Modeling and Performance Analysis of Relay-based Cooperative OFDMA Networks

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Next generation wireless communication networks are expected to provide ubiquitous high data rate coverage and support heterogeneous wireless services with diverse quality-of-service (QoS) requirements. This translates into a heavy demand for the spectral resources. In order to meet these requirements, Orthogonal Frequency Division Multiple Access (OFDMA) has been regarded as a promising air-interface for the emerging fourth generation (4G) networks due to its capability to combat the channel impairments and support high data rate. In addition, OFDMA offers flexibility in radio resource allocation and provides multiuser diversity by allowing subcarriers to be shared among multiple users.

One of the main challenges for the 4G networks is to achieve high throughput throughout the entire cell. Cooperative relaying is a very promising solution to tackle this problem as it provides throughput gains as well as coverage extension. The combination of OFDMA and cooperative relaying assures high throughput requirements, particularly for users at the cell edge. However, to fully exploit the benefits of relaying, efficient relay selection as well as resource allocation are critical in such kind of network when multiple users and multiple relays are considered. Moreover, the consideration of heterogeneous QoS requirements further complicate the optimal allocation of resources in a relay enhanced OFDMA network. Furthermore, the computational complexity and signalling overhead are also needed to be considered in the design of practical resource allocation schemes. In this dissertation, we conduct a comprehensive research study on the topic of radio resource management for relay-based cooperative OFDMA networks supporting heterogeneous QoS requirements. Specifically, this dissertation investigates how to effectively and efficiently allocate resources to satisfy QoS requirements of 4G users, improve spectrum utilization and reduce computational complexity at the base station. The problems and our research achievements are briefly outlined as follows.

Firstly, a QoS aware optimal joint relay selection, power allocation and subcarrier assignment scheme for uplink OFDMA system considering heterogeneous services under a total power constraint is proposed. The relay selection, power allocation and subcarrier assignment problem is formulated as a joint optimization problem with the objective of maximizing the system throughput, which is solved by means of a two level dual decomposition and subgradient method. The computational complexity is finally reduced via the introduction of two suboptimal schemes. The performance of the proposed schemes is demonstrated through computer simulations based on OFDMA network. Numerical results show that our schemes support heterogeneous services while guaranteeing each user's QoS requirements with slight total system throughput degradation.

Secondly, we investigate the resource allocation problem subject to the satisfaction of user QoS requirements and individual total power constraints of the users and relays. The throughput of each end-to-end link is modeled considering both the direct and relay links. Due to non-convex nature of the original resource allocation problem, the optimal solution is obtained by solving a relaxed problem via two level dual decomposition. Numerical results reveal that the proposed scheme is effective in provisioning QoS of each user's over the conventional resource allocation counterpart under individual total power constraints of the users and relays .

Lastly, decentralized resource allocation schemes are proposed to reduce the computational complexity and CSI feedback overhead at the BS. A user centric distributed (UCD) scheme and a relay centric distributed (RCD) scheme are proposed, where the computation of the centralized scheme is distributed among the users and relays, respectively. We also proposed suboptimal schemes based on simplified relay selection. The suboptimal schemes can be combined with the distributed schemes to further reduce of signalling overhead and computational complexity. Numerical results show that our schemes guarantee user's satisfaction with low computational complexity and signalling overhead, leading to preferred candidates for practical implementation.

The research results obtained in this dissertation can improve the resource utilization and QoS assurance of the emerging OFDMA networks.

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Dedication

To my father ***Md Abdul Kader***
and
my mother ***Sufia Khatun***

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List of Abbreviations

QoS	Quality-of-Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
CSI	Channel State Information
BWA	Broadband Wireless Access
LTE	Long Term Evolution
EPA	Equal Power Allocation
EPAR	Equal Power Allocation with Refinement
UCD	User Centric Distributed
RCD	Relay Centric Distributed
ITU	International Telecommunication Union
WiMAX	Worldwide Interoperability for Microwave Access
3GPP	Third Generation Partnership Project
E-UTRA	Evolved UMTS Terrestrial Radio Access
WRAN	Wireless Regional Area Networks
BS	Base Station
RS	Relay Station
eNodeB	Evolved Node B
UE	User Equipment
ISI	Inter Symbol Interference
PHY	Physical
MAC	Medium Access Control
IDFT	Inverse Discrete Fourier Transform
DFT	Discrete Fourier Transform
RLC	Radio Link Control

RRM	Radio Resource Management
WLAN	Wireless Local Area Network
RT	Real Time
NRT	Nonreal Time
RC	Rate Constrained
AF	Amplify-and-Forward
DF	Decode-and-Forward
CRC	Cyclic Redundancy Check
RB	Resource Block
CSD-RB	Channel State Dependent Round Robin
AMC	Adaptive Modulation and Coding
SC-FDMA	Single Carrier Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
SR	Source-to-Relay
SD	Source-to-Destination
RD	Relay-to-Destination
GBR	Guaranteed Bit Rate
AMBR	Aggregate Maximum Bit Rate
MRC	Maximal Ratio Combining
MINLP	Mixed Integer Nonlinear Programming Problem
KKT	Karush-Kuhn-Tucker
SI	Satisfaction Index
SNR	Signal-to-Noise Ratio
TSRS	Time Slotted Relay Selection
SRS	Single Relay Selection
CCI	Co-channel Interference
CA	Carrier Aggregation
CC	Component Carrier

List of Symbols

n	Path loss exponent
d	Distance between the transmitter and receiver
d_0	Reference distance
X_σ	Zero-mean Gaussian distributed random variable
σ	Standard deviation
a_p	Amplitude
$f_{D,p}$	Multipath Doppler frequency
φ_p	Multipath phase
τ_p	Multipath propagation delay
$\delta(.)$	Dirac impulse function
v	Terminal velocity
c	Speed of light
f_c	Carrier frequency
ϑ_p	Angle of arrival
K	Total number of users
N	Total number of relays
M	Total number of subcarriers
R	Cell radius
$P_{s,k}^m$	Transmit power of the kth user in the mth subcarrier
$P_{r,n}^m$	Transmit power of the nth relay in the mth subcarrier
$P_{t,k}^m$	Total power allocated to the mth subcarrier of the kth user
d_{SD}	Distance between source-to-destination
d_{SR}	Distance between source-to-relay
d_{RD}	Distance between relay-to-destination
$\sigma_{k,D}^2$	Noise variances of the source-to-destination links

$\sigma_{k,n}^2$	Noise variances of the source-to-relay links
$\sigma_{n,D}^2$	Noise variances of the relay-to-destination links
κ_1	GBR user class
κ_1	AMBR user class
Q_k	QoS requirement of the kth user
$R_{k,n}^m$	Achievable rate for the kth user in the mth subcarrier using the nth relay
R_k	Total achievable rate for the kth user
$\left\|h_{k,D}^m\right\|^2$	Channel coefficients between the kth user and the destination
$\left\|h_{k,n}^m\right\|^2$	Channel coefficients between the kth user and the nth relay
$\left\|h_{n,D}^m\right\|^2$	Channel coefficients between the nth relay and the destination
$\rho_{k,n}^m$	Relay selection and subcarrier allocation variable
P_T	Total power available in the network
λ	Dual variable associated with QoS constraints
μ	Dual variable for total power constraint
β	Dual variable associated with relay power constraints
δ	Dual variable corresponds to relay selection and subcarrier allocation
t	Iteration index
S_k	Set of subcarriers

Chapter 1

Introduction

1.1 Overview of Relay-based Cooperative OFDMA Systems

With the rapid development in broadband wireless access (BWA) technology and explosive growth in demand for new wireless cellular services, it is expected that the next generation cellular network will support a wide variety of communication services such as online gaming, video conferencing, real-time video, voice services, streaming media, web browsing, etc. These services have diverse quality-of-service (QoS) requirements. International Telecommunication Union (ITU) defined the emerging fourth generation (4G) networks as future IMT-Advanced system which will support heterogeneous services simultaneously. According to the performance and technical requirements of 4G networks defined in [2], future IMT-Advanced systems will provide very high peak data rates for mobile users, up to 1 Gb/s in static and pedestrian environments, and up to 100 Mb/s in high-speed mobile environment.

In order to support high-data-rate heterogeneous applications with different QoS requirements, high-spectral-efficiency schemes are required in conjunction with aggressive resource reuse strategies to ensure prudent use of the scarce radio resources. Orthogonal Frequency Division Multiple Access (OFDMA) is accepted as the most appropriate air interface for the 4G networks due to it's inherent ability to combat frequency-selective fading and higher spectral efficiency. OFDMA is a multi-user version of the popular Orthogonal Frequency Division Multiplexing (OFDM) digital modulation scheme which splits the available system bandwidth into orthogonal subbands, each supported by a subcarrier.

This allows simultaneous low data rate transmission from several users on different portions of the broadband spectrum. Each user's data is divided into several parallel data streams and modulated on the multiple subcarriers allocated to the user in an OFDMA system. Additionally, different numbers of subcarriers can be allocated to users depending on their QoS requirements. The main advantage of OFDMA is that it provides multiuser diversity by allowing subcarriers to be shared among multiple users. OFDMA is popularly used in 4G wireless systems of wideband communications such as Worldwide Interoperability for Microwave Access (WiMAX) [3], Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) [4], and Evolved UMTS Terrestrial Radio Access (E-UTRA) [5], a candidate access method for the IEEE 802.22 Wireless Regional Area Networks (WRAN), and so on.

4G networks are designed to be able to provide high throughput and support heterogeneous services with high traffic requirements. Such networks are envisaged to provide service to a cellular area in the order of Kilometers. In such large areas, users in different parts of a cell usually experience different signal qualities and users at the cell edge often suffer from bad channel conditions. Additionally, shadowing by various obstacles can degrade the signal quality significantly, specially in an urban environment. Often it is not possible to improve the signal qualities to these under-serviced areas by increasing the transmission power since it also increases the intercell interference. Reducing the cell size and deploying more base stations will improve the situation, but this is often not possible due to the associated high operating cost. The use of relay is a very promising cost effective solution to tackle this problem as it provides throughput gains as well as coverage extension [6–8]. Deploying relays is a feasible solution since typical relays are cheaper than base stations and they do not need their own wired backhaul. Fig.1.1 shows an illustration of relay deployment scenarios in cooperative cellular networks.

The introduction of relay nodes has several performance benefits [9]. A relay works on behalf of the BS to increase the network coverage. If the number of relays required and their placement are optimized, then most user-terminals will be close to one or more relays than to a BS. The primary advantages of this are as follows: 1) The path loss is lowered since the radio propagation paths are shortened. In addition, the effects of shadowing can be eliminated since the radio path essentially can be routed around obstacles. As a result, higher data rates can be achieved on the links between relays and users, and thereby increasing throughput; 2) The transmit power required for a relay to transmit to a user and vice versa is significantly lower than for a BS since relay stations are closer to the individual user terminals. This results in energy saving. Thus, the practical rationale for the deployment of relay enhanced OFDMA networks is to ensure that the QoS of a user in

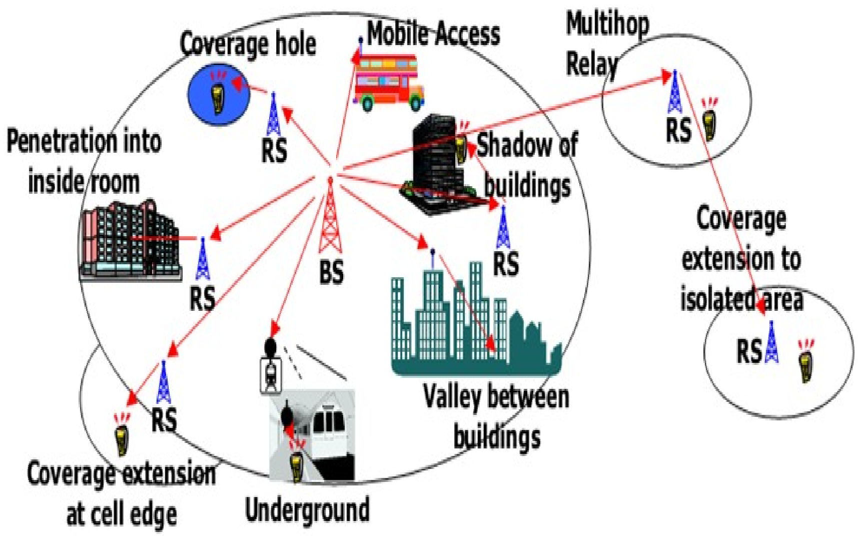

Figure 1.1: Illustration of a relay deployment scenarios in cooperative cellular networks.

terms of data rate, delay, outage probability, etc. does not wholly depend on its location and distance from the base station.

1.2 Motivation and Objectives

The combination of OFDMA and cooperative relaying assures high throughput requirements particularly for users at the cell edge. However, the introduction of relays will increase the operational complexity as the number of relays grows and uncoordinated transmission from additional relays might degrade the performance of the system by increasing the interference in the system. In a relay-based OFDMA system, spectrum efficiency can be improved and multi-user diversity can be fully exploited by efficient resource allocation, including relay selection, subcarrier assignment and power allocation. So, to fully exploit the benefits of relaying in 4G networks, efficient relay selection as well as resource allocation are crucial in multi-user and multi-relay environment.

In multi-user multi-service scenario, different users have different QoS requirements in terms of data rate, delay, etc. So, not all users require a relay to cooperate. There is no need for the relay to forward the user's data if the direct link between the user and the destination is of high quality, i.e., fulfill the QoS requirements. In such a situation, we need to address the following questions: When to cooperate?, Whom to cooperate with? and How much resource to allocate? Hence, relay selection and resource allocation in OFDMA relay systems have drawn much attention and studied heavily in recent years. Most of the existing works aim to maximize the system throughput or achieve fairness among users considering a single source-destination pair. However, it is not easy to apply resource allocation schemes for a single source-destination pair to a multi-user OFDM relay network which consists of multiple sources, multiple relays, and a destination and vice versa. Furthermore, the future network will be a network with multi-user multi-traffic (multi-service), and different services/traffics will have completely different characteristics and QoS requirements. Thus multiple traffic transmissions in future OFDMA-based cooperative relay networks have given great challenge to resource allocation and management. However, many current studies have not considered the traffic transmission in such system, especially the multi-user multi-service transmission under the QoS constraints. Additionally, relay selection and resource allocation considering QoS requirements have been studied separately in many existing literature, but these issues should be considered simultaneously for efficient resource allocation in practice. Another challenge in the design of resource allocation schemes is to reduce the computational complexity and CSI overhead at the resource allocation unit. Most existing works focus on resource allocation in cooperative communications by means of a centralized resource allocation unit which has high computational burden in terms of CSI overhead and computational complexity specially for large networks. The commercial growth of the networks with multicarrier transmission and heterogeneous traffic types strongly depends on proposing efficient resource allocation schemes that consider the aforementioned issues.

To address these issues, the objective of this thesis is to develop a relay selection and resource allocation scheme for cooperative OFDMA system considering heterogeneous applications with different QoS requirements. Specifically, we will develop a joint optimal relay selection, subcarrier assignment and power allocation scheme considering perfect CSI at the RAU under the constraints of total and individual power constraints of users and relays. Additionally, we will develop some low complexity suboptimal schemes which are suitable for the practical network. Furthermore, we will study the decentralized implementation of our proposed optimal schemes in next generation OFDMA networks.

1.3 Research Contributions

In this dissertation, we particularly focus on the issues of radio resource allocation for cooperative OFDMA based networks supporting heterogeneous applications in the avenues of QoS assurance, throughput melioration, reduction of computational complexity and system performance balancing. The research contributions of this dissertation are summarized as follows.

- **QoS aware resource allocation under total power constraints [10], [11]**: We study a QoS aware optimal joint relay selection, power allocation and subcarrier assignment scheme for uplink OFDMA system considering heterogeneous services under a total power constraint. The resource allocation problem is formulated as a joint optimization problem with the objective of maximizing the system throughput, which is solved by means of a two level dual decomposition and subgradient method. We also propose two suboptimal schemes which has reduced computational complexity. The performance of the proposed schemes is demonstrated through computer simulations based on OFDMA network. Numerical results show that our schemes support heterogeneous services while guaranteeing each user's QoS requirements with slight total system throughput degradation. Our findings reveal that how to allocate resources in a centralized fashion can affect the solution space of a performance tradeoff between QoS provisioning and throughput maximization.

- **QoS aware resource allocation under individual power constraints [12]**: We investigate the resource allocation problem subject to the satisfaction of user QoS requirements and individual total power constraints of the users and relays. The throughput of each end-to-end link is modeled considering both the direct and relay links. Due to non-convex nature of the original resource allocation problem, the optimal solution is obtained by solving a relaxed problem via two level dual decomposition. The proposed optimal resource allocation scheme with individual power constraints provides more realistic results as of practical networks. Our results show that the consideration of individual power constraints still guarantee each user's QoS requirements by sacrificing additional throughput compared to the previous scheme [11].

- **Decentralized resource allocation [13]**; The computational complexity to implement the optimal scheme by the centralized eNodeB is still very high. To reduce the time complexity and CSI feedback overhead at the eNodeB, we propose two distributed schemes, where the computation of the centralized optimal scheme is distributed among the users and relays. These schemes will significantly reduce the processing time at the eNodeB. In addition, two suboptimal schemes based on simplified relay selection are presented to reduce the signalling overhead of the distributed schemes. The suboptimal schemes can be combined with the distributed scheme to further reduce the signalling overhead. Simulation results show that our schemes guarantee user's satisfaction with low computational complexity and reduced signalling overhead, leading to preferred candidates for practical implementation.

1.4 Outline of Dissertation

Chapter 2 provides some background of wireless channel, relay system, resource allocation and discusses the preliminary literature review, which serves as a stepping stone for this research. A comprehensive description of the existing research efforts to solve similar problems is presented in this Chapter.

Chapter 3 describes the architecture of the system in detail. This includes the network model, wireless channel model, traffic model and transmission modes adopted in this thesis.

In **Chapter 4**, we focus on relay selection and resource allocation in multi-user cooperative OFDMA networks with fixed relays when users have heterogeneous rate requirements. This chapter describes the problem formulation and solution approach to solve the throughput maximization problem. Two suboptimal schemes are also presented based on equal power allocation, with and without power refinement to reduce computational complexity. The computational complexity of each scheme is also analyzed. At the end of the chapter, there is a comparison of the proposed schemes with existing schemes in the literature.

In **Chapter 5**, the resource allocation scheme under individual user and relay power constraints is presented. The revised problem formulation under individual power constraints, the transforation of the optimization problem under relaxed condition and subcarriers classifications are described. The chapter concludes by showing the performance comparisons with the previous schemes proposed in Chapter 4.

Chapter 6 describes the distributed resource allocation schemes under individual power constraints. In addition, two simplified relay selection strategies are proposed. The computational complexity and overhead analysis of each scheme are also discussed in this chapter. The performance tradeoff between throughput, QoS satisfaction and computational complexity are explained.

Chapter 7 draws the conclusions of the research and summarizes the major contributions of this dissertation. The dissertation also sheds light on the possible future research directions.

Chapter 2

Background and Literature Review

In this chapter, an overview of the OFDMA system along with a brief explanation of its operations is presented. Cooperative relaying strategies and different relay types for next generation wireless networks are discussed. Finally, a literature survey related to resource allocation in cooperative OFDMA based cellular networks is presented.

2.1 Wireless Channel

Wireless communication simply refers to the transfer of information over a wireless channel without any wired infrastructure. The wireless propagation channel constrains the information communication capacity between a transmitter and a receiver. The design of coding, modulation, signal processing schemes and multiple access scheme for wireless communication system is based on the channel model. The nature of wireless channel is generally time-varying, space-varying, frequency-varying [14], dependent on the particular environment and the transmitter and receivers location. Due to the randomness generated from each type of variations, wireless channel is extremely unpredictable and hard to analyze. Furthermore, wireless channel impairments significantly degrade the signal propagation over wireless channel. The wireless channel impairments can be categorized as the following phenomena and effects:

- Noise: Additive white Gaussian noise (AWGN) is the main impairment in any communication channel. AWGN has a constant spectral density, so it affects broadband signals more than narrow-band signals. As AWGN is additive, it can be formulated by simple and tractable mathematical models.

- Path Loss: Path loss is the reduction in power density of an electromagnetic wave as it propagates through space. Path loss is a major component in the analysis and design of the link budget of a telecommunication system. Path loss indicates how the mean signal power decays with distance between the transmitter and receiver. In free space, the mean signal power decreases with the square of the distance between the transmitter and receiver. Broadband signals experience significant path loss. In addition, path loss is worse in nonline-of-sight (NLOS) transmission. Path loss is a large-scale fading type because its effects are dominant in extended geographical networks. The combination of analytical and empirical path loss models are used to determine practical link budget [15]. For example, the log-distance path loss model is represented by

$$\bar{P}L(dB) = \bar{P}L(d_0) + 10n\log(\frac{d}{d_0}) \tag{2.1}$$

  where n is the path loss exponent, d is the distance between the transmitter and the receiver and d_0 is the reference distance.

- Shadowing: Large obstacles in the propagation path, such as buildings, hills, walls and trees, shadow the signal transmission. Compared to fast fading, longer distances have to be covered to change the shadowing constellation significantly. Shadowing phenomenon causes slow variations of a transmitted signal with respect to the signal duration, so shadowing is sometimes referred to slow fading in the literature [16]. The net path loss considering the shadowing is given by

$$\bar{P}L(dB) = \bar{P}L(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma \tag{2.2}$$

  where X_σ is a zero-mean Gaussian distributed random variable in dB with the standard deviation σ in dB.

- Multipath: The objects located around the path of the wireless signal reflect the signal. Some of these reflected waves are also received at the receiver. Since each of these reflected signals takes a different path, it has a different amplitude and phase. Depending upon the phase, these multiple signals may result in increased or decreased received power at the receiver. Even a slight change in position may result in a significant difference in phases of the signals and so in

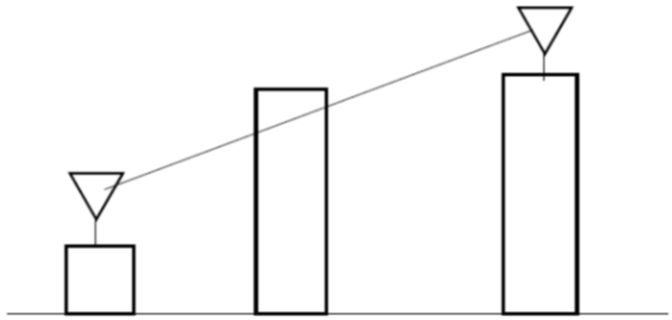

Figure 2.1: Shadowing.

the total received power. Multipath channel caused by diffraction, scattering, and reflection is shown in Fig. 2.2. Multipath propagation causes frequency

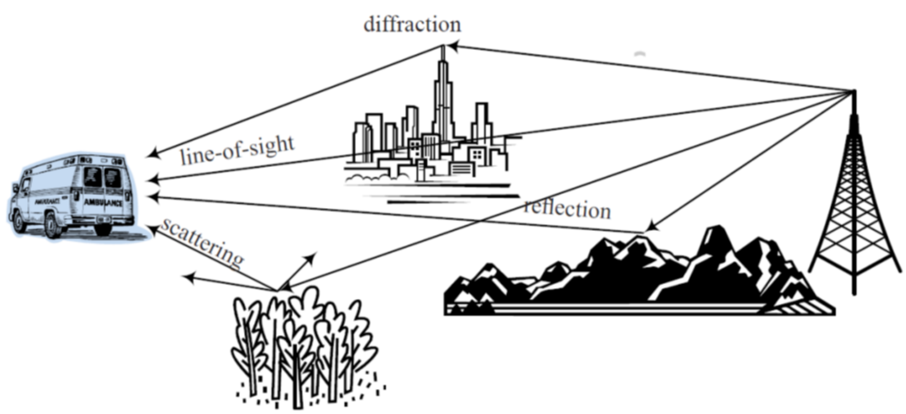

Figure 2.2: Multipath Channel.

selective fading and intersymbol interference (ISI). The frequency selectivity results from destructive interference of transmitted signal with itself due to multipath reflections. A frequency selective fading channel cause deep fading in some frequency components of the transmitted signal. The locations of the deep fades may change because the interference pattern changes with reflectors movement or changes. The effect of path loss, shadowing and multipath in the channel response are shown in Fig. 2.3 [17].

