Resource Allocation for Device-to-Device Communication Underlaying Cellular Network

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Dedicated to my parents

Dissertation Approval

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Abstract

Device-to-Device (D2D) communication is expected to play a major role for enhancing system capacity in the fifth generation wireless networks. The gains are expected due to the possibility of reusing resources allocated to the cellular users (CUs) for the D2D underlay network. This allows for the resource reuse in the same cell and thus may lead to a significant interference. The key challenge is to devise resource allocation schemes for the D2D communication that does not adversely affect CU's communication. Resource allocation can be done to achieve various performance objectives like maximizing network throughput, minimizing delay, achieving fairness among user data rates, etc. In this work, our aim is to propose a polynomial time proportional fair (PF) resource allocation scheme that respects the rate requirements of the CUs. The proposed scheme can potentially work with any resource allocation scheme for CUs and can adapt to the time and location varying channel conditions. Our scheme allows for allotting more than one resource block to a D2D pair. The performance of the proposed scheme is validated through the simulations.

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Chapter 1

Introduction

With the ushering in of new applications, the requirement of high data rates have increased tremendously over the past few years. However, due to the spectrum shortage, supporting such growing data rate requirements has been a technical challenge. The fifth generation of wireless networks promises to address this problem. In this context, D2D communication is expected to play a major role to improve network throughput and spectral efficiency by offloading traffic at the base station (BS) and enhance the performance and quality of service (QoS) of local area services, context-based applications, etc. [1]. However, to increase the spectral efficiency of the network for D2D communication, reusing the resources of the CUs in an efficient manner is critical as this may cause severe interference to the CUs. One of the main constraints in resource reuse is that the D2D communication should not disrupt CUs communication. Once this requirement is met then one needs to address how resource allocation for D2D communication should be done. Resource allocation can be done to achieve various performance objectives. In this work, we focus on PF resource allocation as it strikes a good trade-off between throughput and fairness among users [2].

In this chapter, we present basic concepts of D2D communication in the licensed spectrum, existing scheduling techniques for cellular networks, some open research problems for D2D resource allocation and our contributions towards solving some of those problems.

1.1 Basics of D2D Communication

D2D communication is envisioned to be a key technology component for the next generation wireless network (5G) to offload network traffic and enable new proximity-based services [1]. D2D communication commonly refers to the communication between two or more devices directly, i.e. single hop communication without any need of infrastructure or BS, while for the existing cellular network user-to-user communication is two hop communication via the BS as an intermediate node.

D2D communication may be categorized [3] in three types:

- *Peer-to-peer communication:* This is like conventional point-to-point (P2P) communication.
- *Cooperative communication:* In this type of communication, devices act as relays to extend cell coverage.
- *Multiple-hop communication:* This is like an extension of cooperative communication where multiple devices form an ad-hoc mesh network to enable data routing between devices.

1.1.1 Configurations of D2D Communication

There are different configurations [3] of the D2D networks discussed below:

- *Network-controlled D2D:* The base station and the core network controls the signalling setup and thereafter resource allocation for both CUs and D2D pairs. The centralized control can result in efficient interference management and resource allocation.
- *Self-organized D2D:* This configuration is distributed in nature. D2D users sense the spectrum holes, collect channel state information (CSI) and possible interferences much like cognitive-radio (CR) and communicate in a self-organizing way to other D2D pairs. Thus, it reduces signalling overhead but may create instability due to lack of centralized control.
- *Network-assisted D2D:* In this scenario, the BS only allocates resources to the D2D users and thereafter users communicate between themselves in a self-organizing way. This method has low signalling overhead and also partial centralized control to avoid communication chaos, but security can be a potential issue.

1.1.2 Device Synchronization and Discovery

Synchronization between CUs and D2D pairs is important for resource allocation and interference management. Proper hand-off of D2D pairs is also possible through the synchronization process. For D2D discovery, one device should keep on transmitting a reference signal (a beacon) and can thus detect devices in its proximity. Accordingly, it can choose the pairing device with the best channel condition. This discovery procedure can be network-assisted or non network-assisted. In network-assisted discovery process, the BS mediates the discovery procedure, thus making it more energy efficient and less time consuming. In non network-assisted discovery, devices keep on searching for its pairing devices blindly, thus can be more power hungry.

1.1.3 Mode Selection

Mode selection is one of the important issues in D2D communication. In conventional cellular mode, data is transmitted via the BS, while in D2D mode data is transmitted directly between users. The BS decides modes according to different scenarios. Modes are generally classified [3] into three categories:

- *Cellular:* All devices in the network communicate in cellular mode.
- *Forced D2D:* All devices are forced to communicate in D2D mode in this scenario.
- *Path-loss D2D:* D2D mode is chosen according to relative channel gains between the communicating devices, one via the BS and another direct channel gain. If the direct channel gain is better, D2D mode can be selected.

1.1.4 Resource Management

Resource allocation for D2D communication can be mainly classified into two categories [3]:

- *Overlay D2D Communication:* In this scenario, allocated channels to the CUs and D2D pairs are orthogonal, thus eliminating any possibility of interference. However, in terms of spectral efficiency no gain is achieved.
- *Underlay D2D communication:* In this scenario, D2D pairs share same channels as the CUs, thus causing potential interference to CUs. However, with

efficient interference avoidance techniques, gain in spectral efficiency can be achieved.

1.1.5 Application Areas

D2D communication can be a key component to offload network traffic and increase spectral efficiency. It can also explore local area and proximity-based services like file sharing, online gaming, video streaming, etc. [3]. In the latest 3GPP releases, D2D communication has also been envisioned to be a key technology component for public safety in the absence of network infrastructure due to some disaster. It can also find applications in Machine-to-Machine communication and Internet of Things. Application areas are shown in the figure below:

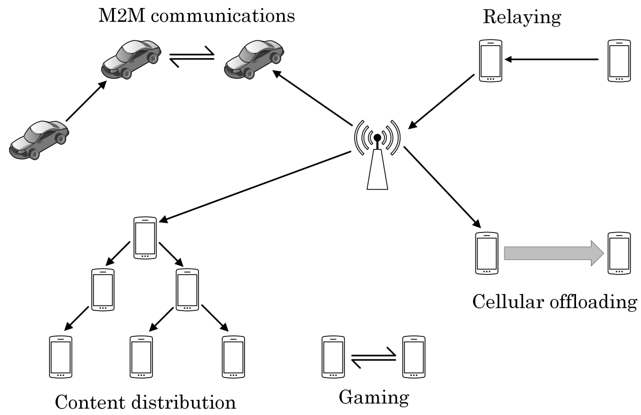

Figure 1.1: Applications of D2D communication.

- *Group communication:* This type of communication is useful when there are similar types of requests from users within a local area like concert or stadium. The BS can offload large traffic by suitably choosing a group of “seed” devices to transfer complete data only to those devices. These seeds can then share this data to other devices using D2D communication.

- *Multihop relay communication:* This type of communication is particularly useful for network coverage extension. When some device is out of coverage of the BS, then devices within coverage area can act as relays to enable D2D communication. This can also be very useful for public safety applications.

- *Collaborative smartphone sensing:* Since smartphones have the capability of locating each other through environment sensing, the data can be aggregated collaboratively to a “sink” node much like wireless sensor networks. Thereafter, the collected data can be sent to the BS.

1.2 Scheduling Techniques in Cellular Network

In wireless communication systems, the need to simultaneously and reliably provide multiple users with high-rate communication links leads to challenging optimization problem. Questions of resource block assignment, interference, and power consumption at the BS and mobile devices have to be answered in the face of time varying and frequency selective channels. Furthermore, delay and data rate requirements may greatly vary among devices and applications. This questions and requirements can be formulated as resource allocation problems.

The medium access control (MAC) scheduler is an important entity of the BS and is responsible for allocating radio resources to the users. It takes into account CSI, rate requirements and fairness among users before any scheduling decision is made. Since long term evolution (LTE) is an all IP network, maintaining QoS for all user requirements is a crucial task. Hence, the LTE MAC scheduler needs to take into account QoS requirements of the CUs. Radio resources are scarce entities, thus must be allocated efficiently to the users. We need to evaluate the efficiency and functionality of existing scheduling algorithms before evaluating scheduling of D2D users. A survey on existing scheduling techniques in LTE has been presented in [4].

Three basic scheduling algorithms namely, round robin (RR), maximum rate (MR) and proportional fair (PF) scheduling can be used in LTE networks. They can be compared in terms of network throughput and fairness among users.

The simplest one is the RR scheduling algorithm. It gives same priority to all the users in a scheduling interval. It doesn’t take into account CSI at all, hence, suffers from low network throughout as some users with deep fade may also be scheduled. Though it provides the best fairness among users, it fails to satisfy QoS requirements in general. It performs well if all the users have similar average signal-to-interference-plus-noise ratio (SINR) all the time which is not the case in a practical scenario.

For the MR scheduler, it takes into account CSI of all the users before scheduling decisions are made. In each scheduling interval, it allocates resources to those users which have good channel conditions, thus achieving higher throughput and spectral efficiency. However, it doesn’t take into account fairness among users at all. A cell edge user with poor channel condition may starve for long.

A PF scheduler strikes a good balance between throughput and fairness among users. It allocates resources to the users according to their long term average channel conditions relative to others. Hence, it takes into account both CSI in the present slot and the long term service rate till the previous slot.

The intuition behind the mathematical formulation of the scheduling algorithms are explained below: Assuming that the scheduler has knowledge of the instantaneous CSI of CU c in sub-frame n on resource block k, it can determine the achievable data rate $R_{c,k}[n]$ that the CU c can achieve on resource block k. It also maintains the moving average throughput $T_{c,k}[n]$ of each CU c on every resource block k, over a past window of length t_w. The parameter t_w maintains the latency of the system. A small value of t_w approaches towards RR algorithm, while a large value approaches towards MR algorithm. Therefore, the value of t_w should to be chosen according to the scheduling policy. The scheduler allocates resource block k to user c^* in sub-frame n if it maximizes the relative channel quality function given by,

$$c^* = \underset{c=1,2,\ldots,C}{arg\ max} \frac{[R_{c,k}[n]]^\gamma}{[T_{c,k}[n]]^\delta} \tag{1.1}$$

- if γ=1, δ=1, the Equation 1.1 describes the PF algorithm.
- If γ=1, δ=0, it describes the MR algorithm.
- If γ=0, δ=1, it describes the RR algorithm.

The scheduler updates the long term average rate $T_{c,k}[n]$ of the UE c in time slot n on the resource block k using an exponential moving average filter [4] of length t_w given below,

$$T_{c,k}[n+1] = \begin{cases} (1 - \frac{1}{t_w})T_{c,k}[n] + \frac{1}{t_w}R_{c,k}[n], & ,c^* = c \\ (1 - \frac{1}{t_w})T_{c,k}[n] & ,c^* \neq c \end{cases}$$

Equation 1.1 is repeated on each resource block k independently to allocate all the resource blocks to the users in each sub-frame n.

1.3 Some Research Issues

In this section we discuss some open research issues in resource allocation of D2D communication. We also discuss our contributions to the research problems which have been discussed in the subsequent chapters.

We have already discussed two resource management techniques in Section 1.1.4 for D2D communication. In overlay mode, orthogonal sharing of resources between cellular and D2D user causes no interference to each other, but no gain in spectral efficiency is achieved. In underlay mode, D2D users share same resources with the CUs while staying under the control of the BS. Thereby the utilization of the spectrum can be increased by limiting harmful interference to the CUs.

There has been considerable amount of research on spectrum-sharing between cellular networks and infrastructure-less networks [5], [6], [7]. Due to heavier download traffic, uplink spectrum is under-utilized in frequency division duplex (FDD) based cellular system with equal bandwidths allocated for the uplink and downlink transmissions. In [5], the transmission-capacity trade-off between the coexisting cellular and mobile ad hoc networks is analyzed for different spectrum sharing methods. The authors suggest that mobile ad-hoc network can co-exist with cellular network while achieving higher transmission capabilities. They have derived bounds on outage probability for different spectrum sharing modes and shown spectrum overlay is more efficient than spectrum underlay in terms of transmission capacity. However, only pathloss channel model has been considered. [6] considers overlaying the cellular uplink and ad hoc networks using two methods. The first is blind transmission where the transmission of ad hoc nodes and mobile users are independent, and the second is frequency mutual exclusion where ad hoc nodes transmit over frequency sub-channels unoccupied by mobile users. They have shown that capacity region for frequency mutual exclusion is larger than that for blind transmission. However, noise component has been neglected for simplicity to calculate SINRs. The authors in [7] suggest that a clustered D2D model improves overall user capacity and spectral efficiency of the network while maintaining minimum SINR of CUs. They have proposed two realistic user models for the D2D users and derived analytical expressions for the probability of existence of a single-hop D2D link that does not cause the cellular link to break. For both models, they have shown that a D2D link can exist with high probability. However, the time varying and frequency selective nature of the channel has been neglected in the simulation scenario.

