INTERFERENCE MITIGATION FOR DEVICE-TO-DEVICE BASED WIRELESS SYSTEMS

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Electronics and Communication Engineering

by
Süleyman Onur Acar

June 2018
İZMİR

We approve the thesis of **Süleyman Onur Acar**

Examining Committee Members:

Assoc. Prof. Dr. Berna ÖZBEK
Department of Electrical and Electronics Engineering, Izmir Institute of Technology

---

Assoc. Prof. Dr. Mustafa Aziz ALTINKAYA
Department of Electrical and Electronics Engineering, Izmir Institute of Technology

---

Assoc. Prof. Dr. Radosveta Ivanova SOKULLU
Department of Electrical and Electronics Engineering, Ege University

29 June 2018

Assoc. Prof. Dr. Berna ÖZBEK
Supervisor
Department of Electrical and Electronics Engineering, Izmir Institute of Technology

---

Prof. Dr. Enver TATLICIOĞLU
Head of the Department of
Electrical and Electronics Engineering

Prof. Dr. Aysun SOFUOĞLU
Dean of the Graduate School of
Engineering and Sciences

ACKNOWLEDGMENTS

Firstly, I would like to thank my advisor Assoc. Prof. Dr. Berna ÖZBEK for her guidance, support and motivation throughout my master study.

Besides my advisor, I would like to thank the rest of my thesis committee members Assoc. Prof. Dr. Mustafa Aziz ALTINKAYA and Assist. Prof. Dr. Radosveta Ivanova SOKULLU for their valuable comments and constructive criticism.

I would like to express my sincere gratitude to Burcu AKBULUT for her continuous support and encouragement during tough times in the MSc pursuit. Lastly, I would like to thank my family for their endless support and love.

ABSTRACT

INTERFERENCE MITIGATION FOR DEVICE-TO-DEVICE BASED WIRELESS SYSTEMS

Device-to-device (D2D) communication provides an effective way to meet growing mobile traffic and capacity demand. D2D communication can improve existing cellular systems in several ways. When UEs are located in close proximity, they can communicate through direct links bypassing the base station (BS). In this way, the transmitter consumes less power while better Quality-of-Service can still be provided. D2D links can also increase both energy and spectrum efficiency by reusing downlink and uplink cellular resources. However, integrating D2D links into the cellular infrastructure complicates the interference situation because D2D communication might increase the co-channel interference and degrade cellular link quality. In this thesis, the interference mitigation techniques including resource allocation, power control and multiple antenna are proposed for D2D communications underlaying cellular systems to increase the data rate of both the cellular users and D2D pairs. The Zero-Forcing technique is carried out for interference mitigation by assuming perfect channel state information at the BS side. The effect of a limited feedback link for downlink cellular communication and channel estimation for uplink communication are considered for underlying multi antenna cellular system.

ÖZET

CİHAZDAN CİHAZA TABANLI KABLOSUZ SİSTEMLER İÇİN GİRİŞİM ÖNLEME

Akıllı cihazların ve mobil uygulamaların kullanımının artması, veri trafik talebinin büyümesini sağladığından, verimlilik ve ölçeklenebilirlik gelecekteki iletişim sistemlerinin geliştirilmesi için büyük öneme sahiptir. Cihazdan cihaza (D2D) iletişim, artan mobil veri trafiğinin üstesinden gelmek ve kapasite talebini karşılamak için etkili bir çözüm sunar. D2D iletişimi, mevcut hücresel sistemi birkaç yönden geliştirebilir. Kullanıcı ekipmanları birbirlerine çok yakın olduklarında, baz istasyonunu atlayarak doğrudan bağlantıyla iletişim kurabilirler. Bu sayede verici daha düşük güç tüketirken, daha iyi hizmet kalitesi sağlayabilir. D2D bağlantıları aynı zamanda aşağı yönlü ve yukarı yönlü spektrum kaynaklarını yeniden kullanarak enerji ve spektrum verimliliğini artırabilir ve etkin yakınlık tabanlı hizmetleri mümkün kılar. Fakat, geleneksel hücresel altyapıya D2D bağlantılarının entegrasyonu, girişim durumunu karmaşık hale getirir, çünkü D2D iletişimleri eş kanal girişimini artırabilir ve hücresel bağlantı kalitesini düşürebilir. Bu tezde, kaynak tahsis ve güç kontrol teknikleri tek ve çoklu antene sahip hücresel ağlar ile cihazdan cihaza (D2D) iletişimin beraber kullanılmasından kaynaklanan girişimi azaltmak bununla beraber hem hücresel kullanıcıların hem de D2D çiftlerinin veri oranını arttırmak için önerilmiştir. Buna ek olarak, sıfır zorlama tekniği baz istasyonunda mükemmel kanal bilgisi ile gerçekleştirilmekte olup, ayrıca aşağı yönlü ve yukarı yönlü bağlantı iletişimi için sınırlı ve tahmini kanal bilgisi ile uygulandığı zamanki etkisi incelenmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
UTRAN	UMTS Terrestrial Radio Access Network
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
3GPP	3rd Generation Partnership Project
EPC	Evolved Packet Core
QoS	Quality of Services
OFDM	Orthogonal Frequency-Division Modulation
OFDMA	Orthogonal Frequency-Division Multiple Access
EVDO	Evolution-Data Optimized
UWB	Ultra Wide Band
BS	Base Station
D2D	Device-to-Device
SINR	Signal-to-Interference-plus-Noise Ratio
LoS	Line-of-Sight
NLOS	Non-Line-of-Sight
ITU	International Telecommunication Union
SNR	Signal-to-Noise Ratio
SAE	System Architecture Evolution
RAN	Radio Access Network
EPS	Evolved Packet System
UL	Uplink
DL	Downlink
UE	User Equipment
CQI	Channel Quality Indicator
MCS	Modulation Coding Scheme
ISD	Inner Side Distance
RB	Resource Block
RVQ	Random Vector Quantization
MRC	Maximal-Ratio Combining
TDD	Time Division Duplex
FDD	Frequency Division Duplex

CSI	Channel State Information

CHAPTER 1

INTRODUCTION

In recent years, the cellular communication industry has encountered a remarkable demand with the number of wireless subscribers. The exponential development of wireless communication, data roaming and high traffic demands are a major challenge for broadband mobile wireless communications. The emergence of new wireless multimedia applications and services have constituted the key drivers to the development of the Long Term Evolution-Advanced (LTE-A) network (Hicham et al., 2016). The growth mainly occurs by usage of popular multimedia applications which are supported by smart devices and consequently, the network resources and wireless link capacity will encounter huge demand.

Additionally, user experiences become a significant issue, besides higher data rates demands. LTE networks can provide good quality-of-service (QoS) in exact places, but they cannot overcome the extreme data traffic for future wireless system where users are located in close proximity to one another, such as shopping malls, festivals, stadiums and office buildings. Due to increasing capacity and connectivity, higher energy consumption and costs will be an important challenge. Hence, user demands will require some specific future needs which are short range services and data intensive short range applications.

In order to overcome these increasing demands, a lot of standards and technologies have evolved namely LTE and LTE Advanced, 3GPP2s Evolution-Data Optimized (EVDO) and Ultra Wide Band (UWB) and Worldwide Interoperability for Microwave Access (Wimax) (Chandrasekhar and Andrews, 2008). However, LTE and LTE-A, which constitute the structure of 4G networks, have reached at a limiting level. Thus, in order to meet the requirements of fully connected society where high capacity is required, fundamental changes are needed to manage heterogeneous networks as well as new trends in user behavior and applications.

Therefore, in order to handle the needs and requirements for the future networks, a new standard has been taken into consideration that refers to the fifth generation (5G). 5G networks are expected to sustain the existing and evolving technologies and, at the same time, incorporate new solutions which have been proposed to satisfy the new requirements. There are a lot of options to meet these new requirements. These could be improving the efficiency of available spectrum resources, the number of antennas and base stations (BS). Therefore, there are many new concepts, design criteria, and scenarios that have been proposed for 5G. One of them is D2D communication which will allow new types of services such as multimedia downloading, video streaming, online gaming and peer-to-peer (P2P) file sharing.

The term D2D generally refers to direct connections between two communicating devices. D2D communication, as a technology component for LTE-A, enables direct communication between nearby mobiles without routing data through a BS or the core network (Wang and Tang, 2016). Direct communications between devices can provide several benefits to users in various applications where the devices are in close proximity with each other, bypassing the base station. Direct communication between nearby mobile devices will improve spectrum utilization, overall throughput, and energy efficiency. Direct short-range communication can save some resources such as transmit power of BS or mobile devices, especially, when the user is located at the cell edge. If D2D users share the same spectrum, direct link can improve the spectrum usage. As a result of that, user data rates and capacity per area unit will be increased and the delay will be reduced.

Using direct link between the UEs can provide good capacity solutions but they encounter some problems. One of the most important challenges of D2D communication is interference mitigation since D2D pairs are likely to be deployed so densely in the future. Furthermore, because of the stochastic nature, they are in need of some intelligent techniques to organize themselves in order to cope with the interference problem. The deployment of dense neighboring D2D pairs or usage of same spectrum with conventional BS may cause frequency reuse and as a result UEs interfere with each other. For this reason, interference mitigation techniques have great importance for D2D communication to ensure that users have good quality of service without any degradation effect in system parameters such as signal-to-interference-noise ratio (SINR).

This thesis investigates how to improve the performance of macro-tier and device-tier communication systems by means of interference mitigation techniques. We consider the resource allocation problem and power control scheme for D2D communication underlaying cellular network in the downink (DL) and uplink (UL). Besides, the power control scheme and zero-forcing technique are jointly implemented for multiple antenna cellular network including the limited and estimated channel information.

This thesis consists of 5 chapters and its outline is given as follows:

- Chapter 2 gives background information about key concepts of this thesis which are

Wireless Channel Properties, LTE Fundamentals and D2D Communication.

- Chapter 3 describes the system model and the graph construction for the considered system scenario for single antenna cellular network. It formulates the Graph-Coloring Based Resource Allocation Algorithm (GOAL) and the proposed resource allocation algorithm including the power control scheme for downlink and uplink communication.

- Chapter 4 examines GOAL algorithm and the proposed resource allocation algorithm for the multiple antenna cellular network to mitigate the interference. It formulates Zero-Forcing (ZF) technique based pre-coding downlink communications through perfect channel state information (CSI) and limited feedback link. It presents ZF based post-coding for uplink communication under both perfect CSI and channel estimation error case.

  for downlink and uplink communication with perfect CSI. Zero-Forcing technique is also performed with the limited and estimated CSI for downlink and uplink communication, respectively.

- Chapter 5 summarizes the final remarks.

CHAPTER 2

BACKGROUND

In this chapter, fundamental concepts related to this thesis are presented. In the first section, wireless channel properties will be summarized. In the following section, LTE principles will be introduced. Finally, D2D communication will be overviewed which is also recognized as one of the technology components of the evolving 5G architecture.

2.1. Wireless Channel Properties

The purpose of a communication system is to convey information through a medium or communication channel separating the transmitter from the receiver. According to the propagation environment, wireless channels can be identified, such as; urban, suburban, indoor, underwater or orbital propagation environments. It contains many parameters like mountains, hills, houses, moving users or other objects. Some of the parameters change over time in unpredictable way and this unpredictable nature of the wireless channel prevents reliable high-speed communication as well.

The radio propagation has three properties which are path loss, shadowing and multipath fading. In order to design and build a proper wireless communication system, each property must be taken into consideration. Unlike shadowing and multipath fading, path loss has a deterministic effect and it is determined with distance between the transmitter and the receiver. Shadowing and multipath fading have stochastic nature, hence they are not deterministic. The related effects of path loss, shadowing, and multipath are illustrated in Figure 2.1.

In the literature, generally there are two types of fading definitions for wireless communication channels namely large-scale fading and small scale fading. Large-scale fading is usually defined as the signal variations or attenuations over large distances. Path loss and shadowing effects can be considered in this category. Small-scale fading is associated with multipath fading affects (Goldsmith, 2005).

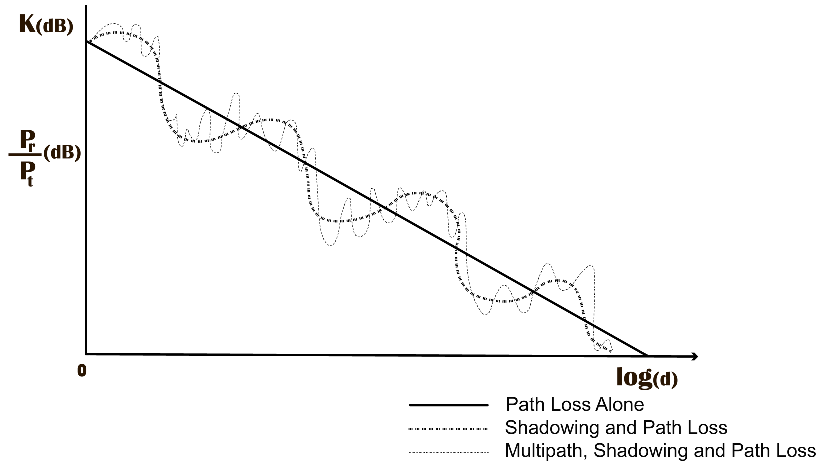

Figure 2.1. Path loss, Shadowing and Multipath versus distance.
(Source: Goldsmith, 2005)

2.1.1. Path Loss

Path loss is the reduction in power density of an electromagnetic wave as it propagates from the transmitter to the receiver. Path loss is caused by dissipation of the radiated power as well as effects of the propagation channel. The simplest path loss model corresponds to propagation in free space, i.e., line-of-sight (LoS) link between the transmitter and receiver. Under this model, the free space path loss (FSPL) is given as:

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{2.1}$$

where λ is the wavelength of the transmitted carrier, and d is the distance between the transmitter and the receiver (meters). The FSPL model cannot be applied for all the propagation scenarios encountered in the real world. Therefore, several different models such as Okumura, Hata, Walfish-Ikegami, (Stuber, 2001), have been examined to model path loss in different propagation environments such as urban, rural, and indoor areas.

The path loss model for D2D communications has not been standardized yet. However, in order to describe path loss model, the International Telecommunication Union's (ITU) recommendations for micro urban environments is used (Xing and Hakola, 2010), (ITU, 2009).

The path loss model is defined as,

$$PL = A + 10a\log_{10}(d) \quad (dB) \tag{2.2}$$

where d is the distance between the transmitter and receiver in meter. A and a are path loss coefficient and path loss exponent, respectively. The values of A and a are given in Table 2.1 for both LoS and non-line-of-sight (NLoS) scenarios (UMTS, 1997).

Table 2.1. Path loss parameters

Device	**Type of PL**	a	A
BS - UE	LoS	2.2	34.04
BS - UE	NLoS	3.67	30.55
UE - UE	Los	1.69	38.84
UE - UE	NLoS	4	28.03

2.1.2. Shadowing

The varying terrain conditions in suburban area and the obstacles such as buildings in urban areas cause shadowing effects between the base station and mobile station. Shadowing measurements have been made under several different conditions and statistical variations which have been observed. Different values of the received signal power were measured for a fixed frequency and distance. Hence, for a given fixed distance, frequency and transmission power, the received signal power is not deterministic but it varies due to the objects in and around the signal path. These stochastic, location dependent variations are called shadowing. Since the different propagation paths are independent, the sum of all losses for a large number of propagation paths converges to a normally distributed random variable (Goldsmith, 2005).

The log-normal shadowing model is given by,

$$p(\psi_{dB}) = \frac{1}{\sigma_{\psi_{dB}}\sqrt{2\pi}} \exp\left(-\frac{(\psi_{dB} - \mu_{dB})^2}{2\sigma^2_{\psi_{dB}}}\right) \tag{2.3}$$

where μ_{dB} is the mean of $\psi_{dB} = 10 \log \psi$ in dB and $\sigma_{\psi_{dB}}$ is the standart deviation of ψ_{dB}, also in dB.

The value of the variation due to the shadowing is then added to the path loss value in dB to obtain the large scale variations.

2.1.3. Multipath

In wireless communication system, a signal might be transmitted to the receiver over multiple reflective paths and this kind of propagation can cause fluctuations in the received signal's amplitude, phase, and angle of arrival. This effect is called multipath fading in the terminology.

There are two ways for the wireless communication channels to be affected by multipath fading which are flat fading and frequency selective fading. In flat fading, all frequencies pass through channel either equally or almost equally. However, frequency selective fading occurs when the multipath fading affects different frequencies across the channel to different degrees. Multipath propagation consists of three phenomena which are reflection, diffraction and scattering. Figure 2.2 illustrates the phenomenas.

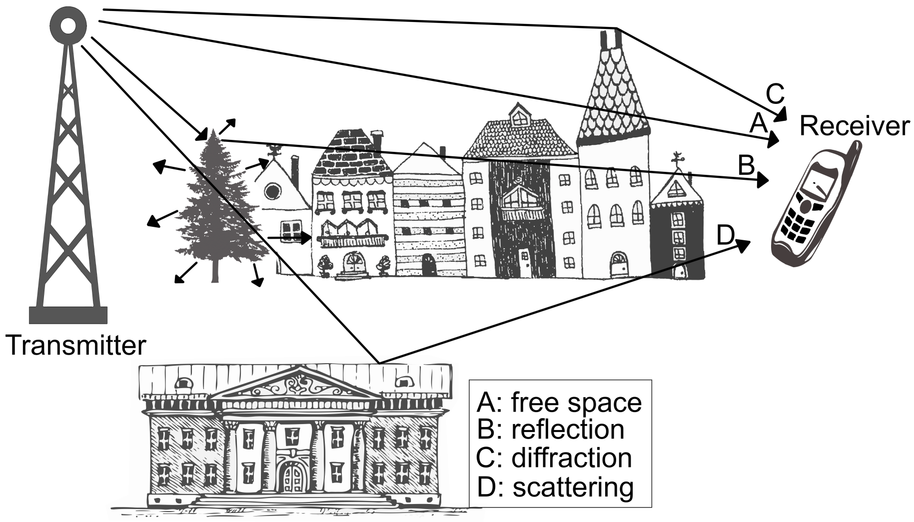

Figure 2.2. Electromagnetic wave propagation types.
(Source: Goldsmith, 2005)

Additionally, when an electromagnetic wave hits an object including buildings, walls and so forth and changes in direction of a wave front, it is called reflection. The multiple reflective paths are large in number and there is no line of sight signal component. Moreover, if there is no object along the path, multipath still can occur because of the reflections from the ground surface. When a communication signal bends around the corners of an obstacle or goes into the region, it is called diffraction. Scattering occurs when a wave bounces off an object and spreads out in many directions.

2.1.4. Channel Capacity

Shannon's Theorem gives an upper bound to the capacity of a link, in bits per second (bps), as a function of the available bandwidth and the signal-to-noise ratio (SNR) of the link (UMTS, 1997).

The theorem states that,

$$C = Blog_2\left(1 + \frac{P_r}{N_0 B}\right) \tag{2.4}$$

where C is the maximum capacity of the channel in bps, called Shannon's capacity limit for the given channel, B is the bandwidth of the channel in Hertz. P is the transmit signal power, P_r is the received signal power and N_0 is the noise power spectral density of Additive White Gaussian Noise (AWGN) channel.

The formulation of P_r is

$$P_r = \frac{P}{PL}\left|h\right|^2 \tag{2.5}$$

where PL represents path loss and shadowing effects. The channel coefficient h includes the multipath fading effect.

2.2. LTE Overview

LTE is a communication technology for wireless data communication and an evolution of the GSM/UMTS standards. The aim of LTE-Advanced is to improve the system capacity and efficiency of wireless data networks, thus LTE-A uses new digital signal processing techniques and modulations. The main purpose of LTE is to provide a high data rate, low latency and packet optimized radio access technology with flexible bandwidth. In order to overcome the increasing demand for wireless multimedia and interactive internet services and provide good QoS, 3GPP started working on two parallel projects, LTE and System Architecture Evolution (SAE). They are intended to define both the radio access network (RAN) and the network core of the system (Release 8). LTE/SAE, also known as the Evolved Packet System (EPS), represents a radical step forward for the wireless industry (Abed et al., 2012).

The specifications of the elements and requirements of the EPS architecture contain two major work items which are LTE and SAE, that led to the specification of the

Evolved Packet Core (EPC), Evolved Universal Terrestrial Radio Access Network (E-UTRAN), and Evolved Universal Terrestrial Radio Access (E-UTRA), each of them corresponds to the core network, radio access network, and air interface of the whole system, respectively. The EPS provides IP connectivity between cellular terminals and an external packet data network using E-UTRAN. The EPC subsystem is a flat all-IP system designed to support high packet data rates and low latency in serving flows. The E-UTRAN is the access network of the LTE system (3GPP, 2009). The main entities of E-UTRAN are the base stations referred to as eNBs (evolved NodeBs) for the macro-cells and HeNBs (Home-eNBs) for the femto-cells and the cellular terminals referred to as User Equipment (UE). The communication between eNBs and UEs consist of 10 ms frames and each frame is divided into 10 subframes of 1 ms and there are two basic subframes categories for eNBs and UE communication, downlink and uplink (Akyildiz et al., 2010).

LTE operates in the frequency range from 700 MHz to 2.6 GHz (3GPP, 2010). Also, LTE can supply a wide range of bandwidth from 1.4 MHz to 20 MHz. If we compare LTE to other existing technology, LTE provides higher peak data rates mainly due to unique features, larger system bandwidth and higher order Multiple Input Multiple Output (MIMO) technology in combination with higher order modulation (up to 64QAM). For downlink, 20 MHz bandwidth gives peak data rates of 326 Mbps using 4x4 MIMO. For uplink, the data rate is limited to 86 Mbps (3GPP, 2011) and the LTE system features are shown in Table 2.2.

Additionally, the LTE system supports Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA). These techniques supply high robustness and spectral efficiency against multipath fading (Mietzner et al., 2009). For uplink, LTE uses Single Carrier FDMA (SC-FDMA) access technique which gives greater coverage. The OFDMA solution leads to high Peak-to-Average Power Ratio (PAPR) requiring expensive power amplifiers. In order to establish low latency and QoS, a new network architecture is designed.

The LTE system can operate low latency packet transmission from network to UE thanks to its radio interface network. LTE can operate with both unicast and multicast traffic and its range is from 10 meters to 10 kilometers, according to transmission power. LTE system also supports FDD (Frequency Division Duplex) and TDD (Time Division Duplex), in its Half-FDD.

Table 2.2. Radio Attribute of LTE system
(Source: Mousavir et al., 2017)

LTE System Features	
Bandwidth	1.25 - 20 Mhz
Duplexing	FDD, TDD, half-duplex FDD
Mobility	350 km/h
Multiple access	Downlink OFDMA
	Uplink SC-FDMA
MIMO	Downlink 2x2, 4x2, 4x4
	Uplink 1x2, 1x4
Peak data rate in 20 MHz	Downlink 173 and 326 Mb/s for 2x2 and 4x4 MIMO, respectively
	Uplink 86 Mb/s with 1x2 antenna configuration
Modulation	QPSK, 16-QAM and 64-QAM
Channel coding	Turbo and Convolutional code
Other techniques	Channel sensitive scheduling, link adaptation, PC, ICIC and,adaptation and hybrid ARQ

2.2.1. Multiple-Input Multiple-Output Systems

In wireless communication, MIMO is used for increasing the capacity of a radio link using multiple transmit and receive antennas. MIMO has become an essential element of wireless communication standards including LTE.

