Multi-Carrier
Cooperative Wireless Communication

Performance Analysis and Resource Allocation

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ABSTRACT

Relay-based cooperative wireless communication is emerging as the major candidate technology for the next generation wireless cellular networks that will support significantly higher data rates than the recent systems. The combination of cooperative relaying with Orthogonal Frequency Division Multiplexing (OFDM) is a very promising design for next generation of wireless networks with increased system throughput and spectral efficiency. The success of this combination, like other wireless networks, relies on the efficient utilization of limited radio resources such as relays, power, subcarriers and antennas.

In this research, resource allocation problems are examined with different relaying techniques and protocols and computationally efficient resource allocation algorithms are proposed. The general objective is to device resource allocation schemes in relay-based cellular networks that maximize the system throughput under different constraints. The main goal of our research is to develop efficient resource allocation algorithms for two different relaying models, namely; one-way relaying and two-way relaying in realistic scenarios for the Third Generation Partnership Project (3GPP) Long Term Evolution Advanced (LTE-Advanced) cellular standard. Performance of the proposed algorithms will be evaluated in terms of not only the throughput but also the computational complexity. In particular, in this thesis we present low-complexity efficient schemes for jointly deciding the selection of relays and subcarriers for the users. Two types of fairness among users, namely; minimum rate proportional fairness and access proportional fairness, are also considered in assigning subcarriers to users in relay networks. A new low-complexity iterative resource block (RB)-pairing and allocation algorithm is also investigated in relay networks.

Finally, we present a brief analysis of inter-cell interference in relay networks. Both theoretical analysis and computer simulations are performed in the performance evaluation of the proposed algorithms. Furthermore, practical implementation issues are also addressed.

DEDICATION

To my **Mother**

(who will always be missed)

ACKNOWLEDGEMENT

First and foremost, all praises are due to Allah, who has given me strength, knowledge and patience to accomplish this work. Without His Blessings, Mercy and Grace, this dissertation would not have been possible.

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LIST OF ABBREVIATIONS

AF	Amplify and Forward
ANC	Analogue Network Coding
APF	Access Proportional Fairness
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BILP	Binary Integer Linear Programming
BS	Base Station
CSI	Channel State Information
DF	Decode and Forward
FRBP	Fixed Order RB-Pairing
HA	Hungarian Algorithm
ICI	Inter-Cell Interference
LB	Load Balancing
LOS	Line- Of-Sight
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
MRC	Maximum Ratio Combining
MRPF	Minimum Rate Proportional Fairness
MRR	Minimum Rate Requirement
MSS	Maximum SNR Scheme
MT	Mobile Terminal
MUI	Multi-User Interference
NLOS	Non Line-Of-Sight
NP	Non-deterministic Polynomial-Time

OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OWR	One-Way Relaying
PFS	Proportional Fairness Scheme
RB	Resource Block
RRS	Round robin Scheme
RT	Relay Terminal
SER	Symbol Error Rate
SINR	Signal-to-Interference-Noise Ratio
SNR	Signal to Noise Ratio
SRBP	Selective Order RB-Pairing
TDBC	Time Division Broadcast
TWR	Two-Way Relaying

NOTATIONS

Symbol	Definition
M	Number of Mobiles Terminals
R	Number of Relay Terminals
K	Number of Resource Blocks
$P_{x,m}^{k}$	Transmission Power of x to m^{th} MT on k^{th} RB
P_{T}^{k}	Total Transmission power for k^{th} RB
$h_{xy,m}^{k}$	Channel Gain form x to y for m^{th} MT on k^{th} RB
σ_{x}^{2}	Noise Power at x
g_{m}^{k}	Scaling/Amplification Factor for m^{th} MT on k^{th} RB
R_{x}	Instantaneous Throughput for x user over the k^{th} RB
γ	Signal to Noise Ratio/ Signal-to-Interference-Noise Ratio

Chapter 1 Introduction

This Chapter provides a brief background about relay-based cooperative communication. The motivation towards this research, aim, scope and objective of the research are also listed in this Chapter.

1.1 Background Information

During the last couple of decades the importance of wireless communication has been increasing remarkably in almost every field of life. The evolution of wireless cellular networks from the First Generation (1G) to the Third Generation (3G) has enabled more reliable, faster and securer communication services [1]. We are now in the Fourth Generation (4G) which is providing even higher data rates and quality of service (QoS).

Signal fading in wireless communication systems due to multipath propagation is a major limitation in the performance of wireless communication systems. Various diversity techniques such as time, frequency and space diversities have been proposed and adopted in practical applications to mitigate this fading effect. Multiple-input multiple-output (MIMO) is a space diversity technique that plays an important role in the improvement of wireless systems. Multiple wireless paths are used in MIMO systems to transmit and receive signals via multiple antennas at transmitters and receivers, respectively.

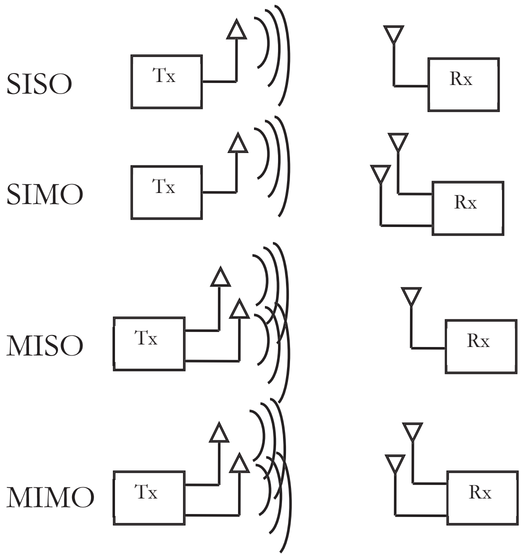


Figure 1.1: Multi-Antenna System

Figure 1.1 illustrates the different classes of multi-antenna systems including single-input multiple-output (SIMO), multiple-input single-output (MISO), MIMO and conventional single-input single-output (SISO). Exploiting multiple wireless paths, MIMO systems improve the quality of the received signal and increase the data transmission rate by using digital signal processing methods [2].