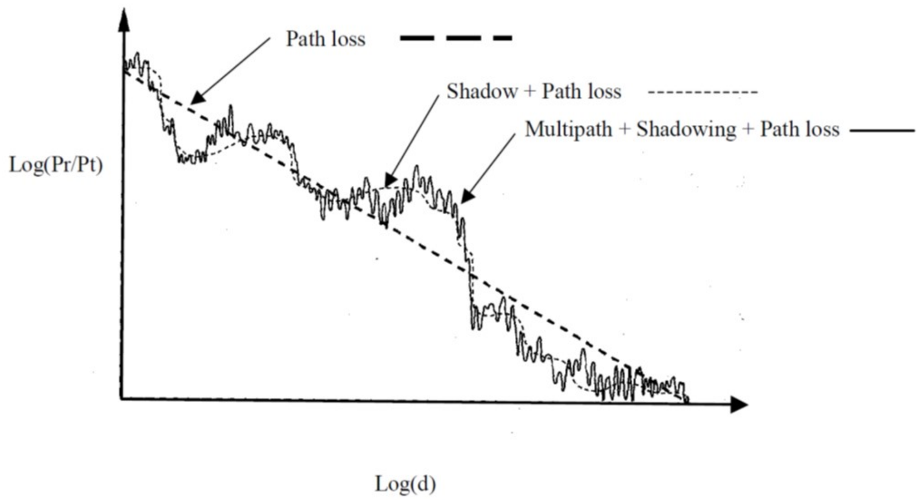

Figure 2.3: Path loss, shadowing and multipath.

– Doppler Shift: Time selectivity which is occurred due to relative motion between a transmitter and receiver causes carrier frequency dispersion called Doppler shift. Doppler shift phenomenon depends on movement speed and carrier frequency. Doppler shift reduces SNR and can make carrier recovery and synchronization more difficult for broadband signals. Doppler shift is a main concern for OFDM based networks, since it can corrupt the orthogonality of the OFDM sub-carriers named intercarrier interference (ICI) [18].

The multipath radio channel can be characterized by the time-variant channel impulse response $h(\tau, t)$. The channel impulse response represents the response of the channel at time t due to an impulse applied at time $t - \tau$. In case of mutipath propagation, the channel impulse response is composed of a large number of scattered impulses received over N_p different paths. The mutipath channel impulse response is given by [16]

$$h(t, \tau) = \sum_{p=0}^{N_p - 1} a_p(t) e^{j(2\pi f_{D,p} t + \varphi_p)} \delta(\tau - \tau_p) \tag{2.3}$$

where

$$\delta(\tau - \tau_p) = \begin{cases} 1, & \text{if } \tau = \tau_p \\ 0, & \text{otherwise} \end{cases} \tag{2.4}$$

and a_p,$f_{D,p}$,φ_p and τ_p represents the amplitude, doppler frequency, phase and propagation delay associated with the pth multipath. The delays are measured relative to the arrival of the first multipath component. The Doppler frequency is given by

$$f_{D,p} = \frac{v f_c \cos(\vartheta_p)}{c} \tag{2.5}$$

where v is the velocity of the mobile, f_c is the carrier frequency, c is the speed of the light and ϑ_p represents the angle of incidence relative to the path p.

The impact of the wireless channel is worse when the channel is broader. So, broadband wireless networks need to be designed to cope with these random variations in received signal strength due to channel impairments. There is no unique solution to all these impairments. However, OFDM is a popular choice for mitigating most of these deficits, particulary frequency selective fading, because it exploits wireless channel fluctuations and multichannel transmission flexibility for efficient transmission of broadband signals.

2.2 Overview of OFDM and OFDMA

2.2.1 Orthogonal Frequency Division Multiplexing (OFDM)

The key concept in OFDM is to split a wideband signal into several orthogonal narrowband signals for transmission. In other words, instead of transmitting digital symbols sequentially over a single wideband channel, OFDM splits this channel into many narrowband subchannels and transmits the digital symbols of longer duration in parallel over these subchannels. OFDM symbols then only undergo flat fading in each subchannel, avoid the ISI problem, and yet, still maintain the high overall data-rate. The subcarriers in an OFDM system are overlapping to maximize spectral efficiency. Ordinarily, overlapping adjacent channels can interfere with one another. However, sub-carriers in an OFDM system are precisely orthogonal to one another. Thus, they are able to overlap without interfering. As a result, OFDM systems are able to maximize spectral efficiency without causing adjacent channel interference [19]. The frequency domain of an OFDM system is represented in Fig. 2.4 .

In an OFDM system, in addition to dividing the frequency spectrum into separate parts, they are shaped as well [16], as shown in Fig. 2.5. Due to this shaping, when a subcarrier is sampled at it's peak, all other subcarriers have zero-crossing at that point. Also, they do not interfere with the subcarrier being sampled. So, data symbol transmitted over each subcarrier and received without interference. Fig. 2.6 depicts

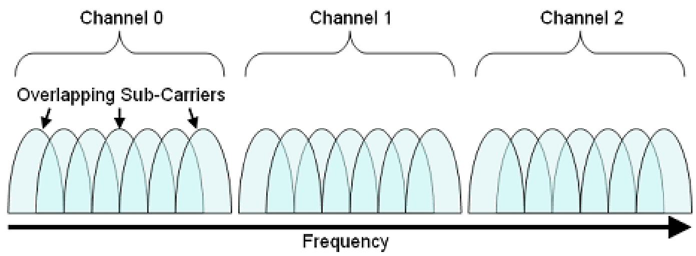

Figure 2.4: OFDM system.

a typical single user OFDM transmitter and receiver block diagram and is used as a reference for discussing the basic operation of a system that implements OFDM at the PHY(Physical) layer.

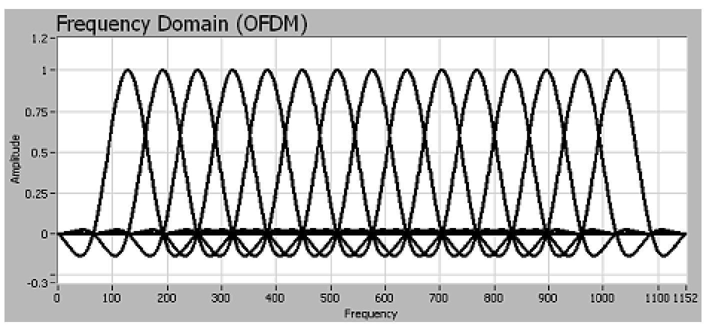

Figure 2.5: OFDM symbols represented using sinc functions.

Assuming a point-to-point transmission, as shown in Fig. 2.6, an incoming stream of data bits is first serial-to-parallel converted into N parallel substreams. Each subcarrier is then modulated by a group of bits in each of these substreams, possibly, with different modulation types. This operation results in N parallel frequency-domain symbols. After passing these N symbols through the inverse discrete Fourier transform (IDFT) operation, an N-point time-domain representation of an OFDM symbol is obtained. A guard period, also called cyclic prefix, is then added to the OFDM symbol to further prevent ISI. After, parallel-to-serial conversion, the input sequence is passed through digital-to-analog converter, then its output is transmitted to the wireless channel. At the receiving end, reverse operations occur. The guard period is first removed. The OFDM symbol then undergoes the discrete Fourier

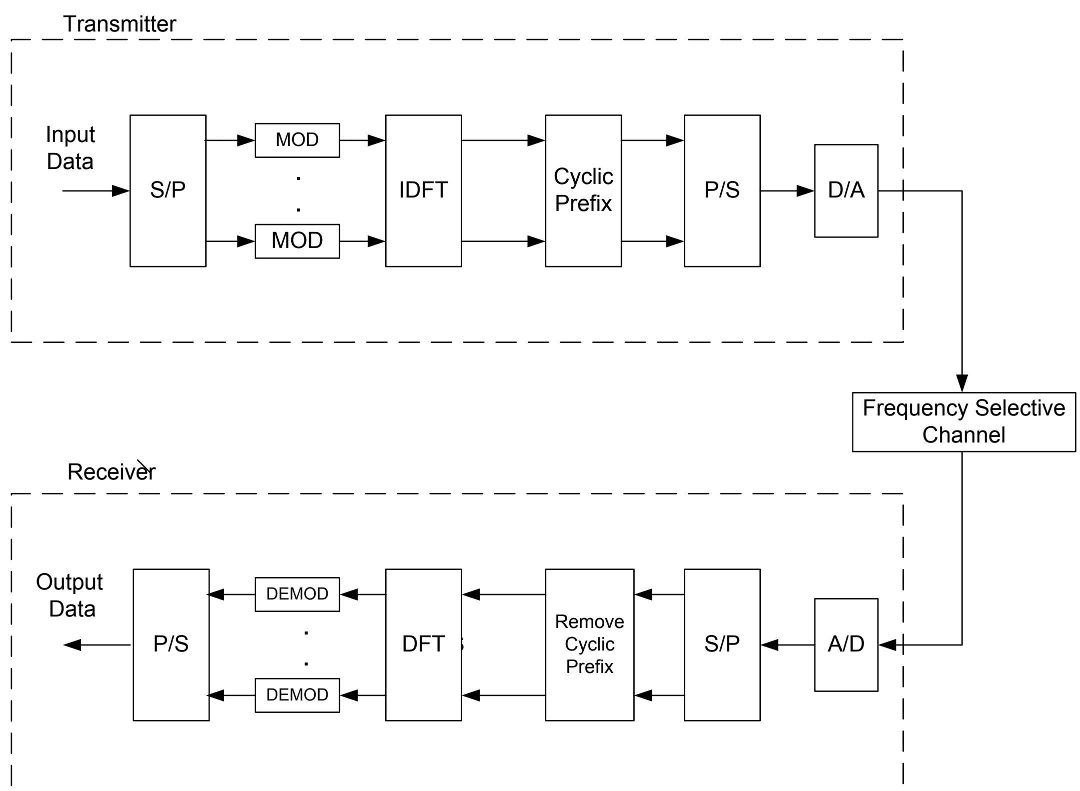

Figure 2.6: The transmitter and receiver structure of OFDM.

transform (DFT) operation which transforms the time domain representation of the transmitted OFDM symbol into the frequency domain representation of the digital symbol for each subcarrier. Each subcarrier is then demodulated accordingly to recover the group of bits for each substream.

2.2.2 Orthogonal Frequency Division Multiple Access

OFDMA is a multi-user version of OFDM. OFDM was originally proposed as a digital modulation or multiplexing technique, where all subcarriers in an OFDM symbol carried only a users' data. However, OFDM can be used as a multi-user transmission technique when subsets of subcarriers in an OFDM symbol are assigned to different users' transmission [20]. Multi-user transmission is possible because of the orthogonality of OFDM subcarriers. In OFDMA, each user is assigned a subset of subcarriers for the duration of allocated time slots. Both time and frequency dimensions thus are exploited in OFDMA.

OFDMA is superior to traditional multiple access mechanisms such as TDMA and CDMA in terms of ability to exploit multiuser diversity [21]. Multiuser diversity is fully exploited in OFDMA by allocating different portions of bandwidth along with transmission power and modulation type for a particular duration of allocated time slots to those users who can best utilize the resources. OFDMA superiority in multiuser diversity gain stems from the fact that the utilization of given resources varies from one user to another. A subcarrier may be in deep fading for one user (e.g., the second subcarrier for user K in Figure 2.7) while it is not for another subscriber (e.g., the same subcarrier for user 1). Allocating this particular subcarrier to the user with higher channel gain permits higher transmission rate. However, to achieve multiuser diversity gain, a scheduler at the MAC sublayer is required to schedule subscribers in appropriate frequency and time slots. Due to the fine granularity of resources units (i.e. subcarriers), OFDMA is quite flexible in terms of resource allocation. The block diagram of OFDMA transmitter and receiver at PHY and MAC operations are shown in Fig. 2.7 [22].

2.3 Relay-based OFDMA

While OFDMA mitigates the channel small-scale fading (e.g., multipath caused ISI), it does not overcome the channel large-scale fading (i.e., propagation loss and shadow-

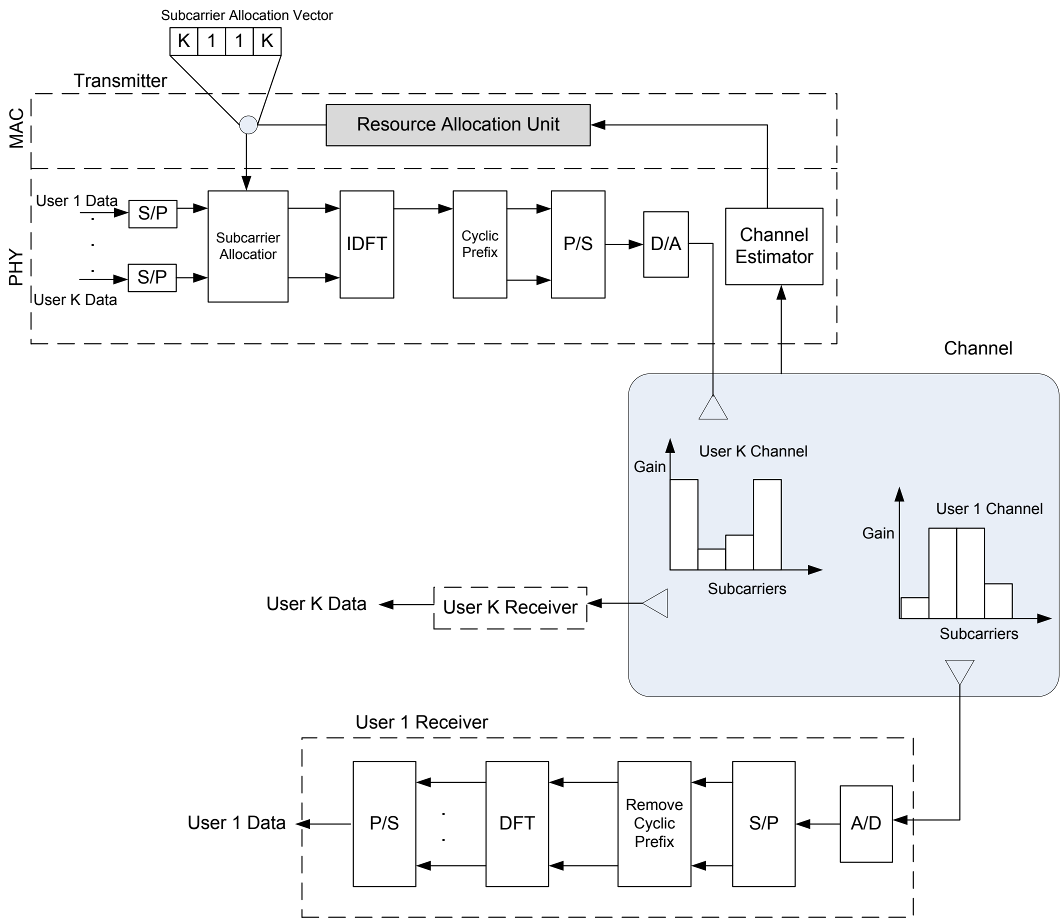

Figure 2.7: OFDMA transmitter and receivers PHY structure and MAC operations.

ing). One of the main challenges faced by 4G networks is to provide high throughput throughout the entire cell. Relaying is a promising solution that overcomes challenges faced by conventional cellular networks. Relaying does not only provide radio coverage extension to cellular networks but also compacts shadowing, enhances capacity through exploiting spatial diversity, and effectively reduces the infrastructure deployment cost [7,23]. As a hot research topic with great application potential, relay technologies have been actively studied and considered in the standardization process of next-generation mobile communication systems, such as 3GPP LTE-Advanced [5] and IEEE 802.16j [3]. The combination of OFDMA and cooperative relaying assures high throughput requirements particularly for users at the cell edge. A relay based OFDMA cellular network architecture is shown in Fig. 2.8.

According to 3GPP, the use of relays will allow the following improvements.

- Provide coverage in new areas
- Temporary network deployment
- Cell-edge throughput
- Coverage of high data rate
- Group mobility

These improvements can be grouped as coverage extension and throughput enhancement. In addition to the previous improvements, the use of relays brings the following advantages.

- **Cost Reduction:** While the base station connects to the backhaul network through wired connection, relay stations connect wirelessly to the base station. Due to the lack of a wired backhaul, the backplane cost and time should be reduced, compared to a base station. Backplane cost includes, land-line network deployment cost, land lease or purchase to run links, construction, permitting, or the cost of using other service providers deployed networks. Additionally, the cost of a relay, by itself, is less than the cost of a base station, assuming that the complexity of a relay is less than the complexity of a base station. In sub-urban areas where land-line network deployment can be financially expensive and the number of subscribers is not large enough to motivate such costly coverage extension, relay stations placement is cost effective alternative to placing a new base station.

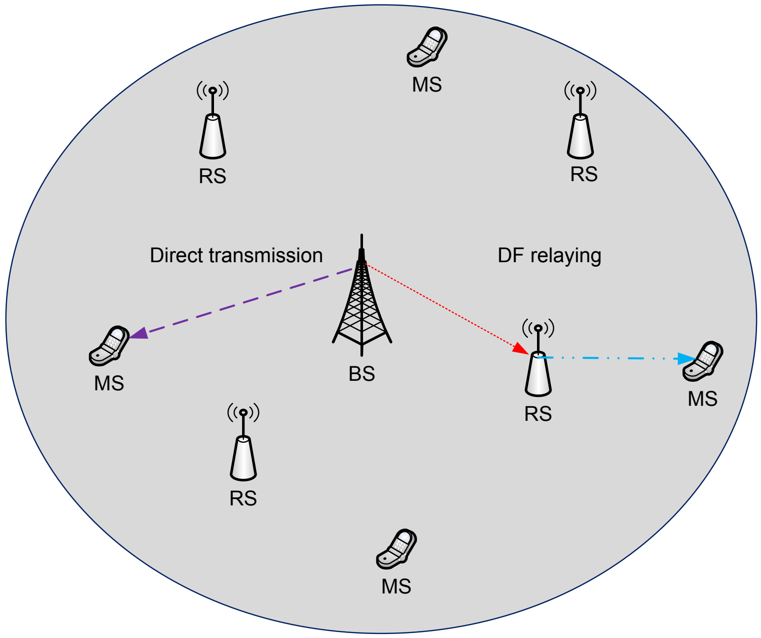

Figure 2.8: An architecture of a relay based OFDMA cellular networks.

– **Power consumption reduction:** By using relay, the single-hop distance between the base station and the user terminal is divided into two distances: the distance from the base station to the relay, and the distance from the relay to the user terminal. If the relay is placed in an appropriate locations, the required transmit power by the base station, relay, and user terminal can be reduced. The power consumption reduction can be simply due to the reduction of the path loss, while further reductions can be achieved through enhanced relaying schemes and interference control. This power consumption reduction also translates into reduced operational costs.

– **Efficient utilization of resources:** Efficient utilization of resources rely on intelligent allocation of frequencies, codes, or time slots in cellular based radio systems. The desired utilization can be achieved by reusing the resources. For instance, completely different frequency channels can be assigned to the neighboring cells to avoid co-channel interference and the same frequency channels can be assigned to the distant cells as long as the distance is large enough to keep the interference within tolerable levels. In addition, Cell sectoring can be used to further reduction of the co-channel interference by using directional antennas, each radiating within a specific sector. Hence, the interference is reduced to a fraction of the co-channel cells rather than the whole co-channel cells [15]. Similarly, relay stations radiate within a limited spatial area causing low co-channel interference to relay stations operating on the same resources (i.e., frequencies, codes, time slots).

2.3.1 Relay Types

It is envisaged that a plethora of relay stations (RS) of different specifications, functionalities, and geographical densities, will be part of the next-generation cellular network architecture. Two types of RSs have been defined in 3GPP: Type-I and Type-II [1]. Specifically, a Type-I RS can help a remote UE (mobile station) unit, which is located far away from an eNodeB (base station), to access the eNodeB. So, a Type-I RS needs to transmit the common reference signal and the control information for the eNodeB, and its main objective is to extend signal and service coverage, as shown in Figure 2.9. Type-I RSs mainly perform IP packet forwarding in the network layer and can make some contributions to the overall system capacity by enabling communication services and data transmissions for remote UE units.

On the other hand, a Type-II RS can help a local UE unit by improving its service quality and link capacity, which is located within the coverage of an eNodeB and has a direct communication link with the eNodeB. So, a Type-II RS does not transmit the common reference signal or the control information, and its main objective is to increase the overall system capacity by achieving multipath diversity and transmission gains for local UE units.

Relaying can be realized at the different layers of the protocol stack [24]. A Layer 1 (L1) relay is also called a repeater. It takes the received signal, amplifies it and forwards it to the next hop, which may be another RS or UE. As its name implies, it works at the L1 of the protocol stack and implements (part of) the PHY layer. However, L1 relays amplify not only the desired signal but also noise and interference. Their advantage is that they can do the forwarding almost immediately, which translates into a small delay that appears as more multipath to the UE.

A Layer 2 (L2) relay is also called decode and forward relay. It works up to the Medium Access Control (MAC) and Radio Link Control (RLC) layers, which enables the relay to perform radio resource management (RRM) functions, i.e. distributed/decentralized RRM. Due to the extra functions performed by an L2 relay, a more significant delay is introduced compared to an L1 relay.

A Layer 3 (L3) or higher layer RSs could almost be considered as wireless eNodeBs

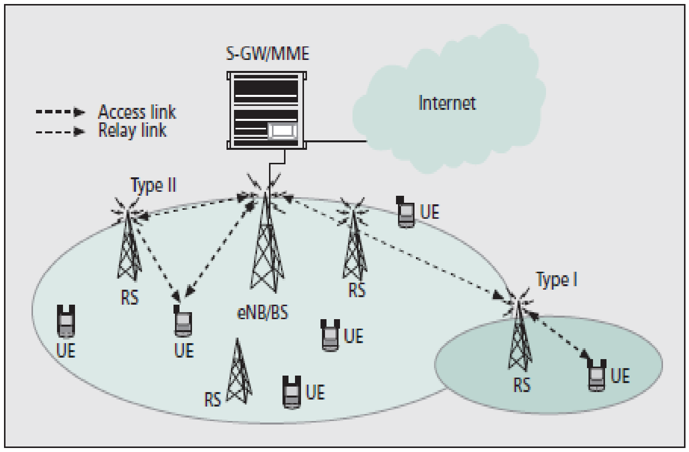

Figure 2.9: Relay Types in next generation cooperative networks [1]

and support all the protocol layers of normal eNodeBs, except that they will not require an expensive backhaul as in a normal eNodeB, and they are assumed to have low transmission power capabilities. In this case the wireless backhaul link would require high efficiency and the signaling overhead will be higher, compared to the L1 and L2 relays.

Relay can be static or dynamic. Static association limits the system to support only stationary RSs, and thus mobile RSs cannot be used. The LTE architecture with dynamic relaying is proposed in [25]. In dynamic relaying, relays can be associated with base stations on a need basis rather than in a fixed manner which is based only on initial radio planning. In order to enable dynamic backhauling, a mechanism is needed for the RSs to discover relay-enabled eNodeBs that can act as their donor eNodeBs. The eNodeBs that support relaying can inform RSs about their relaying capability by including this information in the message blocks they broadcast regularly to the whole cell. This will not affect backward compatibility as the UEs can simply ignore this extra information.

Home eNodeB is also considered as a relay in LTE-Advanced network. 3GPP is currently standardizing home eNodeBs, also known as femto-cells [25]. Home eNodeBs are small base stations for use within indoor environments to improve coverage and capacity which are similar to WLAN access points, and will be installed in residence and office buildings where there is already an access to Internet, for example, via a wired system. They will appear as normal eNodeBs to the UEs and they will access the core network of the operator via the Internet. Home eNodeBs seem to be an attractive solution for nonreal time (NRT) services as well as some real time (RT) services that does not have very strict QoS requirements.

RSs can operate in inband or outband. In the inband case, the backhaul link between the RS and eNodeB uses the same frequency band that the donor eNodeB uses in the donor cell. In the outband case, this backhaul link will use another frequency band or any other type of wireless link. A combination of inband and outband will allow several interfaces for the backhaul link, which allows provisioning load balancing and high availability.

2.3.2 Relay Transmission Schemes

Many relay transmission schemes have been proposed to establish two-hop communication between an eNodeB and a UE unit through an RS [26, 27]. In conventional relaying, for example, the UEs are receiving data either from the serving eNodeB or the RS. However, in cooperative relaying, the UEs can receive and combine the signals from several RSs and the eNodeB.

Amplify and Forward

In this scheme, an RS receives the signal from the eNodeB (or UE) in the first phase, then it amplifies this received signal and forwards it to the UE (or eNodeB) in the second phase as shown in Fig. 2.10. The base station combines the information sent by the UE and RS, and makes a final decision on the transmitted bit. The Amplify and Forward (AF) scheme is very simple and has very short delay, but it also amplifies noise. Although noise is amplified by cooperation, the eNodeB receives two independently faded versions of the signal and can make better decisions on the detection of information.