Several authors have studied D2D communication over cellular architecture in the context of P2P file sharing [8], [9]. In [8], the authors suggest that an extended peer (non cellular user) from P2P network can communicate with cellular users as a client/server based communication between them. In this way cellular users can participate indirectly in the P2P network, using the extended peers as proxies and also avoid the costly competition for resources. [9] proposes a P2P file sharing application for cellular users using session initialization protocol (SIP) as control protocol and then elaborates the modifications that should be made to SIP in order to meet the requirements of that application.

D2D session setup, management and thereafter resource allocation for the D2D underlay networks have also been considered in literature [10], [11]. In [10], the authors propose D2D session setup and management in existing LTE-Advanced architecture and formulate the resource allocation problem as a mixed integer non-linear programming (MINLP). They have suggested a novel greedy heuristic technique to schedule D2D users that achieves a higher network throughput while maintaining QoS of both cellular and D2D users. However, frequency selective nature of channel has not been considered. The authors in [11] suggest that D2D communication can enable local area services with limited interference to the CUs and validated it through simulation results. They have also proposed D2D session setup and management in existing cellular architecture and analyzed feasibility of D2D communication in local area cellular network. However, only shadow fading has been considered and the effects of the time varying nature of channel on scheduling has not been investigated.

Joint power control and resource allocation for both D2D overlay and underlay networks have been considered in [12], [13], [14]. In [12], the authors employ a simple power control scheme for D2D users to limit the SINR degradation of the CUs to a certain level. They have shown that the statistics of SINR of D2D users are similar or better than that of CUs, thus achieving higher network throughput in a scenario where only limited interference coordination between cellular and D2D users is available. However, only pathloss channel model has been considered for simulation purpose. The authors in [13] consider joint power control and resource allocation to optimize sum rate subject to spectral efficiency restrictions, and maximum transmit power constraints. They have shown that with non-orthogonal sharing, the optimal power allocation resides within a finite set, while in orthogonal sharing, optimal power allocation can be found in closed form. However, only distant-dependent pathloss model has been considered. The authors in [14] propose a joint resource block scheduling and power control for D2D communication. The formulated resource allocation problem maximizes spectral efficiency while maintaining limited interference to the CUs and satisfying QoS of the D2D users. An increase in sum throughput and spectral efficiency is validated through simulation results. However, the effects of the time varying and frequency selective nature of channel on scheduling has not been investigated.

In Chapter 2, we propose a greedy heuristic algorithm for the D2D underlay network. Proposed scheme can work with any resource allocation scheme for CUs. Unlike existing literature, our scheme can potentially work with any time varying and frequency selective channel conditions. We consider a scenario in which scheduling of resource blocks for CUs is already done at the BS. We propose to reuse these resource blocks for D2D users without hampering CU's communication. We ensure that CUs get a minimum required rate to maintain their QoS in each sub-frame. We show that the problem of resource allocation can be framed as a mixed integer non-linear programming. Since, finding an optimal solution of this optimization problem within a sub-frame duration of 1 ms is very hard, we propose a suboptimal solution which exploits the relative channel gains between eNodeB and users (cellular/D2D), and that between cellular and D2D users, to greedily allocate resources to D2D users.

1.3.1 PF Resource Allocation in D2D Communication

As discussed in Section 1.1, resource allocation can be done to achieve various performance objectives. Here, we focus on PF resource allocation for the D2D underlay network as it strikes a good balance between throughput and fairness among users.

Though PF algorithm has been studied for orthogonal frequency division multiple access (OFDMA) networks, e.g. [2] and [15], its application to D2D networks has not been extensively considered yet.

For D2D networks, authors of [16] employ proportional fair algorithm for CUs and a greedy heuristic algorithm for mode selection and resource block allocation to D2D users. However, only shadow fading has been considered and the effects of the time varying nature of channel on scheduling has not been investigated. In [17], the joint power control and PF scheduling of CUs and D2D pairs are considered. A resource block is allocated to a CU and a D2D pair jointly such that the product of PF metrics obtained for both the CU and D2D pair is maximized over all combinations of CUs and D2D pairs. However, they have replaced the actual PF objective function with a simplified one that leads to a scheduling policy which may not be optimal. Similarly, [18] considers the joint PF scheduling of both CUs and D2D pairs. As the optimal PF algorithm for joint scheduling is computationally complex, the authors adopt a heuristic algorithm to reduce the computational complexity. But, it does not consider any rate constraints or QoS guarantees for either the CUs or the D2D pairs. Further, the interference caused by D2D transmitters during scheduling of CUs is also not accounted for.

In [19], the weighted network sum-rate is maximized considering uplink transmissions while guaranteeing a certain minimum rate to CUs with proportional fairness among D2D users. The optimization problem formulated, nevertheless, is a mixed integer non-linear program (MINP) and is NP-hard. Hence, the authors propose an iterative algorithm where sub-carriers and power allocation are performed sequentially till convergence is attained, which is sub-optimal. [20] proposes D2D-assisted opportunistic strategies to form clusters among mobile users. The D2Ds simply aid in the formation of clusters and in opportunistically selecting cluster heads within each cluster. The authors in [21] employ max-sum, max-min and proportional fairness algorithms to partition the spectrum between D2D users and cellular users in overlay mode using techniques from stochastic geometry. [22] undertakes a simulation based study to understand the consequences of D2D communication on the decision making of a cellular PF scheduling policy. The authors have shown that if the interference from D2D communication is huge and the channel estimation is erroneous, a PF scheduling policy may select the same users again and again and get stuck in an infinite loop.

In Chapter 3, we propose a novel PF algorithm for the D2D underlay network. Proposed scheme can potentially work with any resource allocation scheme for CUs and can adapt to time and location varying channel conditions. We consider a scenario in which scheduling of resource blocks for CUs is already done at the BS. We propose to reuse these resource blocks for D2D users without hampering CU's communication. We ensure that CUs get a minimum required rate to maintain their QoS in each sub-frame. If the actual received SINR for CU at the BS is more than the SINR threshold required to guarantee a minimum rate to CUs, then this SINR gap can be exploited to allocate power to D2D users. We show that the problem of resource allocation for D2D users can be mapped to finding maximum weight bipartite matching (MWBP) in a complete bipartite graph where the two vertex sets of the graph are the set of resource blocks and the set of D2D pairs. We use MWBP to allocate both single as well as multiple resource blocks to D2D users.

1.4 Motivation for the Thesis

D2D communication underlaying cellular network is envisioned to play a major role in enhancing system capacity and increasing spectral efficiency for the next generation of wireless networks [1], [2], [3]. Gain in performance is expected due to the possibility of reusing radio resources allocated to the CUs with D2D underlay network. This may cause interference to CUs, thus possibly hampering CU's communications. Hence, the main challenge in D2D communication is to limit interference to CUs such that their QoS is maintained. Once this criteria is satisfied, one needs to address how the resource allocation for D2D communication can be done. Resource allocation can be done to achieve various performance objectives like maximizing network throughput, minimizing delay, achieving fairness among user data rates, etc. RR resource allocation scheme achieves good fairness among user data rates but provides low network throughput. On the other hand, MR resource allocation scheme provides high network throughput but fails to maintain good fairness among user data rates. However, the PF resource allocation scheme strikes a good balance between throughput and fairness among users. Therefore, in this thesis we focus on the PF resource allocation scheme for D2D communication which can potentially work with any resource allocation technique, employed by the BS for the CUs.

1.5 Organization

The organization of this thesis is as follows. This chapter presents the basics of D2D communication, existing scheduling techniques in cellular network, identification of some open research problems for D2D resource allocation and summarizes our contributions towards solving some of these problems. Chapter 2 presents scheduling of D2D users using a greedy heuristic algorithm. Chapter 3 presents a novel PF algorithm for D2D communication using bipartite graph matching technique. Finally, Chapter 4 concludes the thesis and provides directions for future research work.

Chapter 2

Greedy Scheduling Algorithm for D2D Communication

2.1 Introduction

From the open literatures discussed in Chapter 1, it is quite evident that resource allocation techniques for D2D underlay network is a challenging research problem. In this chapter, we present a greedy resource allocation scheme for D2D users. We consider a scenario in which scheduling of resource blocks for CUs is already done at the BS. We propose to reuse these resource blocks for D2D users without hampering CU's communication. We ensure that CUs get a minimum required rate to maintain their QoS in each sub-frame. We show that the problem of resource allocation can be framed as a mixed integer non-linear programming. Since, finding an optimal solution of this optimization problem within a sub-frame duration of 1 ms is very hard, we propose a suboptimal solution which exploits the relative channel gains between eNodeB and users (cellular/D2D), and that between cellular and D2D users, to greedily allocate resources to D2D users.

The rest of this chapter is organized as follows. In Section 2.2, we describe the network model and problem definition. In Section 2.3, we analyze problem formulation for both uplink and downlink scenarios. Both problems are formulated as optimization problems. In Section 2.4, we propose a greedy heuristic algorithm to schedule D2D users. Simulation results have been presented in Section 2.5. Finally, Section 2.6 concludes the chapter and provides directions of future work.

2.2 Network Model and Problem Definition

The network models for interference analysis in the downlink and the uplink scenarios are depicted in Fig. 2.1 and 2.2 respectively. In the downlink scenario, Evolved Node B (eNodeB) causes interference to the D2D receiver and D2D transmitter causes interference to the CU, if CU and D2D pair share same resources. Similarly, in the uplink scenario, D2D transmitter causes interference to the eNodeB and CU causes interference to the D2D receiver.

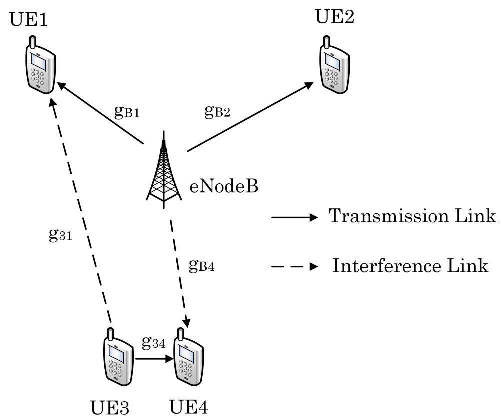

Figure 2.1: Interference scenario for a CU and a D2D pair communicating over common downlink resource blocks.

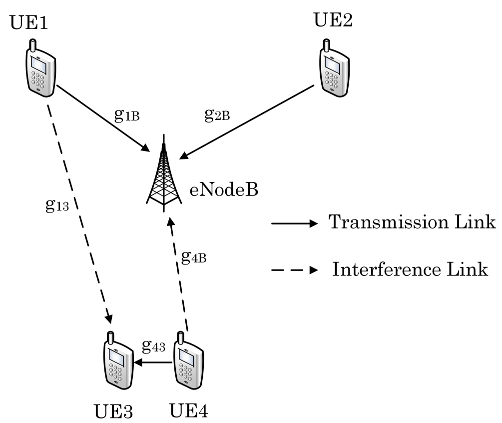

Figure 2.2: Interference scenario for a CU and a D2D pair communicating over common uplink resource blocks.

Fig. 2.1 and 2.2 illustrate the interference scenarios when CUs share the same radio resources as the D2D users. During the downlink scenario (Fig. 2.1), when

CU UE1 shares its resources with D2D pair UE3 and UE4, D2D receiver UE4 is exposed to interference from the eNodeB, while CU UE1 suffers interference from D2D transmitter UE3. Similarly, for the the uplink scenario (Fig. 2.2), when CU UE1 shares its resources with D2D pair UE3 and UE4, D2D receiver UE3 is exposed to interference from CU UE1, while the eNodeB suffers interference from D2D transmitter UE4. Since, eNodeB is responsible for D2D discovery, D2D session setup and thereafter radio resource management, we assume both devices forming D2D pair need to be in the same cell for D2D connection establishment.

