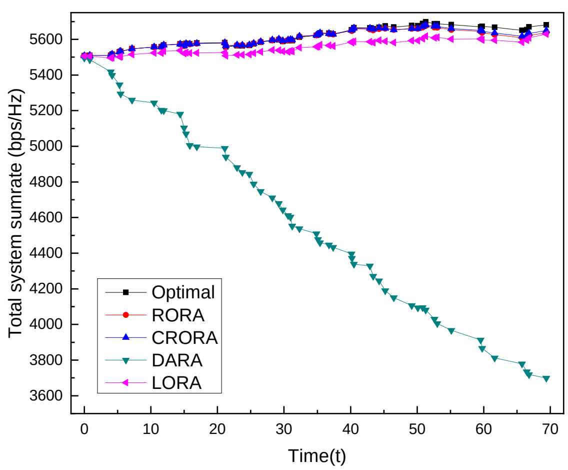
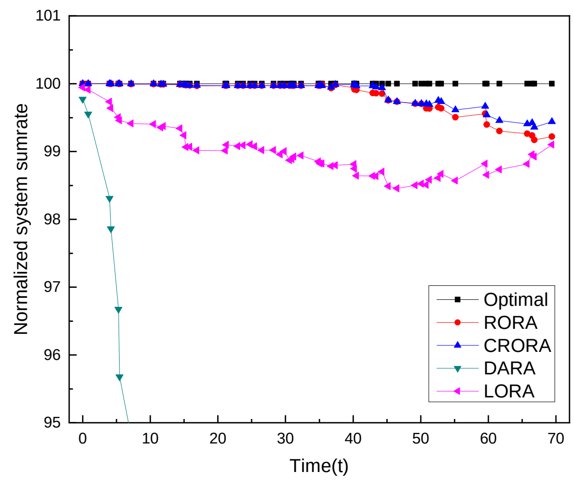


Figure 3.17: Cumulative number of changes in each state of the system for the restricted assignment scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

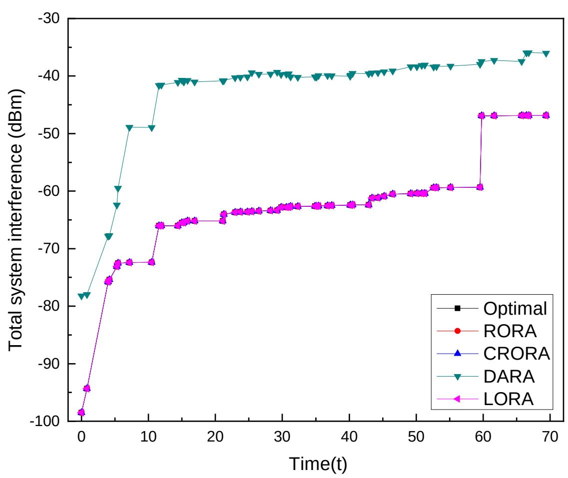
lular UE of 200 and maximum D2D entry of 5 at a certain time. It can be observed from Fig. 3.18a that, the total system sumrate of the proposed algorithms is significantly close to the optimal algorithm (Hungarian) although, CRORA outperforms RORA by a slight margin. LORA performs next to RORA whereas the performance of DARA is considerably inferior to the rest. Similar performance can also be noticed from Fig. 3.18b for normalized system sumrate. In this particular experiment, DARA shows the maximum system interference followed by LORA and the rest. In the case of the optimal Hungarian algorithm and the proposed algorithms, total system interference is almost similar to LORA. Figure 3.18d shows that RORA and CRORA require a less cumulative number of changes than that of the optimal algorithm. On the other hand, LORA requires even more changes than the optimal algorithm.



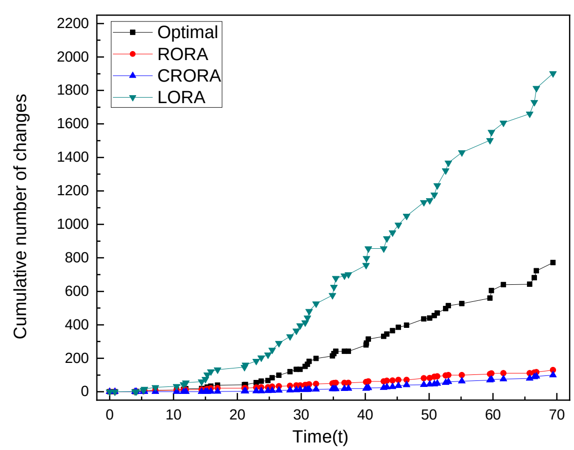
(a) Total system sumrate



(b) Normalized system sumrate (w.r.t. optimal algorithm)

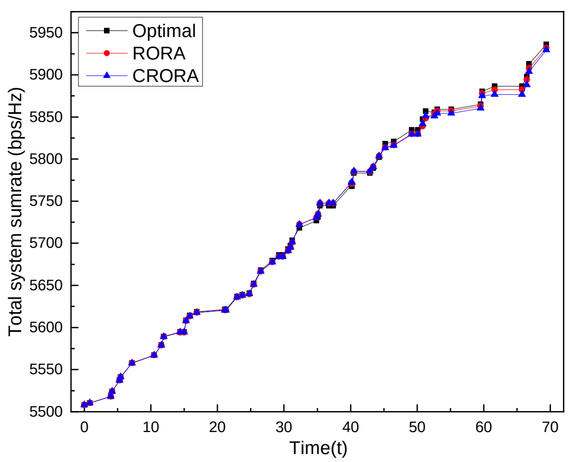


(c) Total system interference

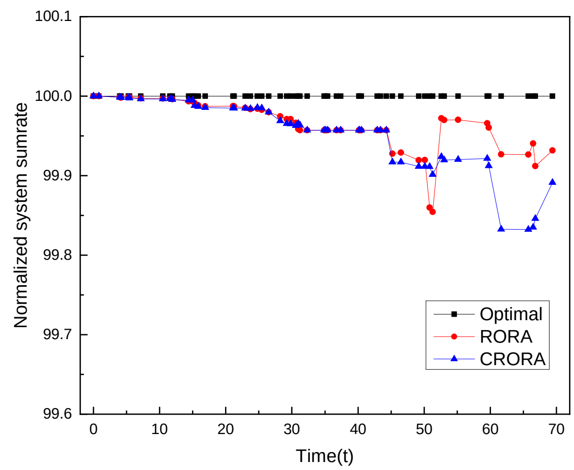


(d) Cumulative number of changes

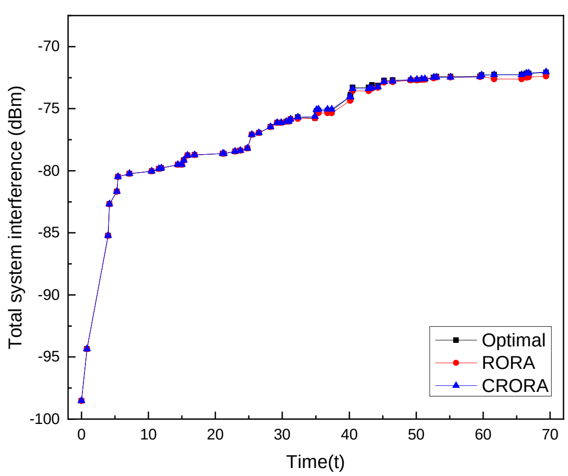
Figure 3.18: The fair assignment scheme (cellular UEs = 200 and maximum number of D2D entry at a time=5)



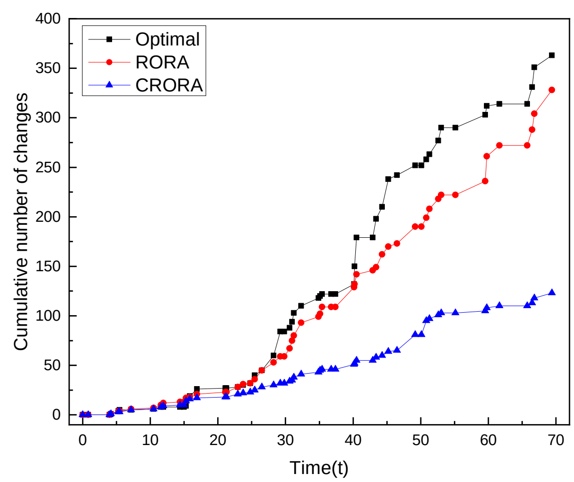
(a) Total system sumrate



(b) Normalized system sumrate (w.r.t. optimal algorithm)



(c) Total system interference



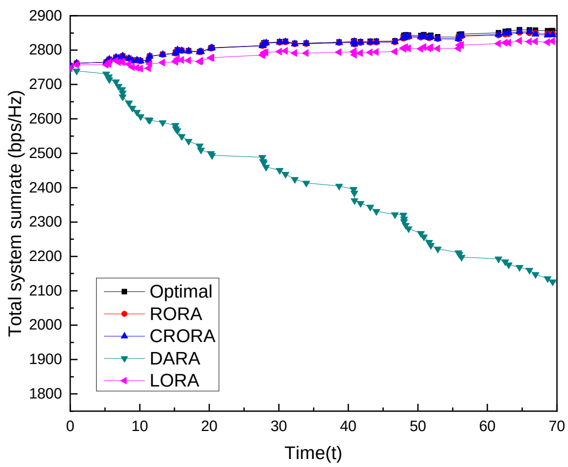
(d) Cumulative number of changes

Figure 3.19: The restricted assignment scheme (cellular UEs = 200 and maximum number of D2D entry at a time=5)

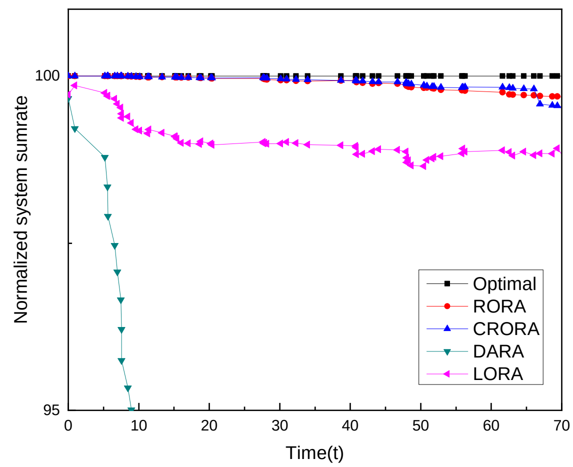
Figure 3.19 shows the performance comparison between the two proposed algorithms and the optimal one is a restricted scheme where the number of cellular UE and maximum D2D count at a certain time is the same as in the previous experiment. Total system sumrate and normalized system sumrate is significantly close among these three algorithms although the optimal algorithm outperforms RORA and CRORA. Unlike the experiment in the fair scheme in Fig. 3.18, RORA outperforms CRORA in both total system sumrate as well as normalized system sumrate. RORA achieves less total system interference than both optimal and RORA but requires more number changes than CRORA, though the optimal algorithm requires the highest number of changes among these three algorithms. While achieving a higher system sumrate our proposed RORA and CRORA obtained very less interference which is close to optimal in both fair and restricted mode as shown in Fig. 3.18c and **??** respectively.