There are three MIMO methods which are precoding, spatial multiplexing and diversity coding which are shown in Figure 2.3. Precoding is multi-stream beamforming and all spatial processing occurs at the transmitter side. The benefit of beamforming is to increase the received signal gain. In spatial multiplexing, a high-rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. When there is no channel knowledge at the transmitter, diversity coding techniques are used. In diversity methods, a single stream is transmitted, but the signal can be coded with space-time coding techniques (Gesbert et al. 2007).

MIMO techniques were first investigated in a point-to-point or single-user communication link. In a MIMO single-user system with N_t transmit and N_r receive antennas, a diversity order of $N_t \times N_r$ can be provided for the system, as illustrated in Figure 2.4. Also, if the channel is perfectly known at the receiver, capacity scales linearly with $min(N_t; N_r)$ relative to a system with just one transmit and one receive antenna. A

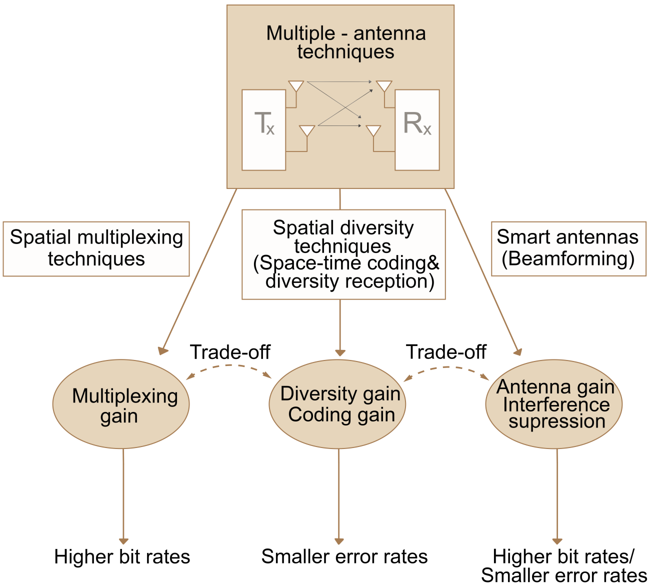

Figure 2.3. Summary of multiple antenna techniques.
(Source: UMTS, 1997)

MIMO system is thus able to provide improved power and bandwidth efficiencies, at the cost of setting up additional antennas.

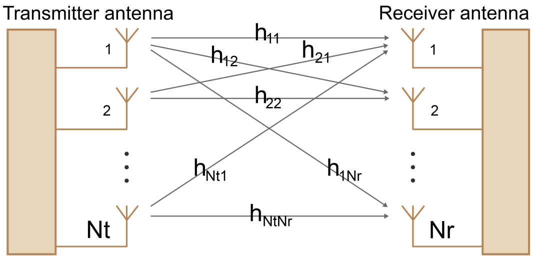

Figure 2.4. MIMO system

MIMO techniques and OFDM or OFDMA modulations are typically combined in order to handle a multi-path channel efficiently. The relationship between a few of the LTE targets and those for LTE-Advanced and International Mobile Telecommunications Advanced (IMT-Advanced) is given in Table 2.3.

The cell and cell-edge spectral efficiency figures are for inter-site distance (ISD) of 500 m.

Table 2.3. Spectral Performance Target of LTE, LTE-Advanced and IMT-Advanced Requirement. (Source: Ali, 2015)

Item	**Sub-category**	**LTE (Rel 8)**	**LTE-Advanced**	**IMT-Advanced**
Peak spectral efficiency (b/s/Hz)	Downlink	16.3 (4x4 MIMO)	30 (8x8 MIMO)	15 (4x4 MIMO)
	Uplink	4.32 (64-QAM SISO)	15 (4x4 MIMO)	6.75 (2x4 MIMO)
Downlink cell spectral efficiency b/s/Hz/user, Microcellular 3 km/h	(2x2 MIMO)	1.69	2.4	2.6
	(4x2 MIMO)	1.87	2.6	
	(4x4 MIMO)	2.67	3.7	
Uplink cell spectral efficiency b/s/Hz/user, Microcellular 3 km/h	(1x2 MIMO)	-	1.2	1.8
	(2x4 MIMO)	-	2.0	
Downlink cell-edge user spectral efficiency, b/s/Hz/ user 5 percentile, 10 user	(2x2 MIMO)	0.05	0.07	0.075
	(4x2 MIMO)	0.06	0.09	
	(4x4 MIMO)	0.08	0.12	
Uplink cell-edge user spectral efficiency, b/s/Hz/user 5 percentile,10 user	(1x2 MIMO)	-	0.04	0.05
	(2x4 MIMO)	-	0.07	

Multiple-Input Single-Output

Multiple Input, Single Output (MISO) is an antenna technology for wireless communications in which multiple antennas are used at the transmitter side and the receiver has only one antenna. In order to minimize errors and optimize data speed the antennas are combined. MISO is one of several forms of smart antenna technology, the others being MIMO and Single Input, Multiple Output (SIMO).

Capacity of MISO Channels

The MISO system channel vector is $\mathbf{h} = [h_{11}, h_{21}...h_{N_t1}]^T$ with the size of $N_t \times 1$. The channel gain is:

$$G = \|\mathbf{h}\|^2 = \sum_{j=1}^{N_t} |h_{j1}|^2 \tag{2.6}$$

where $\mathbf{h}$ is channel vector including fading effect and then capacity formula of MISO channel is obtained as follows (Park and Heath, 2016),

$$C_{MISO} = B\log_2\left(1 + \frac{P_rG}{N_0B}\right) \tag{2.7}$$

2.2.2. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a frequency-division multiplexing method and it is used for encoding digital data on multiple carrier frequencies, as illustrated in Figure 2.5. In order to transmit data on variety of parallel data streams or channels, time and/or frequency division access techniques and closely spaced orthogonal sub-carrier signals are used. Downlink sub-frame is transmitted by base station to user equipments and uplink sub-frame is transmitted by multiple UEs to the base station. Both frames consist of more than one OFDM symbols and each symbol is created from sub-carriers. The single carrier systems are not as resistant as OFDM technique to frequency selective fading. OFDM divides the overall channel into sub-channels and these sub-channels become narrowband signals. In this way, these are affected individually as flat fading sub-channels.

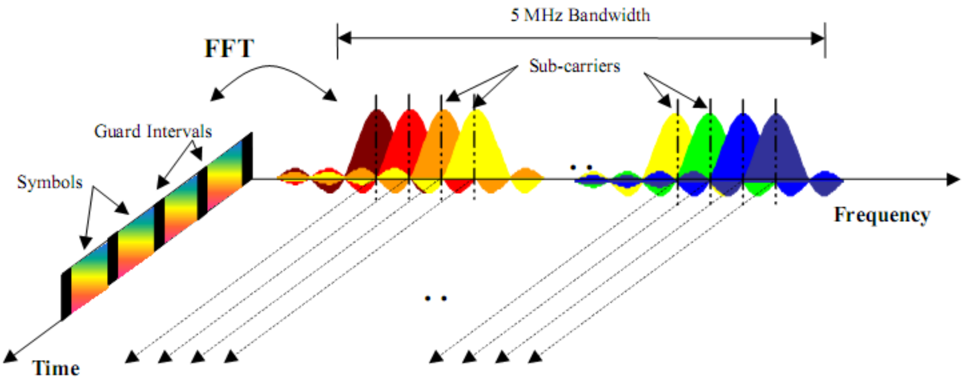

Figure 2.5. Frequency-Time representative of an OFDM signal.
(Source: 3GPP, 2006)

2.2.3. Orthogonal Frequency-Division Multiple Access (OFDMA)

OFDMA is a multiple access type of the OFDM scheme. Multiple access is obtained by allocating subsets of sub-carriers to UEs, in this way, simultaneous data transmission can be achieved for several users. In OFDMA, UEs can locate the same sub-channel however they use different sub-carriers to transmit the data. One symbol can comprise more than one sub-channel and each sub-channel can comprise distributed subcarriers.

In OFDMA, each symbol is used by more than one UE to transmit and receive the data. OFDMA system has sub-channelization concept thus it can support more UEs compared to OFDM. In order to implement OFDM and OFDMA process at transmitter and receiver respectively, IFFT and FFT operations are used (Xiao et al., 2011).

2.2.4. Sub-Carrier and Resource Allocation

The OFDMA defines every user with a sub carrier. While the number of users are high, this method is particularly useful in downlink. When the data rate required is low, the scheme can be adapted as it consumes less resource and the delay can be decreased effectively. The mobile users can be synchronized in time domain and frequency domain. In this way, the uplink are orthogonal and in synch (Ikuno et al., 2010). In the frequency domain, each subframe utilizes scalable bandwidth up to 20 MHz (and up to 100 MHz through the carrier aggregation mechanism) divided into subcarriers of 15 KHz spacing. The subcarriers are organized into resource blocks (RBs) of 180 KHz each, i.e., 12 subcarriers define one RB, shown in Figure 2.6, the minimum allocation unit in the network.

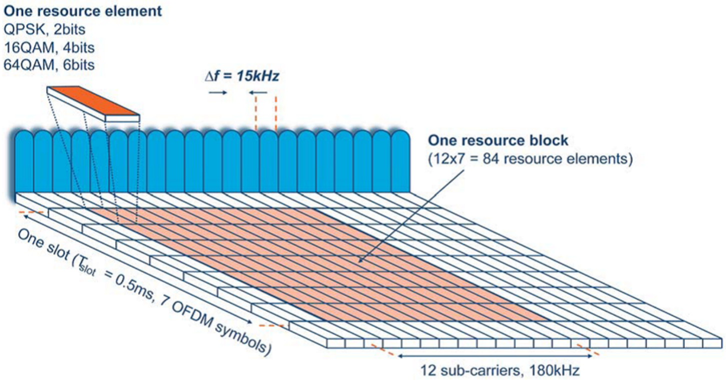

Figure 2.6. The overall sub-frame structure from LTE Resource.
(Source: 3GPP, 2007)

2.2.5. Frame Structure

The LTE frame structure is based on FDD and TDD topology. Total Frame duration is about 10ms. There are a total of 10 subframes in a frame. Each subframe consist of 2 time slots. These subframes compose of 14 OFDM symbols. Each Sub Frame is sub divided into two time slots containing 6-7 OFDM symbols, depending up to the length of the cyclic prefix. The time slot duration is 0.5ms. The frame structure is shown in Figure 2.7 (3GPP, 2007).

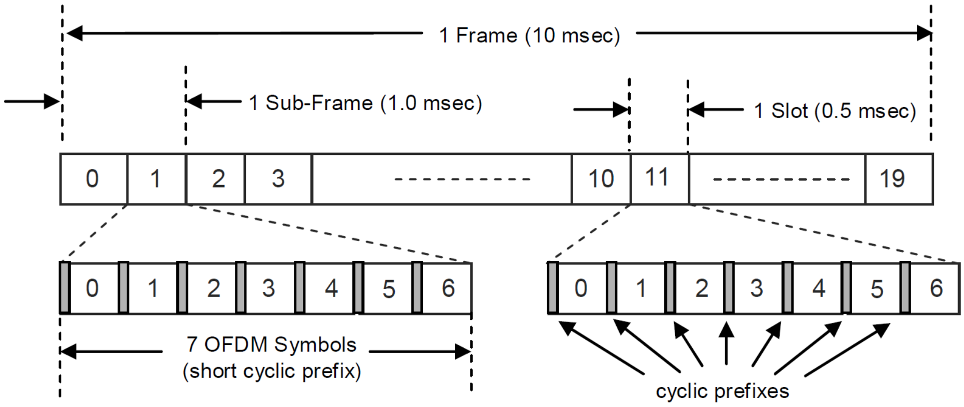

Figure 2.7. LTE Generic Frame Structure.
(Source: 3GPP, 2007)

2.2.6. Channel Quality Indicator

The Channel Quality Indicator (CQI) contains information which is conveyed from a UE to the BS in order to indicate an appropriate downlink transmission data rate. CQI is a 4-bit integer and it is predicated on the detected SINR at the UE, as is shown in Table 2.4. The number of antennas and the type of receiver is used for the CQI estimation process. When the same SINR value is obtained, the modulation scheme coding (MCS) level that can be supported by a UE. It requires to be considered to select an optimum MCS level for the transmission. The CQI reported values are used by the BS for downlink scheduling and link adaptation, which are important features of LTE (Kawser and Hamid, 2012).

Table 2.4. 4-bit CQI table

CQI Index	Modulation Order	Code Rate x 1024	Efficiency
0	-	-	-
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

2.3. D2D Overview

Device-to-Device(D2D) communication indicates to a wireless communication technology that makes possible devices to communicate directly with each other. By this definition, any kind of direct communication links can be called D2D communication. This thesis focuses on D2D links created on licensed cellular bands and which are integrated with cellular networks.

Typically, existing cellular systems are designed as a network-centric perspective. However, 5G networks do not need to be network-centric and move towards device-centric systems (Kawser and Hamid, 2012). The intelligence of the UEs has a great importance for 5G networks to support D2D connectivity and is a strong motivation for operators to offload traffic from the core network and move to device-centric systems. Device manufacturers and network operators undertake that D2D communications will be a main part of future 5G networks.

The D2D communications concept is considered by the third generation partnership project (3GPP) in LTE-A cellular systems standards. During the 3GPP meeting held in June 2011, Qualcomm submitted the concept of D2D discovery and communication. In the 3GPP meeting which is held in August 2011, LTE Direct (LTE-D) description and the service requirement were submitted for direct over-the-air LTE D2D discovery and communications. After the LTE Release-11, 3GPP introduced the schedule for Release-12, which was introduced at a workshop in June 2012. At that workshop, machine type and short-range communication scenarios were agreed for new traffic types. Afterwards, RAN 58th plenary meeting which is held in December 2012 agreed to start the study of LTE D2D proximity service (ProSe) that consists of D2D discovery and D2D communication (Kawser and Hamid, 2012).

The main purpose of the D2D communication is that when two UEs want to communicate with each other, they are able to connect through a direct link. Normally, cellular links exist between UEs and BS but now BS can be excluded from the information exchange. In this structure, when UEs are communicating to each other through direct link in D2D mode, also other UEs can communicate via BS in cellular mode which are illustrated in Figure 2.8. As well, D2D will be the main communication protocol for national security and public safety in case BS fails to work.

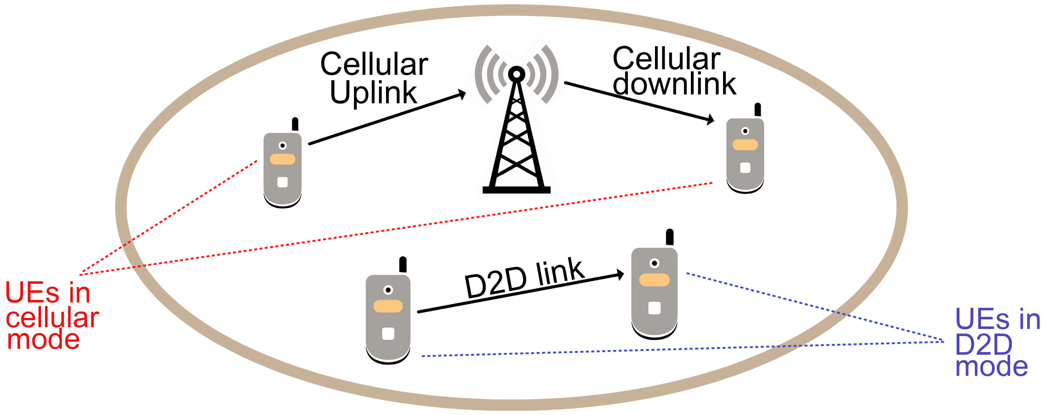

Figure 2.8. D2D communication in a cellular system.

Generally, communicating D2D devices are placed closely to each other. Therefore, D2D communication can provide low-power and energy-efficient transmission because of their physical proximity. In this way, higher bit rates, lower delays, consuming less energy can be supported. Additionally, spectrum efficiency can be increased by using D2D communication since only one communication link is occupied. Moreover, the same radio resources can be used with cellular and D2D links in a cell and this concept is called resource reuse and it provides an efficient radio resource utilization. In Figure 2.9, the potential benefits of D2D communications are represented.

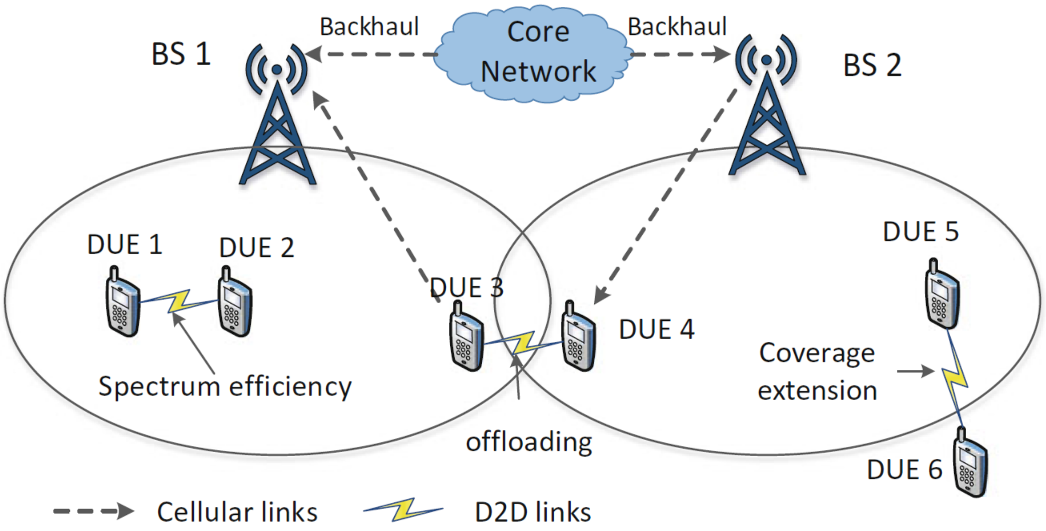

Figure 2.9. Potential benefits of D2D communications.
(Source: Wang and Tang, 2016)

In cellular systems, interference is one of the main problems when D2D links share same radio resources with the cellular links or neighboring D2D peers. In LTE systems, users are allocated orthogonal spectrum which makes interference negligible. However, when D2D users share their resources with other D2D or cellular links, orthogonality is lost and interference should be taken into consideration. For interference situations, power control and zero-forcing techniques will become very important techniques to provide reliable communication. Therefore, how power control should be done and how zero-forcing technique should be implemented when the same resources are used by D2D pairs have great importance.

Proximity Services (ProSe)

In D2D communication, in order to commence communication, UEs have to find potential devices in proximity and verify the identification of the discovered peers. Thus, the capability of discovering nearby UEs is needed for both commercial scenarios e.g. social networks, advertising, etc., and public safety deployments e.g. police, ambulance, etc. The potential usage of UEs proximity might be classified as commercial/social usage and enhanced networking.

In commercial/social usage, proximity base services can include mobile and fixed devices such as smart devices, sensors or advertising gadgets owned by private users, public sectors, etc. One usage example is social discovery. In this setting, UEs can discover and link nearby people by social network, with mutual interests or attending the same event. Additionally, interactive local guidance can provide benefits to customers, tourists, commuters and users of commercial and public services by using smart beacons and sensors. For instance, people can get advertisements from nearby restaurants/stores, transportation information, exhibitions in museums etc. Moreover, D2D-enabled devices can carry out as a controller of Machine-to-Machine (M2M) and Vehicle-to-Vehicle (V2V) networks. They can behave as gateways between M2M/V2V and cellular networks (Kuruvatti et al., 2015).

In enhanced networking, the D2D ProSe mechanism increases the connectivity of devices and provides access to the internet or operator services. For this system, traffic offload is one of the main advantages. The D2D communication can occur with operator's licensed band or in unlicensed band (Wi-Fi) if both devices are equipped with WLAN antenna. In this way, D2D offloading may improve the link quality and decrease the power usage between two proximate devices. Furthermore, one or more devices can act as relays or access gateways. In this way, a device achieves a connection to the internet or cellular network through the assistance of these relays. Hence, coverage and network connectivity are provided in indoor areas, at the edge of cell or in case of failure of local base stations.

Also, three principle functionalities appear in LTE D2D system to realize the above mentioned potential services.

- D2D discovery: This mechanism provides that devices can discover each other by using LTE technology in physical proximity. Typically, the discovery mechanism occurs under the control of the operator within cellular coverage. However, this mechanism can be performed with partial or no network coverage. The use of licensed spectrum can provide reliable and larger discovery range comparing to other D2D technologies.

- D2D data communication: This mechanism allows direct information exchange between D2D UEs instead of using BS. In this way, the operators can offload their traffic charge by switching data traffic from cellular link to a direct D2D link.

- D2D relay: D2D relays create multi-hop links to convey information between cellular network and an endpoint UE. This mechanism is used to improve data throughput of cell-edge users and extend network coverage for indoor and outdoor UEs.

In order to carry out the requirements of D2D discovery, the procedure begins with proximity detection and is followed by identity detection (Kuruvatti et al., 2015). Firstly, for proximity detection, UEs should be aware of the existence of other ProSe-enabled UEs. A scan/search method by using beacon sequences is an essential way to perform this detection. When a UE wants to be detected by nearby UEs, it could broadcast beacon sequences. The first contact of two device-to-device user equipments happens with detection of these beacon sequences. D2D pairs may be unsynchronized and they should decode asynchronous beacon sequences, thus it is preferred that synchronization might be obtained by way of beacon sequence at the initial stage of D2D discovery. After the sending of a beacon sequence for proximity detection, the UE can detect the identification of nearby ProSe-enabled UEs.

2.3.1. Classification of D2D Communication

In cellular networks, D2D communication can be categorized into both Inband D2D and Outband D2D based on the spectrum in which D2D communications occurs, as shown in Figure 2.10 (Lin et al., 2015).

Figure 2.10. Device-to-Device communication classification.

Furthermore, both unlicensed and licensed spectrum resources can be occupied by D2D users for communication.