2.3 Problem Formulation

We assume, scheduling of CUs is done by the eNodeB by some existing online or offline scheduling algorithm in each sub-frame n. Now, we want to allocate same resources to D2D pair d as CU c. We formulate this resource allocation problem as an optimization problem. We assume time division duplex (TDD) system with identical split of the uplink and downlink resources. Suppose, the number of available resource blocks for the uplink and downlink are M and N respectively. In our model, we assume perfect CSI at the receiver. Hence, all the channel gains between BS and CUs, that between the D2D users and the interfering links between the BS and D2D transmitter as well as the link between the CU to the D2D receiver are known to the BS before scheduling decisions are taken. We assume full buffer traffic i.e. number of users in the cell is constant and every user has infinite amount of data to transmit in each sub-frame n. Let, the eNodeB serves a set $\mathcal{C} = \{1, \ldots, N_C\}$ of CUs and a set $\mathcal{D} = \{1, \ldots, N_D\}$ of D2D pairs. We also assume $N_C \geq N_D$ as it is practical to assume more CUs than D2D pairs in a cell.

2.3.1 Downlink Resource Allocation Analysis

In the downlink scenario, CU is exposed to interference from D2D transmitter and D2D receiver suffers interference from the eNodeB if they share same radio resources. This interference depends on the transmit power of the device or eNodeB and channel gains between them. Let g_{cd} denote the channel gain between CU c and D2D user d, g_{Bc} denotes the channel gain between the eNodeB and CU c, g_{Bd} denotes channel gain between the eNodeB and D2D user d and g_{dd} denotes channel gain between D2D pair d. Let, P_B, P_c and P_d denote transmit powers of eNodeB, CU and D2D transmitter respectively. We also assume no power control, i.e. all the transmit powers are fixed. Now, if the d^{th} D2D pair shares same downlink resource blocks as the CU c, the received SINR of the CU c is given by,

$$\gamma_c^{DL} = \frac{P_B g_{Bc}}{N_0 + \sum_d x_c^d P_d g_{cd}}. \tag{2.1}$$

Similarly, the received SINR at the d^{th} D2D receiver is given by,

$$\gamma_d^{DL} = \frac{\sum_c x_c^d P_d g_{dd}}{N_0 + \sum_c x_c^d P_B g_{Bd}}. \tag{2.2}$$

Here, N_0 denotes the thermal noise power spectral density at the receiver and the optimization variable x_c^d is an indicator function defined as,

$$x_c^d = \begin{cases} 1, & \text{if D2D pair } d \text{ shares resource blocks with CU } c, \\ 0, & \text{otherwise.} \end{cases}$$

Let, r_c^{DL} and r_d^{DL} represent the rates corresponding to the SINRs γ_c^{DL} and γ_d^{DL} respectively as determined by the Shannon's Capacity Theorem. The goal here is maximize total system sum throughput constrained on satisfying minimum rate requirements of both CUs and D2D pairs. For simplicity, we assume maximum one CU can share its resource blocks to one D2D pair and vice versa. Then, in the sub-frame n, the resource allocation problem can be formulated [10] as an optimization problem given as,

$$\text{Maximize} \quad \sum_c m_c r_c^{DL} + \sum_d \sum_c x_c^d m_c r_d^{DL}, \tag{2.3}$$

$$P_B g_{Bc} \geq \gamma_{c,tgt}^{DL} \left(N_0 + \sum_d x_c^d P_d g_{cd} \right), \quad \forall c \in \mathcal{C}, \tag{2.4}$$

$$\sum_c x_c^d P_d g_{dd} \geq \gamma_{d,tgt}^{DL} \left(N_0 + \sum_c x_c^d P_B G_{Bd} \right), \quad \forall d \in \mathcal{D}, \tag{2.5}$$

$$\sum_c x_c^d \leq 1, \quad \forall d \in \mathcal{D}, \tag{2.6}$$

$$\text{and} \quad \sum_d x_c^d \leq 1, \quad \forall c \in \mathcal{C}. \tag{2.7}$$

Here, m_c denotes the number of downlink resource blocks allocated to the CU c in sub-frame n. Also, $\gamma_{c,tgt}^{DL}$ and $\gamma_{d,tgt}^{DL}$ denote minimum target SINRs of CU c and D2D pair d respectively. Equations 2.4 and 2.5 ensure maintaining minimum rate requirements for both CU c and D2D pair d, while Equations 2.6 and 2.7 ensure that one D2D pair can be allocated at most one CU's resources and one CU can share its resources to at most one D2D pair respectively.

2.3.2 Uplink Resource Allocation Analysis

In the uplink scenario, eNodeB is exposed to interference from D2D transmitter and D2D receiver suffers interference from CU if they share same radio resources. Now, if the d^{th} D2D pair shares same uplink resource blocks as CU the c, the received SINR at the eNodeB is given by,

$$\gamma_B^{UL} = \frac{P_c g_{Bc}}{N_0 + \sum_d y_c^d P_d g_{Bd}}. \tag{2.8}$$

Similarly, the received SINR at the d^{th} D2D receiver is given by,

$$\gamma_d^{UL} = \frac{\sum_c y_c^d P_d g_{dd}}{N_0 + \sum_c y_c^d P_c G_{cd}}. \tag{2.9}$$

Here, the optimization variable y_c^d is an indicator function defined as,

$$y_c^d = \begin{cases} 1, & \text{if D2D pair } d \text{ shares resource blocks with CU } c, \\ 0, & \text{otherwise.} \end{cases}$$

Let, r_B^{UL} and r_d^{UL} represent the rates corresponding to the SINRs γ_B^{UL} and γ_d^{UL} respectively as determined by the Shannon's Capacity Theorem. The goal here is maximize total system sum throughput constrained on satisfying minimum rate requirements of both CUs and D2D pairs. For simplicity, we assume maximum one CU can share its resource blocks to one D2D pair and vice versa. Then, in the sub-frame n, the resource allocation problem can be formulated [10] as an optimization problem given as,

$$\text{Maximize} \quad \sum_c n_c r_B^{UL} + \sum_d \sum_c y_c^d n_c r_d^{UL}, \tag{2.10}$$

$$P_c g_{Bc} \geq \gamma_{B,tgt}^{UL} \left(N_0 + \sum_d y_c^d P_d g_{Bd} \right), \quad \forall c \in \mathcal{C}, \tag{2.11}$$

$$\sum_c y_c^d P_d g_{dd} \geq \gamma_{d,tgt}^{UL} \left(N_0 + \sum_c y_c^d P_c g_{cd} \right), \quad \forall d \in \mathcal{D}, \tag{2.12}$$

$$\sum_c y_c^d \leq 1, \quad \forall d \in \mathcal{D}, \tag{2.13}$$

$$\text{and} \ \sum_d y_c^d \leq 1, \quad \forall c \in \mathcal{C}. \tag{2.14}$$

Here, n_c denotes the number of uplink resource blocks allocated to CU c in sub-frame n. Also, $\gamma_{B,tgt}^{UL}$ and $\gamma_{d,tgt}^{UL}$ denote the minimum target SINR of CU c and D2D pair d respectively. Equations 2.11 and 2.12 ensure maintaining minimum rate requirements for both CU c and D2D pair d, while Equations 2.13 and 2.14 ensure that one D2D pair can be allocated at most one CU's resources and one CU can share its resources to at most one D2D pair respectively.

2.4 Greedy Scheduling Algorithm for D2D Users

The optimization problems formulated above for the downlink and uplink scenarios are mixed integer non-linear programming (MINLP). Since, it is very difficult to a get an optimal solution within a scheduling interval of 1 ms, we can use a suboptimal greedy heuristic algorithm to allocate resources to D2D users. The proposed algorithms are as follows:

For the downlink scenario, as we can observe from Equation 2.1, the lower the channel gain between CU and D2D pair sharing same radio resources or larger the channel gain between CU and eNodeB, higher the system sum throughput. Therefore, intuitively, a CU with high channel quality indicator (CQI) can share its resource blocks with a D2D pair, which causes minimum interference to that CU.

Similarly for the uplink scenario, we can observe from Equation 2.8, the lower the channel gain between D2D pair and eNodeB or larger the channel gain between CU and eNodeB sharing same radio resources, higher the system sum throughput. Therefore, intuitively, a CU with high CQI can share its resource blocks with a D2D pair which causes minimum interference to eNodeB on those resource blocks.

Algorithm 1 Downlink D2D Resource Block Allocation

$\mathcal{C}$: Sorted list of CQIs for all CUs in decreasing order
$\mathcal{D}$: set of D2D pairs in the network
g_{cd}: Channel gain between CU c and CU d
g_{dd}: Channel gain between D2D pair d
g_{Bc}: Channel gain between eNodeB and CU c
g_{Bd}: Channel gain between eNodeB and D2D pair d
P_c: Transmit power of CU c
P_d: Transmit power of D2D transmitter d
P_B: Transmit power of eNodeB
m_c: Number of resource blocks allocated to CU c
$c \leftarrow 1$
while $\mathcal{D} \neq \phi$ or $c == C$ **do**
  Pick resource blocks with c^{th} largest value;
  Find the D2D user d with minimum channel gain to the CU associated with the c^{th} largest value;
  ${\gamma_c}^{DL} \leftarrow \frac{P_B g_{Bc}}{N_0 + \sum_d x_c^d P_d g_{cd}}$;
  $\gamma_d^{DL} \leftarrow \frac{\sum_c P_d g_{dd}}{N_0 + \sum_c x_c^d P_B G_{Bd}}$;
  if $\gamma_c^{DL} \geq \gamma_{c,tgt}^{DL}$ and $\gamma_d^{DL} \geq \gamma_{d,tgt}^{DL}$ **then**
    Share all resource blocks of CU associated with the c^{th} largest value with D2D pair d;
    $\mathcal{D} = \mathcal{D}$ - $\{d\}$;
  else
    Do not assign resource blocks to D2D pair d;
  end if
  $c \leftarrow c + 1$;
end while

Algorithm 2 Uplink D2D Resource Block Allocation

$\mathcal{C}$: Sorted list of CQIs for all CUs in decreasing order
$\mathcal{D}$: set of D2D pairs in the network
g_{cd}: Channel gain between CU c and CU d
g_{dd}: Channel gain between D2D pair d
g_{Bc}: Channel gain between eNodeB and CU c
g_{Bd}: Channel gain between eNodeB and D2D pair d
P_c: Transmit power of CU c
P_d: Transmit power of D2D transmitter d
P_B: Transmit power of eNodeB
m_c: Number of resource blocks allocated to CU c
$c \leftarrow 1$
while $\mathcal{D} \neq \phi$ or $c == C$ **do**
  Pick resource blocks with the c^{th} largest value;
  Find the D2D user d with minimum channel gain to eNodeB on this resource blocks;
  $\gamma_B^{UL} \leftarrow \frac{P_c g_{Bc}}{N_0 + \sum_d y_c^d P_d g_{Bd}}$;
  $\gamma_d^{UL} \leftarrow \frac{\sum_c y_c^d P_d g_{dd}}{N_0 + \sum_c y_c^d P_c g_{cd}}$;
  if $\gamma_B^{UL} \geq \gamma_{B,tgt}^{UL}$ and $\gamma_d^{UL} \geq \gamma_{d,tgt}^{UL}$ **then**
    Share all resource blocks of CU associated with the c^{th} largest value with D2D pair d;
    $\mathcal{D} = \mathcal{D}$ - $\{d\}$;
  else
    Do not assign resource blocks to D2D pair d;
  end if
  $c \leftarrow c + 1$;
end while

2.5 Simulation Methodology and Results

2.5.1 Simulation Setup

To evaluate the performance of the greedy heuristic algorithm, system level simulations have been performed in MATLAB. A single hexagonal cell with Inter-Site Distance (ISD) of 500 m has been considered. Omni-directional Single Input Single Output (SISO) antenna configuration has been considered. System bandwidth of 10 MHz is considered for both the uplink and downlink scenarios. CUs and D2D transmitters are distributed uniformly within the cell. We define the range of D2D communication, R_{D2D} to be the distance of the D2D receiver from its transmitter. D2D receivers are uniformly distributed around the D2D transmitters within a specified range. To understand the system level performance with different values of this range, we vary it from 5 m to 50 m in steps of 5 m. Each RB is grouped into 12 adjacent sub-carriers and duration of one Transmit Time Interval (TTI), namely 0.5 millisecond and consists of 6 or 7 OFDM symbols. Scheduling decisions are taken in every sub-frame of duration 2 TTIs (1 millisecond). In LTE, multiple access scheme for the uplink is single carrier frequncy division multiple access (SC-FDMA) due to its characteristics of low peak-to-average power ratio (PAPR) and physical properties of SC-FDMA requires resource blocks allocated to a single user must be contiguous in frequency. However, for the downlink, there is no such constraint on contiguous bandwidth allocation due to orthogonal frequency division multiple access (OFDMA) technology. The power profile is considered to be consistent over all available sub-carriers. All the simulation related parameters are summarized in Table 2.1.