Decode and Forward

In this scheme, an RS decodes (channel decoding) the received signal from the eNodeB (or UE) in the first phase. If the decoded data is correct using cyclic redundancy check (CRC), the RS will perform channel coding and forward the new signal to the

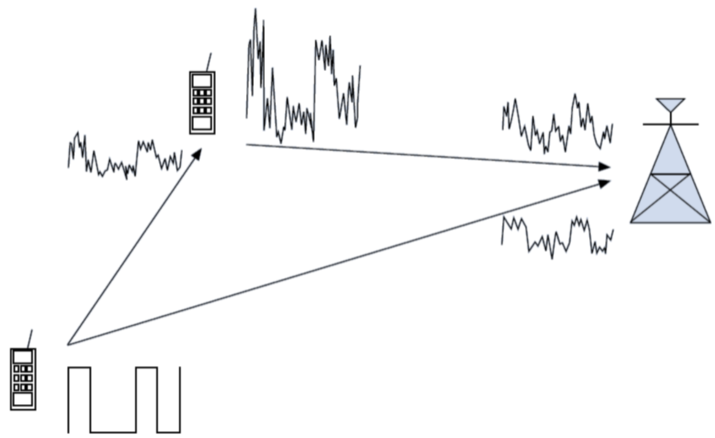

Figure 2.10: Amplify and forward

UE (or eNodeB) in the second phase. This scheme is shown in Fig. 2.11. This Decode and Forward (DF) scheme can effectively avoid error propagation through the RS, but the processing delay is long. This scheme has the advantage of simplicity and adaptability to channel conditions. However, it is possible that detection by the RS is unsuccessful, in which case cooperation can be detrimental to the eventual detection of the bits at the eNodeB.

Demodulation and Forward

In this scheme, an RS demodulates the received signal from the eNodeB (or UE) and makes a hard decision in the first phase (without decoding the received signal). It modulates and forwards the new signal to the UE (or eNodeB) in the second phase. This Demodulation and Forward (DMF) scheme has the advantages of simple operation and low processing delay, but it cannot avoid error propagation due to the hard decisions made at the symbol level in phase one.

2.4 Resource Allocation in Cooperative OFDMA Networks

From the radio resource allocation point of view, the performance of OFDMA transmission systems can be optimized through three main mechanisms: (1) scheduling,

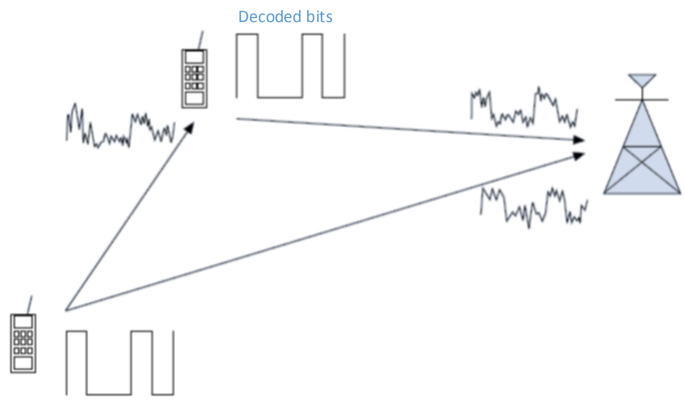

Figure 2.11: Decode and forward

(2) relay selection, and (3) power allocation. These basic resource allocation schemes are discussed in the following subsections.

2.4.1 Scheduling

A scheduling algorithm is responsible for allocating the available radio resources (e.g., subcarrier) among the users in an OFDMA symbol duration. Scheduling is the main component of the MAC layer that helps to assure QoS to various service classes. The scheduler works as a distributor to allocate the resources among users. The allocated resource can be defined as the number of resource block (RB) as defined in LTE, where each RB is a group of multiple physical subcarriers. After the scheduler logically assigns the resource in terms of number of RBs, it may also have to consider the physical allocation, e.g., the subcarrier allocation. In systems with OFDM PHY, the scheduler considers the modulation schemes for various subcarriers and decides the number of subcarriers allocated. Based on user's service classes, the scheduler needs to take into consideration the fact that a subset of subcarriers is assigned to each user. The goal is to minimize power consumption and bit error rate and to maximize the total throughput.

Based on different network criteria, different scheduling policies are available for the selection of users to be served. The most common scheduling algorithms are the following:

- Round-robin scheduler: The Round-robin scheduler is a user-centric and fairness-conscious scheduler. It assigns the same amount of physical resources to users in turn. Conventional round-robin scheduler does not guarantee quality of service, since it does not consider the queue state and the channel variability in the scheduling policy, thereby sacrificing the inherent multiuser diversity and achievable network capacity.

- Max-min scheduler: This scheduler maximizes the usage of resources while ensures fairness of transmission rate. In this case, all flows at the bottleneck link are assigned with fair rates, and then the scheduler tries to maximize the rates of all flows [28].

- Max-SINR scheduler: This scheduler fully exploits multiuser diversity inherent in the OFDMA network. This is the best in terms of total capacity maximization at the price of fairness.

- Proportional-fair scheduler: This scheduler provides an intermediate solution between multiuser diversity and fairness. It exploits the multiuser diversity gains while maintaining fairness across users. In this scheduler, subcarriers are allocated to the user which maximizes the ratio of its achievable rate to its exponentially weighted average rate on that subcarrier. However, queue stability is not guaranteed in proportional fair scheduling even for low traffic loads.

Additionally, many other schedulers such as the fair throughput, early-deadline-first, Channel State Dependent Round Robin (CSD-RR) and energy efficient schedulers, are also discussed in the literature [29, 30]. Among them, the early-deadline-first scheduler is particularly suitable for real-time applications since priority services are allowed in this scheduler. A survey of the state-of-the-art of scheduling approaches in conventional OFDMA-based systems is provided in [31]. The future cooperative OFDMA-based networks have many optimization parameters and the scheduling techniques mentioned above may not deliver optimum performance in such networks.

2.4.2 Relay Selection or In-Cell Routing

Relay selection is a key issue of cooperative networks. This can be viewed as the process of establishing efficient connectivity between nodes over multihop links allowing coverage extension, throughput, and fairness improvement. Relay selection schemes are extensively studied in the last few years. In general, relay selection can be classified into two categories, either multiple-relay selection or single relay selection. In the former, more than one relay is selected to help a user for cooperative transmission, whilst in the latter only one relay is selected. In [32], several relay selection scheme for both of single relay selection and multiple relay selection scheme are discussed. The performance of multiple-relay participation is fundamentally limited by the orthogonal partitioning of system resources, inefficient usage of power, or difficult synchronization among cooperative nodes [33]. To overcome these problems, opportunistic relay selection is preferred in many cases. According to opportunistic relaying [34], a single relay among a set of relay nodes is selected, depending on which relay provides the "best" end-to-end path between source and destination.

In the single-relay selection category, many selection criteria have been proposed, such as the distance-based criterion where the relay nearest to the source was selected, the utility-based criterion where ratio of throughput to the source power was considered, the outage probability based strategy where a relay giving rise to the minimum outage probability was selected, the power-aware strategy where a relay with the least power consumption is selected, the channel quality based strategy where the relay node providing the maximum end-to-end channel quality was selected, or equivalently the mutual information based strategy provided that transmit powers of nodes were predetermined. Different relay selection criteria for OFDMA and non-OFDMA based wireless networks are discussed in [35–37].

Since different selection schemes are expected to differently affect the system performance in terms of throughput, delays, and signaling overhead, several relay selection strategies and relaying criterion are employed in the resource allocation schemes as an initial step followed by scheduling user packets on the chosen path(s). However, performing joint routing and scheduling is known to produce superior performance results, as compared with decoupled scheduling and routing. Therefore, resource allocation in cooperative OFDMA networks is indeed a joint scheduling and routing problem. However, it is quite challenging to devise efficient resource allocation schemes that tackle the joint problem.

2.4.3 Power Control

Transmit power control is an important interference combating mechanism. It is regarded as a means for improving the network throughput by reducing the co-channel interference and facilitating frequency reuse. The purpose of transmit power control is not only to optimize the throughput but also to meet the power constraint. In general, the transmitted power at an UE is limited. As a result, the maximum power allowable is introduced as one of the constraints. Least amount of transmission power is preferred for mobile users due to their limited battery capacities and also to reduce the radio interference. Additionally, the resource allocation schemes earmarked for the future wireless systems are envisioned to be aggressive in reusing the scarce licensed spectrum enabling the operation of many active devices ranging from nomadic relays to femtocell access points [33]. It is essential for such dense and inevitably frequency reuse-aggressive networks to employ efficient mechanisms to mitigate the co-channel interference and to provide prudent energy utilization which is important in terms of the so-called green wireless initiative in designing future wireless networks.

2.5 Previous Works in Resource Allocation for Cooperative OFDMA Networks

Resource allocation algorithm for non-OFDMA relay networks are well studied. Resource allocation in OFDMA-based cellular networks without relay has been introduced in [38,39]. Choosing the best relay and allocating the resources in an OFDMA relay network with single user and multiple relays are straightforward and presented in [40]. In [40], each relay node operates in a time-division half duplex mode using the amplify-and-forward protocol. A joint allocation of three resources (power, subcarriers and relay nodes) is described. The objective is to maximize the end-to-end transmission rate subject to individual or total power constraints. The problem is formulated as a subcarrier-pair based resource allocation and solved using dual method which is asymptotically optimal. However, the network model considers only single user without minimum rate requirements. Under the sum-rate maximization objective without QoS requirements, users with bad channel conditions are starved since all resources are assigned to users with good channel conditions.

In the presence of multiple users and multiple relays, relay selection and resource allocation are complicated due to the interactions among the users. A downlink single-cell network with multiple fixed RSs is studied in [41]. The objective of this work is to maximize the total average throughput of both the direct and relayed links. Authors proposed two algorithms to improve the overall cell-throughput while maximizing the total average throughput of both links. In both algorithms, relays are always used by the BS in the second phase. The first algorithm is a suboptimal algorithm which performs subcarrier allocation with a predetermined equal power allocation. The second algorithm is an optimal joint power and subcarrier allocation algorithm. Simulation results show that with the increase of relay stations, the sum rate is increased, while the joint optimal allocation algorithm continues to outperform the fixed power allocation algorithm. When no relays are used, the joint algorithm provides a marginal gain especially at high SINR regime, and the power allocation part becomes equivalent to water-filling.

An isolated relay assignment and power allocation scheme for cooperative networks for homogeneous traffic is proposed in [42]. A heuristic algorithm is presented to find a near optimal relay assignment and power allocation where each user is supported by a single relay. However, this scheme can not achieve the optimal solution because of the isolated design approach and the relay selection criterion only based on the maximum allocated power. In [43], the authors use the Lagrange dual-decomposition method to show that a modified water-filling algorithm can solve the optimal power-allocation with fixed subchannel allocation. However, if AMC is used, power allocation does not contribute much to system performance improvement. In [44], a utility based resource allocation in OFDMA relay networks, considering service differentiation, is proposed. The authors formulate a joint optimization problem for the relay selection, subcarrier assignment and power allocation but only solved it heuristically.

Since mobile stations have limited resources, efficient resource allocation is very important for the uplink system. There have been numerous research works considering the downlink OFDMA systems [41, 44–47]. However, those algorithms may not be applicable for the uplink due to the distributive nature of power constraints [48]. A survey on resource allocation schemes for the uplink OFDMA system is presented in [49]. A multi-user joint distributed resource allocation scheme for uplink cooperative OFDMA system is proposed in [50]. They provided an optimal solution and distributed implementation based on the primal-dual decomposition method. However, relay selection is performed for each user and all subcarriers allocated to that user use the same relay. Also, they did not consider each user's QoS requirement in their joint design.

A most recent work [51] proposed a low complexity suboptimal algorithm for subcarrier assignment, power allocation and partner selection for amplify-forward cooperative multicarrier systems where mobile station works as a relay. They consider a network that consists of multiple cooperative pairs that employ a two phase cooperation scheme. In phase I, the users first transmit their own message on each of their subcarriers and relay the message of their partners in phase II. The resource allocation problem is solved in three steps. First, the authors proposed a relaxed problem formulation and derive the optimal power allocation. Second, an efficient subcarrier allocation policy is then derived based on the resultant power allocation. Third, with the subcarrier allocation scheme, they further developed an iterative suboptimal solution for the joint allocation of power among both phases. However, homogeneous users with same service and demand are considered.

Resource allocation supporting each user's QoS requirements has been considered in several works [23, 37, 48]. In [23], a rate adaptive joint subcarrier and power allocation algorithm under interference and QoS constraints is proposed for cooperative OFDMA based broadband wireless access networks. However, the problem is solved heuristically. A cross layer approach for uplink OFDMA based cellular networks supporting heterogeneous services is introduced in [48]. The authors formulated two different optimization problems to support two types of uplink flows and determined cross-layer trade-off between uplink service rate and power consumption of users. Finally, they solved the problem using dual decomposition. In addition, Optimal and suboptimal resource allocation schemes considering user QoS requirements for the uplink are proposed in [11,52,53]. These schemes are designed assuming a single total power constraint for all the users and relays, as this assumption allows classifying subcarriers into non-cooperative or cooperative mode in advance. However, this assumption limits the applicability of these schemes in realistic scenarios, since each user and relay have separate individual total power constraint for the uplink communications. Furthermore, with individual total power constraints, subcarrier classification is complicated since it depends not only on the channel conditions, but also on the user and relay power constraints. The power allocation scheme proposed in [40, 54] optimizes throughput under individual power constraints. However, the system consists of a single user, and the user's QoS requirements are not considered.

Moreover, resource allocation in cooperative networks can be performed in a centralized manner [46,55] or distributed manner [50,56] or semi-distributed manner [57]. In centralized allocation, resource allocation decisions are made at a central entity, i.e., BS. Centralized scheduling can reduce the complexity of RSs, but has a high system overhead for control message exchange, since the BS requires full knowledge of the CSI of each link as well as the queue length in every RS, while every RS needs to be informed about the BSs allocation. Converse to centralized resource allocation, both users and RSs have more autonomy in making transmission decisions in distributed schemes and semi-distributed allocation is the combination of both the centralized and distributed resource allocation.

A relay centric distributed resource allocation scheme is proposed in [56]. In the proposed scheme, each relay can calculate it's own power based on the information available from neighbouring nodes and hence can reduce the overall signalling overhead as well as processing complexity at the BS. However, a user is allowed to use maximum of two relays and user QoS requirements are not considered in the joint objective.

In [57], a semi-distributed resource scheduling scheme for multi-cell OFDMA downlink systems with DF relaying is proposed. Using dual decomposition, the optimization problem is separated into a master problem and several subproblems which can be solved by the proposed semi-distributed iterative algorithm. Each BS solves its own problem by utilizing its local CSI and exchanges partial interference information with all BSs through the concept of pricing. Therefore, the computational complexity at the BS and the CSI feedback overhead are both significantly reduced compared to optimal centralized scheduling which requires global CSI.

2.6 Chapter Summary

Extensive research has been done for resource allocation in OFDMA networks with and without relay. However, these works cannot be directly applied to a cooperative multi-user OFDMA networks which has diversified QoS requirements. So, developing a resource allocation scheme which strikes a balance between optimality of resource utilization and computational complexity, while guaranteeing QoS requirements and satisfying constraints related to 4G technologies, is still an open issue. Our work will focus on developing a practical resource allocation schemes for next generation broadband wireless access networks addressing practical issues such as limited computational power, and the support of multiple services with diverse QoS requirements by employing cooperative transmission technologies.

Chapter 3

System Model

3.1 Network Model

We consider a single cell relay enhanced OFDMA-based uplink system with K users (UE) ($1 \leq k \leq K$) and N fixed relays ($1 \leq n \leq N$), where relays are shared by all users. The cell is divided into two ring shaped boundary regions and users are uniformly distributed between inner and outer boundaries. The reason is that the users located between inner boundary and outer boundary may require relays in most cases due to heavy blockage and long distance transmission [58]. Users located inside the inner boundaries are not considered because they do not require relays in most cases due to good channel condition since they are closer to the eNodeB. Resource allocation for these users may be done separately with simple algorithm. The distance of the relays from the base station (eNodeB) is δR and the relay's angle relative to the base station is uniformly distributed in $[0, 2\pi]$, where R is the radius of the cell and δ is the distance factor. The cell spectrum is divided into subbands, each supported by a subcarrier. The subcarriers are grouped into resource blocks (RB). Each RB consists of 12 subcarriers. The total number of subcarriers used in the system is M ($1 \leq m \leq M$). The transmit power of the kth user in the mth subcarrier is $P_{s,k}^{m}$, and the transmit power of the nth relay in the mth subcarrier is $P_{r,n}^{m}$. Assume that each node is equipped with a single antenna and the relays operate in a half duplex mode. The system model is shown in Fig. 3.1.

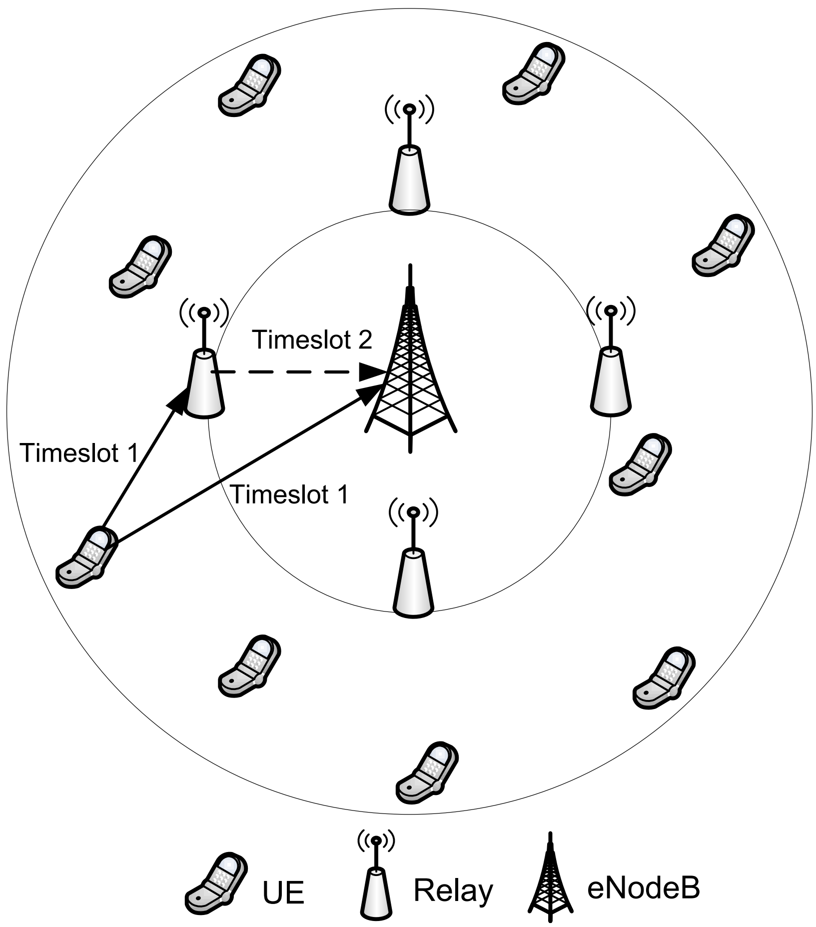

Figure 3.1: System Model

3.2 Channel Model

Since radio signals are transmitted in an open space, they suffer from signal reflection, diffraction, and scattering. In this thesis, we consider both large scale path loss attenuation and small scale fading in the channel model. Path loss attenuation is mainly determined by the geographical environment and distance between the receiver and the transmitter. 3GPP suggests several propagation models for predicting path loss [59]. In noncooperative networks, a single path loss model is used for macro eNodeB to UE connection which is based on the traditional formulae for NLOS propagation environment. A new large scale fading model is proposed in 3GPP Release 10 for relay backhaul link (eNodeB-to-RS) and access link (RS-to-UE). Those models are based on the real measurements reflecting the typical relay deployment. In this thesis, we assumed the following path loss models based on [59] considering NLOS communication for all links at 2 GHz band.

$$\begin{aligned} PL_{SD}[dB] &= 131.1 + 42.8 \log_{10}(d_{SD}) \\ PL_{SR}[dB] &= 145.4 + 37.5 \log_{10}(d_{SR}) \\ PL_{RD}[dB] &= 125.2 + 36.3 \log_{10}(d_{RD}) \end{aligned} \tag{3.1}$$

where d_{SD} d_{SR} and d_{RD} in Km are the source-to-destination (SD), source-to-relay (SR), and relay-to-destination (RD) separation, respectively. The log-normal shadowing of an 8dB standard deviation are assumed. The broadband channel is assumed to be frequency-selective Rayleigh fading channels with exponential power delay profile based on ITU pedestrian B model [4]. The channels for different users in each subcarrier are assumed to be independent. Then the effective channel gain over an RB is deduced from the subcarrier granularity. Relay selection is performed per RB since RB is the smallest resource unit for the next generation network (for example, LTE). We assumed that the destination node (eNodeB) has perfect channel state information (CSI) of all links. The noise variances of the source-to-relay (SR) links, relay-to-destination (RD) links and source-to-destination (SD) links per subcarrier are denoted by $\sigma^2_{k,n}$, $\sigma^2_{n,D}$, and $\sigma^2_{k,D}$, respectively.

Table 3.1: Channel parameters for ITU pedestrian B model

Tap	Relative delay (ns)	Average power (dB)
1	0	0
2	200	-0.9
3	800	-4.9
4	1200	-8
5	2300	-7.8
6	3700	-23.9

3.3 Traffic Model

The next generation networks are expected to support various kinds of applications with different QoS requirements. We consider two types of users, Guaranteed Bit Rate (GBR) users and Aggregate Maximum Bit Rate (AMBR). The users are differentiated on the basis of minimum required data rate. GBR users have a specific rate requirement (e.g., real-time gaming) and AMBR users have a flexible service rate (e.g., best-effort and non-real-time service). The GBR users are represented by user class κ_1, which have specific rate requirements (also called rate constrained (RC) user) and the AMBR users under the user class κ_2, which have a flexible service rate requirements. The traffic class of a user is determined based on the applications. The minimum QoS requirement of the kth user is denoted by Q_k.

3.4 Transmission Mode

Both the cooperative and non-cooperative transmission modes are considered in our proposed schemes. Based on QoS requirement, a user can transmit directly to the destination or transmit using cooperative communication. In cooperative scenario, the communication between the user and the eNodeB is carried out in two phases. In the first phase, the user transmits to the eNodeB which is overheard by the selected relay as well. In the second phase, the selected relay forwards to the eNodeB using the regenerate-and-forward cooperative protocol. The data received in both time slots are combined together by the eNodeB using maximal ratio combining (MRC) [60].

The achievable rate in bits/sec/Hz for the regenerate-and-forward scheme for the kth user in the mth subcarrier when the nth relay is selected is given by

$$R_{k,n}^m = \begin{cases} \frac{1}{2}\min\left[\log_2(1+P_{s,k}^m\alpha_{k,n}^m)\ ,\right. \\ \left.\log_2(1+P_{s,k}^m\alpha_{k,D}^m + P_{r,n}^m\alpha_{n,D}^m)\right], \text{cooperative mode} \\ \log_2(1+P_{s,k}^m\alpha_{k,D}^m), \quad \text{non-cooperative mode} \end{cases} \tag{3.2}$$

where $\alpha_{k,D}^m = \frac{\left|h_{k,D}^m\right|^2}{\sigma_{k,D}^2}$, $\alpha_{k,n}^m = \frac{\left|h_{k,n}^m\right|^2}{\sigma_{k,n}^2}$ and $\alpha_{n,D}^m = \frac{\left|h_{n,D}^m\right|^2}{\sigma_{n,D}^2}$ and $\left|h_{k,D}^m\right|^2$, $\left|h_{k,n}^m\right|^2$ and $\left|h_{n,D}^m\right|^2$ are the channel coefficients between the kth user and the destination, the kth user and the nth relay and the nth relay and the destination in the mth subcarrier, respectively.

We consider binary relay selection and subcarrier allocation characterized by the parameter $\rho_{k,n}^m$, where $\rho_{k,n}^m = 1$ means that relay node n performs as a relay for user k in the mth subcarrier. Otherwise, it is equal to 0. We assume that each user can have only one relay, but each relay can support several users and a subcarrier is allocated to only one source and one relay, so that there is no interference between sources. The same subcarrier will be used by the relay in the second time slot.

3.5 Chapter Summary

In this Chapter, we present the system model under consideration in this thesis. In specific, we focus on an uplink transmission of a single cell relay enhanced OFDMA networks. We consider both GBR and AMBR users, where half of the users are GBR users, which are selected randomly from the total set of users. Multipath Rayleigh fading channel with exponential power delay profile based on ITU pedestrian B model [4] is considered for small scale fading model.

Chapter 4

QoS Aware Resource Allocation under Total Power Constraint

4.1 Introduction

Resource allocation is a very broad topic in telecommunication field due to the extended scope of targets, e.g., diverse service provisioning, different infrastructure accommodation, or mobility support and various forms of relays. In this chapter, we focus on relay selection and resource allocation in multi-user cooperative OFDMA networks with fixed relays when users have heterogeneous rate requirements. The joint relay selection and resource allocation for the uplink OFDMA based system is investigated. The resource allocation problem is formulated as a maximization of the total system throughput by satisfying the individual users' QoS requirements subject to a total power constraint. A major challenge in solving the optimization problem is non-convexity caused by the combinatorial nature of sub-carrier assignment problem and/or non-convex objective functions. By relaxing the integer constraints, we derive an optimal solution for this relaxed problem by a two level dual decomposition with reduced computational complexity. We also proposed two suboptimal schemes based on equal power allocation, with and without power refinement to reduce computational complexity. The problem formulation and solution approaches are discussed in details. The computational complexity of each scheme is also analyzed.