- **Experiment-3**

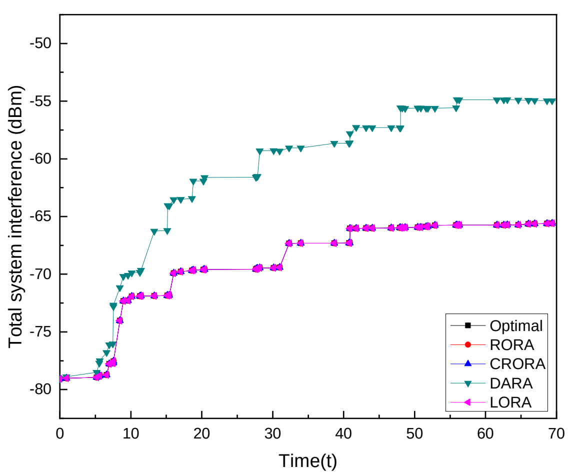
In case of the fair assignment scheme with a fixed number of cellular UE of 100 and a maximum number of D2D entries at a time of 1, it can be noticed from Fig. 3.20 that for most of the time, the total system sumrate of the proposed algorithm is better than LORA and DARA, but similar to the optimal algorithm. From Fig. 3.20a, it can also be observed that for the last 10% of the time, LORA outperforms RORA and CRORA by a slight margin. This same phenomena is also observed in Fig. 3.20b. It should be mentioned that, in the case of DARA, the normalized system sumrate drastically falls at the beginning of the experiment and stays almost the same for the rest of the time. For this particular experimental setup, DARA achieves the highest system interference whereas the system interference is almost identical for the rest of the algorithms depicted in Fig. 3.20c. Throughout the time, CRORA requires



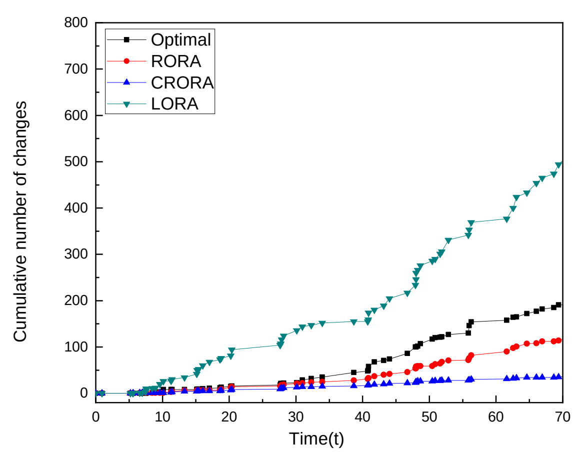
(a) Total system sumrate



(b) Normalized system sumrate (w.r.t. optimal algorithm)



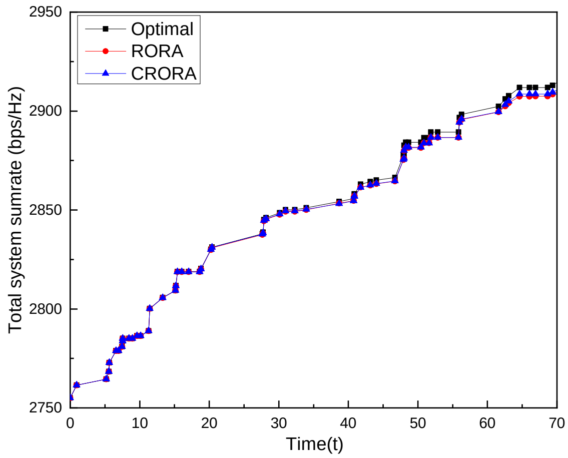
(c) Total system interference



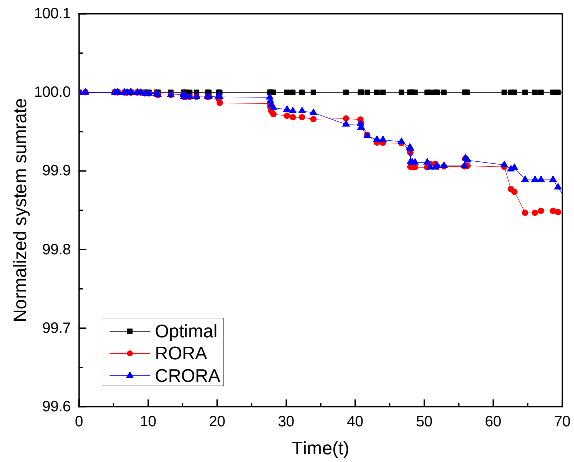
(d) Cumulative number of changes

Figure 3.20: The fair assignment scheme (cellular UEs = 100 and maximum number of D2D entry at a time=1)

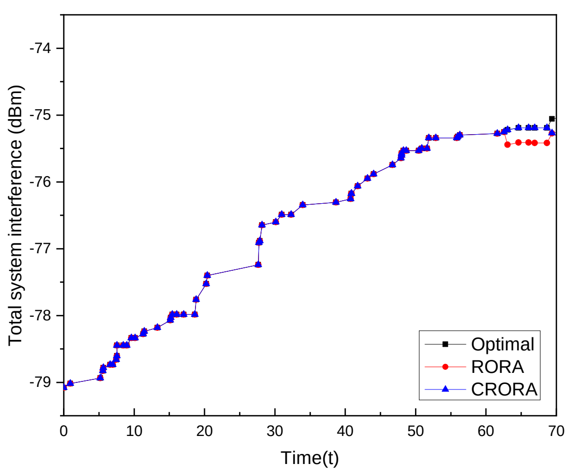
the least cumulative number of changes followed by RORA, optimal algorithm, and DARA in increasing order.



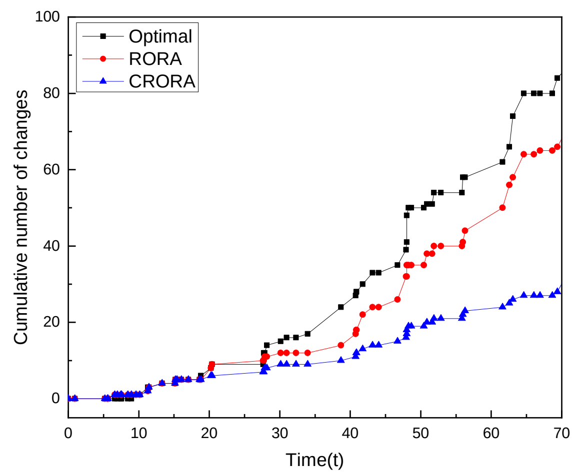
(a) Total system sumrate



(b) Normalized system sumrate (w.r.t. optimal algorithm)



(c) Total system interference



(d) Cumulative number of changes

Figure 3.21: The restricted assignment scheme (cellular UEs = 100 and maximum number of D2D entry at a time=1)

Figure 3.21 represents the restricted scheme with the same UE and D2D configuration as the former experiment, Optimal algorithm outperforms RORA and CRORA in total system sumrate as well as normalized system sumrate. Between RORA and CRORA, CRORA outperforms RORA by a slight margin. Throughout the experiment, RORA achieves the least total system interference followed by CRORA and the optimal algorithm. The optimal algorithm requires the most cumulative changes and CRORA requires the least. In this experiment as well, our proposed algorithms provided satisfactory performance for interference in both fair and restricted environment that is illustrated in Fig. 3.20c and 3.21c.

3.7.3.2 Result comparison for One-to-Many sharing approach

Different Algorithms for Performance Comparison: To the best of our knowledge, there are no existing online resource allocation algorithms for One-to-Many sharing approach which addresses the same research problem. However, to validate the proposed algorithms, we have implemented the online version of some of the existing offline algorithms. We compare the proposed algorithms with some variants of greedy algorithms (restricted greedy, open greedy, Hungarian greedy) and the CORAL algorithm. We discuss the key points of all of the algorithms in the next subsection. Then we discuss how the proposed algorithm performs compared to the existing algorithm with the numerical result in the following subsections. We use the same experimental environment discussed in Section 3.7.1

Restricted Greedy Algorithm(RGA): RGA [85] is based on the concept of the candidate set. A candidate set represents the feasible cellular UEs, that a D2D pair might share with the RBs. The eligibility to enter the candidate set is governed by the fact that a cellular UE can be a member of the candidate set of a D2D device only if they both produce positive sumrate gain. RGA follows an approach where a single D2D pair can share the RBs of multiple cellular UEs and the highest weight needs to be selected for sharing each time and it does not care about the number of D2D pairs assigned in the medium. If the RBs of a cellular UE are shared, that cellular UE is removed from the candidate sets of all other D2D pairs. Hence, a number of D2D devices with a non-empty candidate set may remain unassigned.

Open Greedy Algorithm(OGA): OGA [85] is a simple variant of RGA where the eligibility of a candidate set is open. More specifically, OGA does not restrict a cellular UE to become a candidate for a D2D pair due to negative sumrate gain. We need to mention that, although OGA does not restrict a cellular UE to be a candidate, we can not say that it ensures the fairness property. OGA always assigns a D2D pair with the highest sumrate gain due to the greedy nature, a number of D2D devices with a non-empty candidate set may remain unassigned.

Hungarian Greedy Algorithm(HGA): HGA [85] is also a variant RGA that Uses a Hungarian algorithm to choose the optimal One-to-One correspondence and then adopts the greedy approach to maximize the system capacity. HGA also incorporates the concept of candidate set and it restricts the cellular UE to be a member of the candidate set of a D2D pair in case of negative sumrate gain. However, the Hungarian algorithm(One-to-One) ensures that all of the D2D pairs with a non-empty candidate set must be assigned with the RBs of at least one cellular UE.

Capacity Oriented Resource Allocation Algorithm (CORAL): CORAL [97] introduces the concept of Capacity Oriented Restricted Region (CORE) where sharing of RBs results in negative system capacity gain. This CORE region is used to calculate the candidate set of a D2D pair. The CORAL algorithm has two phases. The first phase finds out the highest ratio of the channel gain of a cellular UE with the base station to the channel gain of a D2D pair with that cellular UE and assigns that D2D pair with the RBs of the cellular UE. After assigning all of the D2D pairs, the second phase starts where the remaining unshared cellular UEs are distributed among the D2D pairs for further capacity gain. It selects the lowest channel gain of a D2D pair with a cellular UE and assigns the RBs of that cellular UE to the D2D pair. The CORAL algorithm selects the cellular UEs for sharing RBs depending on the channel gain. However, system capacity does not depend on the channel gain solely. It also depends on the transmission power and position of the receiver with respect to the other transmitters using the same RBs. In the first phase, CORAL selects the optimal cellular UEs for each of the D2D pairs and similarly, in the second phase, it chooses the optimal D2D pairs for the remaining unshared cellular UEs. So, it is observable that CORAL does not return the overall optimal or best result rather it is a greedy approach that might be stuck in a local optimum.