2.3.1.1. Inband Communication

The advantage of selecting Inband communication is the high control over cellular spectrum since it has been indicated that interference in the unlicensed spectrum is uncontrollable. There are two main categories for Inband communication which are underlay

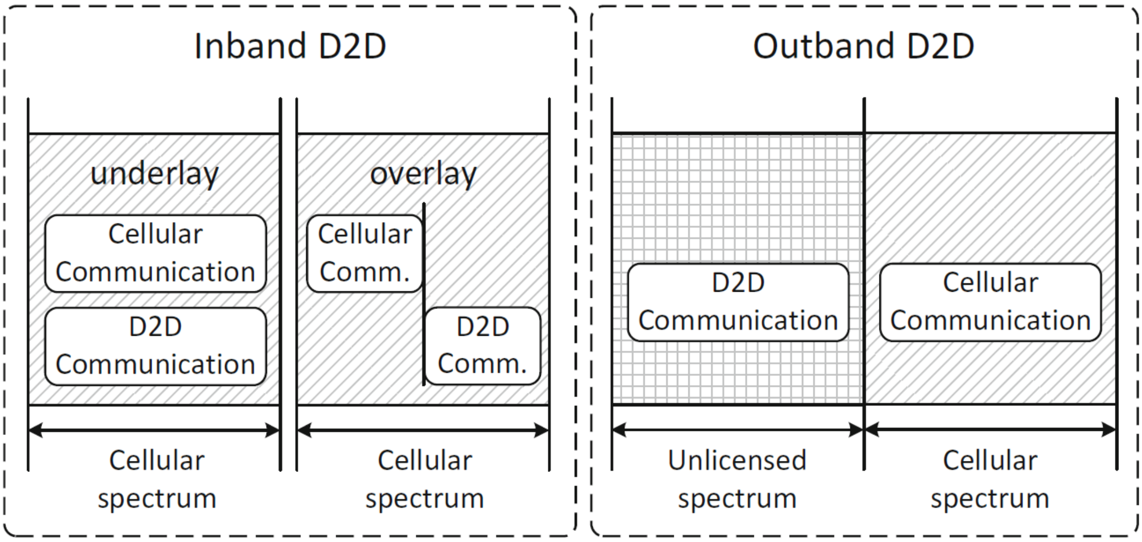

Figure 2.11. Inband versus outband D2D communications.
(Source: Wang and Tang, 2016)

and overlay, as shown in Figure 2.11. In underlay D2D communication, cellular and D2D communication share the same radio resources. In contrast, in overlay communication, D2D links use dedicated cellular resources. Underlay D2D communication can improve the spectrum efficiency of cellular networks by reusing spectrum resources. On the other hand, in overlay D2D communication, dedicated cellular resources are used for direct connection between the transmitter and the receiver. However, the biggest disadvantage of inband D2D is the interference caused by D2D users to cellular communications (Hicham et al., 2016). Moreover, D2D communication can use downlink and uplink resources (see Figure 2.8 for illustration).

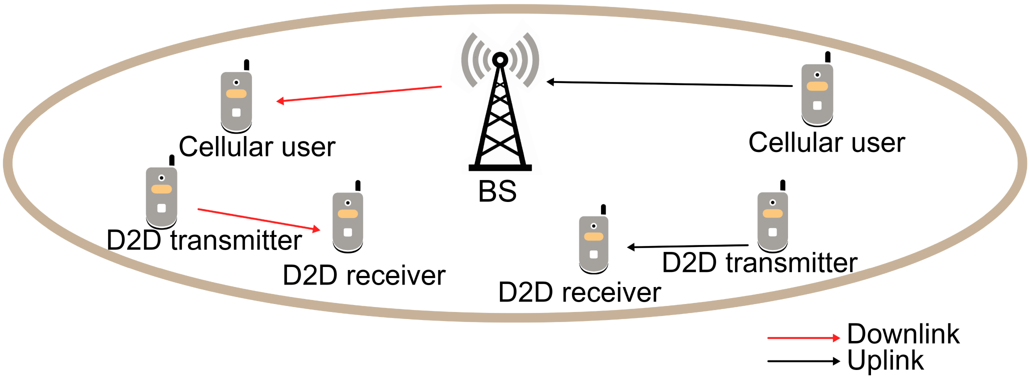

Figure 2.12. Device-to-Device communication links.

Underlay Inband D2D Communication

In underlay D2D communication, D2D pairs can share the same spectrum resources with other D2D pairs and/or cellular users. Thus, spectrum efficiency and network throughput can be improved with spectrum sharing. D2D pairs can reuse downlink or uplink resources or both in cellular networks. For this reason, the interference between D2D pairs and cellular users may cause losses on the system performance. Therefore, interference between cellular and D2D communication is the most important issue in underlaying D2D communications. For that matter, interference mitigation techniques are applied to increase the overall system capacity.

Overlay Inband D2D Communication

D2D links working in overlay communication mode are allocated dedicated cellular resources and those cellular resources cannot be used from cellular users to eliminate interference for the D2D communication on cellular transmissions (Asadi et al., 2014). Additionally, the overlay D2D communication mode could give better system performance without co-channel interference under dedicated resources but it is not an optimal way in terms of spectrum efficiency.

2.3.1.2. Outband Communication

In outband communication, the main aim of outband D2D communications is to eliminate the interference between D2D and cellular links. Therefore, D2D communication uses unlicensed spectrum such as ISM 2.4G. Using unlicensed spectrum needs an extra interface and generally adopts other wireless technologies such as Wi-Fi, ZigBee, or Bluetooth. Also, only cellular devices with two wireless interfaces (e.g., LTE and Wi-Fi) can use outband D2D, therefore, users can have simultaneous D2D and cellular communications (Hicham et al., 2016). Outband D2D communication can be divided into two types namely controlled and autonomous communications, as shown in Figure 2.11.

Controlled Outband D2D Communication

In controlled mode, D2D communication can be managed by the cellular network. In other words, coordination between radio interfaces is done by cellular networks. The D2D communication can be performed on LTE infrastructure by using the Wi-Fi technology and without making a major change in LTE protocols.

Autonomous Outband D2D Communication

Currently, there are very few works on this category. In this mode, the cellular network controls all communications but it leaves D2D communication to the D2D pairs. Therefore, the second (extra) interface/technology is independent of cellular networks, similar to the current Wi-Fi links (Hicham et al., 2016).

Advantages and Disadvantages of Inband and Outband

Table 2.5. Advantages and Disadvantages of Inband Communication

Advantages of Inband D2D	Disadvantages of Inband D2D
Underlay D2D increases the spectral efficiency of cellular spectrum.	Challenging interference management techniques.
Any mobile equipement can use Inband D2D communication.	Complex resource allocation and power control procedure.

Table 2.6. Advantages and Disadvantages of Outband Communication

Advantages of Outband D2D	Disadvantages of Outband D2D
No interference between D2D and cellular users.	Necessity to decode and to encode packets.
Possibility of simultaneous transmission for D2D and cellular users.	Necessity of efficient power management.

2.3.2. Type of D2D Communication

In D2D communication system, the BS will maintain the service to devices as usual. However, at cell edges or densely deployed areas, devices will be allowed to communicate with each other creating an ad-hoc mesh network. In fact, in D2D communication, the operator can have different kind of control levels. Therefore, four main types of device-tier communication can be defined (Tehrani et al., 2014).

Device relaying with operator controlled link establishment (DR-OC)

A device at the edge of a cell or in a poor coverage area can communicate with the BS by relaying its information via other devices, shown in the left side of Figure 2.13. In this way, the device can obtain a higher QoS and save its battery life. The operator establishes the partial or full control link with the relaying devices and the cellular network.

Direct D2D communication with operator controlled link establishment (DC-OC)

The transmitting and receiving D2D peers exchange information with each other without BS. However, they are assisted by an operator for the link establishment, shown in the right side of Figure 2.13.

Device relaying with device controlled link establishment (DR-DC)

Instead of the operator, the transmitting and receiving D2D pairs are responsible for coordinating the communication using relays between each other and for the process of link establishment, shown in the left side of Figure 2.14.

Direct D2D communication with device controlled link establishment (DC-DC)

The source and destination devices have direct communication with each other without any operator control, shown in the right side of Figure 2.14.

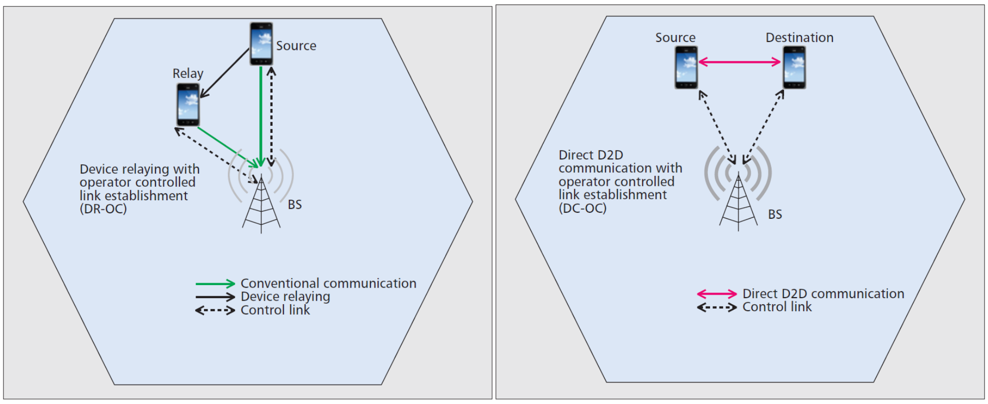

Figure 2.13. DR-OC and DC-OC.
(Source: Tehrani et al., 2014)

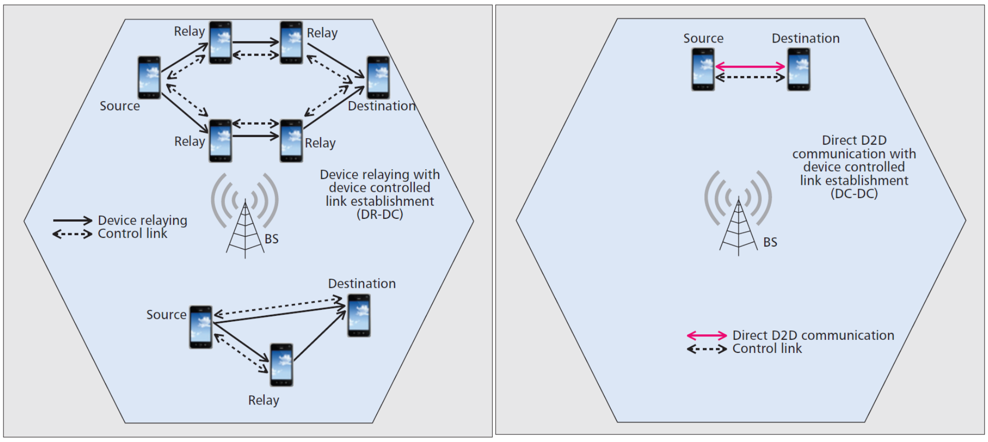

Figure 2.14. DR-DC and DC-DC.
(Source: Tehrani et al., 2014)

2.3.3. Technological aspects of D2D Communication

In 3GPP Release 12, it is obvious that D2D technology is the major part of the future development investigation. Mobile network operators can achieve significant improvement with coordinated and network-assisted D2D technologies. However, introducing D2D technology into today's network infrastructure brings about some challenges, therefore, D2D technology cannot be integrated into the current communication infrastructure until the implementation challenges are resolved. In following, some research challenges for the integration of D2D communication are discussed.

Synchronization

In LTE infrastructure and network-assisted D2D scenarios, D2D peers are synchronized with the BS and synchronized D2D transmissions can be managed with synchronization beacon signals. In addition, the BS implies slot and frame timing, and thus frequency synchronization is achieved. However, UEs could be ready only during predetermined time slots in order to receive discovery signals for time synchronized device discovery, which consumes significantly less energy. There are two main reasons about synchronization challenges. Firstly, two UEs, which are candidates for D2D pair, can be associated with different BSs that are not synchronized. Secondly, in the same cell, the UE's distance to the BS can be different, thus another timing advance adjustment can be required (Wang and Tang, 2016).

Device Discovery

In a D2D-based network, UEs should search and find suitable devices to create a communication link in proximity area and because of that the device discovery mechanism has a great importance. For proximity device discovery, a UE searches continuously available peers within its physical proximity. In order to perform proximity discovery procedure, only valid D2D links are taken into consideration for successive D2D procedure. Therefore, the main challenge of device discovery is to find potential pairs to establish D2D links.

In the process of device discovery, the first approach is discovery signal design. A UE transmits discovery signals so that other UEs can detect this signal. Obviously, the discovery signal has information about the discovery procedure and this signal should be scheduled carefully. During the discovery process, the amount of information of the sending signal can affect many design factors. These are the required amount of radio resources and the design of discovery signal or channel structure (Lin et al. 2014). The second approach are the synchronous and asynchronous discovery signals. When compared to asynchronous signaling method, synchronous discovery signaling is a more efficient way to provide higher spectrum efficiency and lower energy consumption. Furthermore, synchronous discovery schemes might give more reliable and faster discovery solutions. However, in the out of coverage scenario, synchronization can be questionable because for public safety, asynchronous discovery capabilities should be considered.

Channel Measurements

To perform efficient interference management, power control, resource allocation and channel measurement is essential to inform networks channel conditions of UEs. In order to achieve initial channel measurement, discovery signals may be used during the process of device discovery. In conventional cellular systems, the downlink channel information can be obtained from UEs and the uplink channel information is readily computed at the base station. However, D2D communication requires extra information on the channel gain. These are channel gain between D2D pairs, channel gain between D2D transmitters and cellular UEs, and the channel gain between BS or cellular user and D2D receivers.

Mode Selection

In traditional cellular networks, UEs communicate with each other through the BS. When D2D technology is realized, UEs can select among multiple mode choices for communication and this is called mode selection. In mode selection, the system performance, network load, channel condition and interference situation must be considered for an optimal outcome. Due to the stochastic nature of radio conditions within the cell and the D2D pairs, timescale for mode selection should be designed carefully. Moreover, how often mode selection and associated channel quality estimations should be implemented and what measurements, reporting mechanisms and algorithms should be used to select different communication modes are other important challenges (Fodor et al., 2012).

Interference Management

Under inband D2D communication, to improve spectrum efficiency, D2D links can reuse the same spectral resources, known as RB, in the same cell. Therefore, the coordinating spectrum sharing mechanism is very significant to guarantee the required QoS for those UEs. The usage of co-channel by UEs can cause different interference scenarios.

When D2D links reuse the downlink resources, D2D receivers and cellular users which use the same spectrum resources, can be affected from interference. For D2D pairs, interference can come from other co-channel D2D pairs and the BS. Usually, D2D links are established between UEs in proximity and the power requirement for D2D communication is much lower than traditional cellular communication. Thus, D2D pairs have to stay far away from high-power BS to prevent themselves from getting overwhelming interference power. For cellular users, the interference can come from all other co-channel. Therefore, D2D pairs should stay away from the cellular users to not cause interference.

On the other hand, in some cases, keeping away the UEs from other UEs or BSs might be impossible and they may need to be located very close in same proximity area or cell. In this situation, power control, resource allocation and zero-forcing schemes are addressed for interference management techniques.

Power Control

In inband D2D networks, power control is a convenient way for interference mitigation, energy conservation and throughput maximization. For that reason, the transmission power should be controlled so that the transmitters cannot cause interference while maintaining minimum SINR requirement of the receivers.

In network-assisted D2D communications, one of the power control design problems are coordination of involved BSs and devices according to timescale of interaction between the network and D2D pairs. To overcome this problem, the BS can be scheduled dynamically on very small timescale. On the other hand, as an alternative way, the BS takes responsibility for long-term power control and it allows D2D peers to schedule their transmit power values autonomously. In this way, control signaling overhead and delay might be reduced.

Resource Allocation

Another important challenge of D2D communication is resource allocation because if Resource Blocks(RBs) are allocated properly during mode selection and D2D communication, interference can be efficiently managed. To guarantee QoS requirements, the interference of cellular users and D2D pairs should be under a certain level, therefore, the allocation of cellular resources become very important situation for reliable communication. Generally, the resource allocation process is considered with mode selection in order to determine which RBs will be allocated to dedicated RBs or shared RBs. In underlay mode, which RBs will be shared and in overlay mode, how many RBs will be dedicated for D2D communications has to be decided.

CHAPTER 3

RESOURCE ALLOCATION FOR D2D BASED CELLULAR COMMUNICATION

In this chapter, we propose a resource allocation algorithm to mitigate the interference for a D2D communication system underlaying a cellular network with a single antenna base station and single antenna UEs. We consider D2D users co-existing with a cellular system where the D2D communication links are sharing the same radio spectrum resources with cellular users in the downlink or uplink. Although there are a lot of advantages associated with sharing the same resources in D2D communications, one major concern is the caused interference. Therefore, we propose interference mitigation mechanisms for D2D communication in cellular networks. In Section 3.1 and 3.2, the downlink and uplink system models are presented. In Section 3.3, power control optimization problem is explained for both downlink and uplink transmission. Section 3.4 describes Graph-coloring resOurce ALlocation (GOAL) and the proposed resource allocation algorithm. The last section presents performance evaluation of resource allocation algorithms.

3.1. System Model for Downlink Communication

We consider a downlink scenario in a single cell system including one BS with single antenna located in the cell center with a circular coverage area of radius *R* as shown in Figure 3.1. Also, there are M cellular users and N D2D pairs $(M \leq N)$ randomly distributed in the cell coverage and the D2D pairs can share the same resources with the cellular users. Each D2D pair consists of one transmitter and one receiver. In the system model, the number of RBs is same with the number of cellular user and these resources are assigned equally to each cellular user. Hence, one RB can be assigned to only one cellular user. The BS coordinates the resource allocation for both the cellular users and the D2D pairs. In this system, the objective is to mitigate interference caused by the resource sharing between the cellular users and D2D pairs. When the same downlink resources are shared by cellular UEs and D2D pairs, three types of interference are occured.

- The first one is that D2D receivers can be exposed interference coming from the

BS.

- The second one is that D2D transmitters can cause an interference at the cellular user.
- The third one is that the transmitter of a D2D pair can affect the receiver of other D2D pairs.

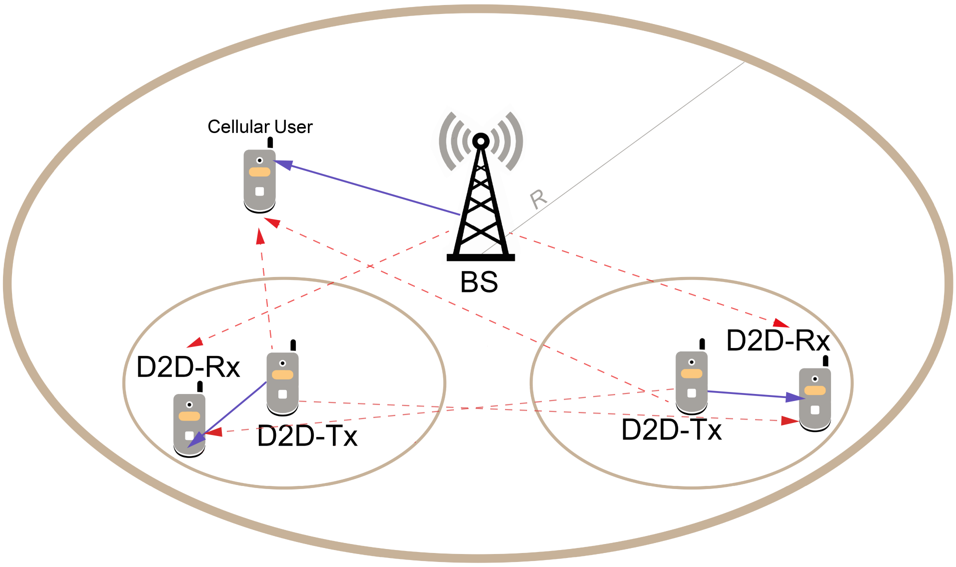

Figure 3.1. Downlink System Model.

In order to represent ith cellular user and jth D2D pair, we use $c_i; i = 1, 2...M$ and $d_j; j = 1, 2...N$, respectively. In the system, d_j^T and d_j^R are denoted for the transmitter and receiver of D2D pair d_j, respectively. The $\mathbf{C}$ and $\mathbf{D}$ represent a set of cellular users and a set of D2D pairs, respectively. P_{b_i} and P_{d_j} denote the transmit power of the BS and the D2D pairs, respectively.

Path loss and shadowing are all denoted by PL_{b,c_i}, from the BS to cellular user c_i, $PL_{d_j^T,d_j^R}$ from the D2D transmitter d_j^T to D2D receiver d_j^R, PL_{b,d_j^R} from BS to the D2D receiver d_j^R, $PL_{d_j^T,c_i}$ from the D2D transmitter d_j^T to the cellular user c_i and $PL_{d_j^T,d_{j'}^R}$ from the D2D transmitter d_j^T to the other D2D receiver $d_{j'}^R$. Additionally, h_{b,c_i} and $h_{d_j^T,d_j^R}$ denote the fading channel coefficients of communication link from the BS to cellular user c_i and from d_j^T to d_j^R, respectively. h_{b,d_j^R}, $h_{d_j^R,c_i}$ and $h_{d_j^T,d_{j'}^R}$ denote the fading channel coefficients of the interference link from the BS to d_j^R, from the d_j^T to c_i and from the d_j^T to $d_{j'}^R$ where $c_i \in \mathbf{C}$, $d_j \in \mathbf{D}$ and $j \neq j'$.

In order to allocate the resources to the D2D pairs, a resource sharing distribution matrix $\Pi = [\pi_{ij}]_{M \times N}$ is determined. When a D2D pair d_j shares the same resources with cellular user c_i, π_{ij} takes one; $\pi_{ij} = 1$. When a D2D pair d_j doesn't share same resources with cellular user c_i, π_{ij} takes zero; $\pi_{ij} = 0$.

Therefore, the instantaneous SINR at cellular user c_i can be calculated as,

$$\gamma_{c_i}^{DL} = \frac{(P_{b_i}/PL_{b,c_i}) \left| h_{b,c_i} \right|^2}{\underbrace{\sum_{d_j \in \mathbf{D}} \pi_{ij} (P_{d_j}/PL_{d_j^T,c_i}) \left| h_{d_j^T,c_i} \right|^2}_{interference\ caused\ by\ D2D\ pairs} + N_0 B} \tag{3.1}$$

and the instantaneous SINR at D2D pair d_j can be calculated as,

$$\gamma_{d_j}^{DL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R}) \left| h_{d_j^T,d_j^R} \right|^2}{\underbrace{\sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'} (P_{d_j}/PL_{d_{j'}^T,d_j^R}) \left| h_{d_{j'}^T,d_j^R} \right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{b_i}/PL_{b,d_j^R}) \left| h_{b,d_j^R} \right|^2}_{interference\ caused\ by\ BS} + N_0 B} \tag{3.2}$$

The sum system capacity is obtained by,

$$R_{sum}^{DL} = \sum_{c_i \in \mathbf{C}} \log_2(1 + \gamma_{c_i}^{DL}) + \sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}} \pi_{ij} \log_2(1 + \gamma_{d_j}^{DL}) \tag{3.3}$$

In this communication system, the purpose is to determine a resource sharing matrix Π. In this way, the sum system capacity can be maximized (Xu et al. 2017) by

$$\text{Objective:} \qquad \max_{\Pi} \quad R_{sum}^{DL} \tag{3.4}$$

subject to:

$$\sum_{d_j \in \mathbf{D}} \pi_{ij} \geq 1 \qquad \forall c_i \in \boldsymbol{C} \tag{3.5}$$

$$P_{b_i} \leq P_{b_i}^{\max} \qquad \forall c_i \in \boldsymbol{C} \tag{3.6}$$

$$P_{d_j} \leq P_{d_j}^{\max} \qquad \forall d_j \in \boldsymbol{D} \tag{3.7}$$

where several D2D pairs can share the same resources and each D2D pair can reuse the resource of more than one cellular user.

3.2. System Model for Uplink Communication

We consider an uplink scenario in a single cell system including one BS with single antenna located in the cell center with a circular coverage area of radius *R* as shown in Figure 3.2. The cellular network system can be modeled as in Section 3.1 where interference mitigation is main objective. When the same uplink resources are shared by cellular user and D2D pairs, three types of interference are occurred.