4.2 Problem Formulation and Solution Approach

Our objective is to maximize the total system throughput subject to a set of constraints. The relay selection and subcarrier assignment constraints are as follows:

$$\sum_{k=1}^{K}\sum_{n=0}^{N}\rho_{k,n}^{m} = 1, \rho_{k,n}^{m} \in \{0,1\}, \forall m \tag{4.1}$$

where $n = 0$, it means user k utilize subcarrier m in non-cooperative mode. The total power allocated to the mth subcarrier of the kth user in both time slots is $P_{t,k}^{m} = P_{s,k}^{m} + P_{r,n}^{m}$ [40, 61] and the total power constraint can be expressed as

$$\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m} P_{t,k}^{m} \leq P_T \tag{4.2}$$

where P_T is the sum of the power available for all users plus relays in the network. Although individual power constraints will lead more accurate power allocation, however, our goal is to maximize the total system throughput subject to a joint total power constraint, considering the simplicity of the problem formulations and lower computational complexity under the sum power constraint. The computational complexity is lower in the studied model since we only need to update one dual variable using subgradient method under the total power constraint compared to updating $K + N$ dual variables simultaneously until all of them are converged when individual power constraints are used. Similar assumptions on the total power constraint are taken in previous studies [40, 61–63].

Maximization of the rate in (3.2) using cooperative communication under total power constraint has advantageous only if $\alpha_{k,n}^{m} > \alpha_{k,D}^{m}$ and $\alpha_{n,D}^{m} > \alpha_{k,D}^{m}$ [62, 64]. First, consider the case when the user to relay channel is weaker (lower Signal-to-Noise Ratio (SNR) due to bad channel condition) than the direct link channel, i.e., $\alpha_{k,n}^{m} < \alpha_{k,D}^{m}$. In such case, from equation (3.2), any power increment will be more beneficial if allocated to the direct link and the use of relay will not be advantageous. Second, consider the case when the user to relay channel is stronger (higher SNR due to good channel condition) than the direct link channel, .i.e., $\alpha_{k,n}^{m} > \alpha_{k,D}^{m}$. Then two cases may happen: 1) if $\alpha_{k,D}^{m} > \alpha_{n,D}^{m}$, the rate benefit will be greater if the power is allocated to the direct link; and 2) if $\alpha_{k,D}^{m} < \alpha_{n,D}^{m}$, the allocation of power to the relay is better under the constraint of $P_{s,k}^{m}\alpha_{k,D}^{m} + P_{r,n}^{m}\alpha_{n,D}^{m} \leq P_{s,k}^{m}\alpha_{k,n}^{m}$. This means that any power increment has to be shared between the user and relay, and the rate will be maximized when the constraint is saturated,.i.e., $P_{s,k}^m \alpha_{k,D}^m + P_{r,n}^m \alpha_{n,D}^m = P_{s,k}^m \alpha_{k,n}^m$. Then the source power allocation is given by

$$P_{s,k}^m = \begin{cases} \frac{\alpha_{n,D}^m}{\alpha_{k,n}^m + \alpha_{n,D}^m - \alpha_{k,D}^m} P_{t,k}^m, & \text{cooperative mode} \\ P_{t,k}^m, & \text{non-cooperative mode} \end{cases} \tag{4.3}$$

and the relay power allocation is given by

$$P_{r,n}^m = \begin{cases} \frac{\alpha_{k,n}^m - \alpha_{k,D}^m}{\alpha_{k,n}^m + \alpha_{n,D}^m - \alpha_{k,D}^m} P_{t,k}^m, & \text{cooperative mode} \\ 0, & \text{non-cooperative mode} \end{cases} \tag{4.4}$$

The computation of the source and relay power can be explained as follows. First, for any subcarrier, when the channel gains are known, the transmission mode can be determined for the given total power on that subcarrier. Second, for the selected transmission mode, the optimal source and relay power are computed. If cooperative mode is selected, $P_{t,k}^m$ will be divided in two time slots depending on the channel condition and the optimal source and relay power are given by (4.3) and (4.4) [40,62]. In case of non-cooperative mode, $P_{r,n}^m = 0$, and $P_{s,k}^m = P_{t,k}^m$ from (4.3). For the non-cooperative transmission mode, there may be two scenarios: transmission can be held in two time slots by dividing the total power, $P_{t,k}^m$ in two time slots, or use only one time slot with power $P_{t,k}^m$. In this work, we assume that the user only transmits in the first time slot using the total power, $P_{t,k}^m$ when non-cooperative transmission mode is selected [65]. Thus, substituting (4.3) and (4.4) into (3.2), the rate expression can be unified as

$$R_{k,n}^m = \frac{1}{2}[\log_2(1 + P_{t,k}^m \alpha_{k,eq}^m)] \tag{4.5}$$

where $\alpha_{k,eq}^m$ is the equivalent channel gain given by

$$\alpha_{k,eq}^m = \begin{cases} \frac{\alpha_{k,n}^m \alpha_{n,D}^m}{\alpha_{k,n}^m + \alpha_{n,D}^m - \alpha_{k,D}^m}, & \text{cooperative mode} \\ \alpha_{k,D}^m, & \text{non-cooperative mode.} \end{cases} \tag{4.6}$$

The total achievable rate of the kth user for all subcarriers allocated to the kth user is given by

$$R_k = \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^m R_{k,n}^m. \tag{4.7}$$

We formulate the joint resource allocation and relay selection problem subject to a minimum data rate constraint for each GBR user. The optimization problem can be formulated as

$$
\begin{aligned}
(P1)\quad \underset{\rho, P_t}{\text{maximize}} \quad & \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^{m} R_{k,n}^{m} \\
\text{subject to} \quad & c1: \rho_{k,n}^{m} \in \{0,1\}, \forall k, m, n \\
& c2: \sum_{k=1}^{K}\sum_{n=0}^{N} \rho_{k,n}^{m} = 1, \forall m \\
& c3: R_k \geq Q_k, \forall k \in \ \kappa_1 \\
& c4: \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^{m} P_{t,k}^{m} \leq P_T \\
& c5: P_{t,k}^{m} \geq 0, \forall k, m, n
\end{aligned}
\tag{4.8}
$$

where constraints $c1$ and $c2$ represent the relay selection and subcarrier allocation and indicate that each user can have one relay to cooperate and can utilize multiple subcarriers to transmit; however, a subcarrier can not be shared by different users. Constraint $c3$ applies minimum QoS requirements for the GBR users in terms of data rate requirement. Finally, the source and the relay power allocation are constrained by $c4$ and $c5$.

The optimization problem in (4.8) is a mixed integer nonlinear programming (MINP) problem. One challenging aspect of this problem in the context of OFDMA uplink is the discrete nature of subcarrier assignment, which, when coupled with QoS constraint, makes the problem even harder to solve. Therefore, finding the optimal solution for this non-convex problem requires searching through all the possible user, relay and subcarrier allocations, which is prohibitively complex to employ in large system. However, to make the problem tractable, we relax the integer constraints, $\rho_{k,n}^{m}$ to take any real value between 0 and 1 via time-sharing condition which allows time sharing of each subcarrier. The duality gap of any optimization problem satisfying the time sharing condition is negligible as the number of subcarriers becomes sufficiently large [66]. Since our optimization problem obviously satisfies the time-sharing condition, it can be solved by using the dual method and the solution is optimal [48, 66]. The relaxed problem is shown in Appendix A.1.

4.2.1 Dual Problem

The Lagrangian function of problem in (4.8) can be written as

$$\begin{aligned} L(\rho, P_t, \lambda, \mu) &= \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m}R_{k,n}^{m} + \sum_{k\in\ \kappa 1}\lambda_k(\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m}R_{k,n}^{m} \\ &\quad -Q_k) + \mu(P_T - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m}P_{t,k}^{m}) \\ &= \sum_{m=1}^{M}\left[\sum_{k=1}^{K}\sum_{n=0}^{N}\rho_{k,n}^{m}R_{k,n}^{m} + \sum_{k\in\ \kappa 1}\lambda_k\sum_{n=0}^{N}\rho_{k,n}^{m}R_{k,n}^{m} \right. \\ &\quad \left. -\mu\sum_{k=1}^{K}\sum_{n=0}^{N}\rho_{k,n}^{m}P_{t,k}^{m}\right] - \sum_{k\in\ \kappa 1}\lambda_k Q_k + \mu P_T \end{aligned} \tag{4.9}$$

where $\lambda = [\lambda_1, \lambda_2, ...\lambda_{\kappa 1}]^T$ is the vector of the dual variables associated with the individual QoS constraints and μ is the dual variable for the power constraint. The Lagrangian dual function can therefore be written as

$$g(\lambda, \mu) = \begin{cases} \max\limits_{\rho, P_t} & L(\rho, P_t, \lambda, \mu) \\ \text{s.t.} & \sum_{k=1}^{K}\sum_{n=0}^{N}\rho_{k,n}^{m} = 1, \forall m \\ & 0 \leq \rho_{k,n}^{m} \leq 1, P_{t,k}^{m} \geq 0. \end{cases} \tag{4.10}$$

Then the dual optimization problem is given by

$$\min_{\lambda,\mu\succeq 0} g(\lambda, \mu). \tag{4.11}$$

The coupling between subcarriers via Lagrangian relaxation can be removed and (4.10) can be decomposed into M subproblems at each subcarrier, which can be solved independently given λ, μ with low complexity. The subproblem at each subcarrier is given by

$$
\begin{aligned}
\max_{\rho, P_t} \; L_m(\rho^m, P_t^m) \quad &= \quad \max_{\rho, P_t} \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^m R_{k,n}^m + \sum_{k \in \; \kappa 1} \lambda_k \sum_{n=0}^{N} \rho_{k,n}^m R_{k,n}^m \\
& \quad -\mu \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^m P_{t,k}^m \qquad (4.12) \\
s.t. \quad & \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^m = 1, 0 \leq \rho_{k,n}^m \leq 1, P_{t,k}^m \geq 0, \forall k, n
\end{aligned}
$$

where ρ^m, P_t^m are the vectors of $\rho_{k,n}^m, P_{t,k}^m$ on the mth subcarrier, respectively. The subproblem can be further decomposed through a second level primal decomposition. The decomposition hierarchy of the dual problem is shown in Fig. 4.1. Thus, we have two subproblems which will be solved in two phases: optimal power allocation and joint relay selection and subcarrier allocation.

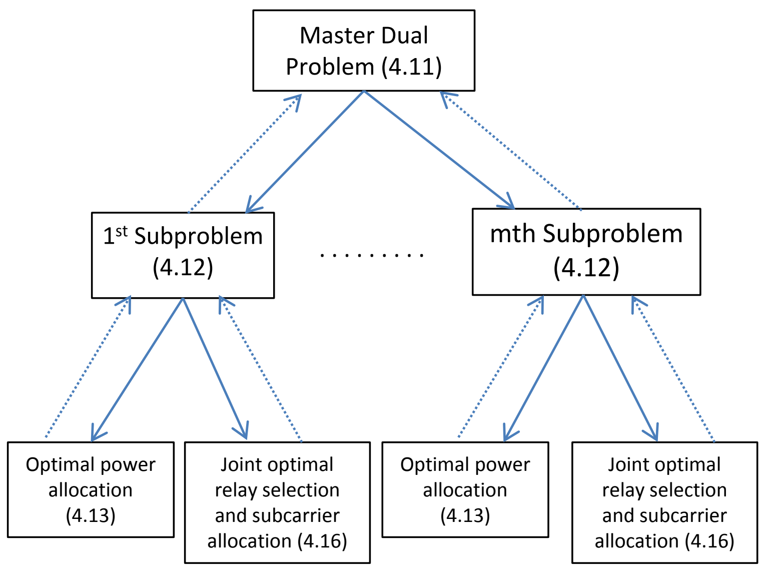

Figure 4.1: Hierarchy of the decomposed dual problem.

Proposition 1 *Considering the convex optimization problem in (4.11), the subgradients of $g(\lambda, \mu)$ denoted by $\Delta\lambda_k$, and $\Delta\mu$ are given by*

$\Delta\lambda_k = \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m\star} R_{k,n}^{m\star} - Q_k, \forall k \in \kappa_1$

$\Delta\mu = P_T - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m\star}P_{t,k}^{m\star}$
where $\rho_{k,n}^{m\star}$, $R_{k,n}^{m\star}$ *and* $P_{t,k}^{m\star}$ *are the optimal solution of the dual objective function in (4.11).*

The proof of proposition 1 is given in the Appendix A.2.

4.2.2 Optimal Power Allocation for a Given Relay Assignment and Subcarrier Allocation

Let subcarrier m be allocated to user k and relay n in a frame of transmission time and $\rho_{k,n}^{m} = 1$. Then optimal power allocation over this subcarrier and relay assignment can be determined by solving the following problem

$$\begin{aligned} \max_{P_{t,k}^{m}} \quad & L_m, \forall k, n \\ \text{s.t.} \quad & P_{t,k}^{m} \geq 0. \end{aligned} \tag{4.13}$$

Differentiating L_m with respect to $P_{t,k}^{m}$, we have

$$\frac{\partial L_m}{\partial P_{t,k}^{m}} = (1+\bar{\lambda_k})\frac{\partial R_{k,n}^{m}}{\partial P_{t,k}^{m}} - \mu \tag{4.14}$$

where

$$\bar{\lambda_k} = \begin{cases} \lambda_k, \forall k \in \kappa_1 \\ 0, \text{Otherwise.} \end{cases}$$

Applying the Karush-Kuhn-Tucker (KKT) [67] condition, we can deduce the optimal power allocation as follows:

$$P_{t,k}^{m\,*} = \left[\frac{1+\bar{\lambda_k}}{2\mu\ln(2)} - \frac{1}{\alpha_{k,eq}^{m}}\right]^{+} \tag{4.15}$$

where $[x]^{+} = max\,[x, 0]$. The derivation the optimal power allocation is shown in Appendix A.3.

4.2.3 Joint Optimal Relay Selection and Subcarrier Allocation

From (4.9), we have an alternative expression of the dual function as

$$
\begin{aligned}
g(\lambda, \mu) \quad &= \quad \max_{\rho} \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^{m} H_{k,n}^{m}(\lambda, \mu) \\
& \quad - \sum_{k \in \ \kappa 1} \lambda_k Q_k + \mu P_T \\
s.t. \quad & \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^{m} = 1, \forall m, 0 \leq \rho_{k,n}^{m} \leq 1
\end{aligned} \tag{4.16}
$$

where the function $H_{k,n}^{m}(\lambda, \mu)$ is defined as follows

$$
H_{k,n}^{m} = \frac{1}{2}(1 + \bar{\lambda_k})[\log_2(1 + P_{t,k}^{m\,*} \alpha_{k,eq}^{m})] - \mu P_{t,k}^{m\,*}. \tag{4.17}
$$

An intuitive explanation for each term in (4.17) is as follows. The first term can be viewed as the rate obtained by selecting subcarrier m by user k and relay n and the second term is the price for the power consumption. Therefore, $H_{k,n}^{m}$ can be interpreted as the gain of transmitting over subcarrier m by user k and relay n and $\mathbf{H} = [H_{k,n}^{m}]$ can be represented as a $K \times N$ profit matrix at each subcarrier m. In other words, the profit matrix $\mathbf{H}$ is different for different value of m. The objective function in (4.16) can be maximized by picking exactly one element of matrix $\mathbf{H}$ for each subcarrier so that the sum of profit is as large as possible. Finally, optimal relay selection and subcarrier allocation should be the one having the maximum value of $H_{k,n}^{m}(\lambda, \mu)$ in (4.17) and is given by

$$
\rho_{k,n}^{m} = \begin{cases} 1, (n^{\star}, k^{\star}) = arg \ \max\limits_{n,k} \ H_{k,n}^{m} \\ 0, \text{otherwise.} \end{cases} \tag{4.18}
$$

In the operation, first, the power allocation for each subcarrier using both transmission modes is computed using (4.15). Then, these power allocation values are used in (4.17) to compute $H_{k,n}^{m}$. After that, for each subcarrier, the user and relay pair is determined using (4.18) that gives the largest $H_{k,n}^{m}$. Non-cooperative mode is the case that no relay is selected, i.e., $n = 0$.

The derived joint relay selection and subcarrier allocation solution in (4.18) state three conclusions: 1) Although time-sharing is assumed for solving the optimization problem, the optimal relay selection and subcarrier allocation indicate that there is no time sharing in any subcarrier, i.e. a subcarrier is only assigned to one user and one relay (in the second time slot); 2) The optimal solution of the original optimization problem is identical to the solution of the relaxed problem; 3) The optimal solution in (4.18) may be infeasible if two user-relay pair have same $H_{k,n}^m$ at the mth subcarrier. However, this case may not happen in the reality since $H_{k,n}^m$ depends not only the channel condition but also the power budget of each user's. In other words, this is only possible if two users have the same channel condition and same amount of power available for transmission.

4.2.4 Variable Update

Since a dual function is always convex by definition, subgradient method can be used to minimize $g(\lambda, \mu)$. Dual variables λ and μ are updated in parallel as follows

$$\begin{aligned} \lambda_k(t+1) &= \left[\lambda_k(t) + \eta(t)\left(Q_k - \sum_{n=0}^{N}\sum_{m=1}^{M}\rho_{k,n}^m(t)R_{k,n}^m(t)\right)\right]^+ \\ \mu(t+1) &= \left[\mu(t) + \theta(t)\left(\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^m(t)P_{t,k}^m(t) - P_T\right)\right]^+ \end{aligned} \tag{4.19}$$

where $\eta(t)$ and $\theta(t)$ are diminishing stepsizes and t is the iteration index. The subgradient method above is guaranteed to converge to the optimal dual variables if the stepsizes are chosen following the diminishing stepsize policy [67]. Based on the mathematical formulations and derivations, the optimal relay selection, subcarrier assignment and power allocation can be computed algorithmically. The pseudocode of the proposed optimal scheme is outlined in Algorithm 1.

4.3 Suboptimal Schemes

The computational complexity of the proposed optimal scheme may still be too high for practical implementation. In this section, we present two suboptimal schemes which have lower computational cost compared to the optimal one.

Algorithm 1 Pseudocode for the proposed optimal scheme

```
Initialize λ_k and μ.
for m = 1 → M do
    for k = 1 → K do
        for n = 1 → N do
            Calculate optimal power using (4.15).
            Calculate H^m_{k,n}(λ, μ) using (4.17).
        end for
    end for
    Find optimal (n*, k*) according to (4.18).
    Allocate subcarrier m to (n*, k*).
end for
for k = 1 → K do
    update λ_k using (4.19).
end for
Update μ using (4.19).
Repeat above steps until convergence.
```

4.3.1 Equal Power Allocation (EPA) Scheme

In this scheme, we determine relay selection and subcarrier allocation assuming that the power is equally distributed over all subcarriers. First, relay selection and subcarrier allocation are performed for the GBR users in two steps considering that AMBR users are absent. In step 1, to ensure fairness among the users, we select the user whose current achievable rate is the farthest away from it's minimum rate requirement. In step 2, for the selected user, we choose the subcarrier and relay that maximize the transmission rates $R_{k,n}^m$, rather than the metrics $H_{k,n}^m$ defined in (4.17). Steps 1 and 2 are repeated until all users are satisfied or the number of unassigned subcarriers are zero. Then the remaining subcarriers and power are distributed among the AMBR users to maximize the sum rate. In this case, to exploit multi-user diversity, subcarriers are allocated to the user and relay pair who can utilize the channel the best. Let S_k be the set of subcarriers assigned to user k and A be the set of unassigned subcarriers. The pseudocode of the EPA scheme is presented in Algorithm 2.

Algorithm 2 Pseudocode for EPA scheme

```
Initialization: set R_k = 0, S_k = φ, ∀k and A = {1, 2, ....M}.
STEP 1: GBR users
while A ≠ φ and R_k < R_Q for all k ∈ κ_1 do
    Select user k* = arg max_{k∈κ_1} (R_Q − R_k).
    For the found k*, find (n*, m*) = arg max_{n,m} R^m_{k,n}.
    Assign the subcarrier m* to (n*, k*) .
    Update S_{k*} = S_{k*} ∪ m*, A = A − m* and R_{k*} = R_{k*} + R^{m*}_{k*,n*}.
end while
STEP 2: AMBR users
while A ≠ φ do
    Find (n*, k*, m*) = arg max_{n,k∈κ2,m} R^m_{k,n}.
    Update S_{k*} = S_{k*} ∪ m*, A = A − m* and R_{k*} = R_{k*} + R^{m*}_{k*,n*}.
end while
```

4.3.2 Equal Power Allocation with Refinement Scheme

In equal power allocation with refinement (EPAR) scheme, we use power refinement after relay selection and subcarrier assignment with equal power distribution. First, relay selection and subcarrier assignment are done for the GBR users considering equal power distribution. Then the power distribution for each GBR user is adjusted individually using analytical solution described in Section 4.2. The objective of the power refinement is to optimize the power while maintaining the basic transmission rate. Subcarrier adjustment is performed after the power refinement. In the subcarrier adjustment substep, some GBR users release additional subcarriers which are over allocated by the EPA scheme and can be used for AMBR users. At the end, the remaining subcarriers and power are allocated to the AMBR users and power refinement is also done by using the analytical solution presented in Section 4.2. Since the subcarrier assignment for the GBR users in the first step is obtained by considering equal power distribution, this scheme is suboptimal. The computational complexity of the power refinement process is much smaller than that of the dual problem because we already have relay selection and subcarrier assignment. The pseudocode of the EPAR scheme is presented in Algorithm 3.

4.3.3 Power Refinement: Method 1

In power refinement method 1, we optimize the power while maximizing the throughput for a given subcarrier and relay assignment, and guaranteeing the minimum rate requirements for each GBR user. In other words, it determines optimal power for a given subcarrier allocation and relay assignment while maximizing the total system throughput and maintaining the basic transmission rates. First, the relay selection and subcarrier allocation are obtained using equal power distribution similar to the EPA scheme. Then, the optimal power allocation is performed on this subcarrier-relay assignment. The optimization problem can be expressed as follows:

$$(P2) \quad \max_{P_t} \quad \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m} R_{k,n}^{m} \tag{4.20}$$

subject to constraints $c3$, $c4$ and $c5$ in (4.8).

Optimization problem $P2$ is a convex optimization problem which can be solved similarly as the optimal power allocation approach described in 4.2.2. The key difference

Algorithm 3 Pseudocode for EPAR scheme

Initialization: set $R_k = 0$, $S_k = \phi$, $\forall k$ and $A = \{1, 2, ...M\}$.

STEP 1: GBR users

while $A \neq \phi$ and $R_k < R_Q$ for all $k \in \kappa_1$ **do**

  Select user $k^\star = arg \quad \max_{k \in \kappa_1}(R_Q - R_k)$.

  For the found $k^\star$, find $(n^\star, m^\star) = arg \quad \max_{n,m} \quad R_{k,n}^m$.

  Assign the subcarrier $m^\star$ to $(n^\star, k^\star)$.

  Update $S_{k^\star} = S_{k^\star} \cup m^\star$, $A = A - m^\star$ and $R_{k^\star} = R_{k^\star} + R_{k^\star,n^\star}^{m^\star}$.

end while

STEP 2: Power Refinement for GBR users

Refine power using power refinement method stated in 4.3.3.

STEP 3: Subcarrier Adjustment

for each user $k \in \kappa_1$ **do**

  while $R_k > R_Q$ **do**

    Find $\acute{m} = arg \quad \min_{m \in S_k}(R_{k,n}^m)$

    if $(R_k - R_{k,n}^{\acute{m}}) \geq R_Q$ **then**

      Update $S_k = S_k - \acute{m}, A = A \cup \acute{m}, R_k = R_k - R_{k,n}^{\acute{m}}$.

    end if

  end while

end for

STEP 4: AMBR users

while $A \neq \phi$ **do**

  Find $(n^\star, k^\star, m^\star) = arg \quad \max_{n,k \in \kappa 2,m} \quad R_{k,n}^m$.

  Update $S_{k^\star} = S_{k^\star} \cup m^\star$, $A = A - m^\star$ and $R_{k^\star} = R_{k^\star} + R_{k^\star,n^\star}^{m^\star}$.

end while

STEP 5: Power Refinement for AMBR users

Refine power using power refinement method stated in 4.3.3.

with the optimal scheme is that there is no need to optimize the subcarrier assignment and relay selection and the computational complexity of the power refinement process is far smaller than that of solving the dual problem in (4.9). The pseudocode of the power refinement method 1 is outlined in Algorithm 4.

Algorithm 4 Pseudocode of the proposed power refinement method 1

Initialize λ_k and μ.

STEP 1: Power Refinement for GBR users

for each user $k \in \kappa_1$ **do**

  for each subcarrier $m \in S_k$ **do**

    Calculate optimal power using (4.15).

  end for

  Update λ_k using (4.19).

end for

Update μ using (4.19).

Repeat above steps until convergence.

STEP 2: Power Refinement for AMBR users

for each user $k \in \kappa_2$ **do**

  for each subcarrier $m \in S_k$ **do**

    Calculate optimal $P_{t,k}^{m\,*} = \left[\frac{1}{2\mu \ln(2)} - \frac{1}{\alpha_{k,eq}^{m}}\right]^{+}$.

  end for

end for

Update μ using (4.19).