- **Experiment-1**

  To illustrate the effectiveness of the proposed algorithms, R-MORA and F-MORA in a One-to-Many sharing scheme, we compare the experimental results with four existing algorithms. The experiments were conducted with different sets of several fixed cellular UE and the maximum number of D2D entries at a certain time. In the first experiment, the number of fixed UE was set to 300 and the maximum D2D entry at a certain time was fixed at 10. While observing the total system sumrate across the six algorithms in Fig. 3.22, it was found that the proposed algorithm R-MORA achieved the highest total system sumrate and the Open Greedy Algorithm (OGA) achieved the least. The performance of the optimal algorithm, HGA was close to R-MORA throughout the experiment timespan. Another proposed algorithm, F-MORA performed slightly better than OGA but the total system sumrate did not improve that much over time. The maximum total system sumrate achieved by the best performing algorithm, R-MORA was 9096.5 whereas, HGA achieved 8977.33. So, the proposed algorithm provides a 1.32% performance improvement in total system sumrate over the previous state-of-the-art algorithm.

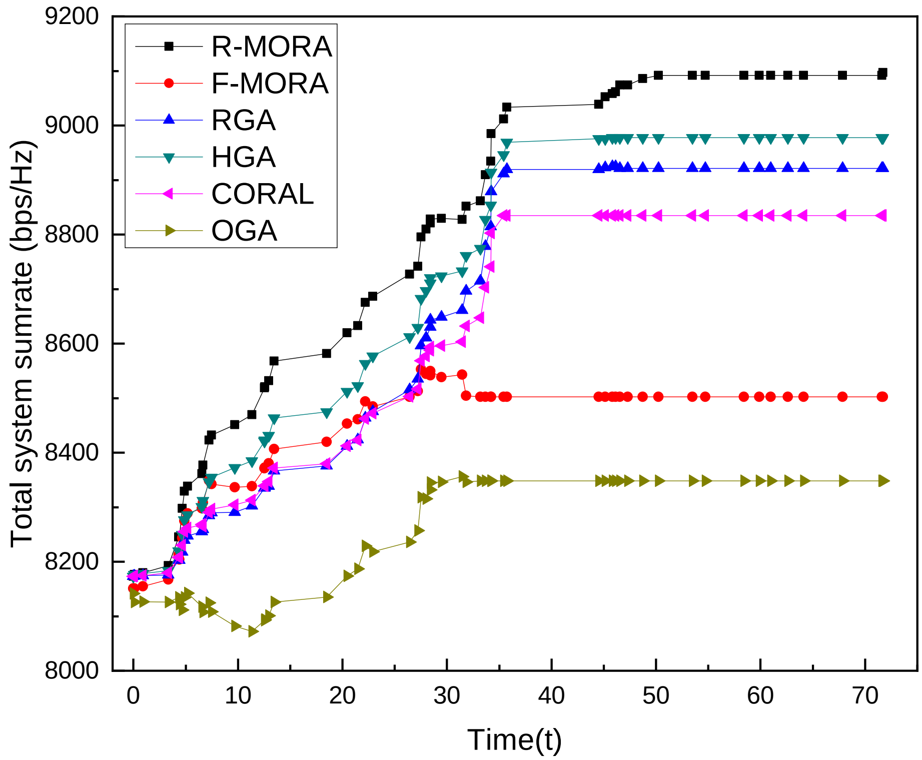


Figure 3.22: Total system sumrate in each state of the system for the One-to-Many sharing scheme (cellular UEs = 300 and maximum number of D2D entry at a time=10)

Among the RA algorithms, R-MORA achieved the least total system interference followed by CORAL and others as shown in Fig. 3.23. Total system interference of OGA was the highest among all six which significantly increased after 10% of the time and remained steady. The maximum total system interference obtained by R-MORA is -67.125. The closest to R-MORA is HGA with a total system sumrate of -63.6415 which gives the proposed algorithm a summit improvement thus, total system interference decreases by 5.47%.

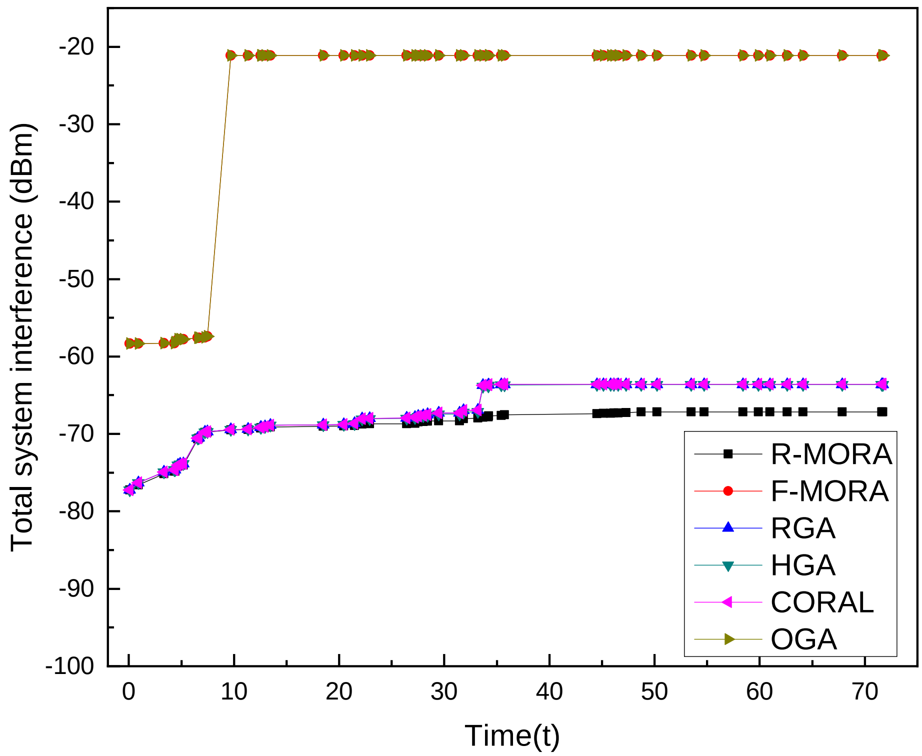


Figure 3.23: Total system interference in each state of the system for the One-to-Many sharing scheme (cellular UEs = 300 and maximum number of D2D entry at a time=10)

Figure 3.24 depicts a comparison between the number of D2D pairs entered into the network and the number of D2D assigned by the six resource allocation algorithms. The proposed algorithm, F-MORA successfully allocated resources for all the D2D that entered the network. F-MORA and OGA achieved a similar ratio for entering vs resource allocation whereas, OGA serves a slightly more number of D2Ds. Among the six algorithms, the maximum number of D2D pairs entered in case of R-MORA followed by RGA and HGA although the number of D2D pairs for those resources has been allocated is almost similar for all six algorithms. Both proposed algorithms assigned a maximum 0f 147 D2D pairs which are greater or equal to other algorithms that are demonstrated here. One interesting fact about this set of experimental results is that although our objective is to maximize total system sumrate, our proposed algorithm, R-MORA performed very well in terms of total system sumrate as well as total system interference which is an important metric in D2D communication. The total system interference comparison of our algorithms with respect to the existing algorithms is depicted in Fig. 3.23.

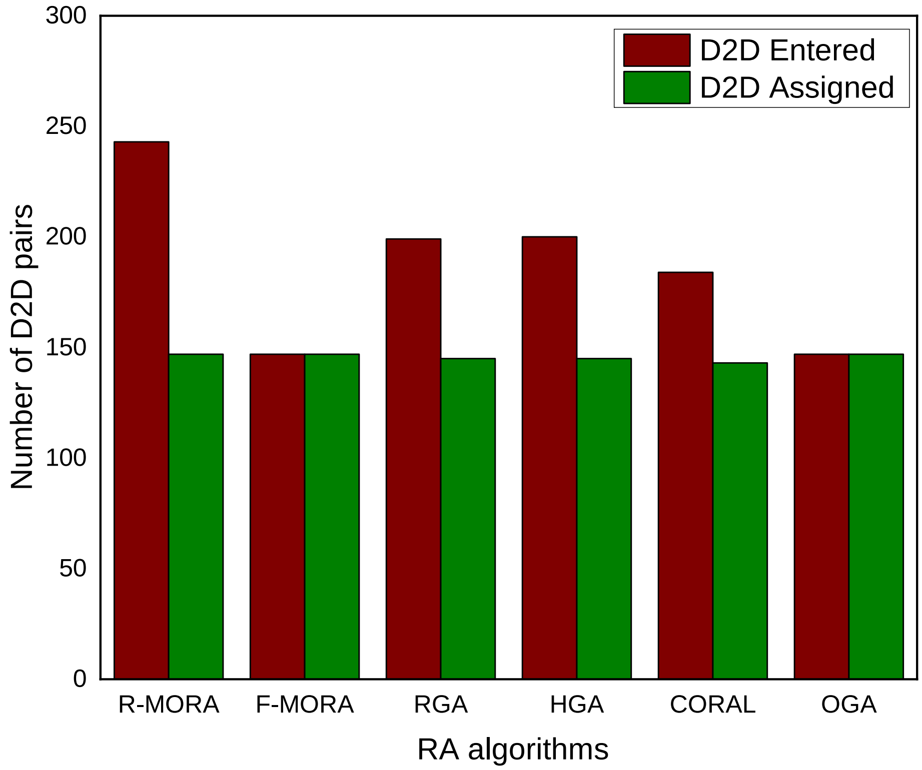


Figure 3.24: Number of D2D pairs entered vs number of D2D assigned by different RA algorithms for the One-to-Many sharing scheme(cellular UEs = 300 and maximum number of D2D entry at a time=10)

- **Experiment-2** We further investigated the performance of the proposed algorithms with the existing ones with a fixed number of cellular UE of 200 and a maximum D2D entry of 5 at a certain time. The experimental results are consistent with the previous one. Similar to experiment-1, of the One-to-Many sharing scheme, the R-MORA algorithm achieved the highest total system sum-rate and OGA achieved the lowest as seen in Fig. 3.25.