- The first one is that D2D receivers can be exposed interference coming from cellular UEs.
- The second one is that D2D transmitters can cause an interference at the BS.
- The third scenario is that D2D transmitters can affect the receiver of other D2D pairs.

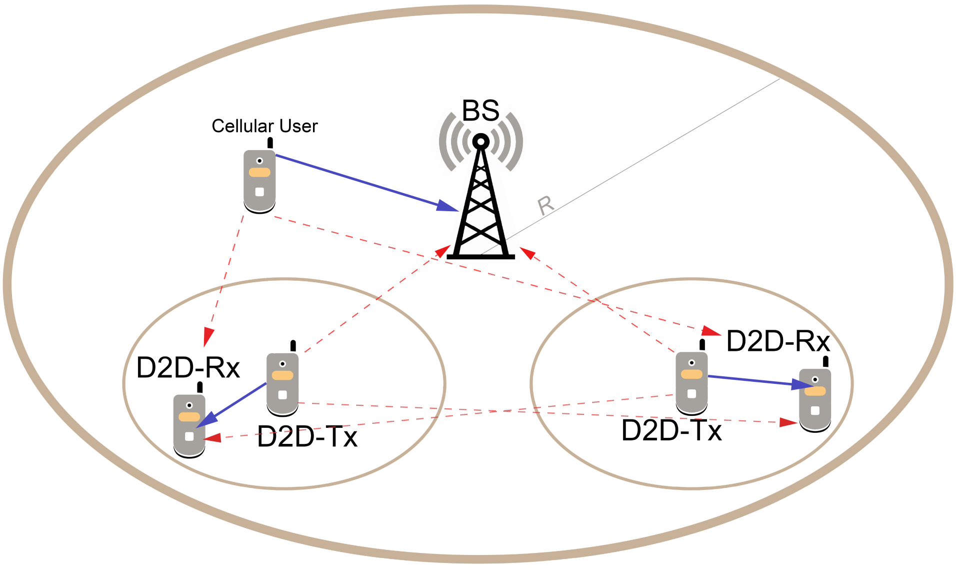

Figure 3.2. Uplink System Model.

In this system model, path loss and shadowing are all denoted by $PL_{c_i,b}$, from the cellular user c_i to the BS, $PL_{d_j^T,d_j^R}$ from the D2D transmitter d_j^T to the D2D receiver

d_j^R, PL_{c_i,d_j^R} from cellular user c_i to the d_j^R, $PL_{d_j^T,b}$ from the d_j^T to BS and $PL_{d_j^T,d_{j'}^R}$ from the D2D transmitter d_j^T to the other D2D receiver $d_{j'}^R$. P_{c_i} denote a cellular user transmit power. Additionally, $h_{c_i,b}$ and $h_{d_j^T,d_j^R}$ denote the fading channel coefficients of communication link from cellular user c_i to the BS and from d_j^T to d_j^R, respectively. h_{c_i,d_j^R}, $h_{d_j^T,b}$ and $h_{d_j^T,d_{j'}^R}$ denote the fading channel coefficients of the interference link from the c_i to d_j^R, from the d_j^T to BS and from the d_j^T to $d_{j'}^R$ where $c_i \in \mathbf{C}$, $d_j \in \mathbf{D}$ and $j \neq j'$. The resource sharing distribution matrix $\mathit{\Pi} = [\pi_{ij}]_{M\times N}$ can be calculated same as section 3.1.

Then, the instantaneous SINR at c_i can be calculated as,

$$\gamma_{c_i}^{UL} = \frac{(P_{c_i}/PL_{c_i,b})\left|h_{c_i,b}\right|^2}{\underbrace{\sum_{d_j\in\mathbf{D}} \pi_{ij}(P_{d_j}/PL_{d_j^T,b})\left|h_{d_j^T,b}\right|^2}_{interference\ caused\ by\ D2D\ pairs} + N_0B} \tag{3.8}$$

and the instantaneous SINR at d_j can be calculated as,

$$\gamma_{d_j}^{UL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R})\left|h_{d_j^T,d_j^R}\right|^2}{\underbrace{\sum_{c_i\in\mathbf{C}}\sum_{d_j\in\mathbf{D},j\neq j'} \pi_{ij}\cdot\pi_{ij'}(P_{d_j}/PL_{d_{j'}^T,d_j^R})\left|h_{d_{j'}^T,d_j^R}\right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{c_i}/PL_{c_i,d_j^R})\left|h_{c_i,d_j^R}\right|^2}_{interference\ caused\ by\ cellular\ user} + N_0B} \tag{3.9}$$

The sum system capacity is obtained by

$$R_{sum}^{UL} = \sum_{c_i\in\mathbf{C}} \log_2(1+\gamma_{c_i}^{UL}) + \sum_{c_i\in\mathbf{C}}\sum_{d_j\in\mathbf{D}} \pi_{ij}\log_2(1+\gamma_{d_j}^{UL}) \tag{3.10}$$

$$\text{Objective:} \qquad \max_{\Pi} \quad R_{sum}^{DL} \tag{3.11}$$

subject to:

$$\sum_{d_j\in\mathbf{D}} \pi_{ij} \geq 1 \qquad \forall c_i \in \boldsymbol{C} \tag{3.12}$$

$$P_{c_i} \leq P_{c_i}^{\max} \qquad \forall c_i \in \boldsymbol{C} \tag{3.13}$$

$$P_{d_j} \leq P_{d_j}^{\max} \qquad \forall d_j \in \boldsymbol{D} \tag{3.14}$$

where several D2D pairs can share the same resources and each D2D pair can reuse the resource of more than one cellular user.

3.3. Resource Allocation

In the cellular systems, UEs are scheduled in time, frequency and space to avoid the interference and there are two communication directions which are called downlink and uplink. The downlink and uplink communication is distinguished in time or frequency to prevent any interference with each other.

In this thesis, inband underlay D2D communication is taken into consideration and D2D communications can either use the downlink or uplink resources. When D2D transmission occupy orthogonal resources, they don't interfere with each other. However, this is not an efficient resource utilization method. In order to obtain higher spectral efficiency, sharing of radio resources between cellular UEs and D2D pairs is an essential method. When D2D communication reuse the downlink or uplink resources, the properties of the interference are different in each case.

Resource allocation for D2D underlay communications aims to improve the spectrum utilization of cellular network and to satisfy the data rate requirements of all D2D pairs by sharing the same resources with cellular users. Therefore, resource allocation is critical to design an efficient spectrum resource allocation algorithm for allocating the spectrum resources of cellular users to D2D pairs.

There are a lot of research into resource allocation algorithms in the literature. In (Janis, 2009), an interference-aware resource allocation algorithm has been studied to reduce interference between cellular users and D2D pairs. In (Xu et al. 2017), the joint channel allocation and power control problem has been considered in order to maximize the energy efficiency of D2D links in an underlay cellular network. In (Ferdouse et al. 2017), a throughput efficient resource allocation method has been addressed while examining sub-carrier and optimal power allocation based D2D networks. In (Lucas and Gozalvez, 2017), decreasing the complexity and signaling overhead of the allocation process has been studied by using location information of the cellular users and D2D pairs at the BS.

This section considers resource allocation algorithms for network assisted D2D communication underlaying cellular networks. In Section 3.3.1 and 3.3.2, the GOAL algorithm and the proposed resource allocation algorithm are formulated for both downlink and uplink communication, respectively.

After the resource allocation algorithm is performed, the Equal Power Allocation (EPA) scheme obtains the maximum allowable transmission power for per RB, denoted by,

$$P_{b_i}^{\max} = P_{BS}^{\max}/M \tag{3.15}$$

$$P_{d_j}^{\max} = P_{D2D}^{\max}/q_j \tag{3.16}$$

where q_j is the number of RBs scheduled to the D2D pair d_j and during the resource allocation process maximum transmit power values are used.

3.3.1. Graph-Coloring Based Resource Allocation Algorithm

In this section, in order to mitigate the interference problem, Graph Coloring Resource Allocation(GOAL) is applied to downlink and uplink communication for resource allocation between D2D pairs and cellular users. GOAL algorithm based on a graph coloring approach, the interference between a couple of D2D pairs are represented as an edge and the resources are represented as a set of colors in a graph. In order to prevent mutual interference between the two D2D pairs, they are not able to share the same spectrum resources when there is an edge between two D2D pairs. Each color corresponds to the different available spectrum resources for the D2D pairs and each one has a set of candidate colors. The cellular users have priority to access the spectrum resources over the D2D users and the cellular users are randomly assigned to the colors, initially. The candidate set of colors for each D2D pair can change with the location. In Figure 3.3, an example of D2D system with 5 D2D pairs and 3 cellular users is illustrated.

For instance, for addressing the GOAL method, a graph $\boldsymbol{G} = (\boldsymbol{D}, \boldsymbol{E}, \boldsymbol{K})$ is constructed for the single cell downlink and uplink system models shown in Figure 3.1 and Figure 3.2. In the graph, a set of D2D pairs is denoted by a $1 \times N$ matrix $\boldsymbol{D} = \left\{d_j, j = 1, 2, ..., N\right\}$, where $d_j \in \boldsymbol{D}$ represents a D2D pair. A set of edges is denoted by a $N \times N$ matrix $\boldsymbol{E} = \left\{e_{j,j'}\right\}$, where $e_{j,j'} = 1$ if $e_{j,j'} \in \boldsymbol{E}$ connects D2D pair d_j and $d_{j'}$,

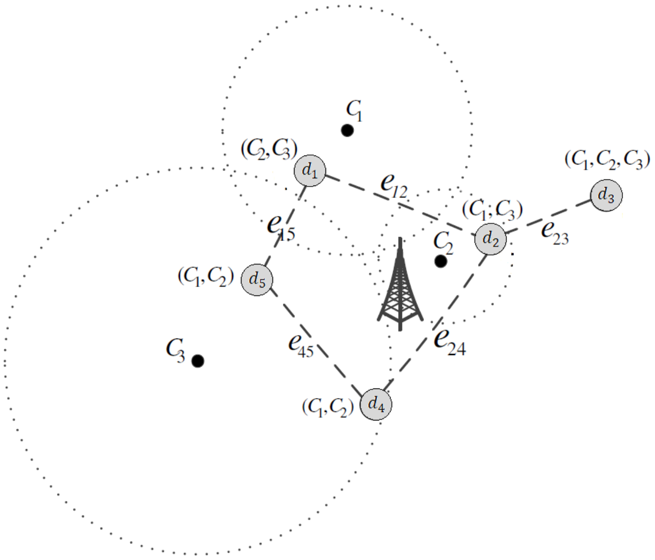

Figure 3.3. Illustration of a graph coloring algorithm.
(Cai et al., 2015)

this means that D2D pair d_j and D2D pair $d_{j'}$ cannot share the same spectrum resources simultaneously. The $M \times N$ coloring matrix is denoted by $\boldsymbol{K} = \left\{k_{i,j}\right\}$, where $k_{i,j} = 1$ indicates that color i (i.e., the resources of cellular user c_i) is available at D2D pair d_j and $k_{i,j} = 0$ otherwise (Cai et al., 2015).

In order to allocate resources properly, the pair distances (*dp*) have an important role for employing these resource allocation schemes because, the distance must be ensured when they share same resources. Therefore, GOAL presents the concept of the interference negligible distance (INS) to allocate the resources properly. Hence, the distance between the transmitter of a D2D pair and the receiver of other D2D pair is larger than a certain value, in this way the interference between the two D2D pairs can be ignored. For this reason, the two D2D pairs will not be linked by an edge in the graph, and both D2D pairs can be allocated to a color, simultaneously.

In GOAL algorithm, each D2D pair can share more than the resource one cellular user and the resource of one cellular user can be allocated by more than one D2D pairs. Additionally, the definition of the correlation degree denoted by ρ_{ij} of D2D pair d_j for color i has a great importance for the system capacity. In graph $\boldsymbol{G} = (\boldsymbol{D}, \boldsymbol{E}, \boldsymbol{K})$, the correlation degree ρ_{ij} of a D2D pair d_j for color i is calculated as the number of d_j's neighbor D2D pairs whose candidate color sets contain color i, when color i is available for a D2D pair d_j. If color i is not available for D2D pair d_j, then $\rho_{ij} = -\infty$. For instance, in Figure 3.3, D2D pair d_2 has three neighbors; d_1, d_3, d_4. However, color 1 is available for d_3, d_3 and d_4. Therefore, the correlation degree of d_2 for color 1 is $\rho_{12} = 2$.

Another important definition of GOAL algorithm is Label factor which is denoted by L_{ij}. The label of D2D pair d_j for the particular color i, if that color is available for D2D pair d_j , is defined as

$$L_{ij} = \frac{\log_2(1+\gamma_{c_i}) + \log_2(1+\gamma_{d_j})}{\rho_{ij}+1} \tag{3.17}$$

where γ_{c_i} and γ_{d_j} refer $\gamma_{c_i}^{DL}$ and $\gamma_{d_j}^{DL}$ by Eq. (3.1), Eq. (3.2) for downlink communication, $\gamma_{c_i}^{UL}$ and $\gamma_{d_j}^{UL}$ by Eq. (3.7), Eq. (3.8) for uplink communication, respectively.

According to these definitions, the value of ρ_{ij} indicates the number of neighbor D2D pairs for d_j whose candidate color sets contain color i. The label of a D2D pair is determined by the correlation degree of the D2D pair for the corresponding color and the summation of the capacity of the cellular user and the capacity of D2D pair which is shared with the resource of the cellular user. Thus, the value of correlation degree affects the system capacity directly. In order to assign the most appropriate D2D pair to a color, GOAL chooses the D2D pair with the largest label.

GOAL algorithm performs the resource allocation method one by one and the spectrum resources of each cellular user are assigned to the D2D pairs. To perform GOAL algorithm, we carry on following procedures. Initially, a subgraph $\boldsymbol{G}_i = (\boldsymbol{D}_i, \boldsymbol{E}_i, \boldsymbol{K}_i)$ of graph $\boldsymbol{G}$ is created for color i. In this subgraph, $\boldsymbol{D}_i$ represents the D2D pairs whose candidate color set of color i. The $\boldsymbol{E}_i$ represents an edge for color i. The $\boldsymbol{K}_i$ represents coloring matrix which denote the availability of assigning color i. After calculation of L_{ij}, a D2D pair with the largest label is chosen for a color and then assigned this color i to the D2D pair, $(d_j \in \boldsymbol{D}_i)$. Then, the color i is removed from the candidate color set of the picked D2D pair and all its neighbors. Finally, the subgraph is updated for color i. Until color's candidate set becomes zero, the D2D pair is chosen according to its label value. These steps are performed for other colors.

3.3.2. Proposed Resource Allocation Algorithm

In this section, in order to solve the interference problem, we propose a resource allocation algorithm so as to maximize the summation of the resource sharing distribution matrix Π. The proposed algorithm is based on Graph Coloring method and the interference between a couple of D2D pair is represented as an edge and the resources are represented as a set of colors in a graph. To mitigate mutual interference between the D2D pairs when they share same resources, they are grouped within colors where no D2D transmitter highly interferes with the other D2D receivers due to the INS concept. In the algorithm, the each color corresponds to the different spectrum resources and two D2D pairs cannot be grouped to the same color when there is an edge between them. The cellular users and D2D pairs have same priority to access the resources. Each D2D pair has a set of candidate colors and each color can include only one cellular user. In Figure 3.4, an example of D2D system with 6 D2D pairs and 2 cellular users is illustrated.

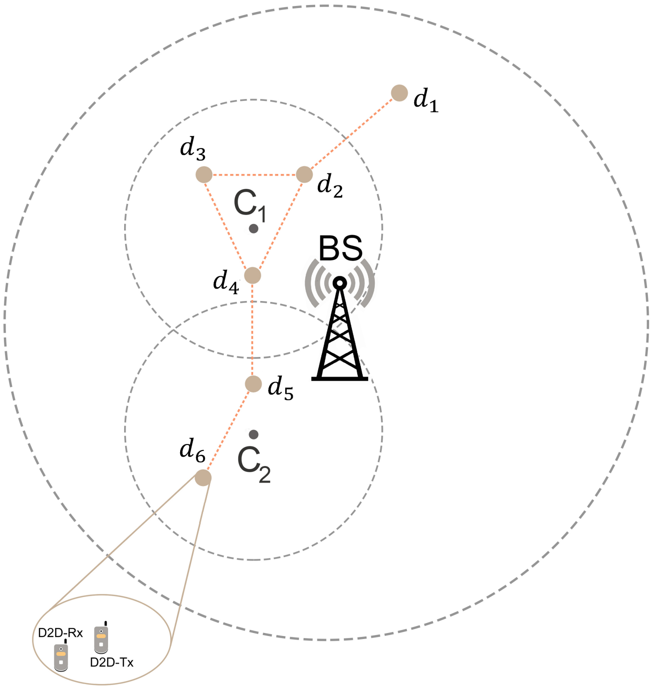

Figure 3.4. Illustration of proposed method.

For addressing the proposed algorithm, two graph $\boldsymbol{G}_i = (\boldsymbol{C}, \boldsymbol{E}_i)$ and $\boldsymbol{G}_j = (\boldsymbol{D}, \boldsymbol{E}_j, \boldsymbol{K})$ are constructed for the single cell system models shown in Figure 3.1 and 3.2. In the graph $\boldsymbol{G}_i$, a set of cellular users is denoted by a $1 \times M$ matrix $\boldsymbol{C} = \left\{c_i, i = 1, 2, ..., M\right\}$. A set of edges for cellular users is denoted by a $M \times N$ matrix $\boldsymbol{E}_i = \left\{e_{i,j}\right\}$, where $e_{i,j} = 1$ if $e_{i,j} \in \boldsymbol{E}_i$ connects c_i and d_j, this means that cellular user c_i and D2D pair d_j cannot share the same spectrum resources simultaneously. In the graph $\boldsymbol{G}_j$, a set of D2D pairs is denoted by a $1 \times N$ matrix $\boldsymbol{D} = \left\{d_j, j = 1, 2, ..., N\right\}$. A set of edges for D2D pairs is denoted by a $N \times N$ matrix $\boldsymbol{E}_j = \left\{e_{j,j'}\right\}$, where $e_{j,j'} = 1$ if $e_{j,j'} \in \boldsymbol{E}_j$ connects D2D pair d_j and $d_{j'}$, this means that D2D pair d_j and D2D pair $d_{j'}$ cannot share the same spectrum resources simultaneously. The $M \times N$ coloring matrix is denoted by $\boldsymbol{K} = \left\{k_{i,j}\right\}$, where $k_{i,j} = 1$ indicates the availability of D2D pair d_j to share the resources with cellular user c_i, and $k_{i,j} = 0$ otherwise. Moreover, the concept of the interference INS is taken into consideration for the algorithm.

In the proposed algorithm, each D2D pair can share more than one cellular user resource and the resource of one cellular user can be allocated by more than one D2D pairs. The definition of the adjacency degree of cellular users and D2D pairs is important for the system capacity denoted by α_{c_i} for c_i and α_{d_j} for d_j. In the graph $\boldsymbol{G}_i = (\boldsymbol{C}, \boldsymbol{E}_i)$, the adjacency degree α_{c_i} of c_i is calculated as the number of c_i's neighbor D2D pairs. In graph $\boldsymbol{G}_j = (\boldsymbol{D}, \boldsymbol{E}_j, \boldsymbol{K})$, the adjacency degree α_{d_j} of d_j is calculated as the number of d_j's neighbor D2D pairs which are not assigned any resources yet. If c_i or d_j are not available for resource sharing , then $\alpha_{c_i} = -\infty$ and $\alpha_{d_j} = -\infty$.

In Figure 3.4, for instance, D2D pair d_2 has four neighbors which are d_1, d_3, d_4 and c_1. Hence, α_{d_2} is 4 and α_{c_1} is 3. If c_2, d_3 and d_1 create a color group (i.e. the second spectrum resources), next time d_2 will have two neighbors. Thus, α_{d_2} will be 2.

The Weight factor W is considered as the main parameter to determine resource-sharing matrix. The Weight W_{c_i} of a cellular user c_i is defined as,

$$\mathrm{W}_{c_i} = \frac{\log_2(1 + \gamma_{c_i})}{\alpha_{c_i} + 1} \tag{3.18}$$

The Weight W_j of a D2D pair d_j is defined as,

$$\mathrm{W}_{d_j} = \frac{\log_2(1 + \gamma_{d_j})}{\alpha_{d_j} + 1} \tag{3.19}$$

In order to perform the most efficient resource allocation scheme, the proposed algorithm chooses the largest weight value from weight cluster, W= (W_{c_i},W_{d_j}).

Algorithm 1 Proposed Graph Coloring Algorithm

```
Initialization
    * Generate $M$ cellular users and $N$ D2D pairs uniformly.
    * Initialize the $\boldsymbol{E}_i$ and $\boldsymbol{E}_j$ as a $M \times N$ and $N \times N$ matrix.
    * Initialize the $\boldsymbol{K}$ as a $1 \times N$ matrix that represents the availability of the D2D pairs for assigning.
Repeat
    * Calculate $\gamma_i$ of cellular user $c_i$ and $\gamma_j$ of D2D pair $d_j$.
    * Determine adjacency degrees $\alpha_i$ and $\alpha_j$ for $c_i$ and $d_j$, respectively.
    * Calculate Weight factor W for $c_i$ and $d_j$, create Weight cluster W= (W$_i$,W$_j$).
        • repeat
        - Pick the largest Weight factor from W, according to $\boldsymbol{E}_i$, $\boldsymbol{E}_j$ and $\boldsymbol{K}$ matrices.
        • until there is no possibility to pick any UE from graphs.
    * Remove the selected D2D pair or cellular user from graphs and assign the next available color.
Until all D2D pairs and cellular users are assigned any color.
    * Find the created sets which only consist of a cellular user and share its resource with a set which has the largest number of D2D pairs.
```

3.4. Power Control for D2D Communication

Power control is a process of setting transmit power levels of base stations or user equipments. In conventional communication systems, maximum transmit power is desirable because it provides higher received power and higher link capacity. However, when maximum transmit power is used by the transmitter, other communication links which share the same resource will be affected by high interference. Therefore, power control is a convenient technique for interference mitigation (Tejaswi and Suresh, 2013).

Power control techniques adjust the transmission power on the different frequency resources to increase system performance (3GPP, 2006). When dense frequency reuse schemes are considered, the transmission power values are significant issues for both D2D pairs and BS. Power control mechanisms improve data throughput and also it can be device specific. However, the excessive use of transmission power generates interference problems and it decreases system performance and spectrum efficiency (Yassin and

Lahoud, 2014).

Power control techniques are an attractive way to manage interference in wireless networks and it is also widely used in current wireless systems. There are a lot of research into power control techniques for D2D underlay communication. In (Yu et al., 2009), the system represents a simple power control technique for a single-cell scenario and a deterministic network model. In order to prevent the cellular links from interference, D2D transmit power is controlled. In (Gu et al., 2011), for a single D2D link communication, a dynamic power control technique has been given. The main idea of this power control technique is to improve the cellular system performance by managing the interference originated from D2D communication by adjusting D2D transmit power via BS. In (Xiao et al., 2011), a power minimization solution has been examined with joint subcarrier allocation, adaptive modulation, and mode selection schemes to provide necessary quality-of-service of D2D and cellular users. Additionally, there is another power control technique which has been carried out by using game theory that is based on Stackelberg game. This technique has been presented in (Park et al., 2015). In (Li et al., 2016), the leader adjusts its power and imposes interference price on followers to maintain its own user's minimum data rate requirements. Subsequently, the followers optimize their power based on the imposed price.