Repeat above steps until convergence.

4.3.4 Power Refinement: Method 2

The previous method still needs to update the Lagrangian multipliers λ and μ to meet the rate and power constraints, respectively. However, to further reduce the computational complexity, we assume that $x_k = \frac{1+\bar{\lambda_k}}{2\mu \ln 2}, \forall k \in \kappa_1$; then from (4.15) we have

$$x_k = P_{t,k}^{m*} + \frac{1}{\alpha_{k,eq}^m} \tag{4.21}$$

where $P_{t,k}^{m*}$ can be represented as $P_{t,k}^m = \frac{P_T}{M}$ under equal power distribution. Rewriting (4.21) as

$$|S_k| x_k = \sum_{m \in S_k} \left[P_{t,k}^m + \frac{1}{\alpha_{k,eq}^m} \right], \forall k \in \kappa_1 \tag{4.22}$$

where $|S_k|$ is the cardinality of S_k.

Finally, x_k can be deduced as

$$x_k = \frac{1}{|S_k|} \left[P_{t,k} + \sum_{m \in S_k} \frac{1}{\alpha_{k,eq}^m} \right], \forall k \in \kappa_1 \tag{4.23}$$

where $P_{t,k} = |S_k| P_{t,k}^m$. Substituting x_k into (4.15), the power allocation refinement can be obtained for GBR users.

For AMBR users, setting $\bar{\lambda_k} = 0$ in (4.15), we get the optimal power allocation for AMBR users as

$$P_{t,k}^{m*} = \left[\frac{1}{2\mu \ln 2} - \frac{1}{\alpha_{k,eq}^m} \right]^+, \forall k \in \kappa_2. \tag{4.24}$$

Letting $y_k = \frac{1}{2\mu \ln 2}, \forall k \in \kappa_2$, y_k can be deduced as

$$y_k = \frac{1}{|S_k|} \left[P_{t,k} + \sum_{m \in S_k} \frac{1}{\alpha_{k,eq}^m} \right], \forall k \in \kappa_2 \tag{4.25}$$

where $P_{t,k}$ is given by

$$P_{t,k} = \frac{|S_k|(P_T - \sum_{k\in\kappa_1}\sum_{m=1}^{M} P_{t,k}^m)}{M - \sum_{k\in\kappa_1}|S_k|}. \quad (4.26)$$

Finally, the power refinement for the AMBR users is obtained by substituting (4.25) into (4.24). The pseudocode of the power refinement method 2 is outline in Algorithm 5.

Algorithm 5 Pseudocode of the proposed power refinement method 2

STEP 1: Power Refinement for GBR users

```
for each user k ∈ κ_1 do
    for each subcarrier m ∈ S_k do
        Calculate P_{t,k}^m = P_T / M.
        Calculate x_k using (4.23).
        Calculate optimal power using (4.15).
    end for
end for
STEP 2: Power Refinement for AMBR users
for each user k ∈ κ_2 do
    for each subcarrier m ∈ S_k do
        Calculate P_{t,k} using (4.26).
        Calculate y_k using (4.25).
        Calculate optimal power using (4.24).
    end for
end for
```

4.4 Complexity Analysis

The computational complexity of the proposed optimal scheme is mainly determined by the complexity of solving the dual problem. The total number of computations needed to perform relay selection is $K(N+1)$ and M allocations are required for all subcarriers. Therefore, the complexity at each iteration is $O(MKN)$. The complexity of the subgradient method is polynomial in the number of dual variables. With the total power constraint, there are $\kappa_1 + 1$ dual variables and the overall complexity is $O(|\kappa_1|^2 MKN)$. The complexity of the whole scheme is polynomial, which is significantly lower than employing the exhaustive search solution to the master primal problem because the number of subcarrier assignment policies increases exponentially with M.

The complexity of the EPA scheme can be analyzed as follows. The complexity of allocating subcarriers to the GBR users is $O(|\kappa_1|MN)$ and the complexity of allocating the remaining subcarriers to the AMBR users is $O(|\kappa_2|(M - |\kappa_1|)N)$. So, the overall complexity of the EPA scheme is $O(|\kappa_1|MN)$ + $O(|\kappa_2|(M - |\kappa_1|)N)$.

The complexity of the EPAR scheme with power refinement method 1 depends on the convergence of the subgradient method. The complexity of allocating subcarriers to both the GBR and AMBR users using the EPAR scheme is same as the EPA scheme. The complexity of the power refinement using method 1 depends on the number of iterations required for the subgradient methods to converge. There are $\kappa_1 + 1$ dual variables and the overall complexity for GBR users is $O(|\kappa_1|^2 M)$. Since there is only one dual variables, the complexity of power refinement method 1 for AMBR users is $O(M - |\kappa_1|)$. Thus, the overall complexity of the EPAR scheme using power refinement method 1 is $O(|\kappa_1|MN)$ + $O(|\kappa_1|^2 M)$+ $O(|\kappa_2|(M - |\kappa_1|)N)$ + $O(M - |\kappa_1|)$.

Power refinement method 2 does not require any update of the dual variables. The overall complexity of the EPAR scheme using power refinement method 2 is $O(|\kappa_1|MN)$ + $O(M)$+ $O(|\kappa_2|(M - |\kappa_1|)N)$ + $O(M - |\kappa_1|)$.

4.5 Performance Evaluation

4.5.1 Simulation Scenario

To evaluate the performance of our schemes, numerical results are generated using a simulation scenario. Consider a single cell OFDMA network with a radius of 1Km, where eNodeB is located at the center of the cell. The fixed relays are located at a radius of δ Km from the eNodeB at equal angular distance where δ varies between 0.2 to 0.8. The relay locations are varied to show the effect of relay locations on the performance. Here, we only consider random variations of the relay distance from the eNodeB as the first step. However, relay placement can be modeled as another optimization problem which is not studied in this thesis. The UE locations are randomly generated and uniformly distributed between 0.5 Km to 1 Km from the eNodeB. Half of the users in the system are assumed to be GBR and the other half are AMBR users. The GBR users are selected randomly from the total set of users. These GBR users have different rate requirements based on the applications. We allocate different applications to different users arbitrarily, and they are fixed for the whole simulation. Multipath Rayleigh fading with exponential power delay profile based on ITU pedestrian B model [4] is considered for small scale fading model. The channels for different users in each subcarrier are assumed to be independent. Then the effective channel gain over an RB is deduced from the subcarrier granularity. The 3GPP LTE path loss model with log-normal shadowing of an 8dB standard deviation are assumed. The system parameters are given in Table I. Having the simulation scenarios and all the system parameters, the optimal relay selection, power allocation and subcarrier assignments are evaluated using Algorithm 1. The stepsize for λ and μ is set to 0.01 divided by $\sqrt{IterationNumber}$. Relay selection is performed per RB since RB is the smallest resource unit for the next generation network. The simulation scenario (user locations, selection of the GBR users and the assignment of the applications to the users) is repeated 100 times to get a fair result. The multipath channel components are repeated over 1000 times.

The optimization problem considered in this work may be infeasible due to the rate requirements constraint. This may happen if the channel condition is very bad (low SNR) and/or the available resources are limited to support the minimum rate requirements of the GBR users. In the simulation, we allocate resources as much as possible for the GBR users on those infeasible cases and also consider them when we calculate the average spectral efficiency. Those situations have been further verified

Table 4.1: Simulation Parameters

Name of the Parameters	Value
Total system bandwidth	5 MHz
Total number of RB	24
Total number of subscribers	288
Number of UEs	24
Number of relays	2, 4, 6, 8
Total power available at UE	23 dBm
Total power available at relay	30 dBm
Noise power spectral density	-174 dBm/Hz
Path loss exponent	3.76

and handled by introducing the user satisfaction index (SI). The user satisfaction index (SI) [68] is calculated as $SI = \frac{1}{K}\sum_{k=1}^{K} SI_k$, where $SI_k = min\left(\frac{R_k}{Q_k}, 1\right)$. SI is less than 1 means there are some cases which are infeasible and the minimum rate requirements for some users are not satisfied.

4.5.2 Numerical Results and Discussion

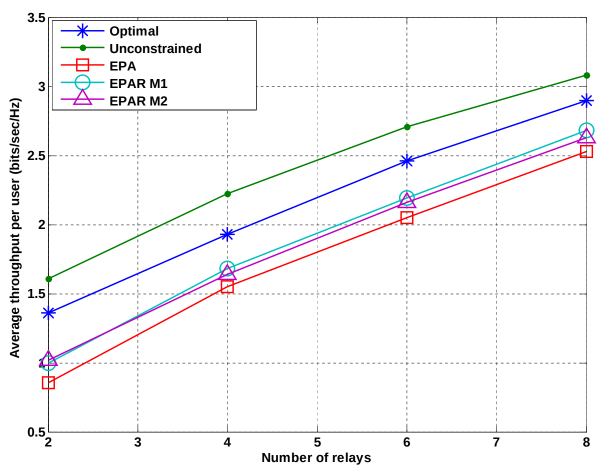

Figure 4.2: Average throughput for 24 users with different number of relays, $\delta = 0.5$.

Fig. 4.2 shows the average throughput per user in bits/sec/Hz for the optimal scheme, suboptimal schemes and traditional unconstrained scheme as a function of the number

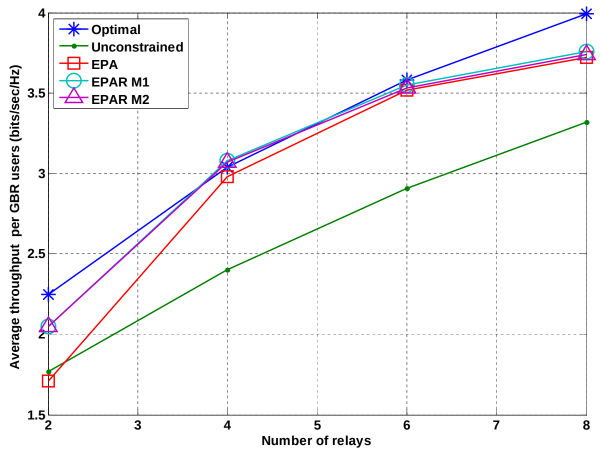

Figure 4.3: Average throughput for GBR users as a function of the number of relays, $\delta = 0.5$.

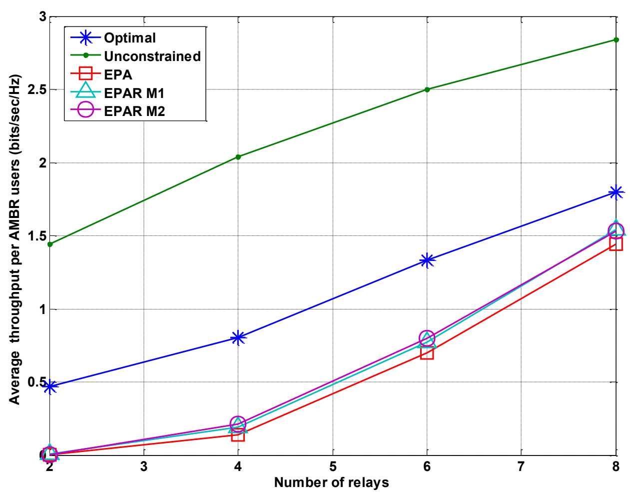

Figure 4.4: Average throughput for AMBR users as a function of the number of relays, $\delta = 0.5$.

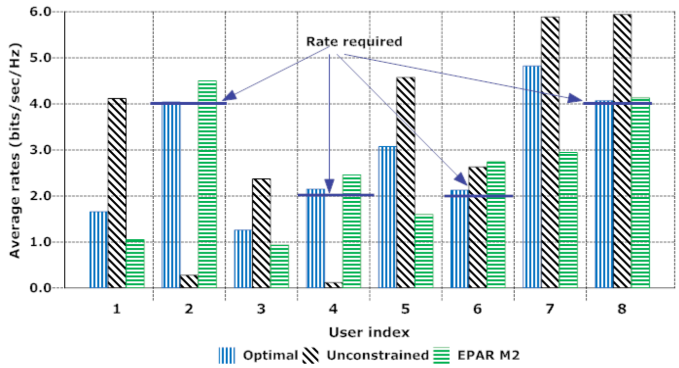

Figure 4.5: User achievable rate with 8 relays, rate required for user 2 and user 8 = 4 bits/sec/Hz and rate required for user 4 and user 6 = 2 bits/sec/Hz, $\delta = 0.5$.

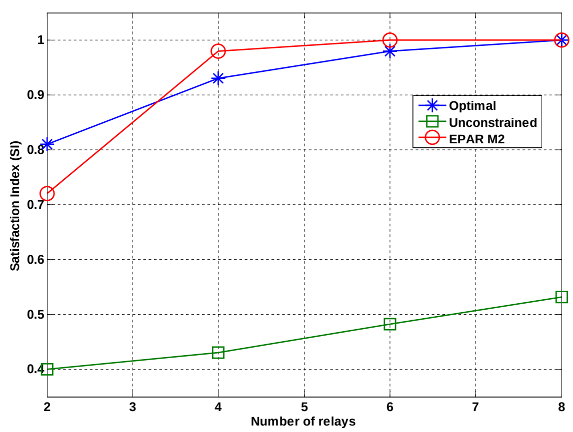

Figure 4.6: Average user satisfaction index for GBR users with different number of relays, $\delta = 0.5$.

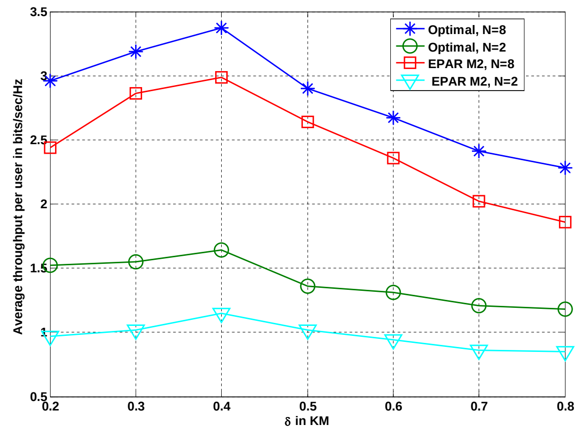

Figure 4.7: Average throughput for 24 users with different relay locations.

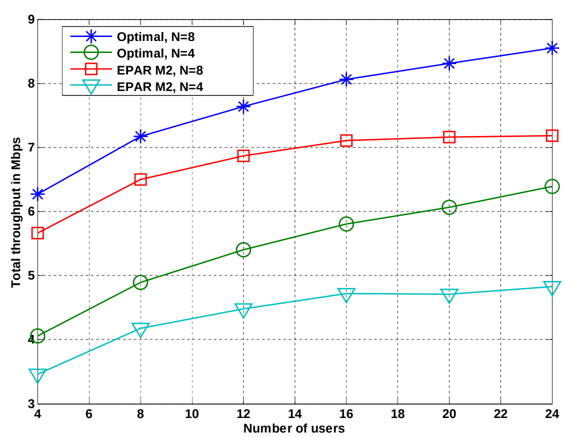

Figure 4.8: Total system throughput with different number of users, $\delta = 0.4$.

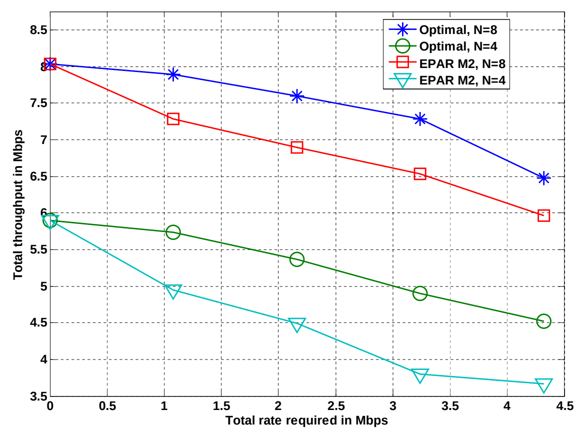

Figure 4.9: Total system throughput for different rate requirements, $\delta = 0.4$.

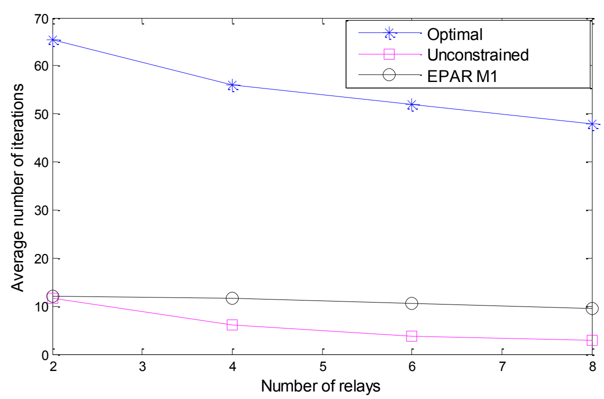

Figure 4.10: Average number of iterations for converging all dual variables with $K = 16$, where 8 GBR users with equal rate requirements of 3 bits/sec/Hz.

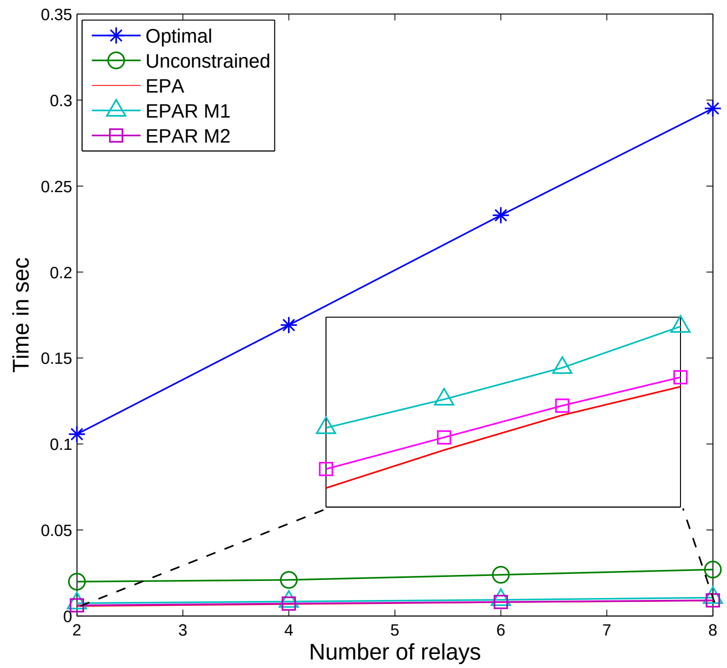

Figure 4.11: Average running time for $K = 16$, where 8 GBR users with equal rate requirements of 3 bits/sec/Hz.

of relays. The optimal scheme provides slightly lower throughput compared to the unconstrained scheme, because the unconstrained scheme always allocates subcarriers by only considering the channel condition. So, some users have very high rate since most of the subcarriers are allocated to those users, whereas others have very low rate because very few or no subcarriers are allocated to them. On the other hand, the optimal scheme considers both minimum rate requirement as well as channel condition, and distributes the subcarriers to the users based on their minimum rate requirement. So, when we average over the total number of channel realizations, the average throughput is higher for the unconstrained scheme but it violates fairness which is also evident in Fig. 4.5. However, the performance gap for the optimal scheme reduces with an increase in the number of relays.

It is noted that all suboptimal schemes provide lower throughput compared to the optimal scheme. Because all suboptimal schemes use equal power distribution for relay selection and subcarrier assignment. However, the EPAR scheme with power refinement method 1 (EPAR M1) and the EPAR scheme with power refinement method 2 (EPAR M2) perform well although they have lower computational complexity compared to the optimal one. Both of the power refinement methods have almost similar performance although power refinement method 2 is computationally simpler. The EPAR scheme has higher rates compared to the EPA scheme. This is due to the power refinement and subcarrier adjustment used in the EPAR scheme.

The average throughput for the GBR users for all schemes as a function of the number of relays is shown in Fig. 4.3. The traditional unconstrained scheme provides the lowest throughput since it does not consider user's minimum rate requirements. The optimal scheme has the highest throughput in all cases. However, all suboptimal schemes exhibit performance close to the optimal scheme as the number of relays increases. The reason is that all suboptimal schemes first allocate subcarriers and power to the GBR users, and when all GBR users are satisfied, the remaining subcarriers and power are then allocated to the AMBR users. So, the reverse characteristic is observed in case of AMBR users for all schemes except the optimal scheme, as shown in Fig. 4.4. Since the AMBR users have no minimum rate requirements, the unconstrained scheme provides the highest throughput. The optimal scheme still provides moderate performance.

Fig. 4.5 shows the average rate obtained by each user for the optimal scheme, unconstrained scheme and EPAR M2 scheme. Since all suboptimal schemes have almost the same performance in case of GBR users, we only show the suboptimal scheme which has good overall throughput with lower computational complexity, i.e., EPAR M2 scheme. In this illustrative example, there are four GBR users with different minimum rate requirements. The minimum rate required for users 2 and 8 are 4 bits/sec/Hz and 2 bits/sec/Hz for users 4 and 6. The remaining users have no minimum rate requirements. It is observed that the minimum rate requirements are not fulfilled for users 2 and 4 when we use the unconstrained scheme. But both the optimal and EPAR M2 schemes satisfy the minimum rate requirement for all GBR users and support all other AMBR users. So, it can be concluded that our proposed optimal and suboptimal scheme with power refinement provide not only fairness and user satisfaction but also support heterogeneous demand as well. This will be more evident via satisfaction index (SI) in Fig. 4.6. $SI = 1$ means all users rate requirements are satisfied. The SI is much higher for the optimal scheme and EPAR M2 scheme compared with the unconstrained scheme. It is also observed that all users are satisfied in case of the optimal scheme and EPAR M2 scheme when the number of relays increases. But all users are not satisfied even for 8 relays in case of the unconstrained scheme due to the same reason as stated above. The EPAR M2 scheme exhibits slightly higher SI than the optimal scheme. Because the EPAR M2 scheme first allocates resources to the GBR users, and when all GBR users are satisfied, the remaining resources are then allocated to the AMBR users.

The average user throughput by varying the relay locations for different number of relays is presented in Fig. 4.7. It is noticed that for all cases, the average throughput using relays increases first for the lower value of δ until it reaches the maximum and then decreases for the larger value of δ. Because, when δ is small, relays are located close to the eNodeB. Hence, relays are not beneficial for the cell edge users due to low SNR of the SR links. Similarly, when relays are furthest from the eNodeB (i.e., high value of δ), the throughput reduces due to low SNR of the RD links.

Fig. 4.8 shows the total system throughput as a function of the number of users, with the number of relays as a parameter. The total throughput increases with the number of users or relays. This gives insight into the scalability of our schemes.

The total throughput as a function of the total rate required for all users is shown in Fig. 4.9. The figure reveals that the total throughput decreases with the increase of total required rate for both schemes. The reason is when the rate requirement of the GBR users continues to increase, the users and relays need to increase their rates by utilizing their maximum power and acquiring more subcarriers. When the total rate requirement is zero, i.e., there are no GBR users, both schemes behave like the unconstrained scheme and provide the same total throughput.

The complexity of the optimal scheme, EPAR M1 scheme and unconstrained scheme, mainly depends on the convergence of the dual variables. The complexity comparison for these schemes can be better illustrated by comparing the convergence of these schemes. However, the EPA scheme and EPAR M2 scheme do not require any update of dual variables. Therefore, we also present the running time comparison of all schemes.

The average number of iterations required to converge all the dual variables for the optimal scheme, EPAR M1 scheme and unconstrained scheme is shown in Fig. 4.10. The optimal scheme requires the highest number of iterations to converge all dual variables. This is due to the minimum rate constraints of each GBR user. In case of the optimal scheme, the number of dual variables is equal to the number of GBR users plus one for the total power constraint. On the other hand, the unconstrained scheme has only one dual variable, hence requires less number of iterations to converge. The EPAR M1 scheme has the same number of dual variables as the optimal scheme, however, it requires less number of iterations since it only reallocates power for a given subcarrier and relay assignment. It can also be seen that the number of iterations reduces with the increase of the number of relays. This is because when the number of relays increases, higher rates can be achieved by using more number of channels with good SNR, which reduces the number of iterations since the rate requirements for the GBR users can be easily obtained. However, the total running time of all these schemes increases with the increase of the number of relays, which is shown in Fig. 4.11.

The average running time of all schemes is shown in Fig. 4.11. The optimal scheme takes the largest amount of time to allocate resources since it requires large number of iterations to terminate all the dual variables. Between the suboptimal schemes, the EPAR M1 scheme takes the largest amount of time since it still needs to update the dual variables. The EPA scheme takes the least amount of time to allocate resources due to its simplicity. The running time of both the EPA and EPAR M2 schemes is very close while EPAR M2 scheme provides the highest throughput among all suboptimal schemes. The total time required to allocate resources for all schemes increases with the increase of the number of relays since the problem dimension and complexity cost increase.