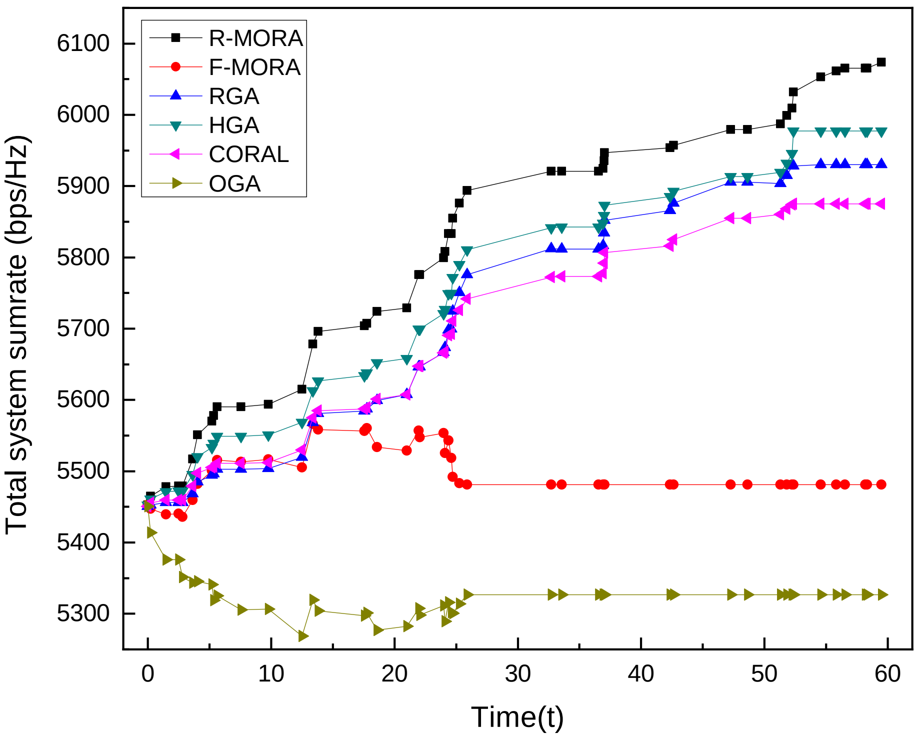


Figure 3.25: Total system sumrate in each state of the system for the One-to-Many sharing scheme(cellular UEs = 200 and maximum number of D2D entry at a time=5)

F-MORA achieved the least total system interference followed by HGA, CORAL, and RGA. The performance of F-MORA and OGA was significantly lagging in case of total system interference as shown in Fig. 3.26.

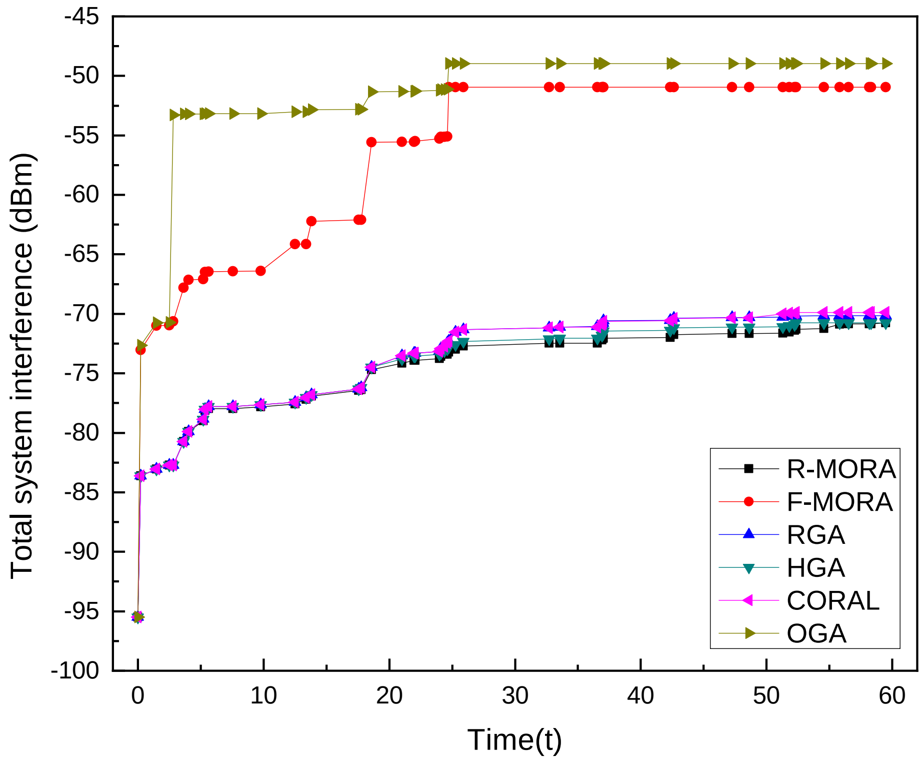


Figure 3.26: Total system interference in each state of the system for the One-to-Many sharing scheme(cellular UEs = 200 and maximum number of D2D entry at a time=5)

Also in experiment-2, the proposed F-MORA allocated resources for all incoming D2D pairs depicted in Fig. 3.27. Although the number of allocated resources to D2D pairs is similar across all algorithms, the number of entered D2D pairs is maximum in case of R-MORA. R-MORA also provided the minimum total system interference compared to the other algorithms as shown in Fig. 3.26.

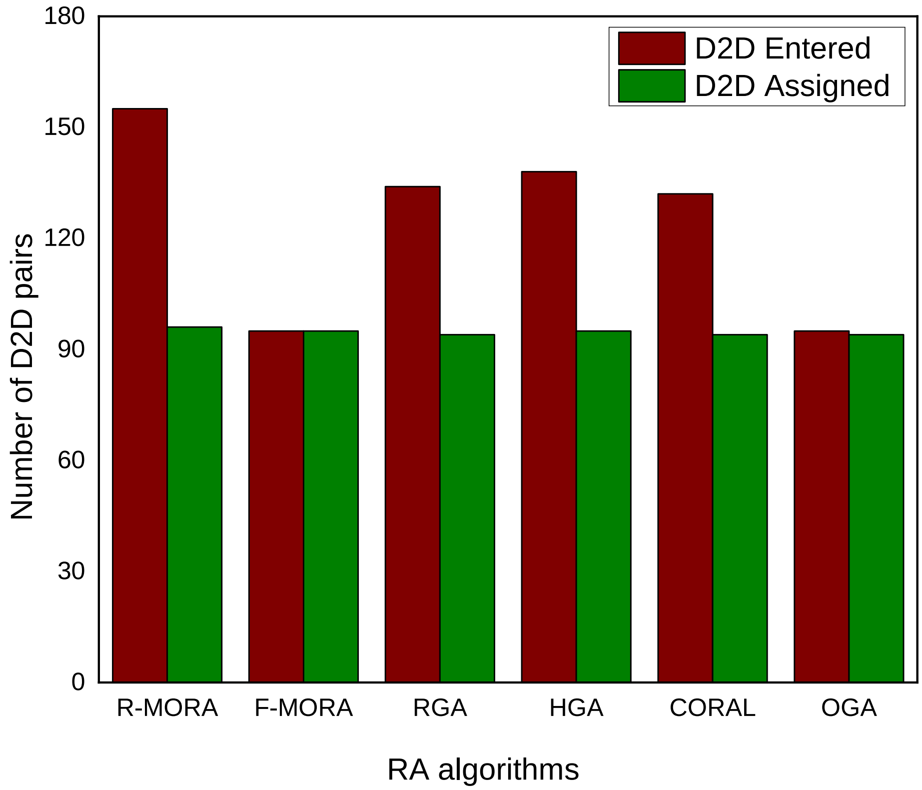


Figure 3.27: Number of D2D pairs entered vs number of D2D assigned by different RA algorithms for the One-to-Many sharing scheme(cellular UEs = 200 and maximum number of D2D entry at a time=5)

- **Experiment-3** In experiment-3, we compared the aforementioned 6 algorithms with a fixed number of UE of 100 and a maximum D2D entry of 1 at a certain time. The performance of the proposed algorithms, F-MORA, and R-MORA is consistent with experiment-1 and experiment-2 as can be observed from Fig. 3.28, 3.29, and 3.30. F-MORA achieved significantly better performance than the optimal and other algorithms in total system rate and total system interference. It also successfully allocated resources for all the D2D pairs that entered the network.

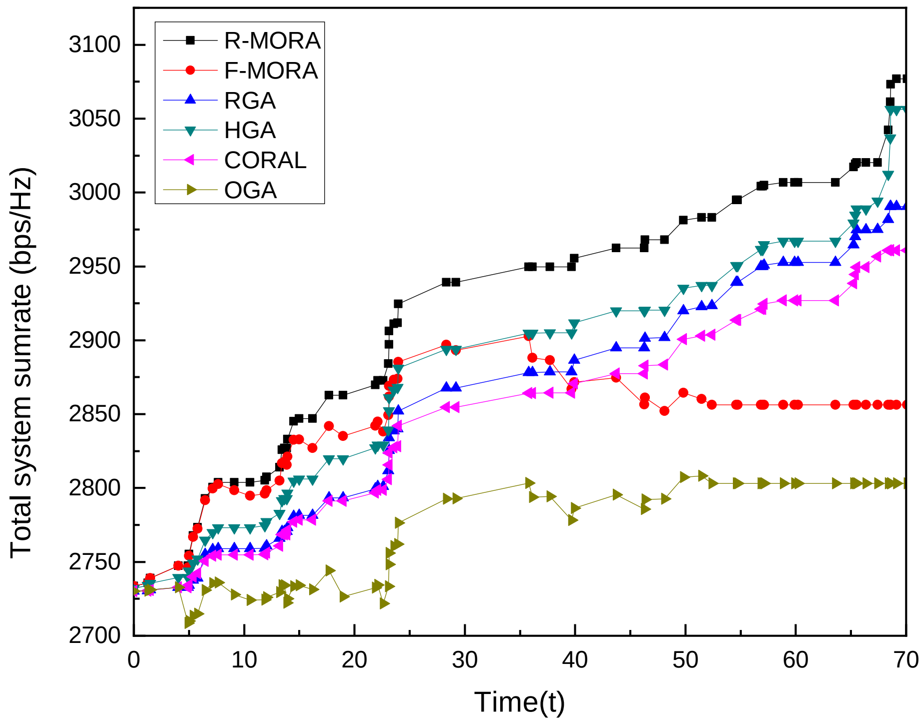


Figure 3.28: Total system sumrate in each state of the system for the One-to-Many sharing scheme(cellular UEs = 100 and maximum number of D2D entry at a time=1)

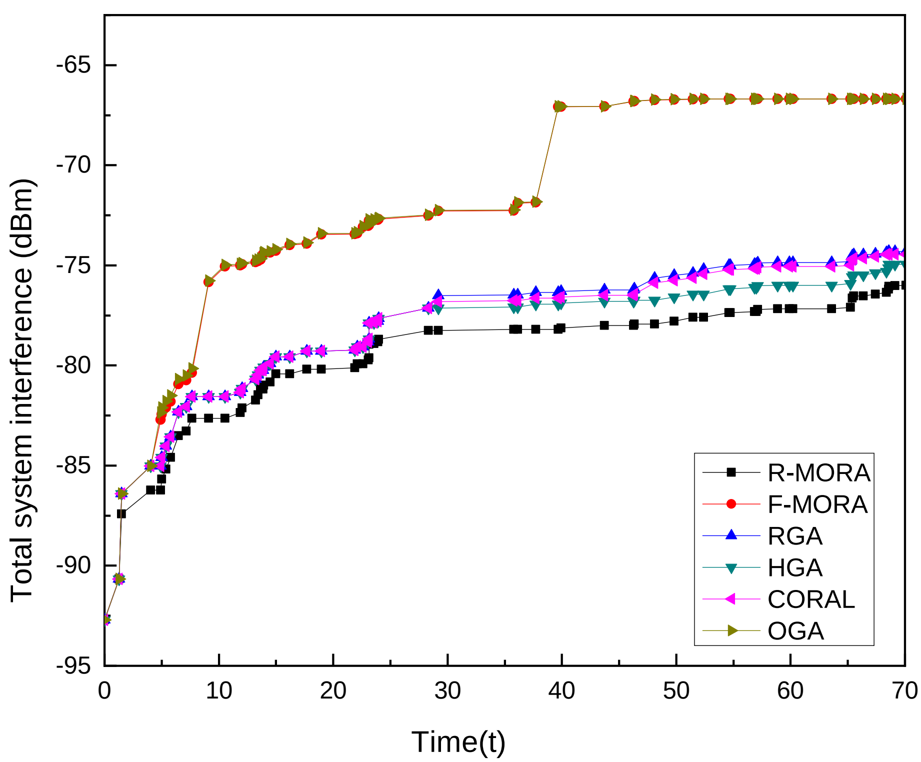


Figure 3.29: Total system interference in each state of the system for the One-to-Many sharing scheme(cellular UEs = 100 and maximum number of D2D entry at a time=1)

Our proposed R-MORA obtained the minimum interference with respect to other RA algorithms as illustrated in Fig. 3.29.