Power control is a key technique for interference avoidance, especially in densely deployed D2D pairs and cellular UEs environments. When D2D transmit power is controlled and optimized by the BS, other D2D receivers and the cellular UEs nearby the D2D transmitter can be protected from interference. Transmit power optimization is done for D2D pairs and cellular systems to guarantee their SINR requirements and to not experience signal degradation. In this way, the D2D and the cellular transmissions can use entire the spectrum and this also protects waste of transmission energy.

This section considers power control methods for network assisted D2D communication underlaying cellular networks. In Section 3.5, the power control optimization problem is formulated for downlink resources and in Section 3.6, the power control optimization problem is formulated for uplink resources. The problem of interference in downlink and uplink communication is performed by considering QoS of the d_j^R and c_i as a function of the received SINR depending on distances.

3.4.1. Power Control for Downlink Communication

In this section, the feasibility of power control during downlink transmission is investigated. Given that in single cell scenario, the SINR of D2D receiver is $\gamma_{d_j}^{DL}$ and the SINR of cellular user is $\gamma_{c_i}^{DL}$, downlink power control problem is formulated by,

Objective:

$$\min \left(\sum_{i=1}^{M} P_{b_i} + \sum_{j=1}^{N} P_{d_j} \right) \tag{3.20}$$

subject to:

$$\gamma_{c_i}^{DL} \geq \gamma_{c_i\_tar}^{DL} \qquad \forall i = 1, 2, ..., M \tag{3.21}$$

$$\gamma_{d_j}^{DL} \geq \gamma_{d_j\_tar}^{DL} \qquad \forall j = 1, 2, ..., N \tag{3.22}$$

where $\gamma_{c_i\_tar}^{DL}$ and $\gamma_{d_i\_tar}^{DL}$ are the target SINR for the c_i and d_j^R, respectively. The target SINR is a minimum required SINR value for cellular users and D2D pairs. $P_{BS}^{\max}$ and $P_{D2D}^{\max}$ are the maximum allowable transmission power of the BS and D2D transmitter.

The constraints that have been written above not only one D2D pair to be protected from downlink interference but also all D2D transmitters and BS to maximize its power efficiency. The solution of this problem provides the required data rate for all the users (Oduola et al., 2014). To check the feasibility of the downlink interference solution, we have to write down SINR equations and check the transmission power of BS and d_j^T satisfy Eq. (3.21) and Eq. (3.22), respectively.

In accordance with the mentioned assumptions, the SINR of c_i given Eq.(3.1) and the SINR of d_j^R given Eq.(3.2) (Oduola et al., 2014), when substituted into Eq.(3.21) and Eq.(3.22), give knowledge of the feasible transmission power range. In other words, in order to satisfy the constraints on the SINR values in Eq.(3.21) and (3.22), the maximum transmit power of BS and d_j^T can be found by substituting Equations (3.2) into (3.21) and (3.1) into (3.22), as follows.

$$\bar{P}_{b_i} \geq \left[\sum_{d_j \in \mathbf{D}} \pi_{ij} (P_{d_j} / PL_{d_j^T, c_i}) + N_0 B \right] \gamma_{c_i\_tar}^{DL} PL_{b, c_i} \tag{3.23}$$

and

$$\bar{P}_{d_j} \geq \left[\sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'} (P_{d_j}/PL_{d_{j'}^T, d_j^R}) + (P_{b_i}/PL_{b_i, d_j^R}) + N_0 B\right] \gamma_{d_j\_tar}^{DL} PL_{d_j^T, d_j^R} \tag{3.24}$$

Firstly, Equations (3.21), (3.23) and (3.25) are satisfied for c_i and secondly, (3.22), (3.24) and (3.26) are satisfied for d_j^R.

By using the transmission power of BS and D2D transmitter, the target SINR values of c_i and d_j^R, the feasibility condition is formulated as,

$$P_{b_i} = \min\left\{P_{b_i}^{\max}, \bar{P}_{b_i}\right\} \tag{3.25}$$

$$P_{d_j} = \min\left\{P_{d_j}^{\max}, \bar{P}_{d_j}\right\} \tag{3.26}$$

In the above case, it is designed to obtain transmission power by providing an optimum transmit power value. Considering the situation that in feasibility condition Eq.(3.25) and Eq.(3.26) the maximum allowable transmit power of $P_{b_i}^{\max}$ and $P_{d_j}^{\max}$ are greater than the transmit power $\bar{P}_{b_i}$ and $\bar{P}_{d_j}$, in that case, BS and d_j^T select lower ones $\bar{P}_{b_i}$ and $\bar{P}_{d_j}$, otherwise; it selects $P_{d_j}^{\max}$ and $P_{b_i}^{\max}$. In two cases above-mentioned, it goes to show that the feasible power condition in Eq.(3.25) and Eq.(3.26) provide BS and d_j^T with efficient power selection.

3.4.2. Power Control for Uplink Communication

In open loop power control (OLPC), the transmitting power is adjusted at the cellular users and D2D pairs using signal parameters and measures obtained from the base station. In this case, there is no feedback link at the cellular users and D2D pairs regarding the power to be used for transmission. The closed loop component is taken into account to increase the performance of power control by compensating fast variations in the channel. In closed loop power control (CLPC), the base station sends feedback to the UE, which is then made corrections to the transmission power (Tejaswi and Suresh, 2013). In this thesis, we only consider OLPC system. Uplink power control problem for interference mitigation is formulated by,

Objective:

$$\min\left(\sum_{i=1}^{M} P_{c_i} + \sum_{j=1}^{N} P_{d_j}\right) \tag{3.27}$$

subject to:

$$\gamma_{c_i}^{UL} \geq \gamma_{c_i\_tar}^{UL} \qquad \forall i = 1, 2, ..., M \tag{3.28}$$

$$\gamma_{d_j}^{UL} \geq \gamma_{d_j\_tar}^{UL} \qquad \forall j = 1, 2, ..., N \tag{3.29}$$

where $\gamma_{c_i\_tar}^{UL}$ and $\gamma_{d_i\_tar}^{UL}$ are the target SINR for the c_i and d_j^R, respectively.

The setting of the c_i and d_j^T transmits power values P_{c_i} and P_{d_j} for the uplink transmission are defined in dBm scale for the single cell scenario (Tejaswi and Suresh, 2013) and $P^{\max}$ refers both $P_{c_i}^{\max}$ and $P_{d_j}^{\max}$. P refers both P_{c_i} and P_{d_j}.

$$P = \min\left\{P^{\max}, P_0 + 10\log_{10}(q) + aPL + \delta_{msc} + \Delta\right\} \quad (dBm) \tag{3.30}$$

where:

- P_0: The power to be contained in one RB. It is cell specific parameter and measured in dBm/RB.
- a: Path loss compensation factor. It is a cell specific parameter in the range [0 1].
- δ_{msc}: Modulation and coding scheme (MCS) dependent offset.
- Δ: Closed loop correction value.

The parameter P_0 is calculated for D2D transmitter as,

$$P_0 = a(\gamma_{tar}^{UL} + P_n) + (1 - a)(P_{\max} - 10\log_{10} q) \quad (dBm) \tag{3.31}$$

P_n is calculated in dB scale as the summation of interference and thermal noise in linear domain (Fodor et al. 2014).

In this architecture, the path loss is measured at the UE side which is based on the reference symbol received power. This information is enough to let the UE initially adjust its transmission power, therefore, it is called as open loop parameters. δ_{msc} is a UE-specific parameter depending on chosen modulation and coding scheme. However, in this thesis, δ_{msc} is not included. Δ is a closed loop correction value and it is signaled by the BS to any cellular user or D2D pair after it adjusts its initial transmit power. Thus, Δ has no effect in the setting of initial transmit power of cellular users and D2D pairs (Tejaswi and Suresh, 2013).

The compensation factor a is the key value of the uplink power control mechanism and the power control scheme can be categorized based on the value of a as (Coupechoux and Kelif, 2011):

- $a = 1$: The scheme totally compensates the path-loss in order to reach the target received power P_0.
- $a = 0$: The transmission power is fixed and does not depend on the path-loss. There is no compensation and in fact no PC at all.
- $0 < a < 1$: In the case of a fractional PC, where path-loss is partially compensated by the PC scheme.

Assuming a constant level of interference and noise, a higher P_0 means an overall SINR increase. However, in a real system, an increase in P_0 will rise the power of all users and hence the level of interference. In the proposed uplink power control procedure, the P_n value is calculated for each case. Therefore, during the uplink power control mechanism, the P_0 is not constant for all users while the term $a \cdot PL$ varies for each cellular user and D2D pair according to its experienced path loss.

3.5. Performance Evaluations

In this section, we compare average data rate and average transmit power for GOAL, the proposed resource allocation algorithm and random resource allocation illustrated them under different number of D2D pairs for downlink and uplink communication, respectively. The simulation parameters are given in Table 3.1. The values of the maximum transmission power for BS and UEs are based on 3GPP LTE standards and a = 0.8

as it has been widely used for power control studies (Xing and Hakola, 2010). In this thesis, MATLAB is used for simulation environment.

Table 3.1. Simulation Parameters

Explanation	**Parameters**	**Value**
Max. transmission power of BS	$P_{BS}^{\max}$	43 dBm
Max. transmission power of BS for per RB	$P_{b_i}^{\max}$	33 dBm
Max. transmission power of UE	$P_{D2D}^{\max}$	24 dBm
Max. transmission power of UE for per RB	$P_{d_j}^{\max}$	16.4 dBm
Pathloss	PL	NLos
Shadowing	σ	4 dB
Target SINR	γ_{target}	10 dB
Number of Cellular User	M	10
Number of D2D Pair	N	20 - 50
Number of Available RB	RB	10
OLPC Compensation Factor	α	0.8
BS Coverage Radius	R	500 m
Maximum DistanceBetween D2D Tx and Rx	dt	50 m
Minimum DistanceBetween D2D Tx and Rx	dt	2 m
Noise power spectral density	N_0	-174 dBm/Hz

In order to evaluate the impact of the number of D2D pairs on the system capacity, we compare the average data rate of cellular users and D2D pairs in Figure 3.5 and Figure 3.7. It is observed that as the number of D2D pairs grows, the average data rate of D2D pairs decrease. This indicates that when the number of D2D pairs becomes high, the data rate is degraded by the system interferences. When the number of D2D pairs increases, more D2D pairs can share the same spectrum resources and it causes large cumulative interferences on the system. Moreover, if we compare the three algorithm, GOAL manages the interference fairly between adjacent links. The proposed algorithm has the highest data rate performance with low number of D2D pairs since it aims to allocate more resource to the D2D pairs by considering amount of interference. However, GOAL starts to give better performance results when high number of D2D pairs are allocated. Since more D2D pairs increases the cumulative interference, GOAL allocates less resources compare to the proposed algorithm. By this way, the performance degradation can be improved caused by the cumulative interference. The random allocation algorithm is simple and it selected colors for each D2D pairs randomly. Additionally, we can see the affect of allocating more resources to the D2D pairs at the cellular user side. Since the amount of the interference is increased, the average data rate of cellular user is decreased. The average data rate of the D2D pairs decreased approximately 35% for downlink, 55% for uplink in the proposed algorithm while the average data rate of the D2D pairs by GOAL decrease 15% for downlink, 30% for uplink depending on the number of D2D pairs. However, the achievable percentage of data rate that can reach up to 65% in the proposed algorithm compared to GOAL when 20 D2D pairs allocated.

In underlay communication, in order to reduce the interference at the receiver side, power control mechanism is also useful. Power control mitigates the critical interferences by preventing adjacent links from transmit power values. It can be seen in Figure 3.6 and Figure 3.8 that the average data rate differences between downlink and uplink is 0.86 Mbps in the proposed algorithm, 0.2 Mbps in the GOAL for 20 D2D pairs and they have approximately same average data rate for 50 D2D pairs.

The power control system provides battery saving. Especially, when we compare the Figure 3.9 and Figure 3.10, it is observed that D2D pairs consume less power in uplink system while satisfying target SINR value. The usage of downlink resources increases the amount of the interference on the D2D pairs because of the high transmit power of BS. As illustrated in Figure 3.11 the usage of uplink cellular resources has the better performance in terms of the interference, which shows that by protecting the D2D communication the overall interference accumulation.

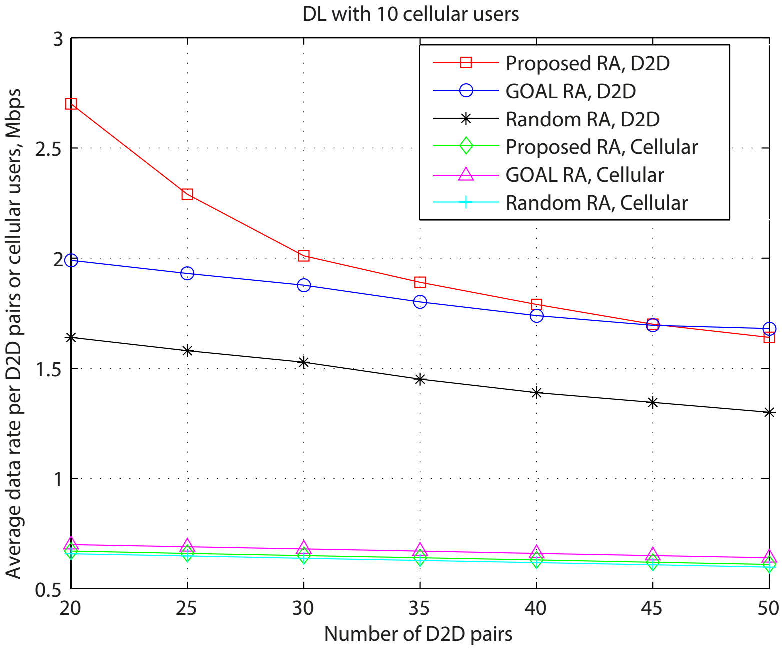

Figure 3.5. Average data rate per cellular user and D2D pair for DL communication.

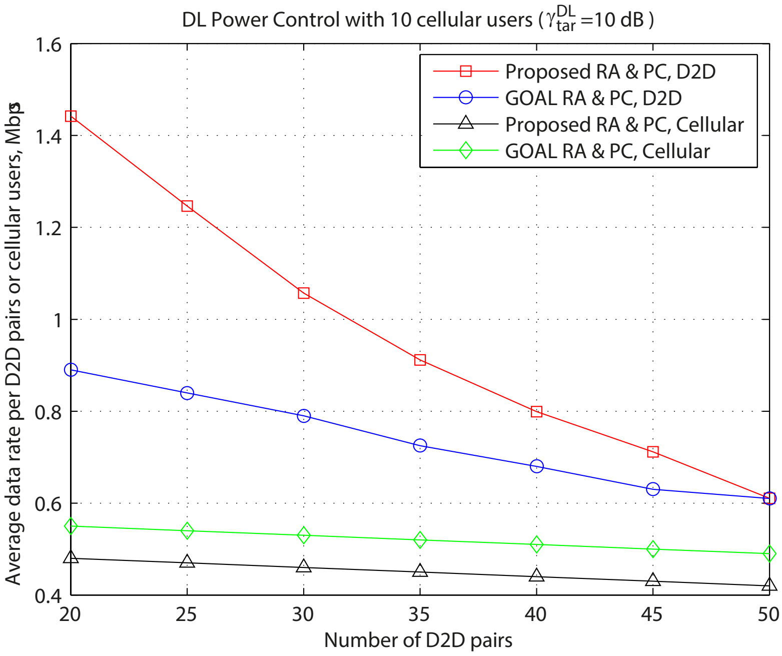

Figure 3.6. Average data rate per cellular user and D2D pair for DL communication with power control.

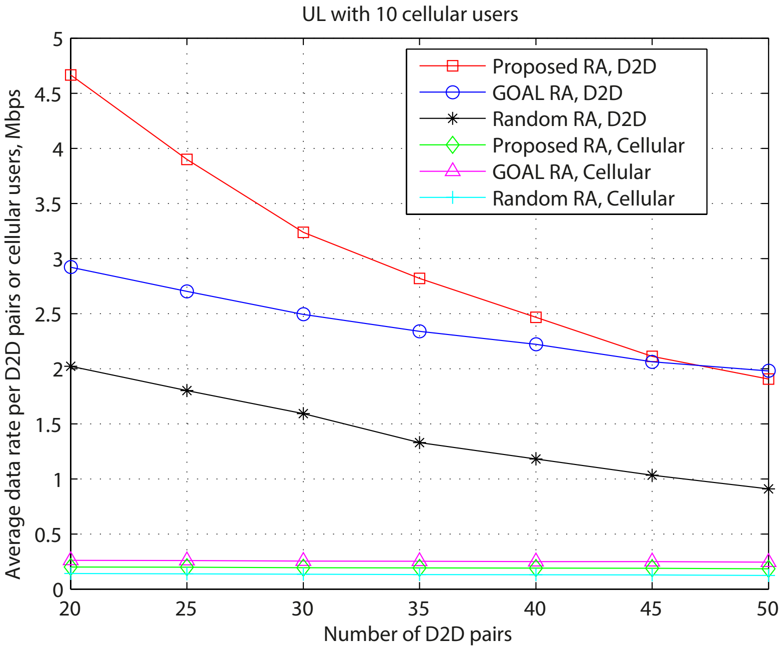

Figure 3.7. Average data rate per cellular user and D2D pair for UL communication.

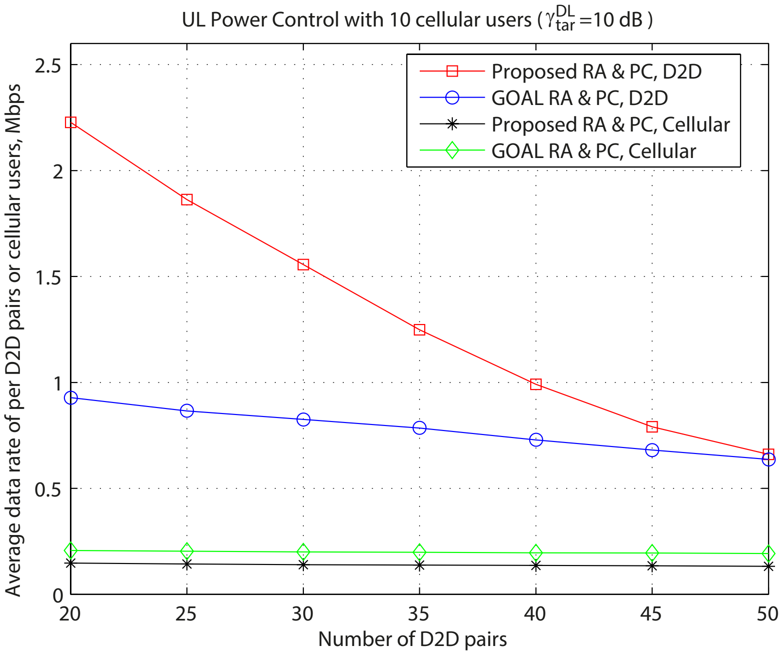

Figure 3.8. Average data rate per cellular user and D2D pair for UL communication with power control.

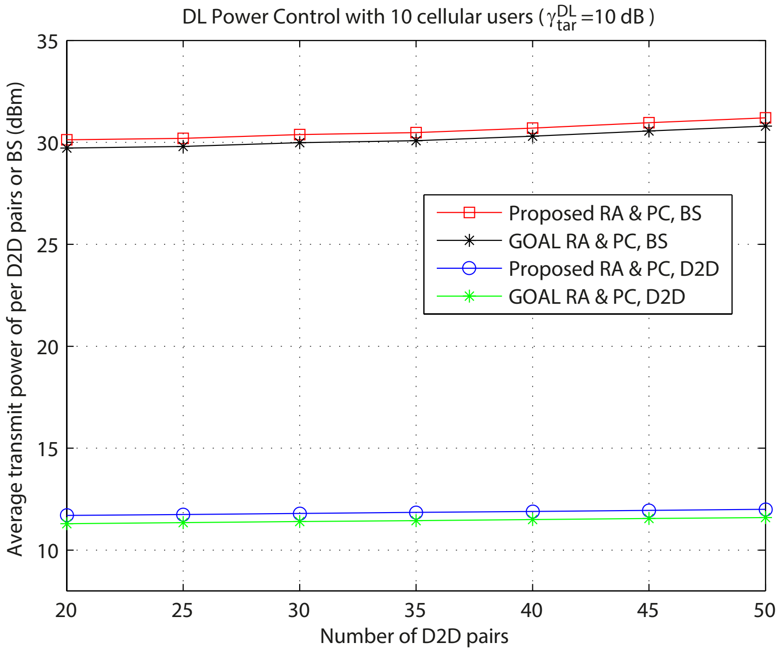

Figure 3.9. Average transmit power per cellular user and D2D pair for DL communication with power control.

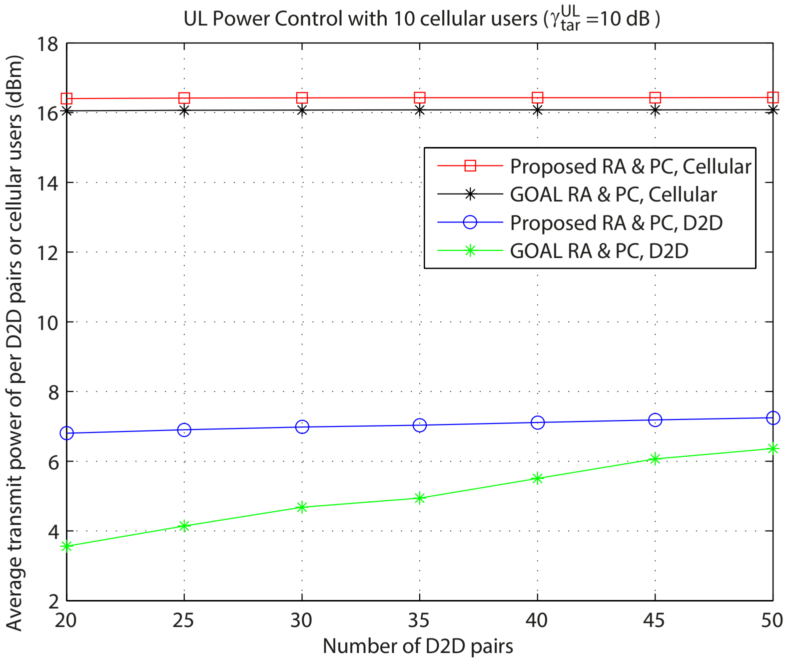

Figure 3.10. Average transmit power per cellular user and D2D pair for UL communication with power control.