4.6 Chapter Summary

In this Chapter, relay selection and resource allocation in a multi-user cooperative OFDMA-based uplink system that simultaneously supports GBR and AMBR traffic have been investigated. A QoS aware optimal joint relay selection, power allocation and subcarrier assignment scheme under a total power constraint has been proposed. A joint optimization problem has been formulated for relay selection and resource allocation with the objective of maximizing the system throughput by satisfying the individual users' QoS requirements. By relaxing the integer constraints, the joint optimization problem has been transformed into a convex optimization problem, which is solved by means of a two level dual decomposition approach. The computational complexity has been finally reduced via the introduction of suboptimal schemes. Numerical results have demonstrated that our schemes support heterogeneous services while satisfy QoS requirements of each user. The polynomial complexity of the optimal scheme facilitates the implementation of this optimization at the base station. However, the suboptimal schemes can be implemented with significantly reduced computational complexity while sacrificing some system throughput.

Chapter 5

Resource Allocation under Individual Power Constraints

5.1 Introduction

Resource allocation considering a single total power constraint for all users and relays in the uplink is unrealistic since each user and relay have separate individual power budget. Under individual power constraints, subcarrier classification is complicated since it depends not only on the channel conditions, but also on the user and relay power constraints. To handle this issue, in this chapter, an optimal joint relay, subcarrier and power allocation scheme is developed for the uplink of an OFDMA based relay assisted cellular network to support heterogeneous applications with different QoS requirements. The objective of resource allocation scheme is to maximize the total system throughput subject to QoS satisfaction and individual power constraints of the users and relay nodes. We consider decode-and-forward relays and both direct and relay links in the problem formulation. As the original resource allocation problem is non-convex, we relax the problem using time sharing condition. The optimal solution for the relaxed problem is found by decomposing the problem into several subproblems by means of dual decomposition. Simulation results demonstrate that the proposed scheme guarantees QoS satisfaction while achieving system throughput slightly lower than that when there are no user QoS requirements.

5.2 Problem Formulation and Solution Approach

The uplink resource allocation problem can be stated as

$$
\begin{aligned}
(P1) \quad & \max_{\rho, P_s, P_r} && \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^{m} R_{k,n}^{m} \\
\text{s.t.} \quad & c1: && \rho_{k,n}^{m} \in \{0,1\}\ , \quad \forall k, m, n \\
& c2: && \sum_{k=1}^{K}\sum_{n=0}^{N} \rho_{k,n}^{m} \leq 1\ , \quad \forall m \\
& c3: && R_k \geq Q_k\ , \quad \forall k \in \kappa_1 \\
& c4: && \sum_{m=1}^{M} P_{s,k}^{m} \leq P_{s,k}\ , \quad \forall k \\
& c5: && \sum_{m=1}^{M} P_{r,n}^{m} \leq P_{r,n}\ , \quad \forall n \\
& c6: && P_{s,k}^{m},\ P_{r,n}^{m} \geq 0\ , \quad \forall k, m, n \\
& c7: && P_{s,k}^{m} \geq t_{m,n}^{m} P_{r,n}^{m}\ , \quad \forall m \in S_R
\end{aligned}
$$

where $t_{m,n}^{m} = \frac{\alpha_{n,d}^{m}}{\alpha_{k,n}^{m} - \alpha_{k,d}^{m}}$. Constraints $c1$ and $c2$ represent the relay selection and subcarrier allocation. The minimum rate requirements of the GBR users are represented by $c3$. The individual total power constraints of the users and relays are given by $c4$ and $c5$, respectively. Constraint $c7$ should be satisfied when kth user operates in the cooperative mode over the mth subcarrier; cooperative mode has an advantage (i.e., achieve a higher rate) over the non-cooperative mode only when $c7$ is satisfied [54].

5.2.1 Transformation of the Optimization Problem

The optimization problem P1 is a mixed integer nonlinear programming (MINP) problem. Therefore, finding the optimal solution for this non-convex problem requires searching through all the possible user, relay and subcarrier allocations. To make the problem tractable, we relax the integer constraints by allowing users to time-share each subcarrier [66]. Consequently, $\rho_{k,n}^{m}$ can take any value between 0 and 1. Next, define $\hat{P}_{s,k}^{m} = \rho_{k,n}^{m} P_{s,k}^{m}$ and $\hat{P}_{r,n}^{m} = \rho_{k,n}^{m} P_{r,n}^{m}$. Then, the relaxed $P1$ can be written as

$$
\begin{aligned}
(P2) \quad \max_{\rho,\hat{P}_s,\hat{P}_r} \quad & \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^{m} \hat{R}_{k,n}^{m} \\
\text{s.t.} \quad & c1: 0 \le \rho_{k,n}^{m} \le 1, \forall k, m, n \\
& c2: \sum_{k=1}^{K}\sum_{n=0}^{N} \rho_{k,n}^{m} \le 1, \forall m \\
& c3: \hat{R}_k \ge Q_k, \forall k \in \kappa_1 \\
& c4: \sum_{m=1}^{M} \hat{P}_{s,k}^{m} \le P_{s,k}, \forall k \\
& c5: \sum_{m=1}^{M} \hat{P}_{r,n}^{m} \le P_{r,n}, \forall n \\
& c6: \hat{P}_{s,k}^{m}, \hat{P}_{r,n}^{m} \ge 0, \forall k, m, n \\
& c7: \hat{P}_{s,k}^{m} \ge t_{m,n}^{m} \hat{P}_{r,n}^{m}, \forall m \in S_R
\end{aligned}
$$

where $\hat{R}_{k,n}^{m} = R_{k,n}^{m}|_{P_{s,k}^{m}=\hat{P}_{s,k}^{m}/\rho_{k,n}^{m}, P_{r,n}^{m}=\hat{P}_{r,n}^{m}/\rho_{k,n}^{m}}$ and $\hat{R}_k = \sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^{m}\hat{R}_{k,n}^{m}$. Problem P2 is a convex optimization problem, and there exists a unique optimal solution which can be obtained in polynomial time. We solve P2 by decomposing it into M subproblems.

The Lagrangian of P2 can be written as

$$
\begin{aligned}
& L(\boldsymbol{\rho}, \hat{\mathbf{P}}_s, \hat{\mathbf{P}}_r, \boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}, \boldsymbol{\eta}) = \sum_{m=1}^{M} L_m \\
& - \sum_{k \in \ \kappa 1} \lambda_k Q_k + \sum_{k=1}^{K} \mu_k P_{s,k} + \sum_{n=0}^{N} \beta_n P_{r,n} + \sum_{m=1}^{M} \delta_m
\end{aligned}
\tag{5.1}
$$

where L_m is a sub-Lagrangian corresponds to the mth subcarrier and given by

$$
\begin{aligned}
L_m(\boldsymbol{\rho}^m, \hat{\mathbf{P}}_s^m, \hat{\mathbf{P}}_r^m, \boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}, \boldsymbol{\eta}) &= \sum_{k=1}^{K} \sum_{n=0}^{N} \Big[\rho_{k,n}^m \\
\hat{R}_{k,n}^m - \mu_k \hat{P}_{s,k}^m - \beta_n \hat{P}_{r,n}^m - \delta_m \rho_{k,n}^m + \zeta_k \hat{P}_{s,k}^m + \eta_n \hat{P}_{r,n}^m \Big] \\
+ \sum_{k \in \ \kappa 1} \lambda_k \sum_{n=0}^{N} \rho_{k,n}^m \hat{R}_{k,n}^m + \sum_{k \in S_R} \gamma_m \sum_{n=1}^{N} (\hat{P}_{s,k}^m - t_{m,n}^m \hat{P}_{r,n}^m)
\end{aligned}
\tag{5.2}
$$

where $\boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}$ and $\boldsymbol{\eta}$ are vectors of dual variables and $\boldsymbol{\rho}^m$,$\hat{\mathbf{P}}_s^m$,$\hat{\mathbf{P}}_r^m$ are vectors of $\rho_{k,n}^m$, $\hat{P}_{s,k}^m$ and $\hat{P}_{r,n}^m$, respectively. Problem P2 is solved by maximizing L_m as follows. First, each L_m is maximized for a given set of $\boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}$ and $\boldsymbol{\delta}$. Second, for all m, $\boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}$ and $\boldsymbol{\delta}$ are updated based on the solution for maximization of L_m. Finally, these two steps are repeated until $\boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}$ and $\boldsymbol{\delta}$ reach optimality. Algorithm 1 shows the proposed algorithm which optimally solves P2.

Maximization of L_m is accomplished in two phases: in the first phase, power is allocated optimally for a given relay and subcarrier allocation; in the second phase, relays and subcarriers are optimally allocated for a given power allocation. These two phases are alternately repeated until the solutions obtained converge to the optimal.

5.2.2 Optimal Power Allocation

Consider $\rho_{k,n}^m = 1$, then the optimal power allocation over this relay and subcarrier assignment can be determined by the following KKT conditions.

$$
\frac{(1+\bar{\lambda}_k^*)\rho_{k,n}^{m*}\alpha_{k,d}^m}{2\ln(2)(\rho_{k,n}^{m*} + \hat{P}_{s,k}^{m*}\alpha_{k,d}^m + \hat{P}_{r,n}^{m*}\alpha_{n,d}^m)} - \mu_k^* + \gamma_m^* + \zeta_k^* = 0 \tag{5.3}
$$

$$
\frac{(1+\bar{\lambda}_k^*)\rho_{k,n}^{m*}\alpha_{n,d}^m}{2\ln(2)(\rho_{k,n}^{m*} + \hat{P}_{s,k}^{m*}\alpha_{k,d}^m + \hat{P}_{r,n}^{m*}\alpha_{n,d}^m)} - \beta_n^* - \gamma_m^* t_{k,n}^m + \eta_n^* = 0 \tag{5.4}
$$

$$
\gamma_m^*(\hat{P}_{s,k}^{m*} - t_{k,n}^m \hat{P}_{r,n}^{m*}) = 0 \tag{5.5}
$$

$$\zeta_k^* \hat{P}_{s,k}^{m*} = 0 \tag{5.6}$$

$$\eta_n^* \hat{P}_{r,n}^{m*} = 0 \tag{5.7}$$

where $\bar{\lambda}_k = \lambda_k, \forall k \in \kappa_1$ and x^* represents the optimal value of variable x. The optimal power allocation on each subcarrier depends on whether the subcarrier is operating on cooperative mode ($m \in S_R$) or non-cooperative mode ($m \in S_D$). To obtain the subcarrier classifications and optimal power allocations, the following three cases are considered.

- **Case-1:** $\frac{\beta_n^*}{\alpha_{n,d}^m} - \frac{\mu_k^*}{\alpha_{k,d}^m} > 0$

  If $\frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m} > \hat{P}_{r,n}^{m*} > 0$, from (5.5), (5.6) and (5.7), we have $\gamma_m^* = 0$, $\zeta_k^* = 0$ and $\eta_n^* = 0$. Substituting these values into (5.3) and (5.4), we get $\frac{\beta_n^*}{\alpha_{n,d}^m} = \frac{\mu_k^*}{\alpha_{k,d}^m}$. However, this is not possible. Thus, $\hat{P}_{r,n}^{m*} = 0$ or $\hat{P}_{r,n}^{m*} = \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m}$. Then, if $\hat{P}_{r,n}^{m*} = \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m}$, from (5.6) and (5.7), we have $\zeta_k^* = 0$ and $\eta_n^* = 0$, respectively. Then, by (5.3) and (5.4), we have $\gamma_m^*(t_{k,n}^m + \frac{1}{\alpha_{k,d}^m}) = \frac{\mu_k^*}{\alpha_{k,d}^m} - \frac{\beta_n^*}{\alpha_{n,d}^m} < 0$. However, this result contradicts our initial assumption. Therefore, $\hat{P}_{r,n}^{m*} = 0$ and subcarrier m operates in non-cooperative mode. The optimal power allocation for the non-cooperative mode is determined by (5.3) and given by

  $$\hat{P}_{s,k}^{m*} = \rho_{k,n}^{m*}\left[\frac{1+\bar{\lambda}_k^*}{\ln(2)\mu_k^*} - \frac{1}{\alpha_{k,d}^m}\right]^+ \tag{5.8}$$

  where $[x]^+ = \max[x, 0]$.

- **Case-2:** $\frac{\beta_n^*}{\alpha_{n,d}^m} - \frac{\mu_k^*}{\alpha_{k,d}^m} < 0$

  If $\hat{P}_{s,k}^{m*} > 0$ and $\hat{P}_{r,n}^{m*} = 0$, from (5.5) and (5.6), we have $\gamma_m^* = 0$ and $\zeta_k^* = 0$. Then, by (5.3) and (5.4), $\frac{\eta_n^*}{\alpha_{n,d}^m} = \frac{\beta_n^*}{\alpha_{n,d}^m} - \frac{\mu_k^*}{\alpha_{k,d}^m} < 0$. However, this is not possible as $\eta_n^* \geq 0$. Therefore, $\hat{P}_{r,n}^{m*} > 0$ and subcarrier m operates in cooperative mode. Next, if $\hat{P}_{r,n}^{m*} < \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m}$, from (5.3) and (5.4), we have $\frac{\beta_n^*}{\alpha_{n,d}^m} = \frac{\mu_k^*}{\alpha_{k,d}^m}$, and this condition contradicts our initial assumption. Therefore, by $c7$, $\hat{P}_{r,n}^{m*} = \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m}$.

By solving (5.3) and (5.4), the optimal power allocations for the cooperative mode are as follows.

$$\begin{aligned}\hat{P}^{m*}_{s,k} &= \rho^{m*}_{k,n} P^{m*}_{s,k} \\ &= \rho^{m*}_{k,n}\left[\frac{1+\bar{\lambda}^*_k}{2\ln(2)(\mu^*_k + \beta^*_n / t^m_{k,n})} - \frac{1}{\alpha^m_{k,n}}\right]^+ \end{aligned} \tag{5.9}$$

$$\begin{aligned}\hat{P}^{m*}_{r,n} &= \rho^{m*}_{k,n} P^{m*}_{r,n} \\ &= \rho^{m*}_{k,n}\left[\frac{1+\bar{\lambda}^*_k}{2\ln(2)(t^m_{k,n}\mu^*_k + \beta^*_n)} - \frac{1}{t^m_{k,n}\alpha^m_{k,n}}\right]^+ \end{aligned} \tag{5.10}$$

The derivation of the optimal power allocation is shown in Appendix B.

- **Case-3:** $\frac{\beta^*_n}{\alpha^m_{n,d}} - \frac{\mu^*_k}{\alpha^m_{k,d}} = 0$
  If $\hat{P}^{m*}_{r,n} = 0$, from (5.5) and (5.6), we have $\gamma^*_m = 0$ and $\zeta^*_k = 0$. By (5.3) and (5.4), we get $\frac{\eta^*_n}{\alpha^m_{n,d}} = \frac{\beta^*_n}{\alpha^m_{n,d}} - \frac{\mu^*_k}{\alpha^m_{k,d}} = 0$, which is possible and subcarrier m will operate in non-cooperative mode. Otherwise, if $\hat{P}^{m*}_{r,n} < \frac{\hat{P}^{m*}_{s,k}}{t^m_{k,n}}$, similar to **case-2**, we have $\frac{\beta^*_n}{\alpha^m_{n,d}} - \frac{\mu^*_k}{\alpha^m_{k,d}} = 0$. Next, if $\hat{P}^{m*}_{r,n} = \frac{\hat{P}^{m*}_{s,k}}{t^m_{k,n}}$, similar to **case-1**, we have $\gamma^*_m(t^m_{k,n} + \frac{1}{\alpha^m_{k,d}}) = \frac{\mu^*_k}{\alpha^m_{k,d}} - \frac{\beta^*_n}{\alpha^m_{n,d}} = 0$; thus, $\gamma^*_m = 0$. Therefore, subcarrier m will operate in cooperative mode.

  From the above explanations, it can be concluded that in **Case-3**, subcarrier m can operate in either non-cooperative or cooperative mode. However, this case is very unlikely to occur since the condition of **case-3** is rarely satisfied. If this case happens, we would assume that subcarrier m will operate in non-cooperative mode.

5.2.3 Optimal Relay and Subcarrier Allocation

The optimal relay and subcarrier allocation can be obtained from the following KKT condition

$$\left.\frac{\partial L_m}{\partial \rho_{k,n}^m}\right|_{\substack{\hat{P}_{s,k}^m=\hat{P}_{s,k}^{m*}\\ \hat{P}_{r,n}^m=\hat{P}_{r,n}^{m*}\\ \rho_{k,n}^m=\rho_{k,n}^{m*}}} = H_{k,n}^m - \delta_m^* = 0 \tag{5.11}$$

where

$$H_{k,n}^m = \begin{cases} (1+\bar{\lambda}_k^*)\Big[\log_2(1+P_{s,k}^{m*}\alpha_{k,d}^m) \\ \quad -\frac{P_{s,k}^{m*}\alpha_{k,d}^m}{\ln(2)(1+P_{s,k}^{m*}\alpha_{k,d}^m)}\Big], \text{non-cooperative mode;} \\ \frac{1}{2}(1+\bar{\lambda}_k^*)\Big[\log_2(1+P_{s,k}^{m*}\alpha_{k,d}^m+P_{r,n}^{m*}\alpha_{n,d}^m) \\ \quad -\frac{P_{s,k}^{m*}\alpha_{k,d}^m+P_{r,n}^{m*}\alpha_{n,d}^m}{\ln(2)(1+P_{s,k}^{m*}\alpha_{k,d}^m+P_{r,n}^{m*}\alpha_{n,d}^m)}\Big], \text{cooperative mode} \end{cases} \tag{5.12}$$

Then, the optimal relay and subcarrier allocation is given by

$$\rho_{k,n}^{m*} = \begin{cases} 1, (n^\star, k^\star) = \underset{n,k}{\operatorname{argmax}} \;\; H_{k,n}^m \\ 0, \text{otherwise.} \end{cases} \tag{5.13}$$

5.2.4 Variable Update

eNodeB solves the problem $P2$ using subgradient method and update the dual variables $\boldsymbol{\lambda}, \boldsymbol{\mu}$ and $\boldsymbol{\beta}$ in parallel as follows.

$$\begin{aligned} \lambda_k(t+1) &= \left[\lambda_k(t) + \eta(t)\left(Q_k - \sum_{n=0}^{N}\sum_{m=1}^{M}\rho_{k,n}^m(t)\hat{R}_{k,n}^m(t)\right)\right]^+ \\ \mu_k(t+1) &= \left[\mu_k(t) + \theta(t)\left(\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^m(t)\hat{P}_{s,k}^m(t) - P_{s,k}\right)\right]^+ \\ \beta_n(t+1) &= \left[\beta_n(t) + \delta(t)\left(\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^m(t)\hat{P}_{r,n}^m(t) - P_{r,n}\right)\right]^+ \end{aligned} \tag{5.14}$$

where t is the iteration index and $\eta(t)$, $\theta(t)$ and $\delta(t)$ are diminishing stepsize. If the chosen stepsizes satisfy the diminishing stepsize policy, the convergence to the optimal solution is guaranteed.

5.2.5 Algorithm Design

The pseudocode of the proposed optimal scheme is outlined in Algorithm 6.

5.3 Complexity Analysis and Implementation Issues

The computational complexity of the proposed scheme depends on the convergence of the dual problem. The convergence of the dual problem depends on the number of dual variables. With the individual user and relay power constraints along with each users QoS requirements, there are total $(\kappa_1 + K + N)$ dual variables. The complexity at each iteration for the relay selection and subcarrier allocation is $O(MKN)$. Therefore, the overall complexity is $O(|(\kappa_1 + K + N)|^2 MKN)$, which is polynomial and significantly lower than the exhaustive search solution. The base station can implement our scheme, however, the feedback of the all channel state information is a major overhead.

5.4 Performance Evaluation

5.4.1 Simulation Setup

The performance of our scheme is evaluated using a simulation scenario based on OFDMA network. Users are assumed to be uniformly distributed over the entire cell area. Equal number of GBR and AMBR users are assumed. Two different rate requirements of 2 bits/sec/Hz and 4 bits/sec/Hz are arbitrarily assigned to GBR users and fixed for the whole simulations of a scenario. The allocation of rates to the GBR users changes with the generation of a new scenario. In each subcarrier, the channels for different users and relays are considered to be independent, and modeled as Multipath Rayleigh fading channels. Resource allocation is performed on each resource block (RB) which consists of 12 subcarriers. Distributed subcarrier mapping is considered. The remaining system parameters are given in Table I.

Algorithm 6 : Optimal relay, subcarrier and power allocation

Initialize $\boldsymbol{\lambda}$, $\boldsymbol{\mu}$ and $\boldsymbol{\beta}$.
for $m = 1 \rightarrow M$ **do**
  for $k = 1 \rightarrow K$ **do**
    for $n = 1 \rightarrow N$ **do**
      if $\frac{\beta_n}{\alpha_{n,d}^m} - \frac{\mu_k}{\alpha_{k,d}^m} > 0$ **then**
        Calculate optimal power using (5.8).
      end if
      if $\frac{\beta_n}{\alpha_{n,d}^m} - \frac{\mu_k}{\alpha_{k,d}^m} < 0$ **then**
        Calculate optimal power using (5.9) and (5.10) .
      end if
      if $\frac{\beta_n}{\alpha_{n,d}^m} - \frac{\mu_k}{\alpha_{k,d}^m} = 0$ **then**
        Calculate optimal power using (5.8).
      end if
      Calculate $H_{k,n}^m$ using (5.12).
    end for
  end for
  Find optimal $(n^\star, k^\star)$ according to (5.13).
  Allocate subcarrier m to $(n^\star, k^\star)$.
end for
for $k = 1 \rightarrow K$ **do**
  update λ_k and μ_k.
end for
for $n = 1 \rightarrow N$ **do**
  update β_n.
end for
Repeat above steps until convergence.

Table 5.1: Simulation Parameters

Name of the Parameters	Value	Name of the Parameters	Value
Cell radius	1 km	System bandwidth	2.5 MHz
Number of RB	13	Number of subcarriers	156
Number of UEs	8	Number of relays	2, 4, 6, 8
UE power	23 dBm	Relay power	30 dBm
Noise PSD	-174 dBm/Hz	Path loss exponent	3.76
Path loss model	3GPP	Shadowing	8 dB

5.4.2 Numerical Results and Discussion

In Fig. 5.1, the average throughput per user achieved by the proposed scheme and the unconstrained scheme [54] are compared with the scheme [52] which uses a single total power constraint for all the users and relays. The proposed scheme with individual user and relay power constraints provides less throughput compared to the scheme with a total power constraint. The reason of that, in case of total power constraint, the users and relays have more flexibility to distribute power between them, whereas, in the proposed scheme, users and relays can not exceed their own maximum allowable power. The unconstrained scheme provides slightly higher throughput compared to the proposed scheme. This is because, in unconstrained scheme, resources are allocated based on multi-user diversity, i.e., resources are allocated to the users and relays who can utilize the channel the best. On the other hand, in the proposed scheme, resources are allocated to satisfy the QoS requirements of GBR users. Further, the throughput gap between these two schemes reduces when the number of relays increases. This is because when the number of relays increases, higher rates can be achieved by the proposed scheme using better relays with higher signal-to-noise ratios.

Fig. 5.2 shows the average throughput for different types of users with respect to the number of relays. Higher throughput is achieved for GBR users when we use the proposed scheme. On the other hand, the unconstrained scheme provides similar rates for both GBR and AMBR users without satisfying the throughput requirements for the GBR users. This can also be observed via outage probability in Fig. 5.3, where outage probability is defined as $Pr(R_k < Q_k), \forall k \in \kappa_1$.

Fig. 5.3 shows the outage probability of the proposed scheme and unconstrained scheme for GBR users. Equal rate requirements of 3 bits/sec/Hz are considered for all GBR users. The proposed scheme has much lower outage probability compared

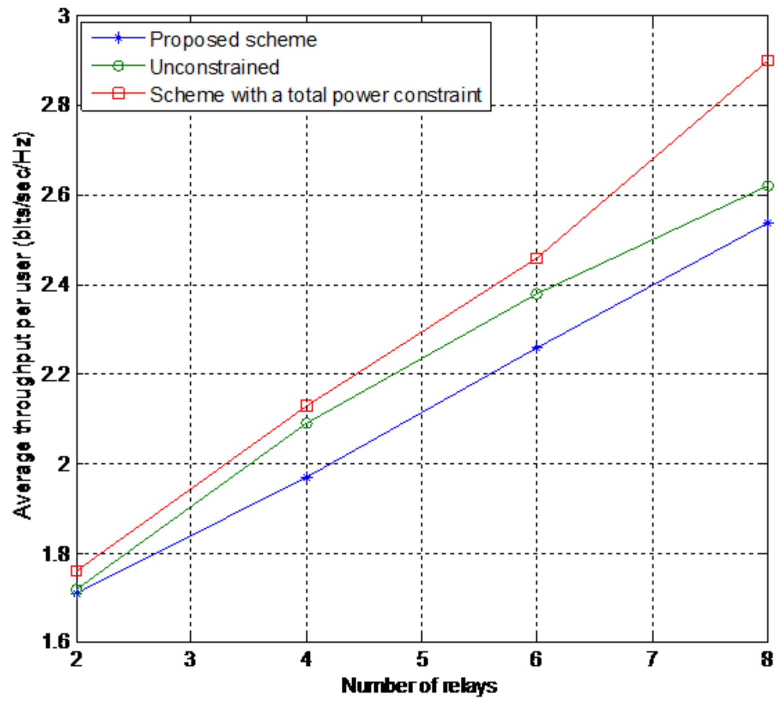

Figure 5.1: Average throughput of 8 users with different number of relays.