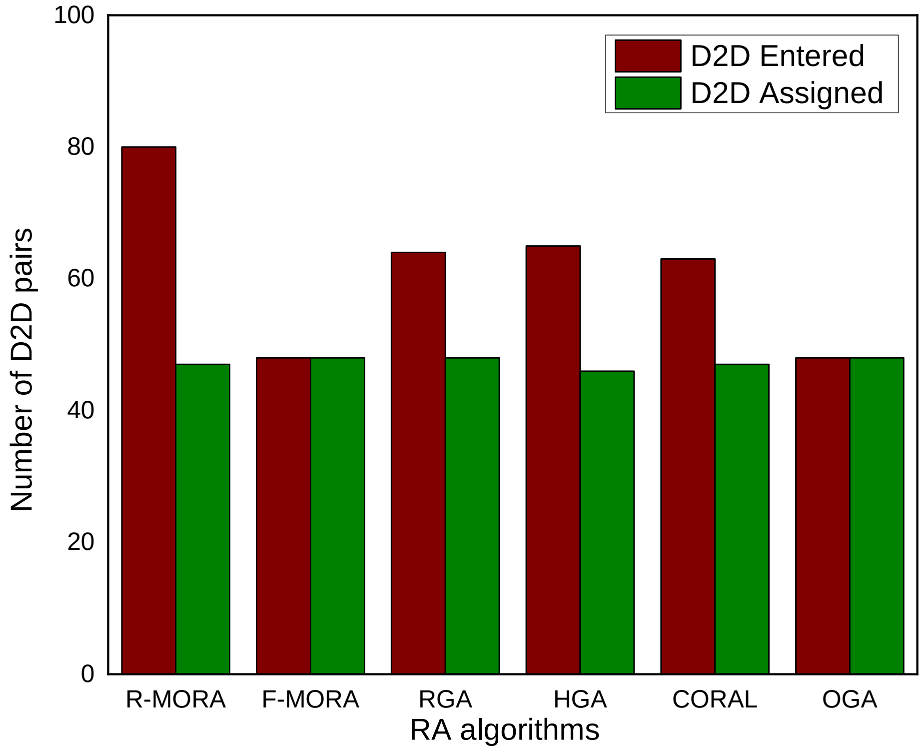


Figure 3.30: Number of D2D pairs entered vs number of D2D assigned by different RA algorithms for the One-to-Many sharing scheme(cellular UEs = 100 and maximum number of D2D entry at a time=1)

3.8 Summary

D2D communication in underlay in-band mode is the most beneficial as sharing the radio resources of existing cellular users with the D2D pairs increases the system capacity. This mode of personal communication is attracting more researchers from academia, standardization bodies, and industry for further insight and a lot more research is still necessary to achieve power and spectral efficiency by developing more efficient resource allocation schemes. This thesis addresses the research problem of maximizing the system sumrate by sharing the RBs among the cellular UEs and the D2D pairs while maintaining the QoS. To the best of our knowledge, most of the existing research works in this area deal with offline resource allocation algorithms.

The addressed research problem can be solved optimally in polynomial time using the weighted bipartite matching algorithm. However, in LTE and beyond (4G and 5G) systems, scheduling algorithms should be very efficient where the optimal algorithm is quite complex to implement. Hence, a low complexity algorithm that returns almost the optimal solution can be an alternative to this research problem. In this chapter, we propose two relax online resource allocation algorithms for D2D communication in in-band underlay mode. Proposed algorithms consider two assignment schemes namely the restricted assignment scheme and the fair assignment scheme. The restricted assignment scheme provides a better system sumrate by avoiding the assignments which contribute to negative sumrate gain. On the other hand, the fair assignment scheme assigns more D2D pairs than the restricted assignment scheme by sacrificing some system sumrate gain. Network providers may choose any one of the schemes based on their needs. We have done extensive numerical experiments to validate the proposed algorithms. Numerical results suggest that proposed algorithms outperform the existing offline algorithms in terms of both total system sumrate and the number of changes in successive allocation. Moreover, the proposed algorithms perform very close to the optimal algorithm in terms of system sumrate with less number of changes in successive allocation. According to the definition of an online stable matching algorithm, our current implementation considers the cellular UEs as a fixed set and D2D pairs as an adversary set. However, assuming both the cellular UEs and the D2D pairs as adversary sets would be an interesting research problem. We plan to investigate this issue in our future work.

Chapter 4

Conclusion

D2D communication in underlay in-band mode is the most beneficial as sharing the radio resources of existing cellular users with the D2D pairs increases the system capacity. This mode of personal communication is attracting more researchers from academia, standardization bodies, and industry for further insight and a lot more research is still necessary to achieve power and spectral efficiency by developing more efficient resource allocation schemes. In this chapter, we summarize the research work on resource allocation of D2D communication underlaying cellular networks presented in this dissertation. We also present some direction for further research in this domain in the future.

4.1 Summary of Research

We considered the optimization problem of resource allocation of D2D communication where the system capacity can be enhanced by efficiently allocating the radio resource of the cellular users. In Chapter 1, we introduced the opportunity, challenges, motivation, and necessity of D2D communication in the modern era of LTE and beyond. In Chapter 2 and Chapter 3, we have formulated the addressed research problem, explained the proposed algorithms with the numerical result, and analyzed them in detail.

The first contribution of this dissertation is the formation of the research problem of interference minimization while maintaining individual target sumrate. This newly formulated research problem accommodates a number of D2D users with heterogeneous data rate demands because of different types of services. Moreover, to meet up the individual demand of a D2D pair in One-to-One mode of sharing might not be sufficient where a D2D might need the RBs of multiple cellular UEs and vice versa. In literature, there are some distributed algorithms addressing One-to-Many and Many-to-Many sharing. However, most of the state-of-the-art centralized algorithms only consider One-to-One sharing for the sake of simplicity. The second contribution is an exploration of the One-to-Many and Many-to-Many sharing modes for the centralized algorithms in the addressed problem domain. We require One-to-Many and Many-to-Many sharing approaches in order to allow different data-intensive services which comply with the media enriched standards like LTE, 4G, 5G, and beyond. In Chapter 2, We construct the problem of interference minimization as a weighted bipartite matching problem and apply our proposed algorithms to allocate RBs to the D2D devices while minimizing the system interference. Our proposed algorithms HIMRA (One-to-One), M-HIMRA (One-to-Many), and HMM-IMRA (Many-to-Many) algorithms apply the Hungarian method to minimize interference whereas SMIMRA (One-to-One) and M-SMIMRA(One-to-Many) apply stable marriage algorithm to solve the assignment problem. Our proposed Many-to-Many algorithm HMM-IMRA is inspired from [31] where they have employed backtracking with the Kuhn-Munkres (Hungarian) algorithm [29] to allow many to many sharing. However, We find that the existing KMB algorithm does not provide any solution for some input sets where a solution exists. We have modified the existing KMB algorithm and used that in HMM-IMRA. We discovered that our suggested method always ensures solutions when they are available. According to numerical results, the proposed resource allocation methods outperform a number of state-of-the-art techniques which ensures the effectiveness of our proposed algorithms.

The third contribution of the dissertation is the proposition of first-ever online resource allocation algorithms in the addressed problem domain where the objective is to maximize the total system sumrate for underlaying D2D communication.

In Chapter 3, we address the research problem of optimizing the system sumrate while ensuring QoS by sharing the RBs among the cellular UEs and D2D pairs. Most contemporary research papers in this field, deal with offline resource allocation methods. The specific research problem can be solved in polynomial time by using the bipartite matching technique. However, scheduling algorithms in LTE and beyond (4G and 5G) systems should be very efficient, as the optimal algorithm is fairly difficult to execute for a large number of inputs. As a result, a low-complexity method that gives a nearly optimal solution could be used to solve this research challenge. We present two relax online resource allocation techniques for D2D communication in in-band underlay mode. The restricted assignment scheme and the fair assignment scheme are both considered in our proposed algorithms. By avoiding assignments that contribute to negative sumrate gain, the restricted assignment method gives a superior system sumrate. By surrendering some system sumrate benefit, the fair assignment strategy assigns more D2D pairs than the restricted assignment scheme. Depending on their needs, network providers can choose from any of the schemes. To validate our algorithms, we conducted rigorous numerical testing. Our suggested algorithms beat existing offline methods in terms of overall system sumrate and number of changes in subsequent allocation, according to numerical data. Furthermore, in terms of system sumrate, our proposed methods perform very close to the optimal algorithm with fewer modifications in successive allocation.

4.2 Future Work

Power control of the D2D pairs and the cellular UEs is not considered in this research. However, joint optimization of power control and interference minimization, as well as capacity maximization, is a potential area to explore in this research domain.

In this thesis, a D2D pair shares either up-link or down-link resources of a cellular network. A joint resource allocation problem including both up-link and down-link resources might be an interesting research direction.

Finding out a solution to a resource allocation problem where the individual interference tolerance is almost equal might be an interesting research problem to look into. Minimization of maximum interference may lead to a path for possible solutions.

In the implementation of our online stable matching algorithm, we consider the cellular UEs as a fixed set and D2D pairs as an adversary set. However, assuming both the cellular UEs and the D2D pairs as adversary sets would be an interesting research problem.

Bibliography

[1] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[2] H. Dai, Y. Huang, C. Li, S. Li, and L. Yang, "Energy-efficient resource allocation for device-to-device communication with wpt," *Iet Communications*, vol. 11, no. 3, pp. 326–334, 2017.