Parameter	Values
Cell layout	Single Hexagonal cell
Inter-site distance (ISD)	500 m
Available spectrum (UL/DL)	10 MHz
Number of subcarriers per RB	12
Subcarrier spacing	15 KHz
RB bandwidth	180 KHz
Number of RBs	50
eNodeB transmit power	20 W
UE (CU/D2D) transmit power	250 mW
Modulation and coding scheme (MCS)	QPSK: 1/6, 1/3, 1/2, 2/3 16QAM: 1/2, 2/3, 3/4 64QAM: 1/2, 2/3, 3/4, 4/5
Sub-frame duration	1 ms
Number of symbols per slot	7 (1 pilot+6 data)
Cell-level user distribution	Uniform
Number of active CUs	10, 20, 30, 40, 50
Number of active D2D pairs	10%, 20%, ...50% of active CUs
User speed	Static
Log-normal shadowing standard deviation	8 dB
Distant dependent Path loss	PL = 128.1 + 37.6log(d)
UE noise figure	5 dB
UE thermal noise density	-174 dBm/Hz
Antenna layout	Omni-directional antenna
Traffic model	Full buffer traffic

Table 2.1: Simulation parameters and values.

In wireless channel environment, link adaptation plays an important role to overcome fluctuations of the time varying and frequency selective channel. It is based on adaptive modulation and coding (AMC) technique specified in 3GPP LTE technology [24]. Different range of SINR values are mapped to different spectral efficiency according to AMC table [24] specified by 3GPP and accordingly, spectral efficiency is mapped to achievable data rates.

2.5.2 Channel Model

We consider a multipath fading channel environment. Since, we have considered users to be static, we assume that fast fading is averaged out over a larger time span. Hence, we have considered only pathloss and shadowing for our model. The overall channel gain (in dB) is given by,

$$g_{j,k} = 128.1 + 37.6 * log(d_{j,k}) + X_\sigma, \tag{2.15}$$

where $g_{j,k}$ is the channel gain between eNodeB j and user k or that between user j and user k (user can be a CU or a D2D user) at a distance of $d_{j,k}$ (in kilometers). X_σ represents the shadow fading random variable having lognormal distribution with a standard deviation of σ. Also, we have assumed omni-directional antenna for this single cell scenario.

2.5.3 Simulation Results

In this section, we present numerical results of our proposed greedy heuristic algorithm. We first evaluate performance of existing scheduling algorithms for the cellular network. Fig. 2.3 shows cumulative distribution functions (CDFs) of network throughput for three scheduling policies, namely RR, PF and MR. It can be observed that RR algorithm provides lowest network throughput as it does not take into account CQIs of CUs, whereas MR algorithm achieves highest network throughput as it greedily schedules those CUs which have good channel conditions. PF algorithm provides a trade-off between the extremes of the achievable fairness range.

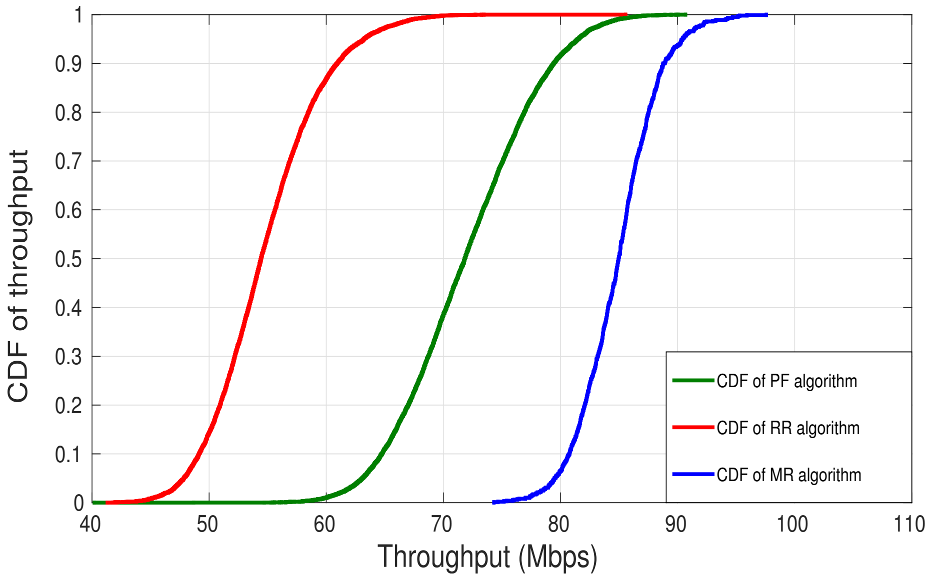

Figure 2.3: CDFs of network throughput for different scheduling algorithms.

Now we evaluate performance of network throughput as the range of D2D communication increases from 5 m to 50 m in steps of 5 m. Results clearly indicate that as the distance between D2D pair increases, total network throughput decreases. Hence, it is quite significant that D2D communication is feasible within a certain range. To exploit performance enhancement in spectral efficiency, D2D pairs should be in close proximity.

Table 2.2 shows % increase in total network throughput with D2D communication compared to the network throughput without D2D communication. Table entries have been obtained for different D2D range with number of D2D pairs, $N_D = 20$ and number of cellular users, $N_C = 100$.

Range of D2D communication (m)	% increase in throughput in downlink	% increase in throughput in uplink
5	39.82	45.61
10	31.34	36.46
15	26.47	31.12
20	23.09	27.35
25	20.53	24.45
30	18.47	22.10
35	16.77	20.13
40	15.32	18.43
45	14.06	17.48
50	12.95	15.65

Table 2.2: % increase in network throughput for different range of D2D communication ($N_C = 100$, $N_D = 20$).

Table 2.3 similarly presents % increase in total network throughput as the number of D2D users in the system increases from 10 to 50 with the number of cellular users, $N_C = 100$ and range of D2D communication, $R_{D2D} = 50$ m. We can interpret from the table entries that as the number of D2D users increases, total network throughput increases due to increase in throughput of D2D users, while there is no appreciable decrease in CU's throughput. Hence, we can infer that D2D users can be accommodated in the system to enhance spectral efficiency while still maintaining QoS of both D2D and cellular users.

Number of D2D pairs	% increase in throughput in downlink	% increase in throughput in uplink
5	8.39	14.21
10	12.95	15.65
15	21.68	20.17
20	29.57	24.88
25	40.91	30.34
30	49.89	35.64
35	54.43	37.22
40	57.09	38.72
45	59.89	39.50
50	61.12	40.17

Table 2.3: % increase in network throughput as number of D2D pairs increases (N_C = 100, R_{D2D} = 50 m).

Fig. 2.4 and 2.5 depict how throughput of CU, D2D and network varies with time for the downlink and uplink respectively. We can observe that all throughput values remains almost same though the channel is time varying.

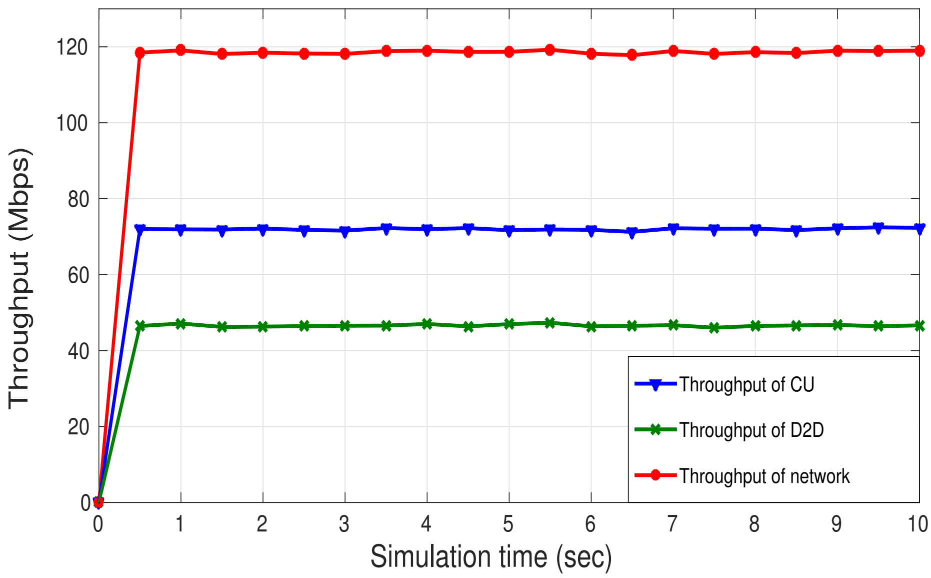

Figure 2.4: Comparison of CU, D2D and network throughput for the downlink scenario (N_C = 100, N_D = 20, R_{D2D} = 50 m).

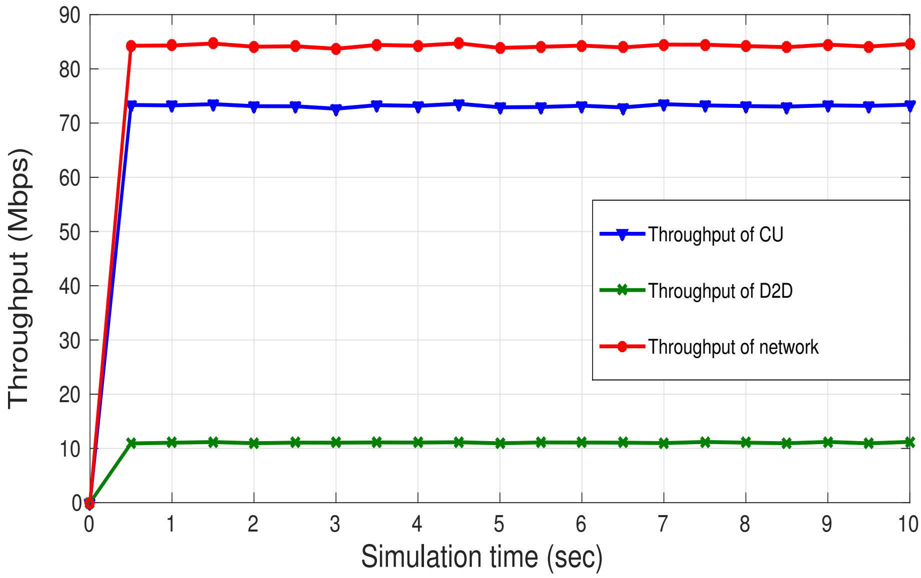

Figure 2.5: Comparison of CU, D2D and network throughput for the uplink scenario ($N_C = 100$, $N_D = 20$, $R_{D2D} = 50$ m).

Similarly, Fig. 2.6 and 2.7 illustrate CDFs of throughput of CU, D2D and network respectively. As we can observe, D2D user's throughput lies around 40 - 50 Mbps, CUs throughput lies around 60 - 90 Mbps and network throughput lies around 100 - 140 Mbps with high probability.

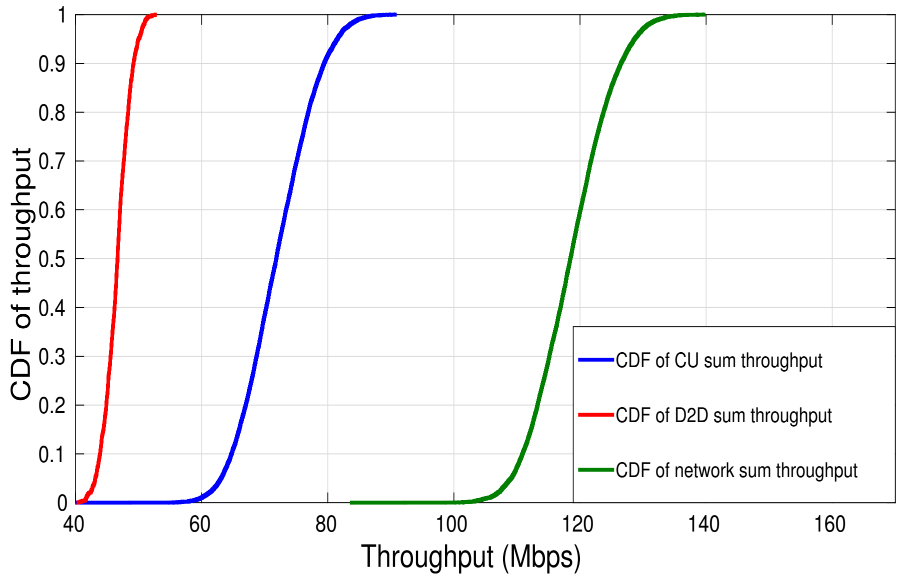

Figure 2.6: CDFs of CU, D2D and network throughput for the downlink scenario ($N_C = 100$, $N_D = 20$, $R_{D2D} = 50$ m).