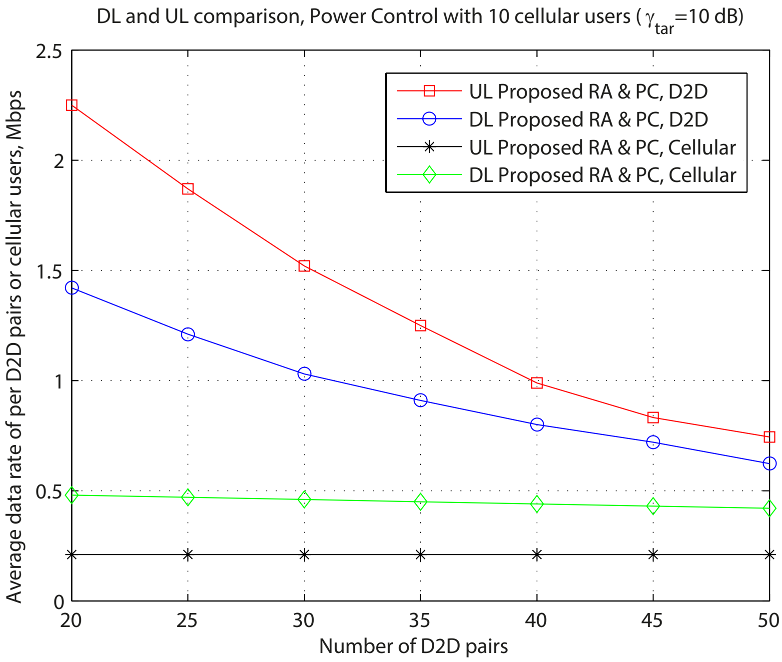

Figure 3.11. Average data rate per cellular user and D2D pair for DL and UL communication with power control.

CHAPTER 4

INTERFERENCE MITIGATION FOR D2D BASED MULTIPLE ANTENNA CELLULAR COMMUNICATION

In this chapter, we propose interference algorithms for a D2D communication system underlaying a cellular network with a multiple antenna base station and single antenna cellular users and D2D pairs. In Section 4.1, zero-forcing pre-coding method is formulated for downlink interference cancellation. In Section 4.2, zero-forcing post-coding method is formulated for uplink interference cancellation. The last section presents performance evaluations of resource allocation algorithms which are GOAL and the proposed algorithm by employing the zero-forcing method.

4.1. System Model for Downlink Pre-coding

When two distributed users contend for the same portion of the wireless spectrum, they interfere with each other. This interference limits the amount of free bandwidth for each user, which in turn limits the performance of each user in this communication system. Therefore, pre-coding technique is a key component for interference-free space and they are used for all users together so that the interference is aligned on subspace of each receiver, while the desired signal can be transmitted and high data rates and small error rates can be achieved.

Pre-coding is a signal processing technology in transmitter side and it works by setting the antenna element weights so that beam patterns can be adjusted to suppress the interference which comes from other directions. The adjustable weight vectors can be used for spatial separation to separate the signals from the interference as illustrated in Figure 4.1. Clearly, pre-coding technology is only possible when multiple antennas are used, and these can be at either transmitter or both side. Additionally, in pre-coding method, other receivers can be affected with any kind of change on the weight vectors, thus, transmitter is responsible from entire network.

There are two main pre-coding methods which are maximum ratio combining (MRC) and zero-forcing pre-coding. In MRC, the main aim is signal strength maximization for each user. On the other hand, in zero-forcing, interference suppression is taken

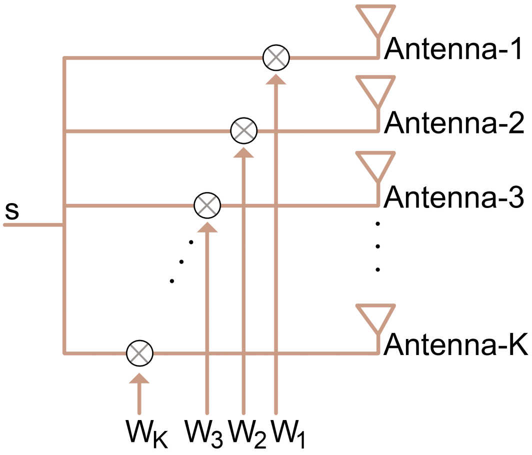

Figure 4.1. Pre-coding method.

into consideration in (Park and Heath, 2016).

D2D communication, which devices is assisted by cellular network, is an attractive approach for proximity-based services. In order to obtain high data rates, it is necessary to have access to all the spectrum for each node. As a result, mutual interference becomes a constraint. In (Lee et al., 2014), a D2D network with multiple receive antennas has been considered. When each receiver uses a beamforming technique such as MRC or zero-forcing, the relationship between the link performance and the number of receive antennas has been discussed (Akoum et al., 2012).

We consider a downlink scenario in a single cell system including one BS with multiple antenna located in the cell center. The cellular network system can be modeled again as Section 3.1 where the objective is to implement pre-coding technique by using a partial zero-forcing method to mitigate interference caused by the resource sharing between the cellular and D2D communication. In this section, for the pre-coding implementation, it is assumed that the BS has perfect CSI for both serving and interfering links.

The path loss and shadowing are all denoted in Section 3.1. Additionally, $\mathbf{h}_{b,c_i}$ denotes the $N_t \times 1$ channel vector of communication link from the BS to cellular user c_i where N_t is the number of transmit antennas at the BS. $h_{d_j^T,d_j^R}$ denotes the fading channel coefficient of communication link from d_j^T to d_j^R. $\mathbf{h}_{b,d_j^R}$ denotes the channel vector of the interference link from the BS to d_j^R. $h_{d_j^T,c_i}$ and $h_{d_j^T,d_{j'}^R}$ denote the fading channel coefficients of the interference link from the d_j^T to c_i and from the d_j^T to $d_{j'}^R$. The resource sharing distribution matrix $\mathit{\Pi} = [\pi_{ij}]_{M \times N}$ can be calculated same as Section 3.1.

The baseband received signal for the d_j^R and c_i are written as (Ni et al., 2016),

$$y_{c_i} = \sqrt{P_{b_i}/PL_{b,c_i}}\mathbf{h}_{b,c_i}^H\mathbf{w}_b^{pre} + \sum_{d_j \in \mathbf{D}} \pi_{ij}\sqrt{P_{d_j}/PL_{d_j^T,c_i}}h_{d_j^T,c_i} + n_{c_i} \tag{4.1}$$

$$\begin{aligned} y_{d_j} = \sqrt{P_{d_j}/PL_{d_j^T,d_j^R}}h_{d_j^T,d_j^R} + \sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'}\sqrt{P_{d_j}/PL_{d_{j'}^T,d_j^R}}h_{d_{j'}^T,d_j^R} \\ + \sqrt{P_{b_i}/PL_{b,d_j^R}}\mathbf{h}_{b,d_j^R}^H\mathbf{w}_b^{pre} + n_{d_j} \end{aligned} \tag{4.2}$$

where $\mathbf{w}_b^{pre}$ is $N_t \times 1$, n_{c_i} and n_{d_j} are the AWGN.

The received SINR $\gamma_{c_i}^{M-DL}$ for c_i and $\gamma_{d_j}^{M-DL}$ for d_j are formulated, respectively, as follows,

$$\gamma_{c_i}^{M-DL} = \frac{(P_{b_i}/PL_{b,c_i})\left|\mathbf{h}_{b,c_i}^H\mathbf{w}_b^{pre}\right|^2}{\underbrace{\sum_{d_j \in \mathbf{D}} \pi_{ij}(P_{d_j}/PL_{d_j^T,c_i})\left|h_{d_j^T,c_i}\right|^2}_{interference\ caused\ by\ D2D\ pairs} + N_0B} \tag{4.3}$$

$$\gamma_{d_j}^{M-DL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R})\left|h_{d_j^T,d_j^R}\right|^2}{\underbrace{\sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'}(P_{d_j}/PL_{d_{j'}^T,d_j^R})\left|h_{d_{j'}^T,d_j^R}\right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{b_i}/PL_{b,d_j^R})\left|\mathbf{h}_{b,d_j^R}^H\mathbf{w}_b^{pre}\right|^2}_{interference\ caused\ by\ BS} + N_0B} \tag{4.4}$$

The sum system capacity is obtained by

$$R_{sum}^{M-DL} = \sum_{c_i \in \mathbf{C}} \log_2(1 + \gamma_{c_i}^{M-DL}) + \sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}} \pi_{ij}\log_2(1 + \gamma_{d_j}^{M-DL}) \tag{4.5}$$

4.1.1. Proposed Interference Mitigation for Downlink

Zero-forcing (or Null-Steering) pre-coding is a method of spatial signal processing by which the multiple antenna transmitter can null multiuser interference signals in wireless communication and the orthogonallity criterion is satisfied after signal transmission. In this section, the aim is to maximize the $\left|\mathbf{h}_{b,c_i}^{H}\mathbf{w}_b^{pre}\right|^2$ and minimize the $\left|\mathbf{h}_{b,d_j^R}^{H}\mathbf{w}_b^{pre}\right|^2$ for the selected D2D pairs. By reason of the multiple antenna feature, the pre-coding technique cannot be applied all D2D pairs. Thus, this technique is performed for the selected cellular user and v number of D2D pairs which share the same resources. These D2D pairs can be selected the nearest D2D pairs to the BS according to the distance and number of BS transmit antenna N_t.

Assuming that u is the number of receiver which share the same resources in a single cell and v is the number elements of a set $\mathbf{V}$ refers to selected D2D pairs for interference cancellation, where $\mathbf{V} \subset \mathbf{D}$. Hence, u equals to the summation of v and one cellular user. This cancellation process can be performed by providing $N_t \geq u$ and satisfying orthogonallity criterion, $\mathbf{h}_{b,d_v^R}^{H}\mathbf{w}_b^{pre} = 0$ for the selected D2D pairs d_v^R. This corresponds to the selection of $\mathbf{w}_b^{pre}$ in the direction of the projection of the channel vector, which is $\mathbf{h}_{b,c_i}$, on the nullspace of $\mathbf{H}_b^{pre} = \left[\mathbf{h}_{b,d_1^R}, \mathbf{h}_{b,d_2^R}, ..., \mathbf{h}_{b,d_v^R}\right]$ with the size of $N_t \times v$. Then, the pre-coding vector is determined as follows (Lee et al., 2014),

$$\mathbf{w}_b^{pre'} = (\mathbf{I} - \mathbf{P})\,\mathbf{h}_{b,c_i} \tag{4.6}$$

where **P** is the projection matrix on $\mathbf{H}_b^{pre}$, **I** is identity matrix and H is Hermitian matrix (transpose conjugate). The projection matrix **P** is formulated as,

$$\mathbf{P} = \mathbf{H}_b^{pre}\left((\mathbf{H}_b^{pre})^H\mathbf{H}_b^{pre}\right)^{-1}(\mathbf{H}_b^{pre})^H \tag{4.7}$$

Finally, the zero-forcing pre-coding vector is,

$$\mathbf{w}_b^{pre} = \frac{\mathbf{w}_b^{pre'}}{\left\|\mathbf{w}_b^{pre'}\right\|^2} \tag{4.8}$$

4.1.2. Proposed Method for Downlink Communication with Feedback Link

Our system has a multiple antenna network by employing partial cooperative transmission. It is assumed that each receive node has knowledge of CSI for the transmission link by using predefined pilot symbols. Each receive node feeds back the quantized bits to the BS via a finite feedback link. The quantization is taken by utilizing a vector quantization codebook which is known on the receiver side and the BS and this process can be applied equivalently to all the receive nodes. A quantization codebook $\mathbb{C}$ consists of $2^B \times N_t$ dimensional unit norm vectors $\mathbb{C} = \{\mathbf{c}_1, \mathbf{c}_2, ...\mathbf{c}_{2^B}\}$ in which B is the number of feedback bits per user.

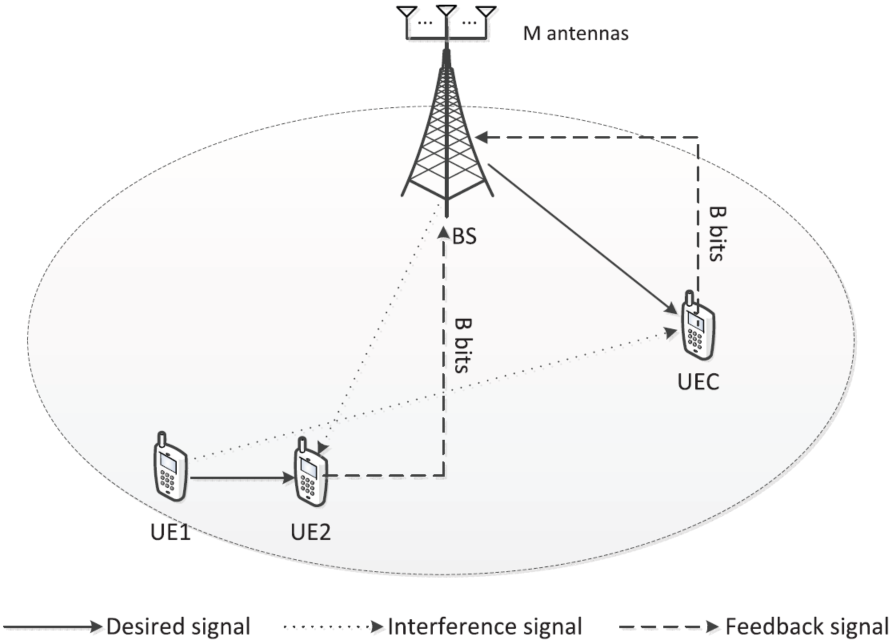

Figure 4.2. The schematic diagram of a D2D communication underlaying cellular network. (Source: Ni et al., 2016)

In the limited feedback system, each user quantizes the channel to the quantization vector that is closest to its channel. In this thesis, random vector quantization (RVQ) methods is used (Park et al., 2015).

The receive node selects the channel codeword that has the maximum inner product with normalized channel vector $\overline{\mathbf{h}}_{b,c_i} = \frac{\mathbf{h}_{b,c_i}}{\left\|\mathbf{h}_{b,c_i}\right\|}$ and $\overline{\mathbf{h}}_{b,d_v^R} = \frac{\mathbf{h}_{b,d_v^R}}{\left\|\mathbf{h}_{b,d_v^R}\right\|}$.

$$i_c = \arg \max_{i=1,\ldots,2^B} \left| \overline{\mathbf{h}}_{b,c_i}^{H} \mathbf{c}_i \right| \tag{4.9}$$

$$i_d = \arg \max_{i=1,\ldots,2^B} \left| \overline{\mathbf{h}}_{b,d_v^R}^{H} \mathbf{c}_i \right| \tag{4.10}$$

The chosen index i_c and i_d are sent to the transmit node for cellular users and D2D pairs, respectively, and the quantized channel vector $\hat{\mathbf{h}}_{b,c_i} = \mathbf{c}_{i_c} \left\| \mathbf{h}_{b,c_i} \right\|$ and $\hat{\mathbf{h}}_{b,d_v^R} = \mathbf{c}_{i_d} \left\| \mathbf{h}_{b,d_v^R} \right\|$ are recovered at the BS.

After quantization process, the received SINR $\gamma_{c_i}^{Mq-DL}$ for c_i and $\gamma_{d_j}^{Mq-DL}$ for d_j are formulated, respectively, as follows,

$$\gamma_{c_i}^{Mq-DL} = \frac{\left(P_{b_i}/PL_{b,c_i}\right) \left| \mathbf{h}_{b,c_i}^{H} \hat{\mathbf{w}}_b^{pre} \right|^2}{\underbrace{\sum_{d_j \in \mathbf{D}} \pi_{ij} (P_{d_j}/PL_{d_j^T,c_i}) \left| h_{d_j^T,c_i} \right|^2}_{interference\ caused\ by\ D2D\ pairs} + N_0 B} \tag{4.11}$$

$$\gamma_{d_j}^{Mq-DL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R}) \left| h_{d_j^T,d_j^R} \right|^2}{\underbrace{\sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'} (P_{d_j}/PL_{d_{j'}^T,d_j^R}) \left| h_{d_{j'}^T,d_j^R} \right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{b_i}/PL_{b,d_j^R}) \left| \mathbf{h}_{b,d_j^R}^{H} \hat{\mathbf{w}}_b^{pre} \right|^2}_{interference\ caused\ by\ BS} + N_0 B} \tag{4.12}$$

This corresponds to the selection of $\hat{\mathbf{w}}_b^{pre}$ in the direction of the projection of the quantized channel vector, which is $\hat{\mathbf{h}}_{b,c_i}$, on the nullspace of $\hat{\mathbf{H}}_b^{pre} = \left[\hat{\mathbf{h}}_{b,d_1^R}, \hat{\mathbf{h}}_{b,d_2^R}, \ldots, \hat{\mathbf{h}}_{b,d_v^R} \right]$ with the size of $N_t \times v$. Then, the quantized pre-coding vector is determined as follows (Lee et al., 2014),

$$\hat{\mathbf{w}}_b^{pre'} = \left(\mathbf{I} - \hat{\mathbf{P}} \right) \hat{\mathbf{h}}_{b,c_i} \tag{4.13}$$

The projection matrix $\hat{\mathbf{P}}$ is formulated as,

$$\hat{\mathbf{P}} = \hat{\mathbf{H}}_b^{pre} \left((\hat{\mathbf{H}}_b^{pre})^H \hat{\mathbf{H}}_b^{pre} \right)^{-1} (\hat{\mathbf{H}}_b^{pre})^H \tag{4.14}$$

Finally, the quantized zero-forcing pre-coding vector is,

$$\hat{\mathbf{w}}_b^{pre} = \frac{\hat{\mathbf{w}}_b^{pre'}}{\left\| \hat{\mathbf{w}}_b^{pre'} \right\|^2} \tag{4.15}$$

The sum system capacity is obtained by,

$$R_{sum}^{Mq-DL} = \sum_{c_i \in \mathbf{C}} \log_2(1 + \gamma_{c_i}^{Mq-DL}) + \sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}} \pi_{ij} \log_2(1 + \gamma_{d_j}^{Mq-DL}) \tag{4.16}$$

4.2. System Model for Uplink Post-coding

Using same resource blocks for cellular systems is a convenient way to improve signal efficiency. However, this spectrum sharing can cause the interference situation and it decrease the amount of free bandwidth for each user. Therefore, post-coding technique is an important method for interference mitigation and they are used for all users together so that the interference is aligned on subspace of the BS, while the desired signal can be received and high data rates and small error rates can be achieved.

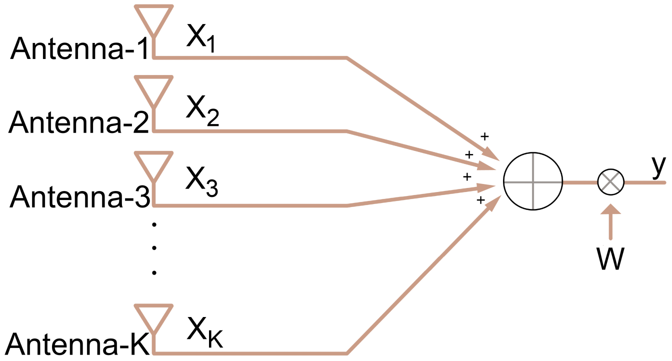

Figure 4.3. Post-coding method at BS.

Post-coding is a signal processing technology in receiver side and it works by setting the antenna element weights. The adjustable post-coding vectors $\mathbf{w}^{post}$ can also be used for spatial separation to separate the signals from the interference. Thus, post-coding technology is only possible when multiple antennas are used, and these can be at either receiver or both side. Additionally, signal processing can be applied at each receiver independently, thus, other links are not affected.by using post-coding method.

We consider an uplink scenario in a single cell system including one BS with multiple antenna located in the cell center as shown in Figure 3.2. The cellular network system can be modeled again as Section 3.1 where the objective is to implement post-coding technique by using a partial zero-forcing method. In this section, for the post-coding implementation, it is assumed that the BS has perfect CSI for both serving and interfering links.

The path loss and shadowing are all denoted in Section 3.2. Additionally, $\mathbf{h}_{c_i,b}$ denotes the channel vector of communication link from the cellular user c_i to BS. $h_{d_j^T,d_j^R}$ denotes the fading channel coefficient of communication link from d_j^T to d_j^R. $\mathbf{h}_{d_j^T,b}$ denotes the channel vector of the interference link from the d_j^T to the BS. h_{c_i,d_j^R} and $h_{d_j^T,d_{j'}^R}$ denote the fading channel coefficients of the interference link from the c_i to d_j^R and from the d_j^T to $d_{j'}^R$. The resource sharing distribution matrix $\mathit{\Pi} = [\pi_{ij}]_{M\times N}$ can be calculated same as Section 3.1.

Therefore, the baseband received signal for the d_j^R and c_i are written as (Ni et al., 2016),

$$\mathbf{r}_{c_i} = \sqrt{P_{c_i}/PL_{c_i,b}}\mathbf{h}^H_{c_i,B} + \sum_{d_j\in\mathbf{D}} \pi_{ij}\sqrt{P_{d_j}/PL_{d_j^T,b}}\mathbf{h}^H_{d_j^T,b} + \mathbf{n}_{c_i} \tag{4.17}$$

$$y_{c_i} = \mathbf{w}_b^{post}\mathbf{r}_{c_i} \tag{4.18}$$

$$\begin{aligned} y_{d_j} = \sqrt{P_{d_j}/PL_{d_j^T,d_j^R}}h_{d_j^T,d_j^R} + \sum_{c_i\in\mathbf{C}}\sum_{d_j\in\mathbf{D},j\neq j'} \pi_{ij}\cdot\pi_{ij'}\sqrt{P_{d_j}/PL_{d_{j'}^T,d_j^R}}h_{d_{j'}^T,d_j^R} \\ + \sqrt{P_{c_i}/PL_{c_i,d_j^R}}h_{c_i,d_j^R} + n_{d_j} \end{aligned} \tag{4.19}$$

where $\mathbf{n}_{c_i}$ and n_{d_j} are the AWGN. The received SINR $\gamma_{c_i}^{M-UL}$ for c_i and $\gamma_{d_j}^{M-UL}$ for d_j, is formulated, respectively, as follows,

$$\gamma_{c_i}^{M-UL} = \frac{(P_{c_i}/PL_{c_i,b})\left|\mathbf{w}_b^{post}\mathbf{h}^H_{c_i,b}\right|^2}{\underbrace{\sum_{d_j\in\mathbf{D}} \pi_{ij}(P_{d_j}/PL_{d_j^T,b})\left|\mathbf{w}_b^{post}\mathbf{h}^H_{d_j^T,b}\right|^2}_{interference\ caused\ by\ D2D\ pairs} + \left\|\mathbf{w}_b^{post}\right\|^2 N_0B} \tag{4.20}$$

$$\gamma_{d_j}^{M-UL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R})\left|h_{d_j^T,d_j^R}\right|^2}{\underbrace{\sum_{c_i\in\mathbf{C}}\sum_{d_j\in\mathbf{D},j\neq j'}\pi_{ij}\cdot\pi_{ij'}(P_{d_j}/PL_{d_{j'}^T,d_j^R})\left|h_{d_{j'}^T,d_j^R}\right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{c_i}/PL_{c_i,d_j^R})\left|h_{c_i,d_j^R}\right|^2}_{interference\ caused\ by\ cellular\ user} + N_0B} \tag{4.21}$$

The sum system capacity is obtained by

$$R_{sum}^{M-UL} = \sum_{c_i\in\mathbf{C}}\log_2(1+\gamma_{c_i}^{M-UL}) + \sum_{c_i\in\mathbf{C}}\sum_{d_j\in\mathbf{D}}\pi_{ij}\log_2(1+\gamma_{d_j}^{M-UL}) \tag{4.22}$$

4.2.1. Proposed Interference Mitigation for Uplink

In this section, the aim is to maximize the $\left|\mathbf{w}_b^{post}\mathbf{h}_{c_i,b}^H\right|^2$ and minimize the $\left|\mathbf{w}_b^{post}\mathbf{h}_{d_j^T,b}^H\right|^2$ for the selected D2D pairs. Assuming that u is the number of receiver which share the same resources in a single cell and it is calculated as post-coding technique. This cancellation process can be performed by providing $N_t \geq u$ and satisfying orthogonallity criterion, $\mathbf{w}_b^{post}\mathbf{h}_{d_v^T,b}^H = 0$ for the selected D2D pairs d_v^T. The number of selected D2D pairs are determined by the nearest location to the BS according to number of antenna N_t. This corresponds to the selection of $\mathbf{w}_b^{post}$ in the direction of the projection of the channel vector, which is $\mathbf{h}_{c_i,b}$, on the nullspace of $\mathbf{H}_b^{post} = \left[\mathbf{h}_{d_1^T,b}, \mathbf{h}_{d_2^T,b}, ..., \mathbf{h}_{d_v^T,b}\right]$ with the size of $v \times N_t$. Then, the post-coding vector is determined as follows (Lee et al., 2014),

$$\mathbf{w}_b^{post'} = (\mathbf{I} - \mathbf{P})\,\mathbf{h}_{c_i,b} \tag{4.23}$$

where **P** is the projection matrix on $\mathbf{H}_b^{post}$, **I** is identity matrix and H is Hermitian matrix (transpose conjugate). The projection matrix **P** is formulated as,

$$\mathbf{P} = \mathbf{H}_b^{post}\left((\mathbf{H}_b^{post})^H\mathbf{H}_b^{post}\right)^{-1}(\mathbf{H}_b^{post})^H \tag{4.24}$$

Finally, the zero-forcing post-coding vector is,

$$\mathbf{w}_b^{post} = \frac{\mathbf{w}_b^{post'}}{\left\|\mathbf{w}_b^{post'}\right\|^2} \tag{4.25}$$

In postcoding the orthogonallity criterion is satisfied when BS received the signal. Therefore, it is assumed that the noise variance is the same across all receivers.