[3] M. Zulhasnine, C. Huang, and A. Srinivasan, "Efficient resource allocation for device-to-device communication underlaying lte network," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2010 IEEE 6th International Conference on*, pp. 368–375, Oct 2010.

[4] M. T. Islam, A. M. Taha, S. G. Akl, and S. Choudhury, "A local search algorithm for resource allocation for underlaying device-to-device communications," in *2015 IEEE Global Communications Conference, GLOBECOM 2015, San Diego, CA, USA, December 6-10, 2015*, pp. 1–6, 2015.

[5] M. Yang, K. Jung, S. Lim, and J. Shin, "Development of device-to-device communication in lte-advanced system," in *2014 IEEE International Conference on Consumer Electronics (ICCE)*, pp. 448–449, Jan 2014.

[6] X. Chen, X. Jin, P. Moorut, R. Love, Y. Sun, W. Xiao, A. Ghosh, and E. Fernandes, "Coexistence analysis involving 3gpp long term evolution," in *2007 IEEE 66th Vehicular Technology Conference*, pp. 225–229, IEEE, 2007.

[7] J. Feng, *Device-to-device communications in LTE-advanced network*. PhD thesis, Télécom Bretagne, Université de Bretagne-Sud, 2013.

[8] C. U. Castellanos, D. L. Villa, C. Rosa, K. I. Pedersen, F. D. Calabrese, P.-H. Michaelsen, and J. Michel, "Performance of uplink fractional power control in utran lte," in *VTC Spring 2008-IEEE Vehicular Technology Conference*, pp. 2517–2521, IEEE, 2008.

[9] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to lte-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, 2009.

[10] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklós, and Z. Turányi, "Design aspects of network assisted device-to-device communications," *IEEE Communications Magazine*, vol. 50, pp. 170–177, March 2012.

[11] S. Stefania, T. Issam, and B. Matthew, "Lte-the umts long term evolution: From theory to practice," *A John Wiley and Sons, Ltd*, vol. 6, pp. 136–144, 2009.

[12] H. Min, W. Seo, J. Lee, S. Park, and D. Hong, "Reliability improvement using receive mode selection in the device-to-device uplink period underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, pp. 413–418, February 2011.

[13] D. Liu, L. Wang, Y. Chen, M. Elkashlan, K.-K. Wong, R. Schober, and L. Hanzo, "User association in 5g networks: A survey and an outlook," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1018–1044, 2016.

[14] A. A. Ali S, "Resource allocation, interference management, and mode selection in device-to-device communication: A survey.," *Trans Emerging Tel Tech. 2017;e3148.*, 2016.

[15] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in lte-advanced networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1923–1940, 2014.

[16] R. Alkurd, R. M. Shubair, and I. Abualhaol, "Survey on device-to-device communications: Challenges and design issues," in *New Circuits and Systems Conference (NEWCAS), 2014 IEEE 12th International*, pp. 361–364, IEEE, 2014.

[17] N. Council, "Six technologies with potential impacts on us interests out to 2025," *Disruptive Civil Technologies*, 2008.

[18] M. T. Islam, A.-E. M. Taha, S. Akl, and M. Abu-Elkheir, "A stable matching algorithm for resource allocation for underlaying device-to-device communications," in *Communications (ICC), 2016 IEEE International Conference on*, pp. 1–6, IEEE, 2016.

[19] H. Zhang, T. Wang, L. Song, and Z. Han, "Graph-based resource allocation for d2d communications underlaying cellular networks," in *Communications in China - Workshops (CIC/ICCC), 2013 IEEE/CIC International Conference on*, pp. 187–192, Aug 2013.

[20] F. Hussain, M. Y. Hassan, M. S. Hossen, and S. Choudhury, "An optimal resource allocation algorithm for D2D communication underlaying cellular networks," in *14th Annual IEEE Consumer Communications & Networking Conference (CCNC 2017)*, (Las Vegas, USA), Jan. 2017.

[21] M. T. Islam, A. M. Taha, S. G. Akl, and S. Choudhury, "A local search algorithm for resource allocation for underlaying device-to-device communications," in *2015 IEEE Global Communications Conference, GLOBECOM 2015, San Diego, CA, USA, December 6-10, 2015*, pp. 1–6, 2015.

[22] G. Gambosi, A. Postiglione, and M. Talamo, "Algorithms for the relaxed online bin-packing model," *SIAM journal on computing*, vol. 30, no. 5, pp. 1532–1551, 2000.

[23] E. Seidel, "3gpp lte-a standardization in release 12 and beyond," *Munich: Nomor Research GmbH*, 2013.

[24] A. Kuhnle, X. Li, and M. T. Thai, "Online algorithms for optimal resource management in dynamic d2d communications," in *2014 10th International Conference on Mobile Ad-hoc and Sensor Networks*, pp. 130–137, Dec 2014.

[25] Y. Xu, R. Yin, T. Han, and G. Yu, "Dynamic resource allocation for device-to-device communication underlaying cellular networks," *International Journal of Communication Systems*, vol. 27, no. 10, pp. 2408–2425, 2014.

[26] M. T. Islam, A.-E. 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)*, pp. 61–66, IEEE, 2015.

[27] M. T. Islam, A. E. M. Taha, S. Akl, and S. Choudhury, "A two-phase auction-based fair resource allocation for underlaying d2d communications," in *2016 IEEE International Conference on Communications (ICC)*, pp. 1–6, May 2016.

[28] M. Y. Hassan, F. Hussain, M. Hossen, S. Choudhury, and M. Alam, "Interference minimization in d2d communication underlaying cellular networks," *IEEE Access*, vol. PP, pp. 1–1, 10 2017.

[29] H. W. Kuhn, "The hungarian method for the assignment problem," *Naval Research Logistics Quarterly*, vol. 2, no. 1-2, pp. 83–97, 1955.

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

[31] H. Zhu, D. Liu, S. Zhang, Y. Zhu, L. Teng, and S. Teng, "Solving the many to many assignment problem by improving the kuhn–munkres algorithm with backtracking," *Theoretical Computer Science*, vol. 618, pp. 30–41, 2016.

[32] P. Mach, Z. Becvar, and T. Vanek, "In-band device-to-device communication in ofdma cellular networks: A survey and challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1885–1922, 2015.

[33] I. Mondal, A. Neogi, P. Chaporkar, and A. Karandikar, "Bipartite graph based proportional fair resource allocation for d2d communication," in *2017 IEEE wireless communications and networking conference (WCNC)*, pp. 1–6, IEEE, 2017.

[34] H. Y. AlSheyab, S. Choudhury, E. Bedeer, and S. S. Ikki, "Interference minimization algorithms for fifth generation and beyond systems," *Computer Communications*, vol. 156, pp. 145–158, 2020.

[35] H. Y. Alsheyab, S. Choudhury, E. Bedeer, and S. S. Ikki, "Near-optimal resource allocation algorithms for 5g+ cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 7, pp. 6578–6592, 2019.

[36] P. R. Saha, S. Choudhury, and D. R. Gaur, "Interference minimization for device-to-device communications: A combinatorial approach," in *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, IEEE, 2019.

[37] Y. Zhang, J. Zheng, P.-S. Lu, and C. Sun, "Interference graph construction for cellular d2d communications," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 3293–3305, 2016.

[38] Y. Hassan, F. Hussain, S. Hossen, S. Choudhury, and M. M. Alam, "Interference minimization in d2d communication underlaying cellular networks," *IEEE Access*, vol. 5, pp. 22471–22484, 2017.

[39] D. Tsolkas, E. Liotou, N. Passas, and L. Merakos, "A graph-coloring secondary resource allocation for d2d communications in lte networks," in *2012 IEEE 17th international workshop on computer aided modeling and design of communication links and networks (CAMAD)*, pp. 56–60, IEEE, 2012.

[40] L. Zhao, H. Wang, and X. Zhong, "Interference graph based channel assignment algorithm for d2d cellular networks," *IEEE Access*, vol. 6, pp. 3270–3279, 2018.

[41] R. Zhang, X. Cheng, L. Yang, and B. Jiao, "Interference graph-based resource allocation (ingra) for d2d communications underlaying cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 64, pp. 3844–3850, Aug 2015.

[42] 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 *Proceedings of IEEE International Conference on Communications, ICC 2012, Ottawa, ON, Canada, June 10-15, 2012*, pp. 445–449, 2012.

[43] K. Huang, V. K. N. Lau, and Y. Chen, "Spectrum sharing between cellular and mobile ad hoc networks: Transmission-capacity tradeoff," in *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2009. WiOPT 2009. 7th International Symposium on*, pp. 1–10, June 2009.

[44] 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*, pp. 617–621, IEEE, 2009.

[45] P. Janis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler, and K. Hugl, "Interference-avoiding mimo schemes for device-to-device radio underlaying cellular networks," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 2385–2389, IEEE, 2009.

[46] Z. Han, D. Niyato, W. Saad, T. Başar, and A. Hjørungnes, *Game theory in wireless and communication networks: theory, models, and applications*. Cambridge university press, 2012.

[47] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication," *IEEE Wireless Communications*, vol. 21, no. 3, pp. 136–144, 2014.

[48] N. Sawyer and D. B. Smith, "Flexible resource allocation in device-to-device communications using stackelberg game theory," *IEEE Transactions on Communications*, vol. 67, no. 1, pp. 653–667, 2018.

[49] D. Wang, S. Zhang, Q. Cheng, and X. Zhang, "Joint interference alignment and power allocation based on stackelberg game in device-to-device communications underlying cellular networks," *IEEE Access*, vol. 9, pp. 81651–81659, 2021.

[50] N. Kumar Jadav, R. Gupta, and S. Tanwar, "A survey on energy-efficient resource allocation schemes in device-to-device communication," *International Journal of Communication Systems*, p. e5112.

[51] R. Yin, G. Yu, C. Zhong, and Z. Zhang, "Distributed resource allocation for d2d communication underlaying cellular networks," in *2013 IEEE International Conference on Communications Workshops (ICC)*, pp. 138–143, IEEE, 2013.

[52] K. Zhu and E. Hossain, "Joint mode selection and spectrum partitioning for device-to-device communication: A dynamic stackelberg game," *IEEE Transactions on Wireless Communications*, vol. 14, no. 3, pp. 1406–1420, 2014.

[53] S. Rajabi, S. Ghorashi, and V. Shah-Mansouri, "Impact of connecting to the nth nearest node in dedicated device-to-device communications," *Electronics Letters*, vol. 54, no. 8, pp. 535–537, 2018.

[54] D. S. Gurjar and P. K. Upadhyay, "Performance analysis of zero-forcing-based multiple-input multiple-output two-way relaying in overlay device-to-device communications," *IET Communications*, vol. 10, no. 6, pp. 699–708, 2016.

[55] Q. Wang, W. Wang, S. Jin, H. Zhu, and N. T. Zhang, "Unified low-layer power allocation and high-layer mode control for video delivery in device-to-device

network with multi-antenna relays," *IET Communications*, vol. 10, no. 10, pp. 1196–1205, 2016.