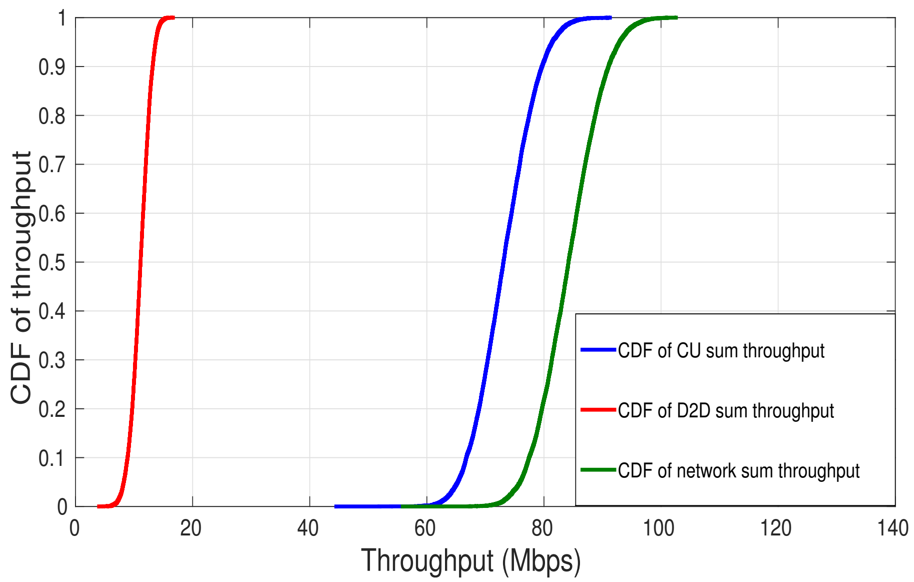

Figure 2.7: CDFs of CU, D2D and network throughput for the uplink scenario ($N_C = 100$, $N_D = 20$, $R_{D2D} = 50$ m).

Fig. 2.8 and 2.9 illustrate comparison of total network throughput with and without D2D communication. We observe that total network throughput increases about 50 % with the inclusion of D2D users. Therefore, allowing D2D communication as an underlay to the cellular network can enhance network throughput and increase spectral efficiency.

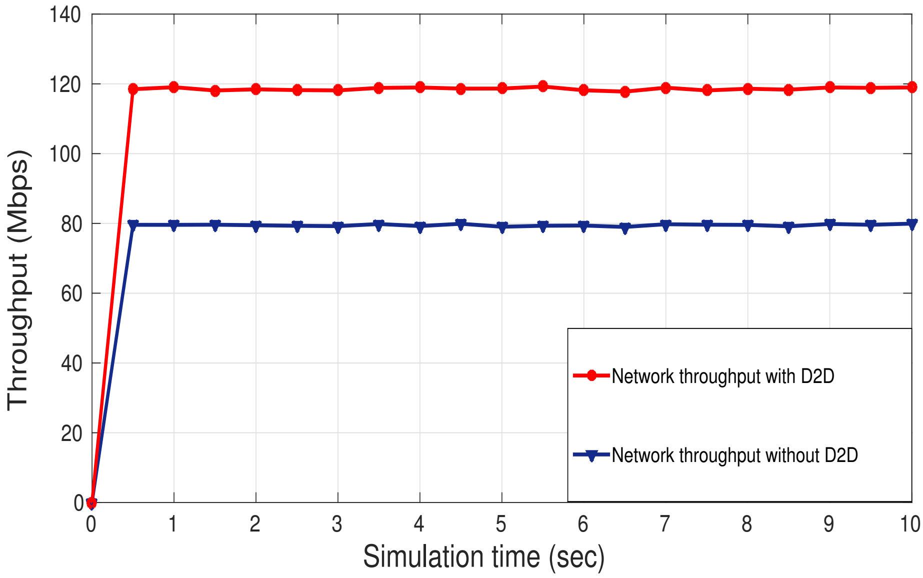

Figure 2.8: Comparison of network throughput for the downlink scenario with and without D2D communication ($N_C = 100$, $N_D = 20$, $R_{D2D} = 50$ m).

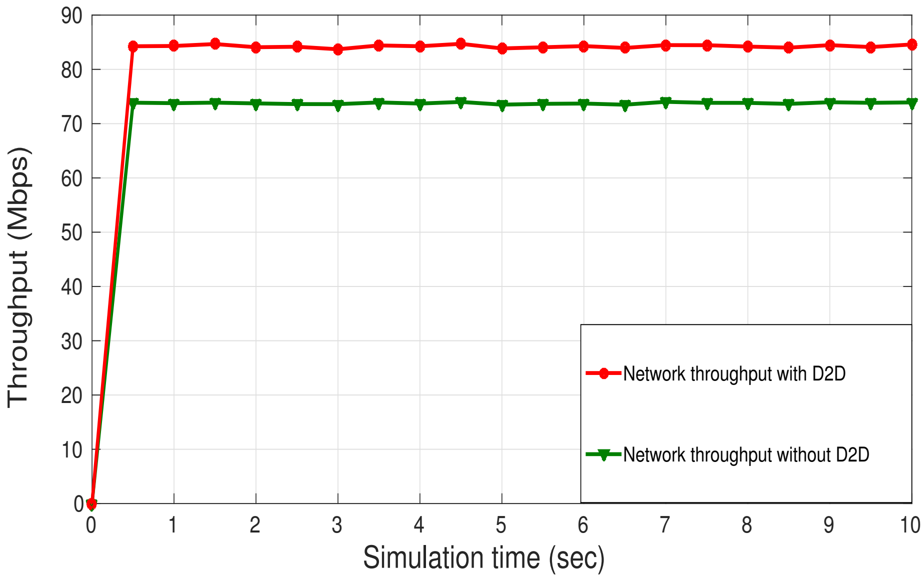

Figure 2.9: Comparison of network throughput for the uplink scenario with and without D2D communication ($N_C = 100$, $N_D = 20$, $R_{D2D} = 50$ m).

Fig. 2.10 shows how network throughput increases as the number of D2D users in the network increases. Initially, it grows rapidly and then saturates as the system does not allow more D2D pairs to maintain QoS of CUs. Hence, eNodeB does not allow inclusion of any arbitrary large number of D2D pairs in the network.

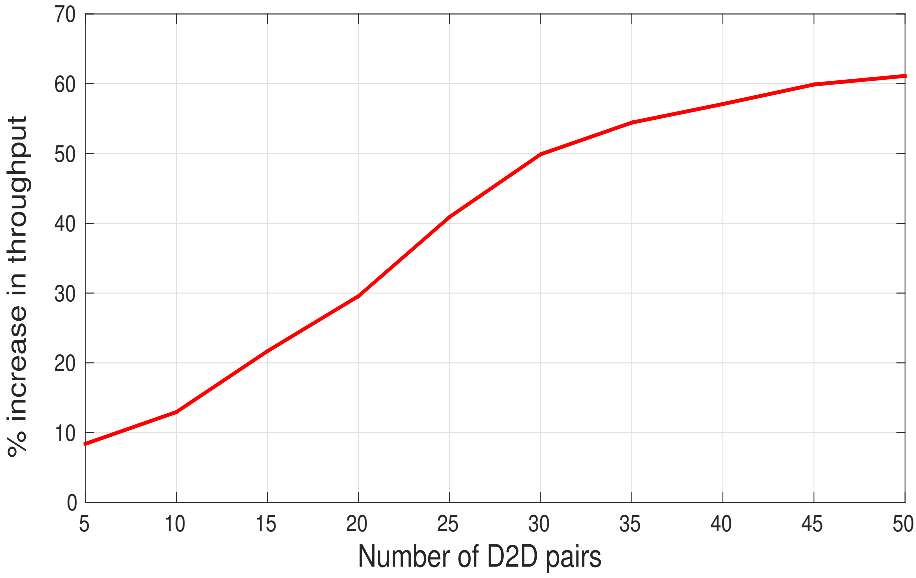

Figure 2.10: Percentage increase in network throughput as the number of D2D pairs increases ($N_C = 100$, $R_{D2D} = 50$ m).

2.6 Conclusions

In this work, we have investigated a greedy heuristic scheduling algorithm for the D2D underlay network. We utilize the knowledge of relative channel gains between the CUs and eNodeB, the interfering link gains between D2D users and CUs and that between D2D users and eNodeB to allocate resources to D2D pairs. In each sub-frame, the CU with high CQI shares its resource blocks to a D2D pair that causes minimum interference to it. Our proposed algorithm is valid for allocating any number of resource blocks to D2D users and potentially work with any resource allocation scheme for CUs. Results show that we can achieve an increase in network throughput and spectral efficiency by allowing D2D communication as an underlay to the cellular network. Further, we observe that throughput of CUs does not degrade much while the throughput of D2D users increases, thus maintaining QoS of both CUs and D2D users. Therefore, as eNodeB remains in control of D2D communication, it may be a promising integration to the LTE Advance network.

Future work involves simulation of the proposed algorithm in a multi-cell scenario, by considering inter-cell interference. Also, we have assumed a perfect CSI at the receiver. However, in practice channel state information may be erroneous. Thus, the method of extending this algorithm for erroneous channel state information is to be researched upon. Another possible research direction is to extend the analysis of scheduling for D2D users when they are no longer static.

Chapter 3

Proportional Fair Algorithm for D2D Communication

3.1 Introduction

As discussed in Chapter 1, resource allocation for the D2D underlay network can be done to achieve various performance objectives like maximizing sum rates of users, minimizing delays, achieving fairness among user data rates, etc. In Chapter 2, we discussed a suboptimal resource allocation scheme for D2D users to maximize the sum throughput of the network while maintaing limited interference to the CUs and satisfying QoS of the D2D users. In this chapter, we propose a novel PF resource allocation for D2D communication. We consider a scenario in which scheduling of resource blocks for CUs is already done at the BS. We propose to reuse these resource blocks for D2D users without hampering CU's communication. We ensure that CUs get a minimum required rate to maintain their QoS in each sub-frame. If the actual received SINR at the BS is more than the SINR threshold required to guarantee a minimum rate to CUs, then this SINR gap can be exploited to allocate power to D2D users. We show that the problem of resource allocation for D2D users can be mapped to finding maximum weight bipartite matching (MWBP) in a complete bipartite graph where the two vertex sets of the graph are the set of resource blocks and the set of D2D pairs. We use MWBP to allocate both single as well as multiple resource blocks to D2D users.

PF resource allocation for the D2D users depends not only on the channel conditions on D2D link but also on the interference D2D communication cause to the CU's transmission. Thus, for the D2D pair in the close proximity of base station, PF rates may be very low. Moreover, the resource allocation for these users can be bursty, i.e. they will receive resources only intermittently. This may be highly disadvantageous for TCP based applications as they timeout and retransmit the same content again. To alleviate this problem, we consider the problem of finding PF resource allocation subject to allotting at most a fixed number of resource blocks to each D2D pair. This reduces the burstyness into the service process. Changing the value of the maximum resource block that can be allotted to a D2D pair, we can strike a balance between increasing the system throughput and being fair (in terms service opportunities) in each sub-frame.

The rest of this chapter is organized as follows. In Section 3.2, we describe the network model. In Section 3.3, we analyze system model and problem formulation of D2D resource allocation in the uplink scenario. In Section 3.4, we discuss power control and optimal resource allocation using bipartite matching. Simulation results have been presented in Section 3.5. Finally, Section 3.6 concludes the chapter and provides directions of future work.

3.2 Network Model

Due to heavier traffic in the downlink, reusing the radio resources in the uplink for the D2D communication can be beneficial to enhance network throughput and spectral efficiency. For the rest of the work, we will only concentrate on the uplink resources.

The network model for interference analysis is shown in Figure 3.1. In the uplink spectrum sharing, CU causes interference to D2D receivers while the BS is exposed to interference from the D2D transmitter, if the CU and the D2D pair share same resources.

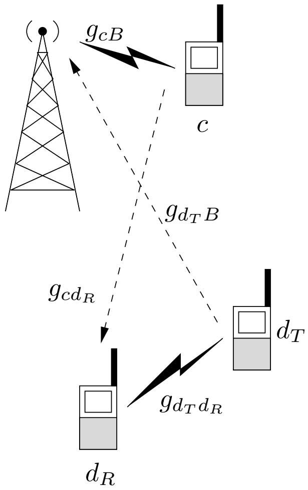

Figure 3.1: Interference scenario for a CU and a D2D pair communicating over common uplink resource blocks.