4.2.2. Proposed Method for Uplink with Channel Estimation

In the practice, the channel vector is not known at the receiver side and an estimate $\tilde{\mathbf{h}}_{c_i,b}$ and $\tilde{\mathbf{h}}_{d_v^T,b}$ are made. They are modeled with a Gausian channel estimation error, as follows;

$$\tilde{\mathbf{h}}_{c_i,b} = \mathbf{h}_{c_i,b} + \mathbf{e}_c \tag{4.26}$$

$$\tilde{\mathbf{h}}_{d_v^T,b} = \mathbf{h}_{d_v^T,b} + \mathbf{e}_d \tag{4.27}$$

where $\mathbf{h}_{c_i,b}$ and $\mathbf{h}_{d_v^T,b}$ denote the perfect channel, $\tilde{\mathbf{h}}_{c_i,b}$ and $\tilde{\mathbf{h}}_{d_v^T,b}$ denote the estimated channel, $\mathbf{e}_c$ and $\mathbf{e}_d$ denote a complex Gaussian distribution vector with independent components with zero mean and independent real and imaginary parts each with a noise variance $\frac{\sigma_e^2}{2}$ for cellular users and D2D pairs.

By using estimated channel information, the received SINR $\gamma_{c_i}^{Me-UL}$ for c_i and $\gamma_{d_j}^{Me-UL}$ for d_j, is formulated, respectively, as follows,

$$\gamma_{c_i}^{Me-UL} = \frac{(P_{c_i}/PL_{c_i,b})\left|\tilde{\mathbf{w}}_b^{post}\mathbf{h}_{c_i,b}^H\right|^2}{\underbrace{\sum_{d_j \in \mathbf{D}} \pi_{ij}(P_{d_j}/PL_{d_j^T,b})\left|\tilde{\mathbf{w}}_b^{post}\mathbf{h}_{d_j^T,b}^H\right|^2}_{interference\ caused\ by\ D2D\ pairs} + \left\|\tilde{\mathbf{w}}_b^{post}\right\|^2 N_0 B} \tag{4.28}$$

$$\gamma_{d_j}^{Me-UL} = \frac{(P_{d_j}/PL_{d_j^T,d_j^R})\left|h_{d_j^T,d_j^R}\right|^2}{\underbrace{\sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}, j \neq j'} \pi_{ij} \cdot \pi_{ij'}(P_{d_j}/PL_{d_{j'}^T,d_j^R})\left|h_{d_{j'}^T,d_j^R}\right|^2}_{interference\ caused\ by\ other\ D2D\ pairs} + \underbrace{(P_{c_i}/PL_{c_i,d_j^R})\left|h_{c_i,d_j^R}\right|^2}_{interference\ caused\ by\ cellular\ user} + N_0 B} \tag{4.29}$$

This corresponds to the selection of $\tilde{\mathbf{w}}_b^{post}$ in the direction of the projection of the estimated channel vector, which is $\tilde{\mathbf{h}}_{c_i,b}$, on the nullspace of $\tilde{\mathbf{H}}_b^{post} = \left[\tilde{\mathbf{h}}_{d_1^T,b}, \tilde{\mathbf{h}}_{d_2^T,b}, ..., \tilde{\mathbf{h}}_{d_v^T,b}\right]$

with the size of $v \times N_t$. Then, the post-coding vector is determined as follows (Lee et al., 2014),

$$\tilde{\mathbf{w}}_b^{post'} = \left(\mathbf{I} - \tilde{\mathbf{P}}\right) \tilde{\mathbf{h}}_{c_i,b} \tag{4.30}$$

The projection matrix $\tilde{\mathbf{P}}$ is formulated as,

$$\tilde{\mathbf{P}} = \tilde{\mathbf{H}}_b^{post} \left((\tilde{\mathbf{H}}_b^{post})^H \tilde{\mathbf{H}}_b^{post}\right)^{-1} (\tilde{\mathbf{H}}_b^{post})^H \tag{4.31}$$

Finally, the zero-forcing post-coding vector is,

$$\tilde{\mathbf{w}}_b^{post} = \frac{\tilde{\mathbf{w}}_b^{post'}}{\left\|\tilde{\mathbf{w}}_b^{post'}\right\|^2} \tag{4.32}$$

The sum system capacity is obtained by

$$R_{sum}^{Me-UL} = \sum_{c_i \in \mathbf{C}} \log_2(1 + \gamma_{c_i}^{Me-UL}) + \sum_{c_i \in \mathbf{C}} \sum_{d_j \in \mathbf{D}} \pi_{ij} \log_2(1 + \gamma_{d_j}^{Me-UL}) \tag{4.33}$$

4.3. Performance Evaluations

In this section, the performance of GOAL and the proposed resource allocation techniques proposed in Chapter 3, are illustrated for multiple antenna case. The same simulation parameters up to in Table 3.1 are used. The BS has 4 antennas. Hence zero-forcing technique can be applied 3 nearest D2D pairs.

The average data rate of the proposed algorithm and GOAL algorithm for the multiple antenna BS are illustrated in Figure 4.4 for downlink with power control. It is also formulated the power control and ZF method with quantized CSI with 8 bit random vector quantizer for downlink communication. The effects of the quantized channel state information on the performance of average sum data rate are shown in underlaying D2D downlink cellular systems. In Figure 4.4, the results show that D2D users can share the spectrum with a cellular link without any performance loss if perfect CSI is available at BS. However, when there is only limited CSI available, D2D communication can reuse the same spectrum band if a small performance loss can be tolerated as shown in Figure 4.5.

When the number of D2D pairs increases, the system interference is increased. Therefore, by using zero-forcing technique with perfect CSI on the BS side, the interference can be eliminated completely. Even though the zero-forcing technique can cancel only limited number of interfering D2D links, it has reduced the total amount of the interference on the D2D pairs by decreasing the transmit power of D2D pairs and BS. As a result of using multiple antenna BS, it is seen the average data rate increment up to 40% for both D2D pairs and cellular users compare to single antenna BS with the Figure 4.6 and Figure 4.7, respectively. It can be seen 30% the average data rate performance degradation when the limited CSI is used for downlink communication in Figure 4.8.

In Figure 4.9, it is evaluated the post-coding technique for uplink communication with perfect channel knowledge. It is also formulated the power control and ZF method with estimated CSI and the variance of channel estimation error σ_e^2 is equal to 10^{-2}. If we use estimated channel for uplink communication as shown in Figure 4.10, 20% average data rate loss can be observed in Figure 4.13. By using multiple antenna BS for uplink communication, the performance increment of the average data rate can be observed up to 50% for both D2D pairs and cellular users compare to single antenna BS with the Figure 4.11 and Figure 4.12, respectively.

The average transmit power of D2D pairs and BS can be shown in Figure 4.14 and in Figure 4.15 for downlink case with perfect and limited CSI, respectively. In Figure 4.16 and in Figure 4.17, the average transmit power of D2D pairs and cellular users can be observed for uplink case with perfect and estimated CSI, respectively. In the multi-antenna BS system, the average D2D and BS transmitted power values are slightly better than single antenna for downlink communication since the interference effect of the BS is very harmful for the D2D pairs because of the high transmit power even if power control scheme reduce the transmit power. However, the average D2D transmitted power values are almost the same for both single and multiple antenna system because of the power allocation.

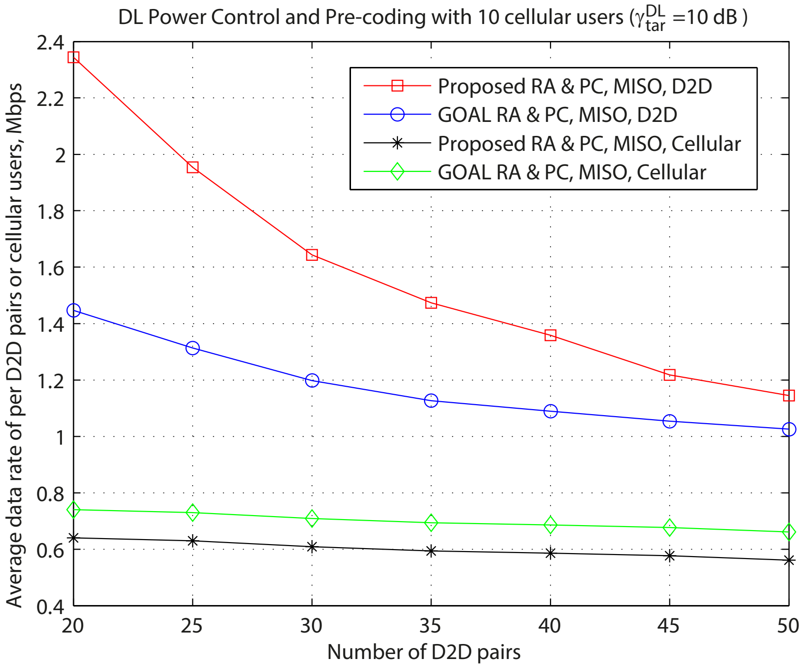

Figure 4.4. Average data rate per cellular user and D2D pair for DL communication with power control and pre-coding.

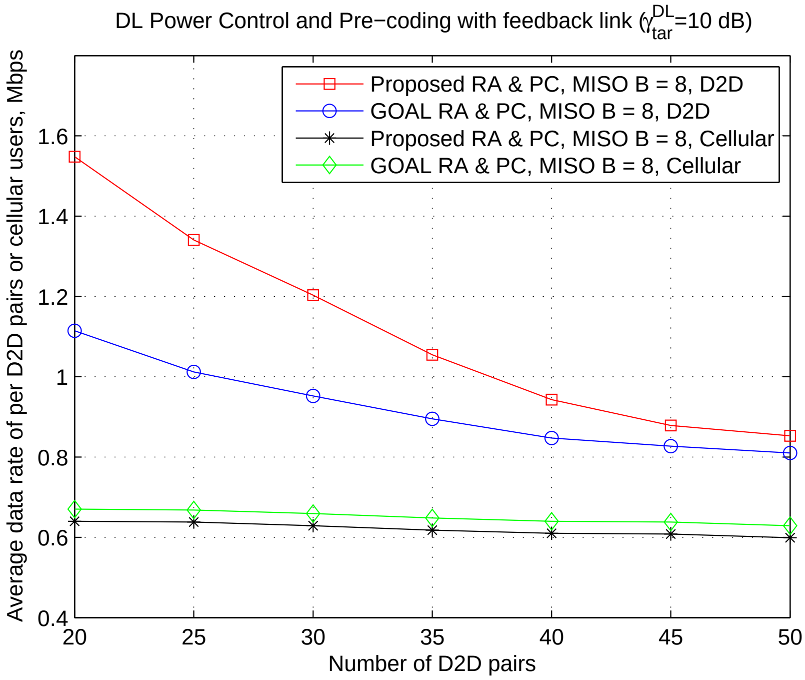

Figure 4.5. Average data rate per cellular user and D2D pair for DL communication with a limited feedback link.

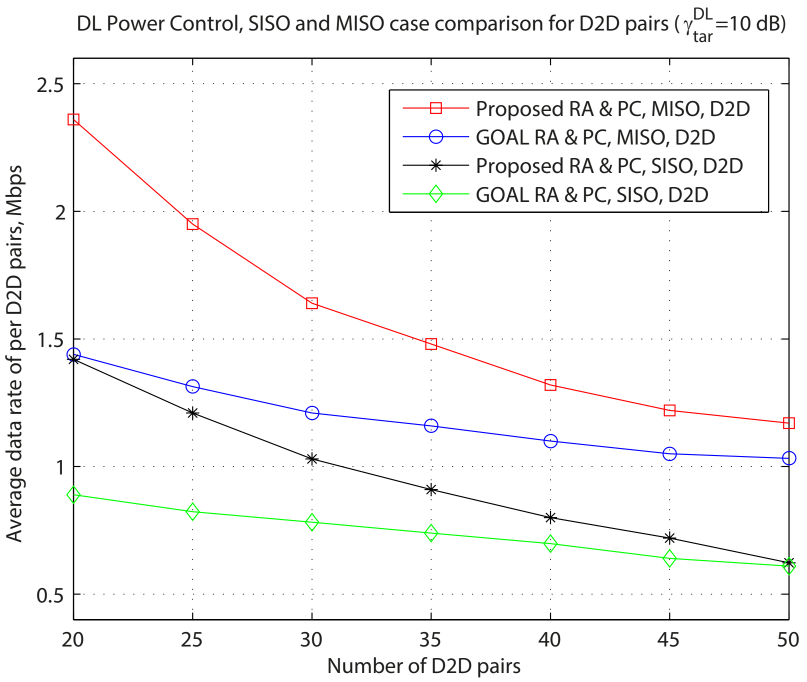

Figure 4.6. Comparison on average data rate per D2D pair for SISO and MISO DL communication.

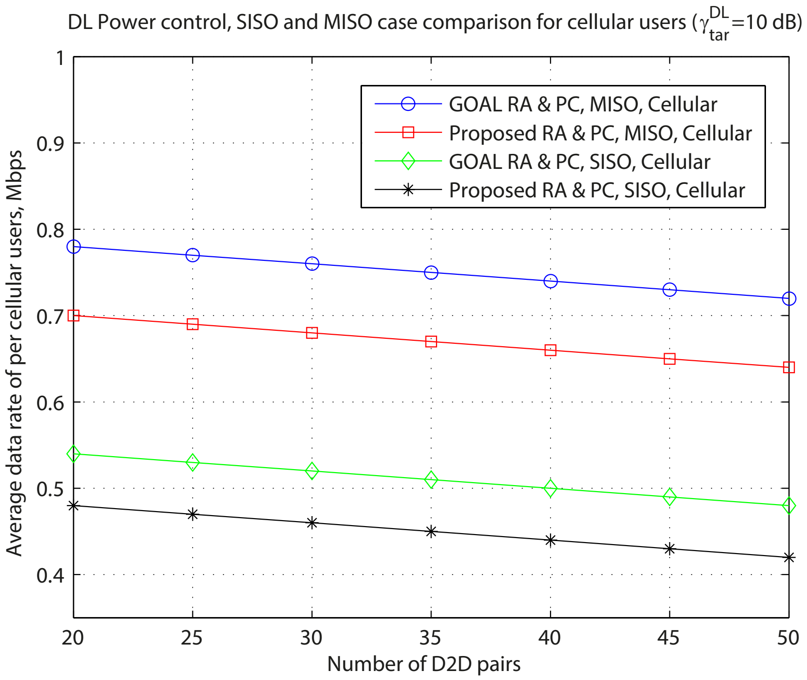

Figure 4.7. Comparison on average data rate per cellular user for SISO and MISO DL communication.

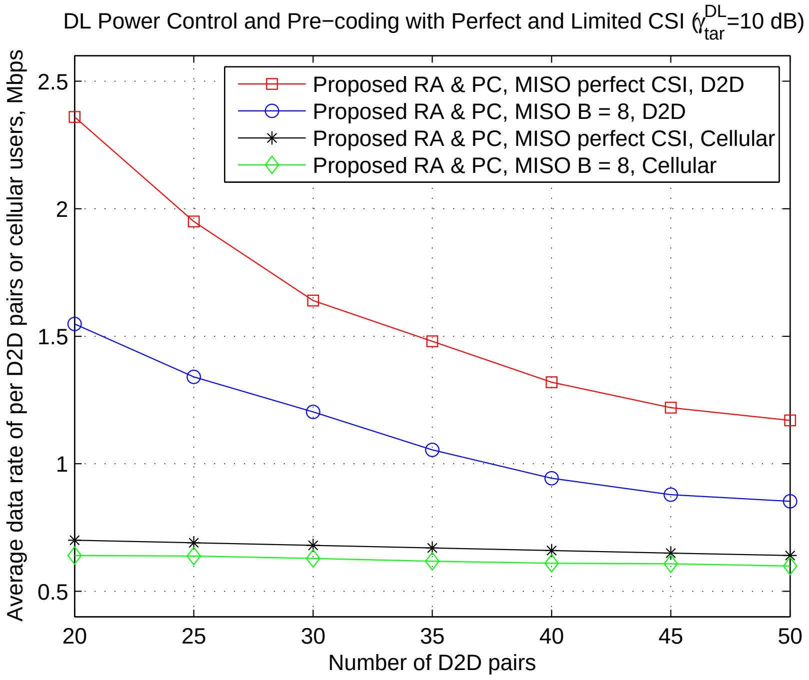

Figure 4.8. Comparison on average data rate per cellular user or D2D pairs for the proposed resource allocation.

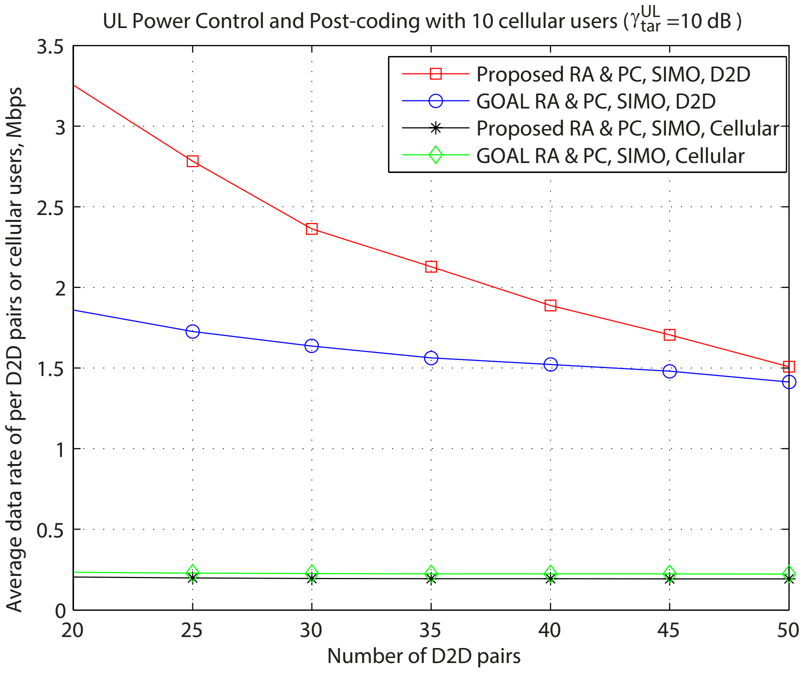

Figure 4.9. Average data rate per cellular user and D2D pair for UL communication with power control and post-coding.

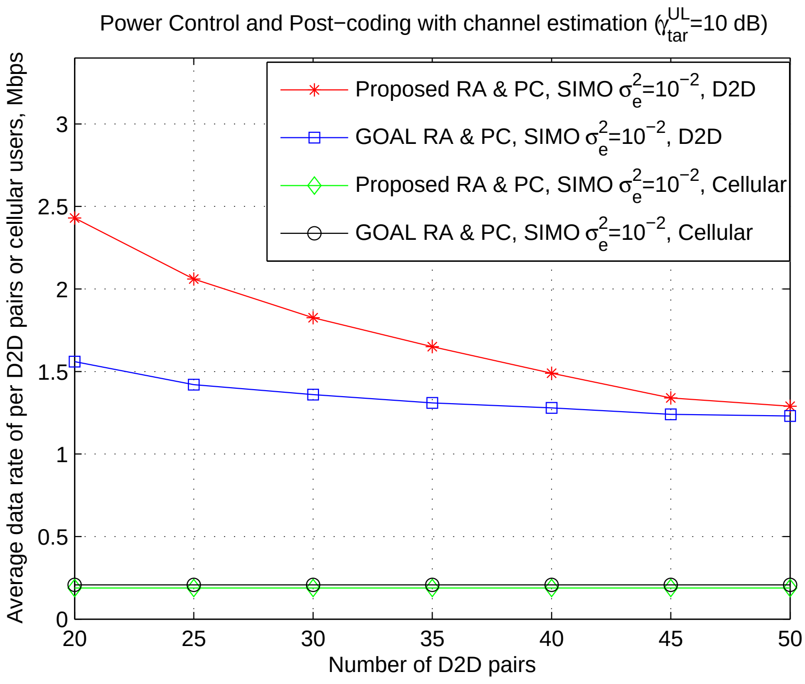

Figure 4.10. Average data rate per cellular user and D2D pair for UL communication with channel estimation.

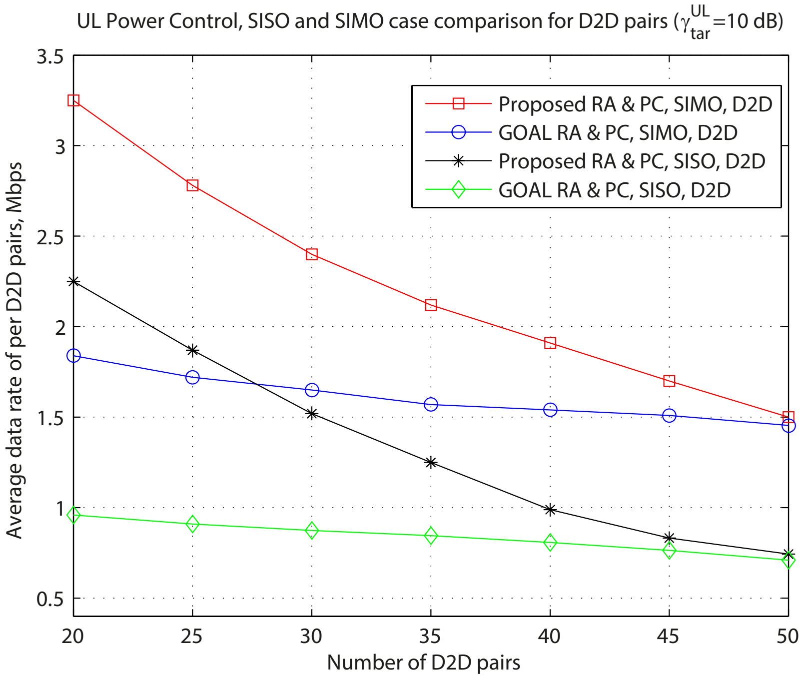

Figure 4.11. Comparison on average data rate per D2D pair for SISO and SIMO UL communication.