[56] T. Elderini, N. Kaabouch, and H. Reyes, "Channel quality estimation metrics in cognitive radio networks: a survey," *IET Communications*, vol. 11, no. 8, pp. 1173–1179, 2017.

[57] S. Joshi and R. K. Mallik, "Analysis of dedicated and shared device-to-device communication in cellular networks over nakagami-m fading channels," *IET Communications*, vol. 11, no. 10, pp. 1600–1609, 2017.

[58] Z. Feng, Z. Feng, and T. A. Gulliver, "Discrete location-aware resource allocation for underlay device-to-device communications in cellular networks," *IET Communications*, vol. 11, no. 16, pp. 2482–2489, 2017.

[59] Y. Qi, H. Wang, L. Zhang, and B. Wang, "Optimal access mode selection and resource allocation for cellular-vanet heterogeneous networks," *IET Communications*, vol. 11, no. 13, pp. 2012–2019, 2017.

[60] C. H. Kai, H. Li, and L. Qian, "Game-theoretic radio resource management for relay-assisted access in wireless networks," *IET Communications*, vol. 12, no. 5, pp. 566–572, 2018.

[61] O. N. Hamoud, T. Kenaza, and Y. Challal, "Security in device-to-device communications: a survey," *IET Networks*, vol. 7, no. 1, pp. 14–22, 2017.

[62] Y. Fang, Y. Zhou, X. Jiang, D. Zhang, and Y. Zhang, "Game theoretic d2d content sharing: joint participants selection, routing and pricing," in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, pp. 1–9, IEEE, 2017.

[63] X. Hu and A. Striegel, "Pass: Content pre-staging through provider accessible storage service," in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, pp. 1–8, IEEE, 2017.

[64] P. K. Mishra, S. Pandey, and S. K. Biswash, "Efficient resource management by exploiting d2d communication for 5g networks," *IEEE Access*, vol. 4, pp. 9910–9922, 2016.

[65] G. A. Safdar, M. Ur-Rehman, M. Muhammad, M. A. Imran, and R. Tafazolli, "Interference mitigation in d2d communication underlaying lte-a network," *IEEE Access*, vol. 4, pp. 7967–7987, 2016.

[66] A. Shahid, K. S. Kim, E. De Poorter, and I. Moerman, "Self-organized energy-efficient cross-layer optimization for device to device communication in heterogeneous cellular networks," *IEEE Access*, vol. 5, pp. 1117–1128, 2017.

[67] X. Mi, L. Xiao, M. Zhao, X. Xu, and J. Wang, "Statistical qos-driven resource allocation and source adaptation for d2d communications underlaying ofdma-based cellular networks," *IEEE Access*, vol. 5, pp. 3981–3999, 2017.

[68] Y. Zhao and W. Song, "Survey on social-aware data dissemination over mobile wireless networks," *IEEE Access*, vol. 5, pp. 6049–6059, 2017.

[69] E. Baccarelli, P. G. V. Naranjo, M. Scarpiniti, M. Shojafar, and J. H. Abawajy, "Fog of everything: Energy-efficient networked computing architectures, research challenges, and a case study," *IEEE access*, vol. 5, pp. 9882–9910, 2017.

[70] A. Rahman, E. Hassanain, and M. S. Hossain, "Towards a secure mobile edge computing framework for hajj," *IEEE Access*, vol. 5, pp. 11768–11781, 2017.

[71] G. Z. Khan, E.-C. Park, and R. Gonzalez, "M 3-cast: A novel multicast scheme in multi-channel and multi-rate wifi direct networks for public safety," *IEEE Access*, vol. 5, pp. 17852–17868, 2017.

[72] S. Li, Q. Ni, Y. Sun, and G. Min, "Resource allocation for weighted sum-rate maximization in multi-user full-duplex device-to-device communications: Approaches for perfect and statistical csis," *IEEE Access*, vol. 5, pp. 27229–27241, 2017.

[73] D. Xu, Y. Li, J. Li, M. Ahmed, and P. Hui, "Joint topology control and resource allocation for network coding enabled d2d traffic offloading," *IEEE Access*, vol. 5, pp. 22916–22926, 2017.

[74] H. M. Islam, D. Chatzopoulos, D. Lagutin, P. Hui, and A. Ylä-Jääski, "Boosting the performance of content centric networking using delay tolerant networking mechanisms," *IEEE Access*, vol. 5, pp. 23858–23870, 2017.

[75] Z. Chu, T. A. Le, H. X. Nguyen, A. Nallanathan, and M. Karamanoglu, "A stackelberg-game approach for disaster-recovery communications utilizing cooperative d2d," *IEEE Access*, vol. 6, pp. 10733–10742, 2017.

[76] M. Höyhtyä, A. Mämmelä, X. Chen, A. Hulkkonen, J. Janhunen, J.-C. Dunat, and J. Gardey, "Database-assisted spectrum sharing in satellite communications: A survey," *IEEE Access*, vol. 5, pp. 25322–25341, 2017.

[77] G. Chandrasekaran, N. Wang, M. Hassanpour, M. Xu, and R. Tafazolli, "Mobility as a service (maas): a d2d-based information centric network architecture for edge-controlled content distribution," *IEEE Access*, vol. 6, pp. 2110–2129, 2017.

[78] T. Salam, W. U. Rehman, and X. Tao, "Cooperative data aggregation and dynamic resource allocation for massive machine type communication," *IEEE Access*, vol. 6, pp. 4145–4158, 2018.

[79] J. Hu, W. Heng, Y. Zhu, G. Wang, X. Li, and J. Wu, "Overlapping coalition formation games for joint interference management and resource allocation in d2d communications," *IEEE Access*, vol. 6, pp. 6341–6349, 2018.

[80] Y. Xiao, K.-C. Chen, C. Yuen, Z. Han, and L. A. DaSilva, "A bayesian overlapping coalition formation game for device-to-device spectrum sharing in cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 4034–4051, 2015.

[81] Y. Zhao, Y. Li, D. Wu, and N. Ge, "Overlapping coalition formation game for resource allocation in network coding aided d2d communications," *IEEE Transactions on Mobile Computing*, vol. 16, no. 12, pp. 3459–3472, 2017.

[82] Y. Sun, F. Wang, and Z. Liu, "Coalition formation game for resource allocation in d2d uplink underlaying cellular networks," *IEEE Communications Letters*, vol. 23, no. 5, pp. 888–891, 2019.

[83] Y. Sun and F. Wang, "Joint resource allocation and interference management in the d2d uplink underlaying cellular networks," *Telecommunication Systems*, pp. 1–8, 2021.

[84] M. Y. Hassan, F. Hussain, M. S. Hossen, S. Choudhury, and M. M. Alam, "A near optimal interference minimization resource allocation algorithm for D2D communication," in *IEEE ICC 2017 Communications QoS, Reliability, and Modeling Symposium (ICC'17 CQRM)*, (Paris, France), May 2017.

[85] F. Hussain, M. Y. Hassan, M. S. Hossen, and S. Choudhury, "System capacity maximization with efficient resource allocation algorithms in d2d communication," *IEEE Access*, vol. 6, pp. 32409–32424, 2018.

[86] M. T. Islam, A.-E. 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)*, pp. 61–66, IEEE, 2015.

[87] B. A. Forouzan, *Data Communications and Networking.* New York, NY, USA: McGraw-Hill, Inc., 3 ed., 2003.

[88] A. Osseiran, J. F. Monserrat, and W. Mohr, "Mobile and wireless communications for imt-advanced and beyond," in *Wiley Publishing*, 2011.

[89] Fujitsu, "High-capacity indoor wireless solutions: Picocell or femtocell?."

[90] R. Jain, *The art of computer systems performance analysis.* john wiley & sons, 2008.

[91] J. Kleinberg and E. Tardos, *Algorithm Design.* Pearson Education, 2011.

[92] A. Celik, R. M. Radaydeh, F. S. Al-Qahtani, and M.-S. Alouini, "Resource allocation and interference management for d2d-enabled dl/ul decoupled het-nets," *IEEE Access*, vol. 5, pp. 22735–22749, 2017.

[93] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Performance impact of fading interference to device-to-device communication underlaying cellular networks," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 858–862, IEEE, 2009.

[94] 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)*, pp. 445–449, IEEE, 2012.

[95] S. Xu, H. Wang, T. Chen, Q. Huang, and T. Peng, "Effective interference cancellation scheme for device-to-device communication underlaying cellular networks," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pp. 1–5, IEEE, 2010.

[96] W. Xu, L. Liang, H. Zhang, S. Jin, J. C. Li, and M. Lei, "Performance enhanced transmission in device-to-device communications: Beamforming or interference cancellation?," in *2012 IEEE Global Communications Conference (GLOBECOM)*, pp. 4296–4301, IEEE, 2012.

[97] H. Min, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 10, no. 12, pp. 3995–4000, 2011.

[98] R. Knopp and P. A. Humblet, "Information capacity and power control in single-cell multiuser communications," in *Proceedings IEEE International Conference on Communications ICC'95*, vol. 1, pp. 331–335, IEEE, 1995.

[99] X. Xiao, X. Tao, and J. Lu, "A qos-aware power optimization scheme in ofdma systems with integrated device-to-device (d2d) communications," in *2011 IEEE vehicular technology conference (VTC Fall)*, pp. 1–5, IEEE, 2011.

[100] M. Jung, K. Hwang, and S. Choi, "Joint mode selection and power allocation scheme for power-efficient device-to-device (d2d) communication," in *2012 IEEE 75th vehicular technology conference (VTC Spring)*, pp. 1–5, IEEE, 2012.

[101] N. Reider and G. Fodor, "A distributed power control and mode selection algorithm for d2d communications," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, p. 266, 2012.

[102] K. Vanganuru, S. Ferrante, and G. Sternberg, "System capacity and coverage of a cellular network with d2d mobile relays," in *MILCOM 2012-2012 IEEE Military Communications Conference*, pp. 1–6, IEEE, 2012.

[103] J. Seppälä, T. Koskela, T. Chen, and S. Hakola, “Network controlled device-to-device (d2d) and cluster multicast concept for lte and lte-a networks,” in *2011 IEEE Wireless Communications and Networking Conference*, pp. 986–991, IEEE, 2011.

[104] G. Fodor, D. Della Penda, M. Belleschi, M. Johansson, and A. Abrardo, “A comparative study of power control approaches for device-to-device communications,” in *2013 IEEE International Conference on Communications (ICC)*, pp. 6008–6013, IEEE, 2013.

[105] 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)*, pp. 140–145, IEEE, 2013.

[106] G. Fodor, “Performance comparison of practical resource allocation schemes for device-to-device communications,” *Wireless Communications and Mobile Computing*, vol. 2018, 2018.

[107] N. Du, K. Sun, C. Zhou, and X. Ma, “A novel access control and energy-saving resource allocation scheme for d2d communication in 5g networks,” *Complexity*, vol. 2020, 2020.