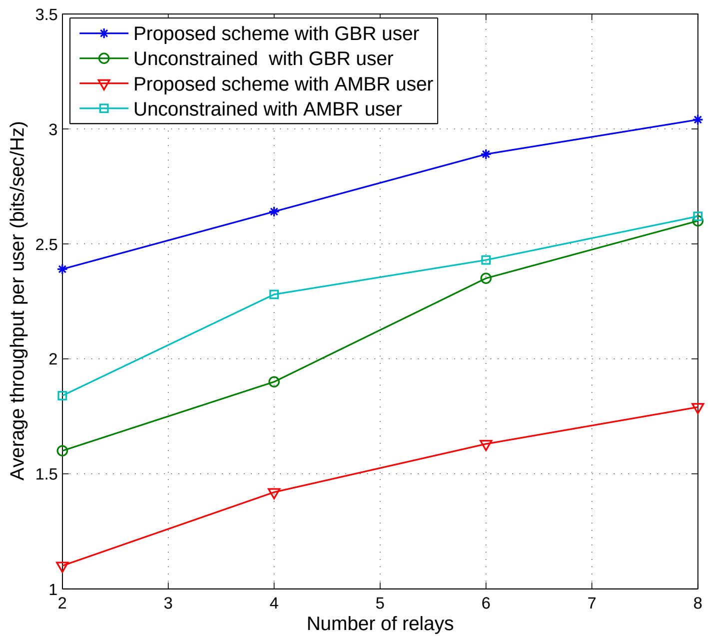

Figure 5.2: Average throughput of different types of users.

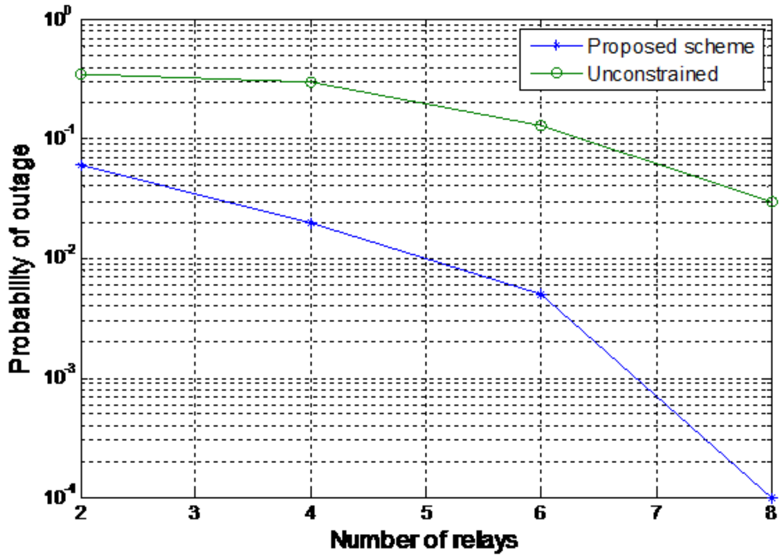

Figure 5.3: Average outage probability for GBR users.

to the unconstrained scheme as the proposed scheme is designed to satisfy the user QoS requirements.

5.5 Chapter Summary

In this chapter, resource allocation for a relay assisted cooperative OFDMA networks with service differentiation has been studied. An optimal resource (relay, subcarrier and power) allocation scheme under individual source and relay power constraints has been proposed. The problem has been formulated with the objective of maximizing the system throughput subject to user QoS satisfaction and solved by decomposing it into several subproblems to reduce computational complexity. Numerical results have shown that the proposed scheme guarantees users' QoS satisfaction at the expense of a slight degradation of the system throughput.

Chapter 6

Decentralized Resource Allocation Schemes

6.1 Introduction

The computational complexity to implement the optimal scheme proposed in the previous Chapter by the centralized eNodeB is still very high. To reduce the CSI feedback overhead and computation time at the eNodeB, in this Chapter, we propose two distributed schemes, where the computation of the centralized optimal scheme is distributed among the users and relays. Each user/relay solves its own subproblem by utilizing its local CSI and exchanges partial information with the eNodeB. So, the computational complexity at the eNodeB and the CSI feedback overhead are significantly reduced compared to optimal centralized scheduling which requires global CSI.

6.2 Distributed Schemes

6.2.1 User Centric Distributed Scheme

In user centric distributed (UCD) scheme, the computation of the optimal scheme is distributed among the users. This is possible because the problem $P2$ in Chapter 5 can be decomposed into K subproblems by dual decomposition. The Lagrangian of

P2 can be written as

$$
\begin{aligned}
&L(\boldsymbol{\rho}, \hat{\mathbf{P}}_s, \hat{\mathbf{P}}_r, \boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}, \boldsymbol{\eta}) && (6.1)\\
&= \sum_{k=1}^{K}\sum_{n=0}^{N}\sum_{m=1}^{M}\left[\rho_{k,n}^{m}\hat{R}_{k,n}^{m} - \mu_k\hat{P}_{s,k}^{m} - \beta_n\hat{P}_{r,n}^{m} - \delta_m\rho_{k,n}^{m} + \zeta_k\hat{P}_{s,k}^{m} + \eta_n\hat{P}_{r,n}^{m}\right]\\
&+ \sum_{k\in\ \kappa 1}\lambda_k\sum_{n=0}^{N}\rho_{k,n}^{m}\hat{R}_{k,n}^{m} + \sum_{k\in S_R}\gamma_m\sum_{n=1}^{N}(\hat{P}_{s,k}^{m} - t_{m,n}^{m}\hat{P}_{r,n}^{m})\\
&- \sum_{k\in\ \kappa 1}\lambda_k Q_k + \sum_{k=1}^{K}\mu_k P_{s,k} + \sum_{n=0}^{N}\beta_n P_{r,n} + \sum_{m=1}^{M}\delta_m && (6.2)
\end{aligned}
$$

where $\boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}$ and $\boldsymbol{\eta}$ are vectors of dual variables. Now, by dual decomposition, the problem can be decomposed into K subproblems. Each user solves it's own subproblem and passes it's local solution to the eNodeB. The subproblem to be solved by each user k is given by

$$
\begin{aligned}
&L_k(\boldsymbol{\rho}, \hat{\mathbf{P}}_s, \hat{\mathbf{P}}_r, \boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}, \boldsymbol{\eta}) && (6.3)\\
&= \sum_{n=0}^{N}\sum_{m=1}^{M}\left[\rho_{k,n}^{m}\hat{R}_{k,n}^{m} - \mu_k\hat{P}_{s,k}^{m} - \beta_n\hat{P}_{r,n}^{m} - \delta_m\rho_{k,n}^{m} + \zeta_k\hat{P}_{s,k}^{m} + \eta_n\hat{P}_{r,n}^{m} + \bar{\lambda}_k\rho_{k,n}^{m}\hat{R}_{k,n}^{m}\right]\\
&+ \sum_{m=1}^{M}\bar{\gamma}_m\sum_{n=1}^{N}(\hat{P}_{s,k}^{m} - t_{m,n}^{m}\hat{P}_{r,n}^{m}) && (6.4)
\end{aligned}
$$

where L_k is a sub-Lagrangian corresponds to the kth user, $\bar{\lambda}_k = \lambda_k, \forall k \in \kappa_1$ and 0, otherwise; and $\bar{\gamma}_m = \gamma_m$, $\forall\ k \in \S_R$ and 0, otherwise. The problem is solved similarly as described in Chapter 5.

The UCD scheme works in three steps. In step 1, each user optimizes the power allocation, subcarrier assignment and relay selection by utilizing local CSI for a given value of β and δ and exchange some information with the selected relays and eNodeB. In step 2, the selected relays update β and feedback the updated β to the corresponding users to repeat step 1 until β converges. In step 3, the eNodeB updates δ and feeds back to the users. Then step 1 and step 2 are repeated until δ converges. The flow chart of the UCD scheme is shown in Fig. 6.1.

The UCD scheme exhibits the best performance in terms of processing time, because the number of users in the system is much higher than the number of relays. Since the computation load can be shared by the users distributively, the complexity order of the UCD scheme can be reduced at the O(K) compared to the centralized solution. However, the main limitation of this scheme is to use of limited UE power for allocating the resources.

6.2.2 Relay Centric Distributed Scheme

A relay centric distributed (RCD) scheme is proposed to overcome the limited power issue of UEs in the UCD scheme. In this scheme, the computation of the centralized resource allocation scheme is distributed among the relays, so that each relay optimizes the resource allocation by utilizing its local CSI without the help from other relays. The Lagrangian of P2 in (6.1) can be decomposed into N subproblems by dual decomposition, where each relay solves one local subproblem with no assistance from the other relays and passes it's solution to the eNodeB. The subproblem to be solved by relay n is given by

$$\begin{aligned} & L_n(\boldsymbol{\rho}, \hat{\mathbf{P}}_s, \hat{\mathbf{P}}_r, \boldsymbol{\lambda}, \boldsymbol{\mu}, \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\delta}, \boldsymbol{\zeta}, \boldsymbol{\eta}) \\ &= \sum_{k=1}^{K} \sum_{m=1}^{M} \left[\rho_{k,n}^m \hat{R}_{k,n}^m - \mu_k \hat{P}_{s,k}^m - \beta_n \hat{P}_{r,n}^m - \delta_m \rho_{k,n}^m + \zeta_k \hat{P}_{s,k}^m + \eta_n \hat{P}_{r,n}^m \right] \\ &+ \sum_{k \in \ \kappa 1} \sum_{m=1}^{M} \lambda_k \rho_{k,n}^m \hat{R}_{k,n}^m + \sum_{k \in S_R} \sum_{m=1}^{M} \gamma_m (\hat{P}_{s,k}^m - t_{m,n}^m \hat{P}_{r,n}^m) \end{aligned} \tag{6.5}$$

The RCD scheme works in two steps. In step 1, each relay determines the local resource usages for a given λ, μ and δ without any assistance from the other relays and passes this information to the eNodeB. In step 2, the eNodeB updates the dual variables, λ, μ and δ and feedbacks to the selected relays. Then Relays repeat step 1 until convergence. The flow chart of the RCD scheme is shown in Fig. 6.2. This scheme will reduce the signaling overhead of the UCD scheme and processing time at the eNodeB significantly. The computational complexity of the RCD scheme reduces at the O(N) compared to the centralized solution.

The motivations of distributed implementation are to reduce computational complexity and signaling overhead of the centralized implementation. However, the use of higher number of relays significantly increases the signalling overhead both in the

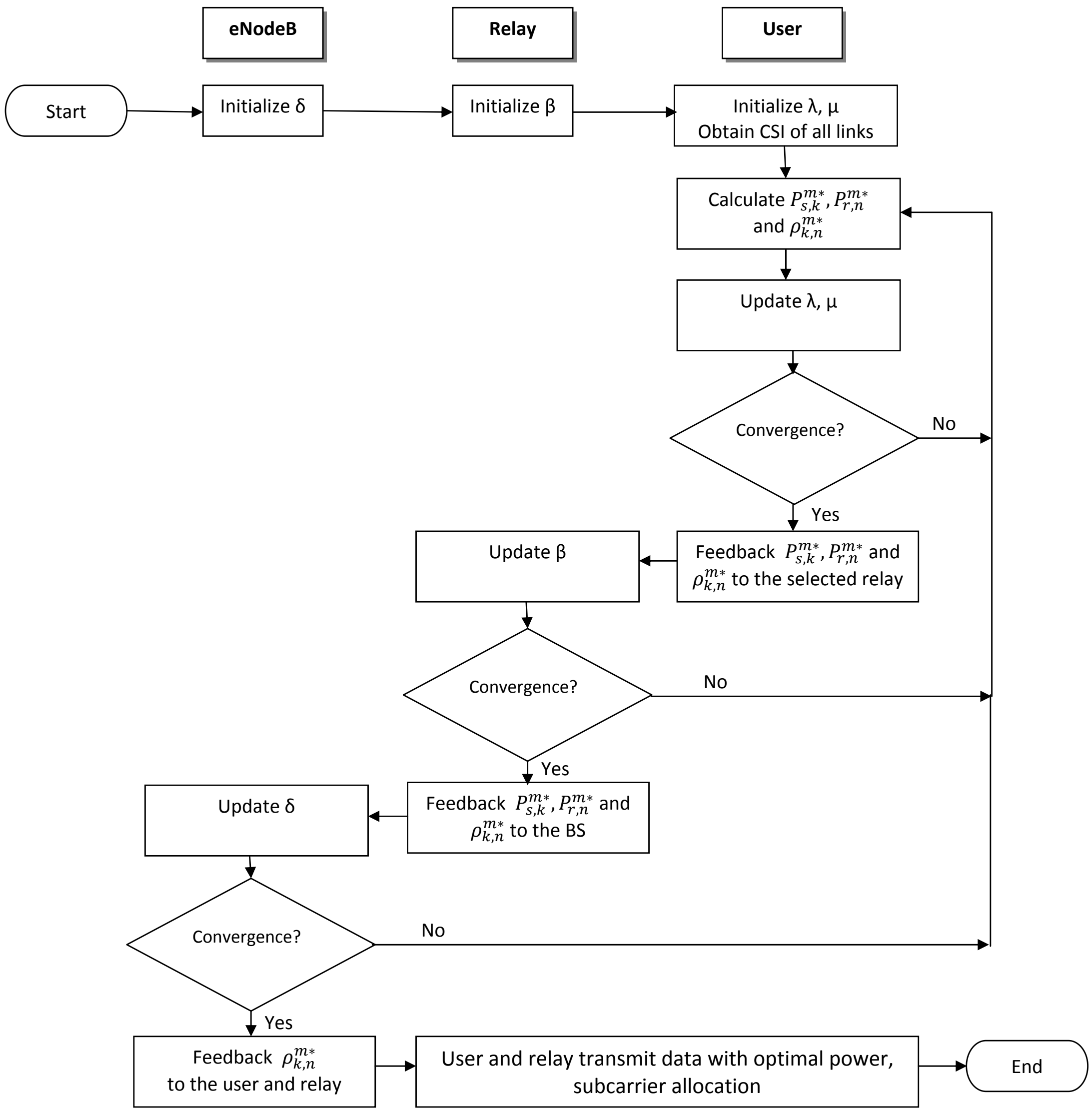

Figure 6.1: Flow chart of UCD scheme

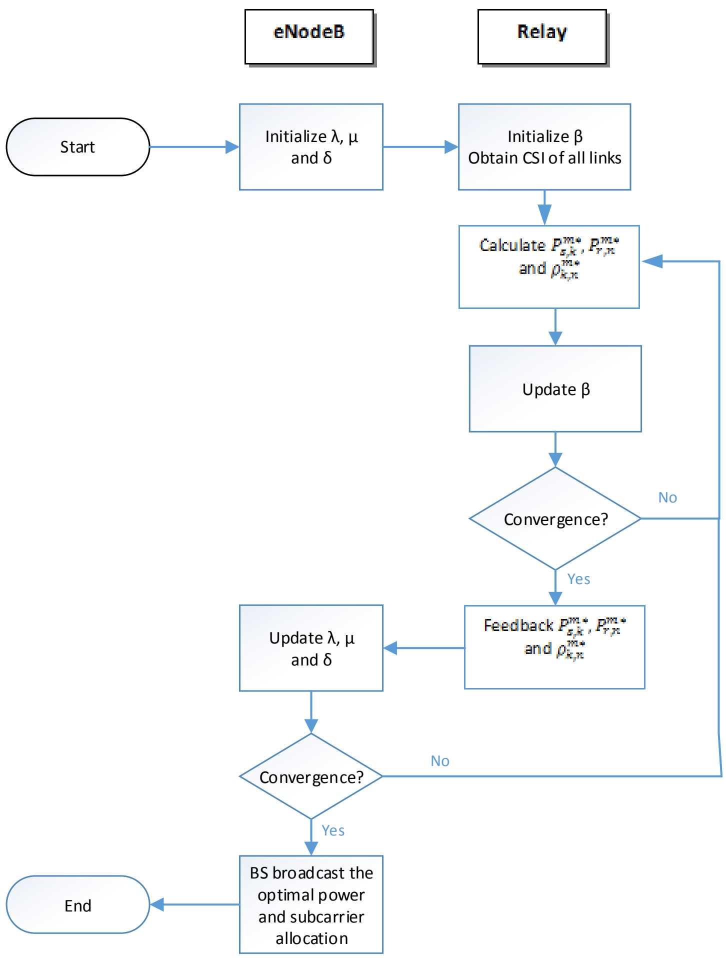

Figure 6.2: Flow chart of RCD scheme

UCD and RCD scheme which degrades the possible benefit of distributed implementation. In order to overcome the above limitations, two suboptimal schemes based on simplified relay selection strategy are proposed.

6.3 Suboptimal Schemes

6.3.1 Single Relay Selection Scheme

A single relay selection (SRS) scheme is proposed to reduce the signalling overhead of the UCD and RCD schemes where the number of relays per user is restricted to be one for all subcarriers. In [42], it is shown that the selection of single relay per user is beneficial in terms of feedback and overhead reduction and exhibits performance close to optimal when perfect CSI is available at all the nodes. The best relay for each user is selected based on the average CSI over all the subcarriers in the system. First, the relay selection is performed, then the power allocation and subcarrier assignment are optimized over the given relay selection. The SRS scheme can be applied to the centralized scheme, UCD scheme and RCD scheme.

6.3.2 Time Slotted Relay Selection Scheme

In the time slotted relay selection (TSRS) scheme, the relay selection is performed in some time intervals. This scheme works similar to the optimal scheme except the relay is not selected on every time subcarriers and power are allocated. For example, Fig. 6.3 shows a LTE frame structure with resource allocation timing point. In LTE network, resource allocation is performed in the subframe level. Each LTE frame consists of 10 subframes of length 1 msec. In TSRS scheme, the subcarriers and power allocations are performed in every subframe, i.e., in every 1 msec, whereas, the relay selection is performed in some intervals, i.e. in every 10 subframes, 20 subframes and so on. The subframes in between the intervals follow the same relay selection as done in the previous time slot. This is useful because it reduces the overall computational complexity and system feedback overhead. Additionally, the TSRS scheme can be used by the centralized scheme, UCD scheme and RCD scheme to further reduce of the complexity and signalling overhead.

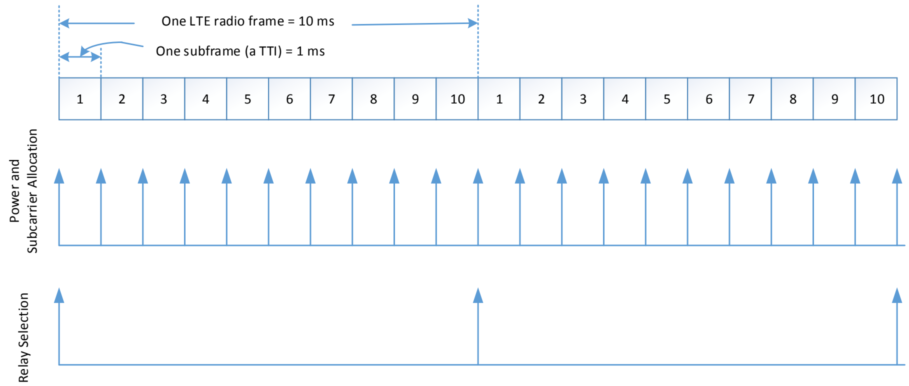

Figure 6.3: Timing point of resource allocation

6.4 Complexity Comparison

The computational complexity of the proposed schemes depends on the convergence of the dual problem. The convergence of the dual problem depends on the number of dual variables. With the individual user and relay power constraints along with each users QoS requirements, there are a total of $(\kappa_1 + K + N)$ dual variables. The complexity at each iteration for the relay selection and subcarrier allocation is $O(MKN)$. Therefore, the overall complexity of the optimal scheme is $O(|(\kappa_1 + K + N)|^2 MKN)$, which is polynomial and significantly lower than the exhaustive search solution. The complexity of the UCD and URD schemes are $O(|(\kappa_1 + K + N)|^2 MN)$ and $O(|(\kappa_1 + K + N)|^2 MK)$, respectively.

6.5 Performance Evaluation

6.5.1 Simulation Setup

The performance of our scheme is evaluated using a simulation scenario based on OFDMA network. Relays are placed uniformly over the circle at a distance 0.5 Km from the eNodeB. Users are uniformly distributed over the entire cell. We have assumed equal number of GBR and AMBR users. The rate requirements of GBR users are 2 bits/sec/Hz and 3 bits/sec/Hz which are assigned arbitrarily and fixed for

Table 6.1: Simulation Parameters

Name of the Parameters	Value	Name of the Parameters	Value
Cell radius	1 km	System bandwidth	2.5 MHz
Number of RB	13	Number of subcarriers	156
Number of UEs	8	Number of relays	2, 4, 6, 8
UE power	23 dBm	Relay power	30 dBm
Noise PSD	-174 dBm/Hz	Path loss exponent	3.76
Path loss model	3GPP	Shadowing	8 dB

whole simulation of one scenario. We have generated 100 scenarios and each scenario is repeated 100 times to get a fair result. The generation of the simulation scenarios and simulation parameters are same as the simulation setup in Chapter 5.

6.5.2 Numerical Results and Discussion

In Fig. 6.4, the average throughput per user achieved by the proposed optimal scheme and suboptimal schemes are compared with the unconstrained scheme [54] and the scheme [11] which uses a single total power constraint for all the users and relays. The optimal scheme with individual user and relay power constraints provides less throughput compared to the scheme with a total power constraint. The reason for this, in case of total power constraint, is that the users and relays have more flexibility to distribute power between them, whereas in the proposed optimal scheme, users and relays can not exceed their own maximum allowable power. The unconstrained scheme provides slightly higher throughput compared to the optimal scheme. This is because, in unconstrained scheme, resources are allocated based on multi-user diversity, i.e., resources are allocated to the users and relays who can utilize the channel the best. On the other hand, in the optimal scheme, resources are allocated to satisfy the QoS requirements of GBR users. Further, the throughput gap between these two schemes reduces when the number of relays increases. This is because when the number of relays increases, higher rates can be achieved by the proposed scheme using better relays with higher signal-to-noise ratios (SNR).

Both suboptimal schemes have lower throughput compared to the optimal scheme. This is because, both the SRS and TSRS schemes use simplified relay selection. However, the throughput difference with the optimal scheme reduces when the number of relays are lower and the number of relays are higher. This is due to the fact that both schemes heavily depends on the relay selection strategy. However, when the number of relays are lower or higher, there is less impact of relay selection on throughput. The TSRS scheme with 10 msec interval has slightly better performance compared with SRS scheme, because the TSRS scheme uses optimal relay selection in every 10 msec, whereas the SRS scheme performs relay selection based on average CSI for all subcarriers every 1 msec. However, when the time interval of the TSRS scheme is increased to 20 msec, the throughput is decreased significantly. Because, the same relay selection is used over 20 msec.

A snapshot of the average throughput obtained by each user for the optimal scheme, suboptimal schemes and unconstrained scheme is presented in Fig. 6.5. Since the SRS scheme and TSRS scheme with 10 msec time interval have similar performance, we only present the TSRS scheme with 20 msec time interval. The system has 8 users and 8 relays, where users 2 and 6 have minimum rate requirements of 3 bits/sec/Hz and the minimum rate requirements for user 4 and 8 is 2 bits/sec/Hz. The remaining users are AMBR users. It is observed that in case of the unconstrained scheme, not all GBR users are satisfied, i.e., user 6 and user 8 are not satisfied, even when 8 relays are used in the system. On the other hand, both optimal and suboptimal schemes satisfy the minimum rate requirements for all GBR users except user 8 is not satisfied in case of the TSRS scheme with 20 msec time interval. It is also noted that our proposed schemes support the AMBR users as well. This can be concluded that our proposed optimal and suboptimal schemes ensure user satisfactions while supporting heterogeneous applications.

Fig. 6.6 shows the outage probability of the proposed optimal scheme, suboptimal schemes and unconstrained scheme, where outage probability is defined as $Pr(R_k < Q_k), \forall k \in \kappa_1$. Equal rate requirements of 3 bits/sec/Hz are considered for all GBR users. The proposed schemes have lower outage probability compared to the unconstrained scheme as the proposed schemes are designed to satisfy the user QoS requirements. It is noted that the suboptimal schemes have higher outage probability compared to the optimal one due to the same reasons as stated above.