3.3 System Model and Problem Definition

We consider a macrocell with a BS at its center and assume that the uplink system bandwidth is divided into m resource blocks. We consider N_C and N_D to be the number of active CUs and D2D pairs respectively. We also assume full buffer traffic i.e. number of users in the cell is constant and every user has infinite amount of data to transmit in every sub-frame n. In each sub-frame, the BS can allocate all the m resource blocks to the CUs and the D2D pairs. A user can get more than one resource block in each sub-frame but each resource block can be assigned to at most one CU and one D2D pair.

Let c and d denote the c^{th} CU and the d^{th} D2D pair respectively. Let d_T and d_R denote the transmitter and the receiver respectively for the d^{th} D2D pair. The parameters corresponding to the four possible link types, namely from the c^{th} CU to the BS, from the transmitter to the receiver of the d^{th} D2D pair, from the transmitter of the d^{th} D2D pair to the BS and from the c^{th} CU to the receiver of the d^{th} D2D pair are differentiated through subscripts $cB, d_T d_R, d_T B$ and cd_R respectively.

We consider a time varying and frequency selective channel. If n be the sub-frame index and k be the resource block index, then the channel gain on resource block k in sub-frame n is $g_{xy}^k[n]$, where $x \in \{c, d_T\}$ and $y \in \{B, d_R\}$. We assume all CUs to transmit at a constant power P_c in each resource block. We allow for power control on D2D links. Let the transmit power of d_T on resource block k in sub-frame n be denoted by $P_{d_T}^k[n]$. We assume $P_{d_T}^k[n]$ is limited by $P_{d_T}^{max}$, i.e. there is a maximum power constraint for d_T in each resource block. Note that if $P_{d_T}^k[n] = 0$, then D2D pair d does not transmit on block k in sub-frame n. Alternatively, k^{th} resource block is not allocated to D2D pair d in sub-frame n.

In our model, we assume perfect CSI at the receiver. Hence, all the channel gains between BS and CUs, that between the D2D users and the interfering links between the BS and D2D transmitter as well as the link between the CU to the D2D receiver are known to the BS before scheduling decisions are taken. The interference scenario is depicted in Figure 3.1.

Thus, for a sub-frame n, when resource block k is shared between CU c and D2D pair d, the received SINR on resource block k at the BS is given by,

$$\gamma_c^k[n] = \frac{P_c g_{cB}^k[n]}{\sigma_N^2 + P_{d_T}^k[n] g_{d_T B}^k[n]},$$

where σ_N^2 is the power spectral density of additive white Gaussian noise at the receiver. Similarly, the received SINR at the D2D receiver is given by,

$$\gamma_d^k[n] = \frac{P_{d_T}^k[n] g_{d_T d_R}^k[n]}{\sigma_N^2 + P_c g_{c d_R}^k[n]}.$$

For each sub-frame, we assume that the BS has already decided the resource block allocation strategy for the CUs through some scheduling algorithm. Given a resource block allocation of CUs in each sub-frame n, we consider CUs having a fixed rate requirements in each resource block allotted to them and possibly a good enough channel to share its resource blocks with D2D pairs while still satisfying their respective rate constraints.

For example, if a certain voice or data user requires a data rate of 500 Kbps, then to satisfy this data rate, received SINR of 7.68 dB will be sufficient according to Shannon's capacity formula if one resource block is allocated to that user in each sub-frame. We denote the target SINR for CU c by γ_c^{tgt}. Now, if the received SINR is 20 dB, then there is a SINR gap of $(20 - 7.68) = 12.42$ dB, which can be used to allocate power to D2D users. We assume that at most $T \in \{1, \dots, m\}$ resource blocks can be allocated to a D2D pair.

Definition 1. *A D2D resource allocation in sub-frame n is a mapping from the set $\mathcal{M} = \{1, 2, \dots, m\}$ of resource blocks to the set $\mathcal{D} = \{1, 2, \dots, N_D\}$ of D2D pairs with associated power allocation for each D2D transmitter.*

Definition 2. *A feasible D2D resource allocation in sub-frame n is an allocation which satisfies: (1) the target SINR requirement on every resource block k is met,* *i.e., for every k, $\gamma_c^k[n] \geq \gamma_c^{tgt}$ for the CU c to whom the resource block k is allotted and (2) each D2D pair is allotted at most T resource blocks.*

Definition 3. *A D2D resource allocation policy π is a rule that provides a feasible resource allocation in every sub-frame n.*

A resource allocation policy can take into account the entire history while making the resource allocation decisions. We also allow for the randomized policies. Let, $r_d^\pi[n]$ be the rate of D2D pair d obtained under scheduling policy π in the sub-frame n. Define, the throughput for D2D pair d under policy π as

$$\hat{R}_d^\pi = \liminf_{N \to \infty} \frac{1}{N} \sum_{n=1}^{N} r_d^\pi[n].$$

Now, PF resource allocation scheme is defined as follows [23]:

Definition 4. *A D2D resource allocation policy π^* is said to be proportionally fair if $\sum_{d \in \mathcal{D}} \log \hat{R}_d^{\pi^*} \geq \sum_{d \in \mathcal{D}} \log \hat{R}_d^\pi$ with probability (w.p.) 1 for any other D2D resource allocation policy π.*

Next, we propose a polynomial time PF resource allocation scheme for the D2D underlay network.

3.4 Proportional Fair Resource Allocation

We break the problem of PF resource allocation in two parts: (1) power control assuming the resource block is allocated to a D2D pair and (2) feasibly assigning resource blocks to the D2D pairs.

3.4.1 Power Allocation for D2D Pairs

Since we assume that in each scheduling sub-frame, the association of resource blocks with CUs is known, that is, the BS has already decided upon which resource blocks are allocated to each CU, therefore we concentrate only on the power allocation and scheduling of D2D users.

Suppose in a sub-frame n, a resource block k is allocated to CU c. Then, our first task is to check whether resource block k can be shared with D2D pair d while maintaining the QoS constraint imposed by CU c. Secondly, we want to quantify the maximum rate a D2D pair can achieve on the resource block without violating the rate requirement of the CU. If $S_c^k[n] = P_c g_{cB}^k[n]$ denotes the received signal power at the BS in the n^{th} sub-frame, then $S_c^k[n]/\sigma_N^2$ is the received signal-to-noise ratio (SNR) at the BS without D2D communication on the resource block k. Let us assume that this received SNR is higher than the target SNR γ_c^{tgt} required at the BS for a successful communication. Now, if a D2D transmitter d_T transmits on resource block k in sub-frame n, then its transmit power should be such that interference caused by it reduces the received SINR of CU c to not less than γ_c^{tgt}. In other words, we are basically exploiting the SINR gap of CUs to allocate power to the D2D pairs.

Since, we have assumed a perfect CSI model, in which the BS knows all the channel gains in a sub-frame, we can readily compute the maximum allowable transmit power for each D2D transmitter d_T on each resource block k allocated to CU c. Suppose, $I_{d_T}^k[n]$ is the interference caused by D2D transmitter d_T on resource block k in sub-frame n, then

$$\frac{P_c g_{c,B}^k[n]}{\sigma_N^2 + I_{d_T}^k[n]} \geq \gamma_c^{tgt},$$
$$I_{d_T}^k[n] \leq \frac{P_c g_{c,B}^k[n]}{\gamma_c^{tgt}} - \sigma_N^2.$$

Now, $I_{d_T}^k[n]$ is nothing but $P_{d_T}^k[n] g_{d_T B}^k[n]$. Therefore, from the above equation, the transmit power can be determined by substituting the value of $I_{d_T}^k[n]$, which is as follows,

$$P_{d_T}^k[n] g_{d_T B}^k[n] \leq \frac{P_c g_{cB}^k[n]}{\gamma_c^{tgt}} - \sigma_N^2,$$
$$P_{d_T}^k[n] \leq \frac{P_c g_{cB}^k[n]}{\gamma_c^{tgt} g_{d_T B}^k[n]} - \frac{\sigma_N^2}{g_{d_T B}^k[n]}.$$

Lemma 1. *For an optimal proportionally fair policy π^*, if a resource block k is assigned to D2D pair d, then the transmit power for D2D transmitter d_T must be*

$$P_{d_T}^k[n] = \frac{P_c g_{cB}^k[n]}{\gamma_c^{tgt} g_{d_T B}^k[n]} - \frac{\sigma_N^2}{g_{d_T B}^k[n]}.$$

Proof. If the power $P_{d_T}^k[n]$ is more than the specified value, SINR constraint stated in *Definition 2* is not satisfied. This results in an infeasible policy π. If it is less, then the rate obtained for resource block k in sub-frame n is not the maximum achievable rate. Hence, in either of these cases, optimal proportional fairness is not achieved. □

Once the optimal power is known for each D2D pair d on resource block k, we know the rate $r_d^k[n]$ in each sub-frame n which is determined by Shannon's Capacity Theorem.

3.4.2 Resource Allocation using Bipartite Matching

The authors in [23] have shown that the PF optimization problem given in terms of the long term time average rates can be mapped to an equivalent problem in terms of the per sub-frame rate. If maximum T resource blocks can be allocated to a D2D pair d, the optimization problem can be transformed to a local gradient maximization problem in each sub-frame n with the following objective function,

$$\begin{aligned} &\max \sum_k \sum_d \frac{x_d^k[n] r_d^k[n]}{\bar{R}_d[n-1]}, \quad \forall\, n, \\ &\text{s.t.} \quad \sum_k x_d^k[n] \leq T, \\ &\text{and} \quad \sum_d x_d^k[n] \gamma_c^k[n] \geq \gamma_c^{tgt}. \end{aligned} \tag{3.1}$$

Here, optimization variable $x_d^k[n]$ is an indicator function defined as,

$$x_d^k[n] = \begin{cases} 1, & \text{if resource block } k \text{ is allocated to user } d, \\ 0, & \text{otherwise.} \end{cases}$$

$\bar{R}_d^{\pi}[n-1]$ is the average rate of d^{th} D2D pair till the $[n-1]^{th}$ sub-frame over an exponential time averaging window. This constrained optimization problem is basically an integer linear programming (ILP) resource allocation problem. It is difficult to obtain its solution directly. We propose an optimal solution using MWBP which can be solved in polynomial time. Let us define a bipartite graph for allocating maximum one resource block with vertex sets as set of D2D pairs and another set of resource blocks. Now each edge weight between d^{th} D2D pair and k^{th} resource block in the sub-frame n is given by $\lambda_d^k[n] = r_d^k[n]/\bar{R}_d[n-1]$, which is called the PF metric. This is depicted in Figure 3.2.

Lemma 2. *Maximum weight bipartite matching for the constructed graph gives optimal solution to the optimization problem given by Equation 3.1.*

Proof. Every $x_d^k[n] = 1$ gives a feasible pairing between d and k. If d_1 and d_2 are any two D2D pairs, then $x_{d_1}^k[n] = 1$ implies $x_{d_2}^k[n] = 0$, $\forall\, d_2 \neq d_1$ as one resource block can be allocated to maximum one D2D pair. Among the set of all feasible

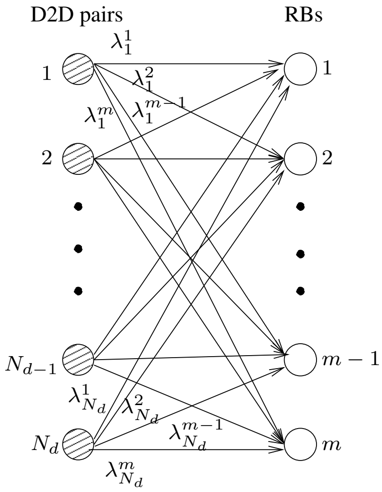

Figure 3.2: Bipartite graph for allocating maximum one resource block ($T = 1$) to a D2D pair.

pairings, MWBP selects that set which maximizes the sum of all edge weights. This is equivalent to maximizing $\sum_d \sum_k x_d^k[n]\lambda_d^k[n]$. Hence, MWBP selects the optimum pairing of nodes in a complete bipartite graph which is an optimal solution. $\square$

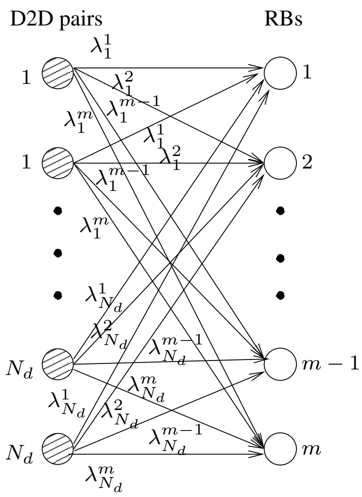

Figure 3.3: Bipartite graph for allocating maximum two resource blocks ($T = 2$) to a D2D pair.