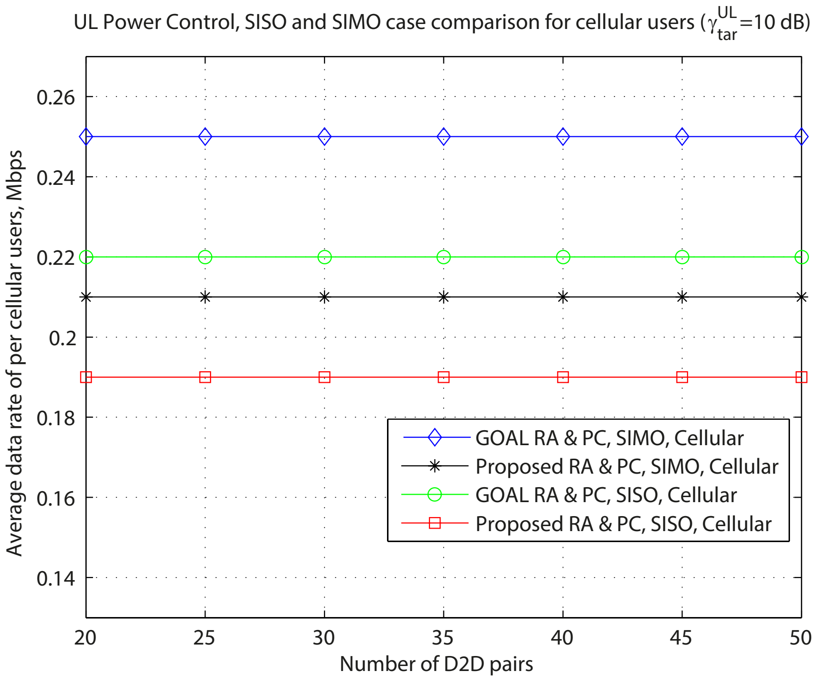

Figure 4.12. Comparison on average data rate per cellular user for UL SISO and SIMO communication.

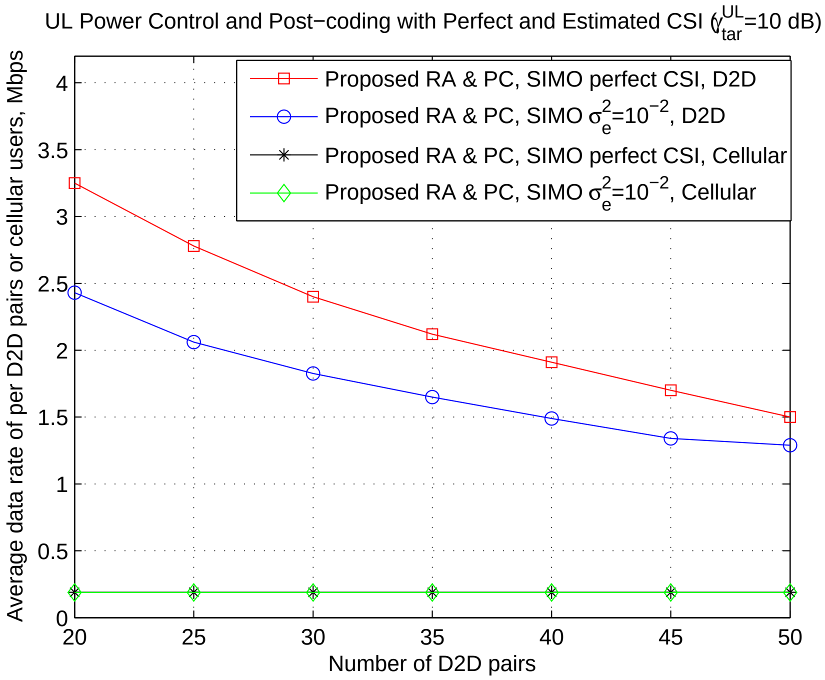

Figure 4.13. Comparison on averagedata rate per cellular user or D2D pair for the proposed resource allocation.

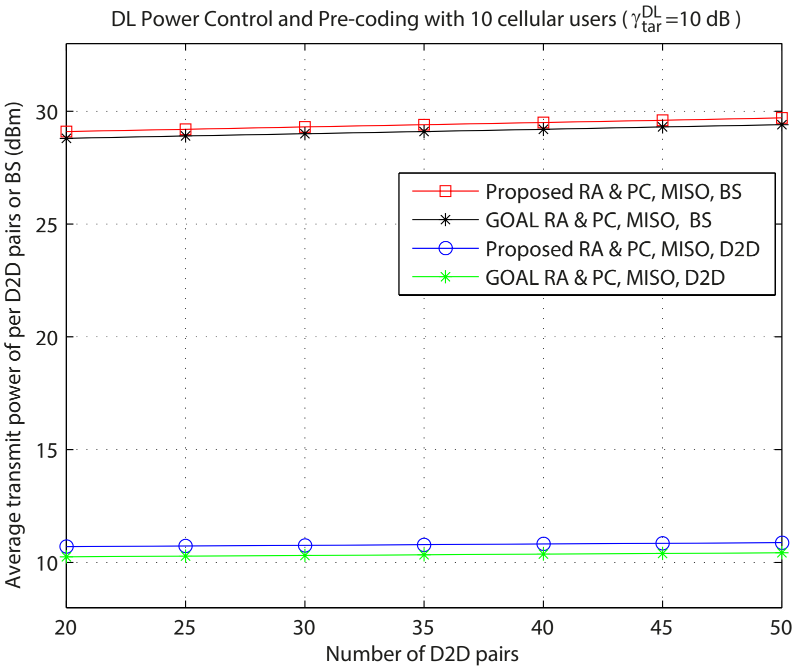

Figure 4.14. Average transmit power per cellular user and D2D pair for DL communication with power control and pre-coding.

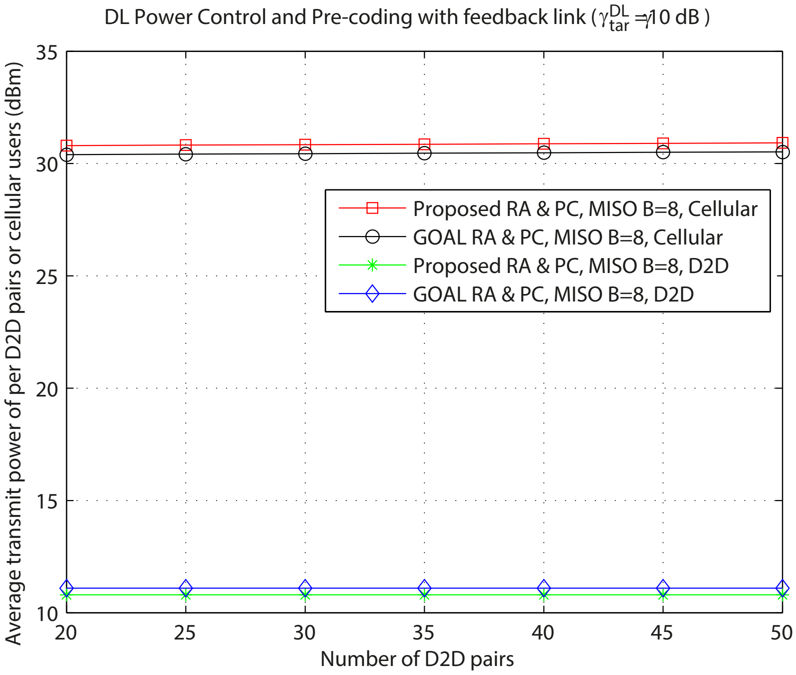

Figure 4.15. Average transmit power per cellular user and D2D pair for DL communication with limited feedback link.

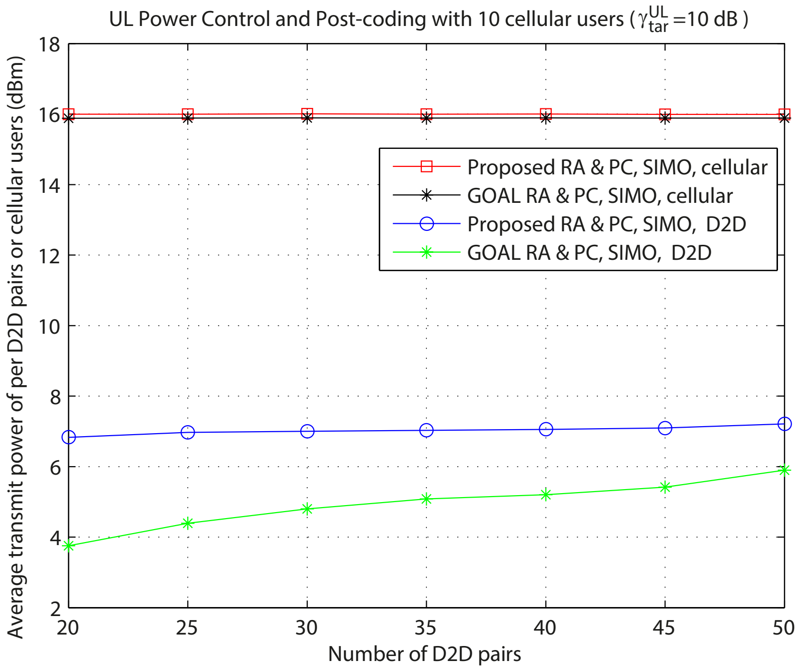

Figure 4.16. Average transmit power per cellular user and D2D pair for UL communication with power control and post-coding.

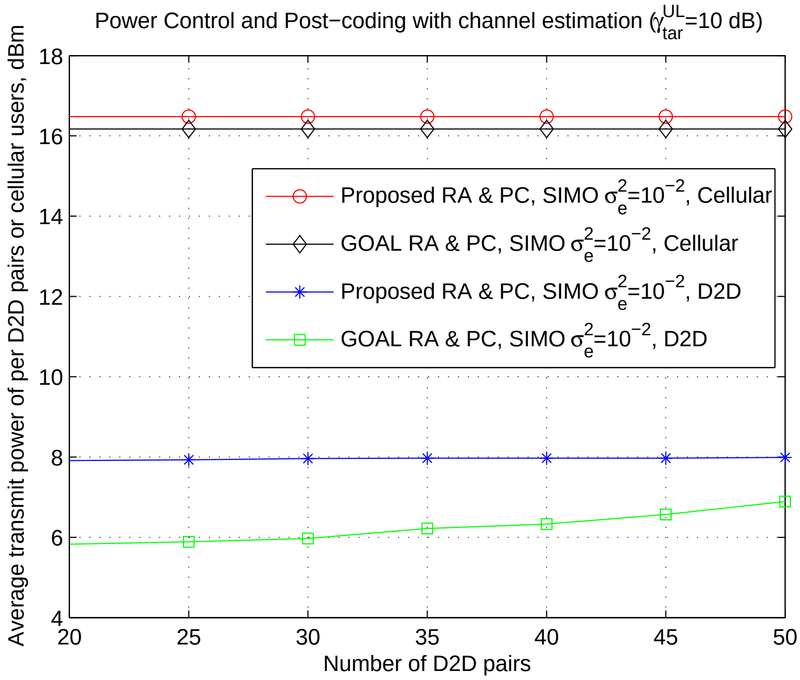

Figure 4.17. Average transmit power per cellular user and D2D pair for UL communication with channel estimation error.

CHAPTER 5

CONCLUSION

D2D communication integrated in cellular networks is a promising technology for improving the performance of proximity-based communication in future 5G systems. The idea of D2D communication is to provide mobile devices in close proximity to communicate directly, bypassing the base station. This improves the spectrum and energy efficiency of the network. It is also possible for D2D links to reuse the radio resources. However, D2D links in a cellular system generate interference with existing cellular networks. Therefore, it is important to investigate interference mitigation techniques that can handle the interference.

In this thesis, we have presented the issue of interference mitigation when D2D links and cellular network share the same resources for both downlink and uplink cellular transmission about power control and resource allocation. To address these scenarios, GOAL and the proposed resource allocation algorithms have been considered which are based on graph coloring technique. In addition to that downlink and uplink communication, power control schemes have been taken into account with single and multiple antenna BS. The zero-forcing technique has been implemented at BS side in the presence of perfect CSI. Furthermore, the zero-forcing technique has been also implemented under the quantized CSI and estimated channel error for downlink and uplink communication, respectively.

We have defined the resource allocation problem as one D2D pair can share the resources with multiple cellular users and one cellular user can share its resource with multiple D2D pairs. Then, we have investigated the feasible number of D2D pairs underlay of the cellular network. We have proposed the resource allocation algorithm and power control optimization scheme to minimize the total transmission power while ensuring no performance loss for D2D receivers. The results have shown that the performance of the resource allocation algorithm and power control are increased the D2D average data rate compared to GOAL algorithm. However, if the number of D2D pairs is increased for both downlink and uplink case, the average data rate of the system might be decreased. Additionally, we have considered the coexistence of D2D pairs under the multiple antenna cellular network. The results have shown that even if zero-forcing method cannot applied for all D2D pairs, it has improved the system performance on average data rate and power consumption. In the case of the limited feedback link, the average data rate of both cellular users and D2D pairs has been degraded for downlink communication. If there is a channel estimation error for uplink communication, the average data rate has been also reduced. However, usage of uplink communication has still provided better performance results on average data rate.

The results have highlighted the importance of considering the influence of interference dynamics on the performance for D2D pairs underlying cellular system. Moreover, regarding the different interference scenarios, it can be observed that the performance of the usage of downlink and uplink has been affected from level of cumulative interference. When the low number of D2D pairs has been allocated in the system, the proposed algorithm have given better results in terms of average data rate. In downlink communication, the high transmit power of the BS has degraded the average data rates of D2D pairs, therefore uplink communication has allowed to reduce interference level while increases the average data rates for D2D pairs. The proposed algorithm has increased the number of allocated resource blocks to the D2D pairs and multiple antenna system can manage interference by performing interference mitigation techniques.

REFERENCES

3GPP Release 7, Physical Layer Aspects for Evolved Universal Terrestrial Radio Access (UTRA), (September 2006), TR 25.814 V7.1.0.

3GPP Release 8, E-UTRA; LTE Physical Layer-General Description, (2007) TS 36.201.

3GPP Release 9, Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA), (LTE-Advanced), Tech. Rep., (December 2009).

3GPP Release 10, Overview of 3GPP release 8, v.0.1.1, Tech. Rep., (June 2010).

3GPP Release 11, Technical Specifications Group Radio Access Network; E-UTRA RF System Scenarios, (2011).

Abed G., Ismail M., Jumari K., The Evolution to 4G Cellular Systems: Architecture and Key Features of LTE-Advanced Networks, International Journal of Computer Networks and Wireless Communications (IJCNWC), Vol. 2, No. 1, (2012), 2250-3501

Akoum S., Kountouris M., Debbah M., Heath R., Spatial interference mitigation for multiple input multiple output ad hoc networks: MISO gains, in Proc. Asilomar Conf. Signal Syst. Comput., (April 2012).

Akyildiz F., Gutierrez-Estevez M., Reyes E., The evolution to 4G cellular systems: LTE-Advanced, Physical Communication, Volume 3, Issue 4, (December 2010), 217-244.

Ali M., An Overview on Interference Management in 3GPP LTE-Advanced Heterogeneous Networks, (2015).

Asadi A., Wang Q., Mancuso V., A Survey on Device-to-Device Communication in Cellular Networks, 29 Apr 2014.

Cisco White Paper., Cisco visual networking index: Global mobile data traffic forecast update, 2014 - 2019., (Feb. 2015).

Chandrasekhar V., Andrews J., Femtocell networks: A survey, IEEE Commun. Mag., vol. 46, no. 9, (September 2008), 5967.

Coupechoux M., Kelif J., How to Set the Fractional Power Control Compensation Factor in LTE?, Sarnoff Symposium, 34th IEEE (2011).

Cai X., Zheng J., Zhang Y., A Graph-Coloring Based Resource Allocation Algorithm for D2D Communication in Cellular Networks, IEEE ICC - Next Generation Networking Symposium, (2015).

Ferdouse L., Ejaz W., Raahemifar K., Anpalagan A., Markandaier M., Interference and throughput aware resource allocation for multi-class D2D in 5G networks, IET Commun., Vol. 11 Iss. 8, (2017), 1241-1250.

Fodor G., Dahlman E., Mildh G., Parkvall S., Reider N., Miklós G., Turányi Z., Design aspects of network assisted device-to-device communications, IEEE Commun. Mag. 50(3), (2012), 170 - 177.

Fodor G., Parkvall S., Sorrentino S., Device-to-Device Communications for National Security and Public Safety, IEEE Access, (2014), 1510 - 1520.

Gesbert D., Kountouris M., Heath R. W., Chae B., Sälzer T., Shifting the MIMO Paradigm: From Single User to Multiuser Communications, IEEE Signal Processing Magazine (Oct 2007).

Goldsmith A., Wireless Communications, Cambridge University Press, (2005).

Gu J., Bae S. J., Choi B., Chung M. Y., Dynamic power control mechanism for interference coordination of device-to-device communication in cellular networks, in Proc. 3rd Int. Conf. Ubiquitous Future Netw., (June 2011)

Hicham M., Abghour N., Ouzzif M., Devıce-To-Devıce (D2d) Communication under Lte-Advanced Networks, International Journal of Wireless and Mobile Networks (IJWMN) Vol. 8, No. 1, (February 2016).

Ikuno J. C., Wrulich M., Rupp M., System level simulation of LTE networks, Vehicular Technology Conference (VTC 2010-Spring), IEEE 71st (2010).

ITU-R Tech. Rep., Guidelines for evaluation of radio interface technologies for IMT-Advanced, International Telecommunication Union, (2009). Available: http://www.itu.int/pub/R-REP-M.2135/

Kawser M. T., Hamid N., Downlink SNR to CQI Mapping for Different Multiple Antenna Techniques in LTE, International Journal of Information and Electronics Engineering, Vol. 2, No. 5, (September 2012).

Kuruvatti N. P., Klein A., Ji L., Sattiraju R., Schotten H. D., Robustness of Location Based D2D Resource Allocation Against Positioning Errors, Vehicular Technology Conference (VTC Spring), (2015) IEEE 81st.

Lee N., Baccelli F., Heath R. W., Spectral efficiency scaling laws in dense random wireless networks with multiple receive antennas, IEEE Trans. Inf. Theory, (2014).

Li F., Li P., Yang Y., Li H., Game Theory Based Interference Control And Power Control For D2D Communication in Cellular Networks, International Journal of Computer Networks and Communications (IJCNC) Vol.8, No.5, (September 2016).

Lin X., Andrews J.G., Ghosh A., Ratasuk R.,An overview of 3GPP device-to-device proximity services, IEEE Commun. Mag. 52(4), (2014), 40-48.

Lin Z., Gao Z., Huang L., Chen C., Hybrid Architecture Performance Analysis for Device-to-Device Communication in 5G Cellular Network, Springer Science

Business Media, New York, (2015).

Lucas M.C., Gozalvez J., Distance-based Radio Resource Allocation for Device to Device Communications, Vehicular Technology Conference (VTC Spring), IEEE 85th, (2017).

Mietzner J., Schober R., Lampe L., Gerstacker W.H., Hoeher P.A., Multiple-Antenna Techniques for Wireless Communications? A Comprehensive Literature Survey, IEEE Communications Surveys and Tutorials, Vol. 11, No. 2, (2009), 87-105.

Mousavir H., Amiri S., Mostafavi M.A., Choon C.Y., LTE physical layer: Performance analysis and evaluation, Applied Computing and Informatics, (2017).

Ni Y., Jin S., Xu W., Beamforming and Interference Cancellation for D2D Communication Underlaying Cellular Networks, IEEE Transactıons on Communıcatıons, vol. 64, No. 2, (February 2016).

Janis P., Interference-aware resource allocation for device-to-device radio underlaying cellular networks, in Proc. Of IEEE VTC-09, Barcelona/Spain, (April 2009), pp. 1-5.

Oduola W., Li X., Qian L., Power Control for Device-to-Device Communications as an Underlay to Cellular System, IEEE ICC Wireless Communications Symposium (2014).

Park S., Choi S., Gi L. B., Game Theory-based Power Allocation Strategy for D2D Communication in Multi-Cell Environment, Information and Communication Technology Convergence (ICTC), International Conference, (2015).

Park J., Heath R. W., Multiple-Antenna Transmission with Limited Feedback in Device-to-Device Networks, IEEE Wireless Communications letters, vol. 5, no. 2, (April 2016).

Stuber G. L., Principles of Mobile Communications, Kluwer Academic Publishers, (2001).

Tehrani M. N., Uysal M., Yanikomeroglu H., Device-to-Device Communication in 5G Cellular Networks: Challenges, Solutions, and Future Directions, IEEE Communications Magazine, (May 2014).

Tejaswi E., Suresh B., Survey of Power Control Schemes for LTE Uplink, International Journal of Computer Science and Information Technologies, Vol. 4 (2), (2013), 369-373.

Universal Mobile Telecommunications System (UMTS) 30.03 version 3.1.0, Selection Procedures for the choice of radio transmission technologies of the UMTS, European Telecommunications Standards Institute (ETSI), (1997).

Xiao X., Tao X., Lu J., A QoS-aware power optimization scheme in OFDMA systems with integrated device-to-device (D2D) communications, in Proc. IEEE Veh. Technol. Conf., (September 2011).

Xing H., Hakola S., The investigation of power control schemes for a device-to-device communication integrated into OFDMA cellular system, in Proc. IEEE Int. Symp. on Personal, Indoor, Mobile Radio Commun. (PIMRC), Istanbul, Turkey, (September 2010), pp. 1775-1780.

Xu H., Xu W., Yang Z., Pan Y., Shi J., Chen M., Energy-Efficient Resource Allocation in D2D Underlaid Cellular Uplinks, IEEE COMMUNICATIONS LETTERS, VOL. 21, NO. 3, (MARCH 2017).

Wang L., Tang H., Device-to-Device Communications in Cellular Networks, SpringerBriefs in Electrical and ComputerEngineering, (2016).

Yassin M., Lahoud S., Ibrahim M., Khawam K., A Downlink Power Control Heuristic Algorithm for LTE Networks, 21st International Conference on Telecommunications, Lisbon, Portugal. (May 2014).

Yu C. H., Tirkkonen O., Doppler K., Ribeiro C., On the performance of device-to-device underlay communication with simple power control, in Proc. IEEE Veh. Technol. Conf., (2009).