Fig. 6.7 shows the average number of iterations required for all the dual variables in all schemes to converge. The result of the TSRS scheme is not shown, because it requires the same number of iterations as the optimal scheme. The only difference with the optimal scheme is that relay selection is done in some time intervals. It is observed that the optimal scheme requires a higher number of iterations to converge all dual variables compared to the unconstrained scheme. The reason is that the optimal scheme has additional number of dual variables due to the minimum rate constraints

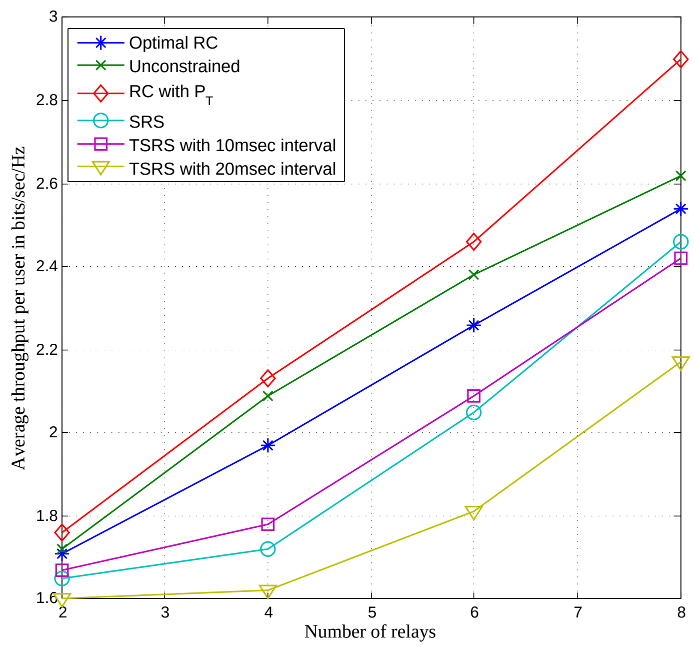

Figure 6.4: Average throughput of 8 users with different number of relays.

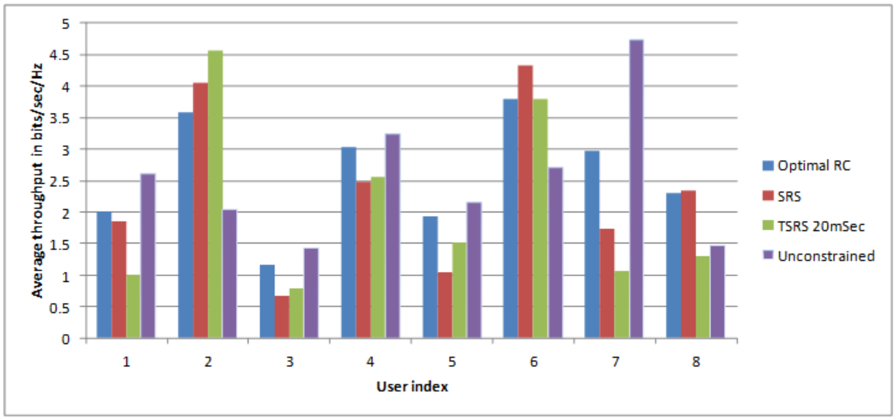

Figure 6.5: User satisfaction.

of each GBR user. The unconstrained scheme has dual variables corresponding to the individual user and relay power constraints. The RCD scheme requires greater number of iterations compared to the UCD scheme. In case of the RCD scheme, the computation is distributed among the relays. On the other hand, in case of the UCD scheme, the computation is distributed among the users. Since, the system has more users compared to the number of relays, the UCD scheme requires a smaller number of iterations to converge. The SRS scheme requires the least number of iterations, because it uses the least number of relays since a user is allowed to use only one relay for all its' subcarriers and the relay selection is performed based on best average CSI before the optimization of resource allocation. If the SRS scheme can be combined with UCD and/or RCD scheme, we can further reduce the number of iterations without sacrificing any throughput. For all schemes, the number of iterations increases with the increase of number of relays.

6.6 Chapter Summary

In this chapter, two distributed schemes have been presented to reduce the computational complexity at the centralized eNodeB. To further reduction of the computational complexity and signalling overhead, suboptimal schemes based on simplified relay selection have been proposed. The suboptimal schemes can be combined with the distributed schemes to further reduce of signalling overhead and system complexity. Numerical results have shown that the proposed schemes guarantees users' QoS

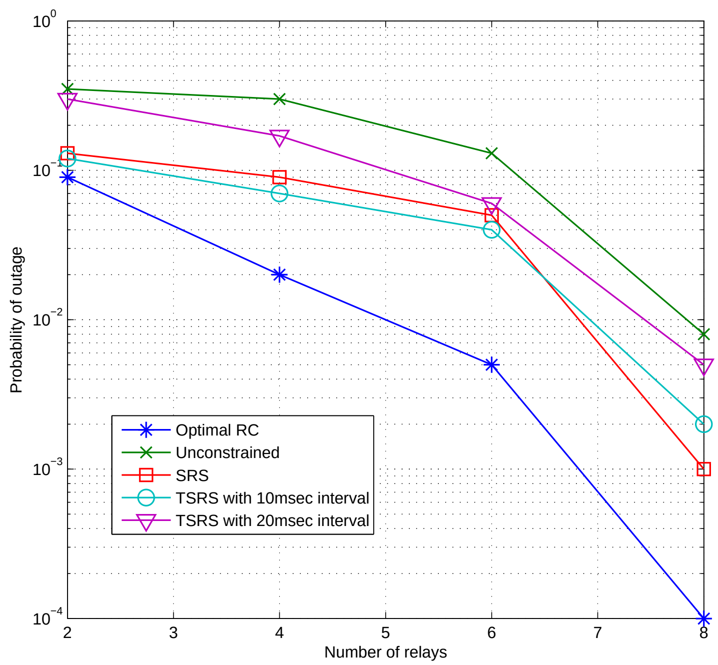

Figure 6.6: Average outage probability for GBR users.

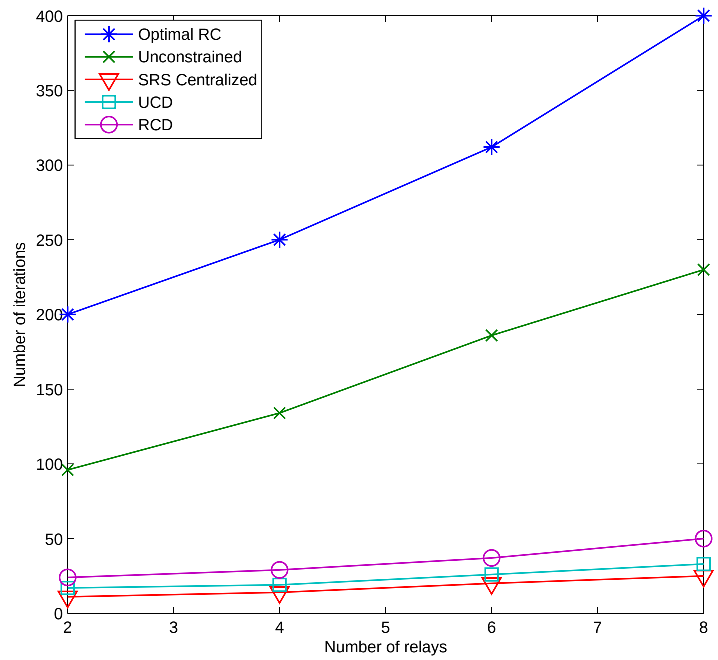

Figure 6.7: Average number of iterations for convergence with $K = 16$.

satisfaction at the expense of a slight degradation of the system throughput. The distributed and suboptimal schemes can be implemented in practical networks with reduced complexity.

Chapter 7

Conclusion and Further Research

7.1 Conclusion

The success of achieving ubiquitous wireless connectivity using relays in 4G networks is contingent upon how resources are allocated to ensure that each user has service availability. With increasing number of users demanding multimedia services (i.e., HD video and rich voice data), the limited spectrum of wireless networks and the need for QoS provisioning make resource allocation techniques indispensable. Therefore, new and realistic paradigms for resource allocation with reduce complexity are necessary to support high throughput and provide QoS guarantees. In this dissertation, we have proposed several novel and effective resource allocation schemes for relay based cooperative OFDMA networks with QoS support and service differentiation. Performance comparison has also been carried out to demonstrate the merits of the proposed resource allocation schemes over their conventional counterparts suggested in the literature. Further, our resource allocation strategies are of low computational complexity, conducing to viable and preferred candidates for practical implementation. The accomplishments in this dissertation are summarized as follows:

- We have investigated relay selection and resource allocation in a multi-user cooperative OFDMA-based uplink system that simultaneously supports GBR and AMBR traffic. A QoS aware optimal joint relay selection, power allocation and subcarrier assignment scheme under a total power constraint has been proposed. A joint optimization problem has been formulated for relay selection and resource allocation with the objective of maximizing the system throughput by satisfying the individual users' QoS requirements. The joint optimization problem has been transformed into a convex optimization problem by relaxing the integer constraints via time sharing condition. Then a two level dual decomposition approach has been used to solve the optimization problem. By dual decomposition, the problem has been decomposed into several subproblems at each subcarriers which have been solved in parallel with reduced complexity. Additionally, two suboptimal schemes have been introduced to further reduce the computational complexity. Numerical results have demonstrated that our schemes support heterogeneous services while satisfy QoS requirements of each user. The polynomial complexity of the optimal scheme facilitates the implementation of this optimization at the eNodeB. However, the suboptimal schemes can be implemented with significantly reduced computational complexity while sacrificing some system throughput.

- To implement our schemes in practical networks, resource allocation for a relay assisted cooperative OFDMA networks with service differentiation has been studied. We have proposed an optimal resource (relay, subcarrier and power) allocation scheme under individual source and relay power constraints. We consider decode-and-forward relays and both direct and relay links in the problem formulation. The consideration of both direct and relay links under individual user and relay power constraints makes the problem complicated since cooperation decision depends not only the channel condition but also the individual user relay power constraints. To handle this issue, we have determined the subcarrier classifications by deriving some cases. As the original resource allocation problem is non-convex, we relax the problem using time sharing condition. The optimal solution for the relaxed problem is found by decomposing the problem into several subproblems by means of dual decomposition. Numerical results have shown that the proposed scheme guarantees users' QoS satisfaction at the expense of a slight degradation of the system throughput. The consideration of individual user and relay power constraints makes the proposed schemes suitable for practical networks.

- The computational complexity and signalling overhead of the centralized resource allocation scheme increases with the increase of network size. The centralized scheme is not suitable for a network with large number of users and relays. So, we have proposed decentralized resource allocation schemes for cooperative OFDMA based networks. Two distributed schemes, user centric distributed scheme and relay centric distributed scheme, have been presented to reduce the computational complexity at the centralized eNodB. The distributed schemes significantly reduce the signalling overhead and processing time at the eNodeB. Additionally, suboptimal schemes based on simplified relay selection have been proposed. The suboptimal schemes can be combined with the distributed schemes to further reduce of signalling overhead and computational complexity. Numerical results have shown that the proposed schemes guarantees users' QoS satisfaction while sacrificing some total system throughput. The distributed and suboptimal schemes can be implemented in practical networks with reduced complexity.

7.2 Further Research

1. **Resource allocation in presence of imperfect CSI:** The design of efficient resource allocation schemes heavily depends on the CSI reported from the PHY layer as a measure of the wireless channel condition. In real environments, large channel feedback delays and estimation errors render the reported CSI erroneous which degrade the resulting system performance. Our current work considers perfect CSI available at the base station. However, to evaluate the performance of our resource allocation schemes in real networks, we will further investigate the design of resource allocation scheme in the presence of imperfect CSI at the base station. Our focus will be the evaluation of the ergodic mutual information which reflects the performance degradation in cooperative OFDMA based networks with inaccurate CSI. The evaluation of ergodic mutual information will be used in the design of joint relay selection and resource allocation scheme. In particular, a resource allocation problem will be formulated to maximize the evaluated ergodic mutual information subject to the network constraints. By dual decomposition, the optimization problem is separated into a master problem and several subproblems. A highly scalable distributed resource allocation scheme is proposed to solve the decomposed problem. In distributed resource allocation scheme, each relay solves its own subproblem by utilizing its local CSI without any help from other relays, whereas the BS solves the master problem using a gradient method and updates the dual variables. The distributed scheme can be implemented with reduced computational complexity compared to the centralized scheme. For the centralized solution,

the BS requires the CSI of all links at the beginning of each scheduling slot. In contrast, for the distributed solution the relays only require their own CSI, whereas BS does not require any CSI. Therefore, the computational complexity at the BS and the CSI feedback overhead are both significantly reduced.

2. **Resource allocation in presence of CCI:** The increase in CCI in next-generation cellular relay networks is another burdensome challenge that need to considered in the design of resource allocation schemes. In fact, CCI is inherent in any multicellular network mainly due to inter-cell and intra-cell resource reuse. Additionally, highly aggressive reuse schemes are envisioned in next-generation networks in order to achieve a much higher spectral efficiency to meet the increasing demand of high data rates. More importantly, relays deployed in one cell bring the interference closer to the cell-edge users in the adjacent cells which potentially increases the level of inter-cell interference and renders a more interference-limited system for the cooperative OFDMA networks in their attempt to attain the desired high spectral efficiency. So, we will further extend our resource allocation schemes taking into account multi-cell interference and heterogeneous user data rate requirements. A modified optimization problem will be formulated considering a time slot allocation strategy into the problem formulation to mitigate the interference. The problem will be solved in a semi-distributed manner by decomposing it into a master problem and several subproblems which have identical structure. In semi-distributed solution, each BS solves one local subproblem by utilizing the local CSI and exchanges some information with other BSs to jointly solve the master problem through a centralized RAU. The subproblem solved at the BS can be further decomposed into smaller subproblems to be solved by the relays.

3. **Resource allocation with Carrier Aggregation (CA):** In order to meet the fulminic growth of the high-data-rate aspiration, the 3rd Generation Partnership Project (3GPP) has proposed some new technologies for LTE-A networks. Specifically, Carrier Aggregation (CA) is a promising technique and actively considered for the next generation network along with the relays. As one of the momentous techniques in LTE-A, CA allows scalable bandwidth extension via aggregating multiple smaller band segments, each called a Component Carrier (CC), into a wider virtual frequency band to transmit at higher rates [29]. With the backward compatibility of LTE-A, both the legacy LTE users and LTE-A users can operate under CA-based LTE-A systems, where LTE

users can use only one CC while LTE-A users can enjoy concurrent multi-CC transmissions exploiting CA.

In order to ensure backwards compatibility with LTE, CA technology must be able to deal with different types of user equipment (UE) with different CC capabilities operating under the same base station. For example, some UEs with high-tech hardware can support all CCs while other, more basic UEs may support only one. It is also challenging to determine precisely how to assign CCs to UEs in such scenarios. Research on resource allocation considering CA in LTE Advanced systems is therefore crucial. The consideration of CA with relaying further complicates the design of resource allocation scheme. We will investigate the joint CC and RB allocation for cooperative LTE-A system. The joint resource allocation problem will be formulated with the objective of maximizing the system throughput subject to QoS requirements and CC constraints of different LTE and LTE-A users. To address the high computational complexity in solving the optimization problem, the suboptimal schemes will be proposed.

APPENDIX A

A.1 Transformation of the Optimization Problem

By relaxing the integer constraint $\rho_{k,n}^{m}$ of $P1$, the relaxed problem can be written as

$$
\begin{aligned}
(P2) \quad \max_{\rho,\hat{P}_s,\hat{P}_r} \quad & \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m}\hat{R}_{k,n}^{m} \\
\text{s.t.} \quad & c1: 0 \leq \rho_{k,n}^{m} = 1, \forall k,m,n \\
& c2: \sum_{k=1}^{K}\sum_{n=0}^{N}\rho_{k,n}^{m} \leq 1, \forall m \\
& c3: \hat{R}_k \geq Q_k, \forall k \in \kappa_1 \\
& c4: \sum_{m=1}^{M}\hat{P}_{t,k}^{m} \leq P_T \\
& c5: \hat{P}_{t,k}^{m} \geq 0, \forall k,m,n
\end{aligned}
$$

where $\hat{R}_{k,n}^{m} = R_{k,n}^{m}|_{P_{t,k}^{m}=\hat{P}_{t,k}^{m}/\rho_{k,n}^{m}}$, $P_{s,k}^{m} = \hat{P}_{s,k}^{m}/\rho_{k,n}^{m}$, $P_{r,n}^{m} = \hat{P}_{r,n}^{m}/\rho_{k,n}^{m}$ and
$\hat{R}_k = \sum_{m=1}^{M}\sum_{n=0}^{N}\rho_{k,n}^{m}\hat{R}_{k,n}^{m}$.

Problem P2 is a convex optimization problem, and there exists a unique optimal solution which can be obtained in polynomial time. We solve P2 by decomposing it into M subproblems.

A.2 Proof of Proposition 1

According to the definition of subgradient [67], vector $c \in R^n$ is a subgradient of a given convex function $f : R^n \rightarrow R$ at the point $y \in R^n$ if $f(x) \geq f(y) + (x-y)^T c$,

$\forall x \in R^n$.

Consider the objective function $g(\lambda, \mu)$ in (12) at two different points (λ, μ) and $(\lambda^{'}, \mu^{'})$, where $\lambda = (\lambda_1, \lambda_2, ..., \lambda_k, ...\lambda_K)$ and $\lambda^{'} = (\lambda_1, \lambda_2, ..., \lambda_k^{'}, ...\lambda_K), \forall k \in \kappa_1$. We have

$$g(\lambda, \mu) = \begin{cases} \max_{\rho, P_t} \quad L(\rho, P_t, \lambda, \mu) \\ s.t. \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^{m} = 1, \forall m, \\ 0 \geq \rho_{k,n}^{m} \leq 1, P_{t,k}^{m} \geq 0. \end{cases} \tag{1}$$

$$g(\lambda^{'}, \mu^{'}) = \begin{cases} \max_{\rho, P_t} \quad L(\rho, P_t, \lambda^{'}, \mu^{'}) \\ s.t. \sum_{k=1}^{K} \sum_{n=0}^{N} \rho_{k,n}^{m} = 1, \forall m, \\ 0 \geq \rho_{k,n}^{m} \leq 1, P_{t,k}^{m} \geq 0. \end{cases} \tag{2}$$

Substituting $\rho_{k,n}^{m}$ and $P_{t,k}^{m}$ with the optimal values, we have the subgradient of $g(\lambda, \mu)$ at λ_k

$[g(\lambda^{'}, \mu^{'}) - g(\lambda, \mu)]$

$$\begin{aligned} &= \max_{\rho, P_t} \quad L(\rho, P_t, \lambda^{'}, \mu^{'}) - \max_{\rho, P_t} \quad L(\rho, P_t, \lambda, \mu) \\ &\geq L(\rho^{\star}, P_t^{\star}, \lambda^{'}, \mu^{'}) - L(\rho^{\star}, P_t^{\star}, \lambda, \mu) \\ &= (\lambda_k^{'} - \lambda_k) \sum_{k \in \ \kappa 1} \left(\sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m^\star} R_{k,n}^{m^\star} - Q_k \right) \\ &\quad + (\mu^{'} - \mu)(P_T - \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m^\star} P_{t,k}^{m^\star}) \end{aligned} \tag{3}$$

The inequality in (30) holds because of the definition of dual function and Lagrange in (11) and (12), respectively. Thus, we have

$$\begin{aligned} g(\lambda^{'}, \mu^{'}) \ &\geq \ g(\lambda, \mu) + (\lambda_k^{'} - \lambda_k) \sum_{k \in \ \kappa 1} \left(\sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m^\star} R_{k,n}^{m^\star} \right. \\ &- \left. \quad Q_k \right) + (\mu^{'} - \mu)(P_T - \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m^\star} P_{t,k}^{m^\star}). \end{aligned} \tag{4}$$

So, the subgradients of $g(\lambda, \mu)$ at the point λ_k are

$\Delta\lambda_k = \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m\star} R_{k,n}^{m\star} - Q_k, \forall k \in \kappa_1,$

$\Delta\mu = P_T - \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=0}^{N} \rho_{k,n}^{m\star} P_{t,k}^{m\star}.$

A.3 Derivation of Optimal Power Allocation

Differentiating L_m in (4.13) with respect to $P_{t,k}^m$ we have

$$\frac{\partial L_m}{\partial P_{t,k}^m} = (1 + \bar{\lambda_k})\frac{\partial R_{k,n}^m}{\partial P_{t,k}^m} - \mu \tag{5}$$

$$\frac{\partial R_{k,n}^m}{\partial P_{t,k}^m} = \frac{1}{2\ln(2)}\frac{\alpha_{k,eq}^m}{(1 + P_{t,k}^m \alpha_{k,eq}^m)} \tag{6}$$

Substituting (6) into (5) and applying KKT condition

$$\begin{gathered} \frac{(1 + \bar{\lambda_k})\alpha_{k,eq}^m}{2\ln(2)(1 + P_{t,k}^m \alpha_{k,eq}^m)} - \mu = 0 \\ \frac{(1 + \bar{\lambda_k})\alpha_{k,eq}^m}{2\ln(2)} - \mu = \mu \alpha_{k,eq}^m P_{t,k}^m \end{gathered} \tag{7}$$

From (7), the optimal power allocation is given by

$$P_{t,k}^{m\,*} = \left[\frac{1 + \bar{\lambda_k}}{2\mu\ln(2)} - \frac{1}{\alpha_{k,eq}^m}\right]^+ \tag{8}$$

where $[x]^+ = max\,[x, 0]$.

A.4 Derivation of $H_{k,n}^m$

The Lagrangian function in 4.9 can be written as

$$\begin{aligned}
L(\rho, P_t, \lambda, \mu) &= \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^m \left[(1+\bar{\lambda_k})R_{k,n}^m - \mu P_{t,k}^m\right] - \sum_{k\in\ \kappa 1} \lambda_k Q_k + \mu P_T \\
&= \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=0}^{N} \rho_{k,n}^m \left[(1+\bar{\lambda_k})\frac{1}{2}\log_2(1+P_{t,k}^m \alpha_{k,eq}^m) - \mu P_{t,k}^m\right] \\
&- \sum_{k\in\ \kappa 1} \lambda_k Q_k + \mu P_T
\end{aligned} \tag{9}$$

APPENDIX B

B.5 Derivation of Optimal Power Allocation in Case-2

From Case-2 in section 5.2.2, we set $\zeta_k^* = 0$ and $\eta_n^* = 0$ in (5.3) and (5.4), respectively. By multiplying (5.3) by $t_{k,n}^m$ and adding to (5.4), we get

$$\frac{(1+\bar{\lambda}_k^*)\rho_{k,n}^{m*}}{2\ln(2)(\rho_{k,n}^{m*} + \hat{P}_{s,k}^{m*}\alpha_{k,d}^m + \hat{P}_{r,n}^{m*}\alpha_{n,d}^m)}[\alpha_{k,d}^m t_{k,n}^m + \alpha_{n,d}^m] - \mu_k^* t_{k,n}^m - \beta_n^* = 0 \tag{10}$$

Setting $\hat{P}_{r,n}^{m*} = \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^m}$, we have

$$\begin{aligned}\frac{(1+\bar{\lambda}_k^*)\rho_{k,n}^{m*}}{2\ln(2)(\rho_{k,n}^{m*} + \hat{P}_{s,k}^{m*}\alpha_{k,d}^m + \hat{P}_{s,k}^{m*}/t_{k,n}^m\alpha_{n,d}^m)}[\alpha_{k,d}^m t_{k,n}^m + \alpha_{n,d}^m] - \mu_k^* t_{k,n}^m - \beta_n^* = 0\\ \frac{(1+\bar{\lambda}_k^*)\rho_{k,n}^{m*}\alpha_{k,n}^m t_{k,n}^m}{2\ln(2)} - \rho_{k,n}^{m*}[\mu_k^* t_{k,n}^m + \beta_n^*] = \hat{P}_{s,k}^{m*}[\alpha_{k,n}^m(\mu_k^* t_{k,n}^m + \beta_n^*)]\end{aligned} \tag{11}$$

where $[\alpha_{k,d}^m t_{k,n}^m + \alpha_{n,d}^m] = t_{k,n}^m\alpha_{k,n}^m$. From (11), the optimal source power allocation is given by

$$\begin{aligned}\hat{P}_{s,k}^{m*} &= \rho_{k,n}^{m*}P_{s,k}^{m*}\\ &= \rho_{k,n}^{m*}\left[\frac{1+\bar{\lambda}_k^*}{2\ln(2)(\mu_k^* + \beta_n^*/t_{k,n}^m)} - \frac{1}{\alpha_{k,n}^m}\right]^+\end{aligned} \tag{12}$$

The relay power allocation is calculated using $\hat{P}_{r,n}^{m*} = \frac{\hat{P}_{s,k}^{m*}}{t_{k,n}^{m}}$ and given by

$$\begin{aligned} \hat{P}_{r,n}^{m*} &= \rho_{k,n}^{m*} P_{r,n}^{m*} \\ &= \rho_{k,n}^{m*} \left[\frac{1 + \bar{\lambda}_k^*}{2\ln(2)(t_{k,n}^{m}\mu_k^* + \beta_n^*)} - \frac{1}{t_{k,n}^{m}\alpha_{k,n}^{m}} \right]^+ \end{aligned} \tag{13}$$

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