Algorithm 3 Uplink D2D resource block allocation with multiple shared resource block

Resource block allocation mapping for CUs with γ_c^{tgt} given
$\mathcal{M}$: Set of resource blocks allocated to CUs
C: Set of active CUs
D: Set of D2D pairs
g_{xy}: Channel gain matrix
for all $k \in \mathcal{M}$ **do**
  Find associated CU c;
  for all $d \in \mathcal{D}$ **do**
    $P_{d_T}^k[n] \leftarrow \frac{P_c g_{cB}^k[n]}{\gamma_c^{tgt} g_{d_T B}^k[n]} - \frac{\sigma_N^2}{g_{d_T B}^k[n]}$;
    $\lambda_d^k[n] \leftarrow r_d^k[n]/\bar{R}_d[n-1]$;
  end for
end for
Repeat D2D pair nodes T times for maximum T resource block allocation;
Use MWBP with edge weights $\lambda_d^k[n]$;
Get optimal pairing;
Compute rates of D2D pairs and CUs;

For multiple resource block allocation to D2D pairs, we are not concerned about the allocation scheme for CUs. Therefore, we can employ any of the existing resource allocation schemes for CUs given in the open literature. We have used an existing greedy heuristic algorithm "*Alg1: carrier-by-carrier in turn* based PF scheduling" given in [23].

As long as resource block allocation of CUs are known (through some existing scheduling algorithms by BS), we can allocate more than one resource block to D2D pairs. We also assume that the minimum SINR requirement $\gamma_c^k[n]$ for CU c on each resource block k in sub-frame n is known even when multiple resource blocks are allocated to the CUs. Once all the powers required for each D2D transmitter on each resource block are known, we can calculate the PF metric $\lambda_d^k[n]$, $\forall\, d \in \mathcal{D}$ and $\forall\, k \in \mathcal{M}$.

If a D2D pair can be allocated at most T resource blocks, then the vertex set of D2D pairs should be repeated T times, while keeping the other vertex set of resource blocks same, to form a new complete bipartite graph. Consequently, edge weights are also repeated. Figure 3.3 illustrates a new bipartite graph formation for this generalized case with $T = 2$.

We now analyze the complexity of the proposed MWBP algorithm. For the general case when a D2D pair can share a maximum of m resource blocks, the complexity for calculating edge weights is $\mathrm{O}(N_D \times m^2)$. To determine maximum weight matching of the complete bipartite graph, we apply Blossom algorithm and the primal dual method [25]. This algorithm has computational complexity of $\mathrm{O}(n^3)$, where n is the total number of nodes in the graph given by $n = (m+1)N_D$. Therefore, overall complexity of the algorithm is $\mathrm{O}(N_D \times m^2 + n^3)$.

3.5 Simulation Methodology and Results

3.5.1 Simulation Setup

To evaluate the performance of our proposed algorithm, system level simulations have been performed in MATLAB. A single hexagonal cell with ISD of 500 m has been considered. Omni-directional SISO antenna configuration has been considered. System bandwidth of 5 MHz is considered for the uplink. CUs and D2D transmitters are distributed uniformly within the cell. We define the range of D2D communications R_{D2D} to be the distance of the D2D receiver from its transmitter. D2D receivers are uniformly distributed around the D2D transmitters within a specified range. To understand the system level performance with different values of the range, we vary it from 10 m to 100 m in steps of 10 m. Each RB is grouped into 12 adjacent sub-carriers and duration of one TTI, namely 0.5 millisecond and consists of 6 or 7 OFDM symbols. Scheduling decisions are taken in every sub-frame of duration 2 TTIs (1 millisecond). In LTE, multiple access scheme for the uplink is single carrier frequency division multiple access (SC-FDMA) due to its characteristics of low peak-to-average power ratio (PAPR) and physical properties of SC-FDMA requires RBs allocated to a single user must be contiguous in frequency. The power profile is considered to be consistent over all available sub-carriers. All the simulation related parameters are summarized in Table 3.1.

Parameter	Values
Cell layout	Single Hexagonal cell
ISD	500 m
Spectrum allocation (uplink)	5 MHz
Number of subcarriers per RB	12
Subcarrier spacing	15 KHz
RB bandwidth	180 KHz
Number of available RBs	50
CU transmit power	250 mW
Max D2D transmit power	250 mW
Modulation and coding scheme (MCS)	QPSK: 1/6, 1/3, 1/2, 2/3 16QAM: 1/2, 2/3, 3/4 64QAM: 1/2, 2/3, 3/4, 4/5
Sub-frame duration	1 ms
Number of symbols per slot	7 (1 pilot+6 data)
User distribution	Uniform
Number of active CU (N_C)	20, 30, 40
Number of D2D pairs (N_D)	10%, 20%, ...100% of active CUs
User speed	Static
Path loss	PL = 128.1 + 37.6log(d)
Shadowing	Log-normal distribution with standard deviation of 8 dB
Fast fading	Multipath Rayleigh distribution
UE noise figure	5 dB
UE thermal noise density	-174 dBm/Hz
Antenna layout	Omnidirectional antenna
Traffic model	Full buffer traffic

Table 3.1: Simulation parameters and values.

In wireless channel environment, link adaptation plays an important role to overcome fluctuations of the time varying and frequency selective channel. It is based on AMC technique specified in 3GPP LTE technology [24]. Different range of SINR values are mapped to different spectral efficiency according to AMC table [24] specified by 3GPP and accordingly, spectral efficiency is mapped to achievable data rates.

3.5.2 Channel Model

We consider multipath fading channel environment. Apart from pathloss, we consider both slow fading and fast fading for our model. The overall channel gain (in dB) is given by,

$$g_{j,k} = 128.1 + 37.6 * log(d_{j,k}) + X_\sigma + Y_{\bar{P},\bar{D}} \tag{3.2}$$

where $g_{j,k}$ is the channel gain between eNodeB j and user k or that between user j and user k (user can be a CU or a D2D user) at a distance of $d_{j,k}$ (in kilometers). X_σ represents the shadow fading random variable having lognormal distribution with a standard deviation of σ. $Y_{\bar{P},\bar{D}}$ represents fast fading random variable having exponential distribution and associated power-delay profile is given by the vectors $\bar{P}$ and $\bar{D}$. Also, we have assumed omnidirectional antenna for this single cell scenario.

3.5.3 Simulation Results

We evaluate the performance of our proposed scheduling algorithm by assessing the fairness of the average user data rates by using Jain's fairness index metric. Let $\bar{R}_i$ be the average data rate of user i over N sub-frames. If the total number of users are U, then Jain's Fairness index is defined as [20],

$$\eta = \frac{\left(\sum_i^U \bar{R}_i\right)^2}{U \sum_i^U \bar{R}_i^2}.$$

If the Jain's fairness index is close to 1, it signifies a good fairness among the user data rates.

Fig. 3.4 and 3.5 illustrate the variation of throughput with increasing distance between the D2D transmitter and the receiver (D2D range) for the single resource block and multiple resource block allocation scheme respectively. We observe from both the plots that the D2D user throughput and network throughput decreases as the D2D range increases while the throughput of CUs remains almost the same. Hence, it is quite significant that D2D communication is feasible within a certain range. To exploit performance enhancement in the network, D2D pairs should be in close proximity.

Fig. 3.6 and 3.7 illustrate how the throughput varies with increasing number of D2D pairs in the cell. We observe that the D2D user throughput and the total

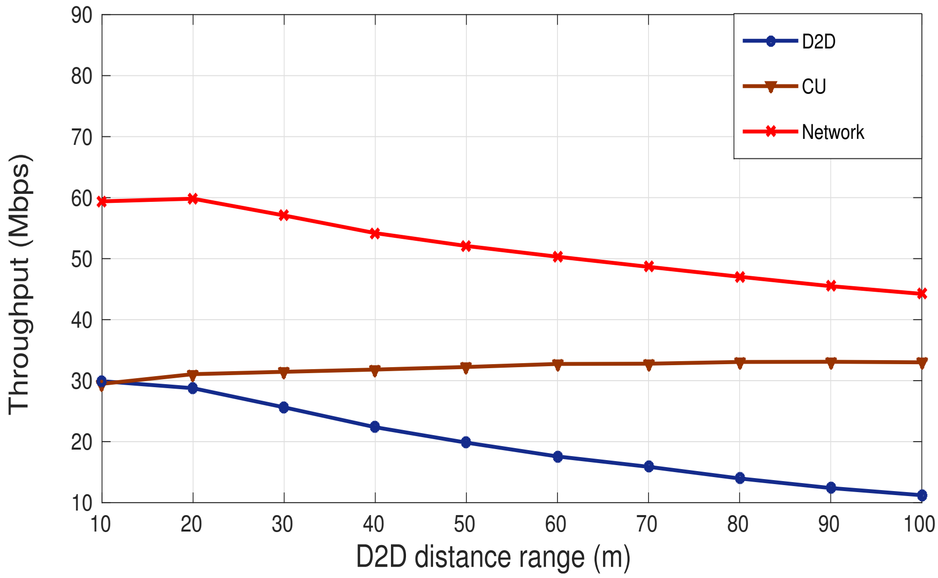

Figure 3.4: Throughput of CUs, D2D pairs and network with increasing D2D range for single resource block allocation ($N_c = 30$, $N_D = 20$, $T = 1$).

network throughput increases. We also observe that the throughput of CUs does not show any appreciable degradation. Therefore, we can infer that the network can accommodate D2D pairs while still maintaining the QoS of CUs. Also, increasing the value of the maximum number of resource block T that a D2D pair can share, results in an increase in total network throughput and D2D user throughput.

If $T = 1$, each D2D user can get atmost one resource block, thus on long term all the D2D users tend to get similar throughput and this algorithm becomes quite similar to RR algorithm. As the value of T increases, D2D users can exploit better diversity. Similarly, if $T = m$, this algorithm converges to general PF algorithm. Since, PF algorithm provides better throughput than RR algorithm, increasing value of T results in an increase of network throughput.

Fig. 3.8 compares Jain's fairness index for PF and MR scheduling for both CUs as well as D2D users with single resource block allocation. We observe that, as the number of D2D pairs increases, the fairness index with MR scheduling decreases unlike PF scheduling, which maintains good fairness among D2D users. Comparison with MR algorithm is important here to illustrate that PF algorithm strikes a good balance between throughput and fairness compared to other scheduling algorithms.

Fig. 3.9 shows similar results with multiple resource block allocation. This illustrates that our proposed algorithm provides good fairness among D2D users.

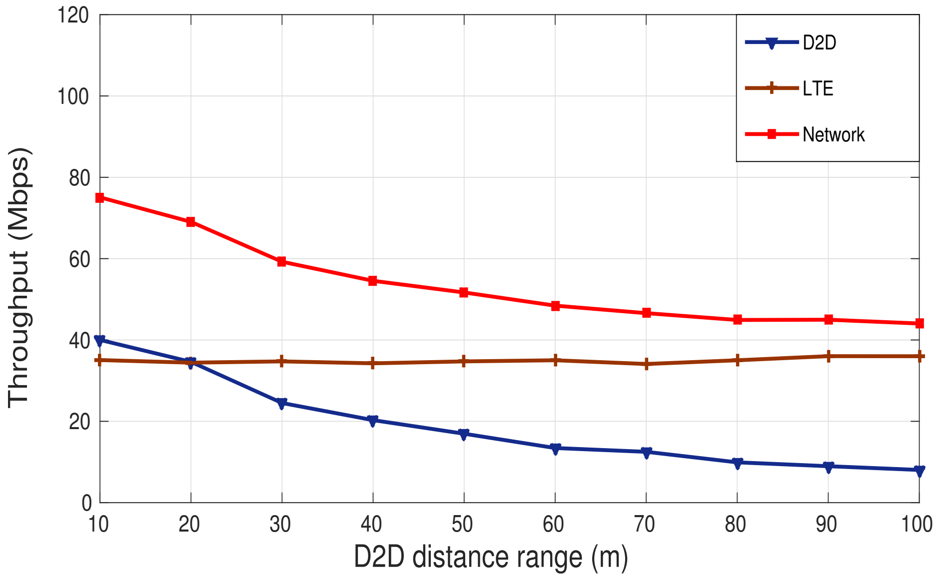

Figure 3.5: Throughput of CUs, D2D pairs and network with increasing D2D range for multiple resource block allocation ($N_c = 20$, $N_D = 20$, $T = 2$).