[108] F. O. Ombongi, H. O. Absaloms, and P. L. Kibet, “Resource allocation in millimeter-wave device-to-device networks,” *Mobile Information Systems*, vol. 2019, 2019.

[109] M. Wang and Z. Yan, “Security in d2d communications: A review,” in *2015 IEEE Trustcom/BigDataSE/ISPA*, vol. 1, pp. 1199–1204, IEEE, 2015.

[110] X. Cheng, Y. Li, B. Ai, X. Yin, and Q. Wang, “Device-to-device channel measurements and models: A survey,” *IET communications*, vol. 9, no. 3, pp. 312–325, 2015.

[111] J. Liu, N. Kato, J. Ma, and N. Kadowaki, “Device-to-device communication in lte-advanced networks: A survey,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1923–1940, 2015.

[112] M. H. Adnan and Z. Ahmad Zukarnain, “Device-to-device communication in 5g environment: Issues, solutions, and challenges,” *Symmetry*, vol. 12, no. 11, p. 1762, 2020.

[113] A. Asadi, Q. Wang, and V. Mancuso, “A survey on device-to-device communication in cellular networks,” *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[114] P. K. Malik, D. S. Wadhwa, and J. S. Khinda, “A survey of device to device and cooperative communication for the future cellular networks,” *International Journal of Wireless Information Networks*, pp. 1–22, 2020.

[115] P. Gandotra, R. K. Jha, and S. Jain, "A survey on device-to-device (d2d) communication: Architecture and security issues," *Journal of Network and Computer Applications*, vol. 78, pp. 9–29, 2017.

[116] M. S. M. Gismalla and M. Abdullah, "Survey on device-to-device communication with internet of things in cellular networks," *Journal of Applied Engineering & Technology (JAET)*, vol. 1, no. 1, pp. 1–8, 2017.

[117] X. Cai, J. Zheng, Y. Zhang, and H. Murata, "A capacity oriented resource allocation algorithm for device-to-device communication in mobile cellular networks," in *Communications (ICC), 2014 IEEE International Conference on*, pp. 2233–2238, June 2014.

[118] X. Cai, J. Zheng, and Y. Zhang, "A graph-coloring based resource allocation algorithm for d2d communication in cellular networks," in *Communications (ICC), 2015 IEEE International Conference on*, pp. 5429–5434, June 2015.

[119] 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 *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pp. 1–5, April 2009.

[120] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Transactions on Communications*, vol. 61, pp. 3541–3551, August 2013.

[121] J. Huang, Y. Yin, Y. Sun, Y. Zhao, C. c. Xing, and Q. Duan, "Game theoretic resource allocation for multicell d2d communications with incomplete information," in *Communications (ICC), 2015 IEEE International Conference on*, pp. 3039–3044, June 2015.

[122] K. Huang, Y. Chen, B. Chen, X. Yang, and V. K. N. Lau, "Overlaid cellular and mobile ad hoc networks," in *Communication Systems, 2008. ICCS 2008. 11th IEEE Singapore International Conference on*, pp. 1560–1564, Nov 2008.

[123] C. H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, "On the performance of device-to-device underlay communication with simple power control," in *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pp. 1–5, April 2009.

[124] X. Liu, X. Li, and C. Liu, "Position-based mode selection and resource allocation for d2d communications underlaying cellular networks," in *2017 9th International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–6, IEEE, 2017.

[125] R. M. Karp, U. V. Vazirani, and V. V. Vazirani, "An optimal algorithm for on-line bipartite matching," in *Proceedings of the twenty-second annual ACM symposium on Theory of computing*, pp. 352–358, ACM, 1990.

[126] S. Khuller, S. G. Mitchell, and V. V. Vazirani, "On-line algorithms for weighted bipartite matching and stable marriages," *Theoretical Computer Science*, vol. 127, no. 2, pp. 255–267, 1994.

[127] P. Salvador, R. Valadas, and A. Pacheco, "Multiscale fitting procedure using markov modulated poisson processes," *Telecommunication systems*, vol. 23, no. 1, pp. 123–148, 2003.

[128] W. J. Stewart, *Introduction to the numerical solutions of Markov chains*. Princeton Univ. Press, 1994.

[129] L. S. S. D. Gale, "College admissions and the stability of marriage," *The American Mathematical Monthly*, vol. 69, no. 1, pp. 9–15, 1962.

List of Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AWGN	Additive White Gaussian Noise
BS	Base Station
CORAL	Capacity Oriented Resource Allocation
CRORA	Conservatively Relax Online Resource Allocation
CQI	Channel Quality Identifier
CSI	Channel State Information
CU	Cellular User
D2D	Device-to-Device
DARA	Deferred Acceptance based Resource Allocation
eNB	evolved Node B
FARA	Fair Assignment Resource Allocation
F-MORA	Fair Multiple Online Resource Allocation
GOAL	Graph Coloring based Resource Allocation
GT	Game Theory

Hetnet	Heterogeneous Networks
HGA	Hungarian based Greedy Algorithm
HIMRA	Hungarian based Interference Minimization Resource Allocation
HMM-IMRA	Hungarian based Many to Many Interference Minimization Resource Allocation
KMB	Kuhn-Munkres Algorithm with Backtracking
LORA	Local Search based Resource Allocation
LTE	Long Term Evolution
M2M	Machine to Machine
MAD	Multiple Allocation in Device to Device Communication
M-HIMRA	Multiple Hungarian based Interference Minimization Resource Allocation
M-SMIMRA	Multiple Stable Marriage based Interference Minimization Resource Allocation
MIKIRA	MInimum Knapsack-based Interference-aware Resource Allocation
MIMO	Multiple Input Multiple Output
MINLP	Mixed Integer Non-Linear Program
NFP	Network Flying Platform
OCFG	Overlapping Coalition Formation Game Theory
OFDMA	Orthogonal Frequency Division Multiple Access
OGA	Open Greedy Algorithm
QoS	Quality of Service
RA	Resource Allocation
RARA	Restricted Assignment Resource Allocation

RGA	Restricted Greedy Algorithm
R-MORA	Restricted Multiple Online Resource Allocation
RORA	Relax Online Resource Allocation
RB	Resource Block
SC-FDMA	Single Carrier Frequency Division Multiple Access
SC	Small Cell
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SMIMRA	Stable Marriage based Interference Minimization Resource Allocation
TAFIRA	Two-phase Auction-based Fair and Interference-aware Resource Allocation
UE	User Equipment
V2V	Vehicle to Vehicle

List of Notations

c_i	Cellular UE
$c_i^{capacity}$	Maximum number of D2D pairs a cellular UE c_i can share with
d_j	D2D pair
d_j^t	Transmitter of D2D pair d_j
d_j^r	Receiver of D2D pair d_j
d_j^{req}	Number of cellular UEs required by a D2D pair d_j to meet up the target sumrate demand
P^{eNB}	Transmission power of base station or eNB
$P^{d_j^t}$	Transmission power of D2D devices
P^{c_i}	Transmission power of cellular users
$PL^{a,b}$	Distance dependent path loss between a and b
$G^{a,b}$	Channel gain between a and b
$G^{c_i,eNB}$	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
$\gamma_{c_i}^{DL}$	SINR of a cellular UE c_i when c_i shares the channel with D2D pair d_j in Downlink
$\gamma_{c_i^0}^{DL}$	SINR of a cellular UE c_i when c_i does not share the channel with any D2D pair in downlink

$\gamma_{d_j}^{DL}$	SINR at the receiver of the D2D pair d_j when it shares the channel with c_i in downlink
$\gamma_{c_i,target}^{DL}$	SINR target for cellular UE c_i in downlink
$\gamma_{d_j,target}^{DL}$	SINR target for D2D pair d_j in downlink
$\gamma_{c_i}^{UL}$	SINR at the eNB when c_i shares the channel with D2D pair d_j in uplink phase
$\gamma_{c_i^0}^{UL}$	SINR at the eNB when the c_i does not share the channel with any D2D pair in uplink
$\gamma_{d_j}^{UL}$	SINR at the receiver of the D2D pair d_j when it shares the channel with c_i in uplink
I_{c_i,d_j}	Total interference due to sharing of resources by cellular UE c_i and D2D pair d_j
$S_{c_i}^{DL}$	Sumrate contribution of a cellular UE c_i using downlink resource
$S_{c_i^0}^{DL}$	Sumrate contribution of a cellular UE c_i if no D2D pair reuses the RBs using downlink resources
$S_{d_j}^{DL}$	Sumrate contribution of a D2D pair d_j using downlink resources
$S_{c_i}^{UL}$	Sumrate contribution of a cellular UE c_i using uplink resources
$S_{c_i^0}^{UL}$	Sumrate contribution of a cellular UE c_i if no D2D pair reuses the RBs using uplink resources
$S_{d_j}^{UL}$	Sumrate contribution of a D2D pair d_j using uplink resources
T_{c_i}	Individual target sumrate of cellular UE c_i
T_{d_j}	Individual target sumrate of D2D pair d_j
p_{c_i,d_j}^{R}	Binary variable to denote the presence of a node c_i in another node d_j ' preference list in restricted mode
$x_{c_i}^{d_j}$	Binary variable that indicates whether a D2D pair d_j shares the RBs of a cellular UE c_i or not
$\triangle R$	Sumrate gain

List of Publications

Journals (SCIE Indexed)

1. **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.

2. Y. Hassan, F. Hussain, **M.S. Hossen**, S. Choudhury and M. M. Alam, "Interference Minimization in D2D Communication Underlaying Cellular Networks," in *IEEE Access*, vol. 5, pp. 22471-22484, 2017.

3. 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.

4. M.Y. Hassan, F. Hussain, **M.S. Hossen** and S. Choudhury, "An online resource allocation algorithm to minimize system interference for inband underlay D2D communications", *International Journal of Communication Systems*, 32(13), p.e4011, 2019.

5. A. Munir, S. Uzzaman, **M.S. Hossen**, M.S., S. Choudhury, and M.M. Alam, "Localized Motion Planning Algorithm for Mobile Wireless Sensor Networks", *International Journal of Unconventional Computing*, 12(5-6), pp.363-391, 2016.

Conference

1. M.Y. Hassan, F. Hussain, **M.S. Hossen**, S. Choudhury. and M.M. Alam, "A near optimal interference minimization resource allocation algorithm for D2D communication. In 2017 IEEE *International Conference on Communications (ICC)*, (pp. 1-6), May 2017.

2. F. Hussain, M.Y. Hassan, **M.S. Hossen**, and S. Choudhury, "An optimal resource allocation algorithm for D2D communication underlaying cellular networks", In 14th IEEE Annual *Consumer Communications Networking Conference (CCNC)*, (pp. 867-872), January 2017.

3. T. I. Aziz, S. Protik, **M.S. Hossen**, S. Choudhury and M. M. Alam, "Degree-based Balanced Clustering for Large-Scale Software Defined Networks," *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1-6, 2019.