Further, we notice that the fairness among CUs is also maintained even with the inclusion of D2D users in the network. Similar to the explanations, how network througput varies as the value of T increases, we can enlighten on another important point that as the value of T increases, Jain's fairness index decreases. Since, increasing the value of T from 1 to m makes the proposed algorithm to converge to a generalized PF algorithm from a RR algorithm, it is reasonable that increasing the value of T will eventually decrease fairness index among D2D user data rates.

We now compare sum of log throughput, $\sum_{d \in \mathcal{D}} \log \hat{R}_d$ for the proposed PF algorithm with the MR algorithm for both single and multiple resource block allocation scenarios. In Section 3.3, we outlined that PF scheduling policy maximizes $\sum_{d \in \mathcal{D}} \log \hat{R}_d$ for any D2D resource allocation policy and validate it through simulation results shown in Table 3.2 and 3.3.

D2D pairs	2	4	6	8	10	12	14	16	18	20
PF Algo.	2.37	4.39	5.86	7.82	9.81	12.07	11.94	10.82	12.97	16.93
MR Algo.	2.12	4.21	5.66	7.02	9.55	11.44	11.24	10.02	12.67	16.74

Table 3.2: Comparison of $\sum_{d \in \mathcal{D}} \log \hat{R}_d$ for PF and MR algorithm ($N_C = 20$, $R_{D2D} = 20$ m, $T = 1$).

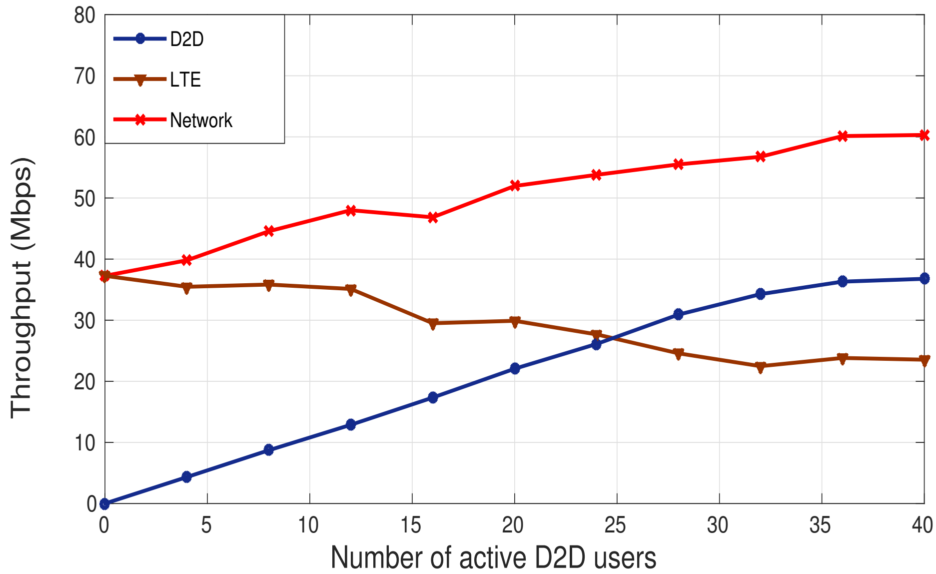

Figure 3.6: Throughput of CUs, D2D pairs and network with increasing number of D2D pairs for single resource block allocation ($N_C = 40$, $R_{D2D} = 20$ m, $T = 1$).

D2D pairs	2	4	6	8	10	12	14	16	18	20
PF Algo.	4.31	8.55	11.93	14.93	19.69	20.82	18.55	14.53	15.62	16.85
MR Algo.	4.13	8.37	11.81	14.82	19.35	-∞	-∞	-∞	-∞	-∞

Table 3.3: Comparison of $\sum_{d \in \mathcal{D}} \log \hat{R}_d$ for PF and MR algorithm ($N_C = 20$, $R_{D2D} = 20$ m, $T = 2$).

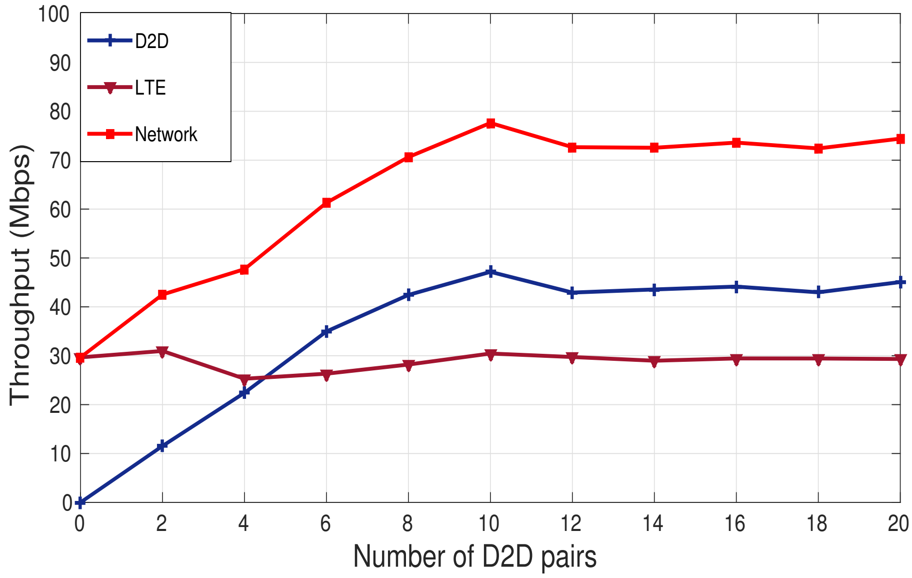

Figure 3.7: Throughput of CUs, D2D pairs and network with increasing number of D2D pairs for multiple resource block allocation ($N_C = 20$, $R_{D2D} = 20$ m, $T = 2$).

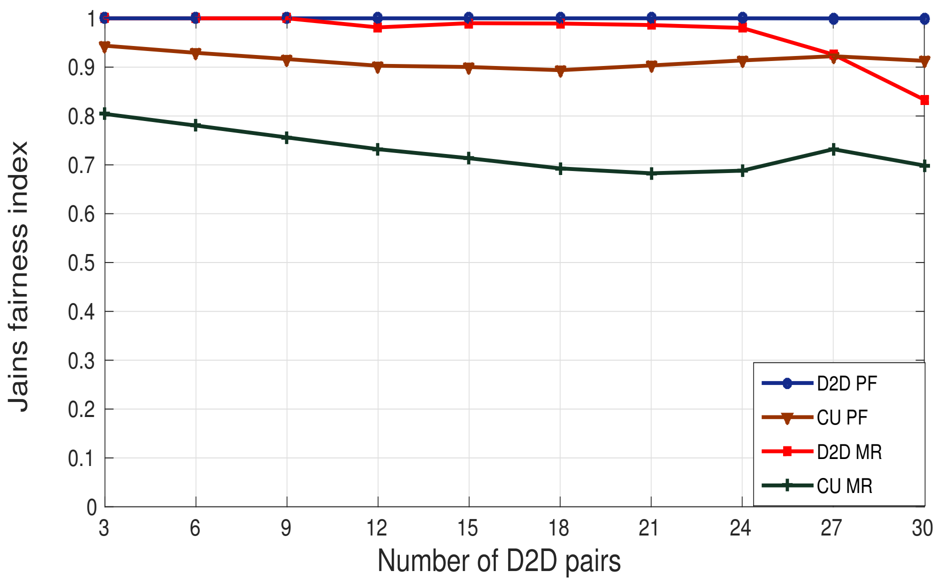

Figure 3.8: Comparison of Jain's fairness index between PF and MR scheduling with increasing number of D2D pairs for single resource block allocation ($N_C = 30$, $R_{D2D} = 20$ m, $T = 1$).

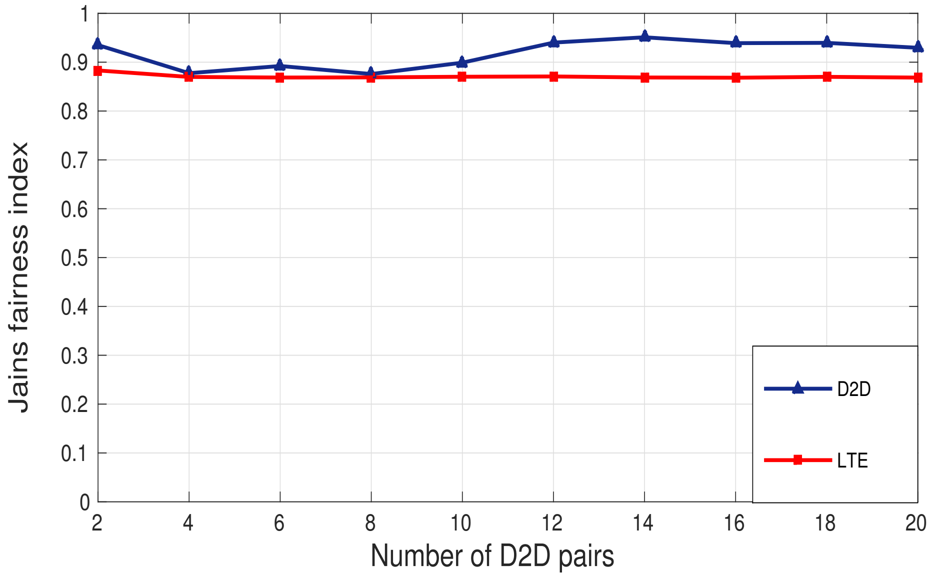

Figure 3.9: Jain's fairness index with increasing number of D2D pairs for multiple resource block allocation ($N_C = 20$, $R_{D2D} = 20$ m, $T = 2$).

3.6 Conclusions

In this work, we have investigated PF scheduling for D2D pairs underlaying cellular network. We utilize the excess SINR of CUs, beyond their required SINR threshold, to allocate powers to D2D pairs such that the minimum SINR of CUs after the inclusion of D2D pairs can still be maintained. Based on this concept, we then determine the optimal pairing between resource blocks and D2D pairs using a bipartite graph based matching algorithm such that each D2D pair gets at most one resource block. We then extend this technique for allocating multiple resource blocks to D2D pairs. Our proposed algorithm is valid for allocating any number of resource blocks with a simple extension. Since in the uplink transmissions, contiguous resource blocks are allocated to CUs, power allocation to D2D pairs while maintaining a minimum rate for CUs is a challenge which we are investigating further. Results illustrate that we achieve high throughput and good fairness for D2D users with both single and multiple resource block allocation. Further, we observe that since the throughput of CUs does not degrade much and at the same time the throughput of D2D users increases as the number of D2D users in the network increases, a net increase in network throughput is achieved. Therefore, as eNodeB remains in control of D2D communication, it may be a promising integration within the cellular network.

Future work involves simulation of the proposed algorithm in a multi-cell scenario, by considering inter-cell interference. Also, this work can be extended to verify how the proposed resource allocation scheme works in a guaranteed bit rate real-time application, by varying the number of maximum allowable resource blocks that can be allocated to a D2D pair.

Chapter 4

Conclusions and Future Work

D2D communication underlaying cellular network can improve system capacity and spectral efficiency of the network, but inclusion of D2D users can cause severe interference to the CUs, thus hampering CU's communication. Therefore, efficient D2D resource allocation techniques need to be devised to enhance spectral efficiency and at the same time, limiting interference to the CUs to maintain their QoS. In this thesis, we address this challenge and propose new algorithms for resource allocation in the D2D underlay network.

In Chapter 2, we have analyzed interference scenarios in both uplink and downlink for the D2D underlay network. We have proposed a greedy heuristic algorithm to schedule D2D users while maintaining QoS for both cellular and D2D users. Simulation results demonstrate that capacity improvement is achieved over the existing cellular network with the inclusion of D2D users. A future research direction is to include power control for D2D users and extend this analysis in a multi-cell environment, by considering inter-cell interference.

In Chapter 3, we have proposed a polynomial time PF resource allocation scheme that respects the rate requirements of CUs. The proposed scheme can potentially work with any resource allocation scheme for CUs and can adapt to time and location varying channel conditions. Simulation results validate capacity enhancement over the existing cellular network and achieve proportional fairness among D2D users in a single-cell scenario. A possible future work is to reformulate the problem with a power constraint for D2D users which we have not considered in our work and extend this analysis in a multi-cell environment. One can also address the problem of resource allocation for D2D users in the scenario when the BS has partial or erroneous CSI.

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Publications

Paper titled "Bipartite Graph Based Proportional Fair Scheduling for D2D Communications, " by I. Mondal, A. Neogi, P. Chaporkar and A. Karandikar is under review in *Proc. IEEE GLOBECOM*, 2016.

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