It is widely accepted that the proposed high data rates for next generation wireless networks can be achieved by MIMO users who have mobile terminals with multiple antennas [2]. MIMO systems also require sufficient separation between multiple antennas to achieve maximum benefits from this diversity. While antenna separation at the base station is easily achievable, it may not be feasible at the mobile terminal due to its small physical size. In fact, the small form factor of portable mobile terminals may make it impossible to accommodate multiple antennas. Furthermore, when a mobile terminal is located far away from the base station, even the use of multiple antennas may not guarantee the communication link quality.

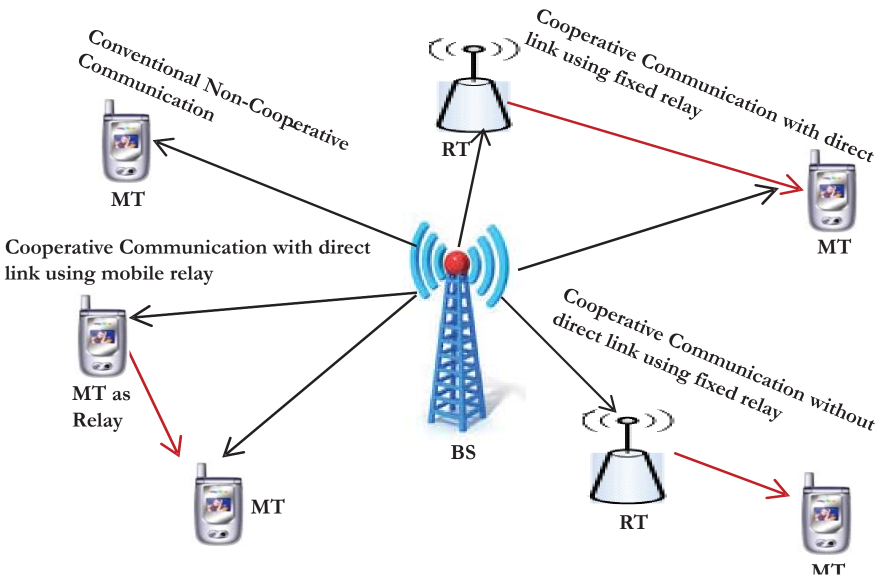


Figure 1.2: Overview of Cooperative Communication

To overcome these limitations, wireless communication systems are being developed departing from the conventional way of point to point communication. Stemming from the broadcast nature of wireless channels and the idea of allowing a network node to forward the information of other node or nodes in multi-hop networks such as sensor and adhoc networks, a new way of wireless communication known as cooperative communication has been developed.

Cooperative communication technology can establish a reliable wireless communication link between a mobile terminal (MT) and a base station (BS) by creating independent wireless propagation paths with the help of other intermediate nodes known as relay terminals (RTs) as shown in Figure 1.2. Cooperative communication can achieve almost the same advantages as MIMO systems.

Multi-carrier transmission known as Orthogonal Frequency Division Multiplexing (OFDM) is a dominant technology in many wireless communication systems and is proposed as a key element in next generation wireless networks [3]. OFDM provides simple equalization solution at the receiver by transforming frequency selective channels into frequency-flat fading channels. The combination of cooperative relaying and OFDM is a very promising design for next generation of wireless networks with increased system throughput and spectral efficiency [4].

Similar to other physical systems, resources such as bandwidth and power are limited in wireless networks. The efficiency of wireless networks depends on the efficient use of these resources. In recent years, solving the problem of resource allocation in multi-user, multi-carrier systems has become an active area of research.

1.2 Motivation and Research Challenges

Future wireless communication demands high speed and reliable transmission with limited resources. Cooperative communication is proposed to fulfill these demands in future wireless networks.

1.2.1 Motivation

There are a number of factors which motivate us to work in the area of cooperative communication with a focus on resource allocation. Firstly, cooperative systems provide most of the benefits of MIMO systems in situations where MIMO systems are not feasible due to size, cost or hardware constraints. Secondly, these networks provide higher spatial diversity. In wireless communication, fading due to multipath propagation is a major channel impairment. In conventional wireless networks, the channel between the source and destination can become poor due to small or large scale fading and retransmission is required, even though the distance between them is not large. But in the same situation, a cooperative network can exploit spatial diversity by using a relay with a good channel to forward the message to the destination. Thus the probability of successful transmission in cooperative networks is potentially higher than that in conventional wireless networks. It is also noted that cooperative networks provide better results against large scale fading (shadowing) as compared to MIMO systems because distributed virtual antennas in cooperative networks experience different shadowing due to their large separation in space. Thirdly, cooperative diversity achieves higher data-rate transmission due to improved spectral efficiency. Fourthly, communication between two distant users requires higher power because the received signal power decreases as the distance between users increases and this leads to power inefficiency. Alternately, cooperative network increases the power efficiency significantly by providing relays between distant users, hence increasing coverage area as well. Fifthly, like other wireless systems, multipath propagation can become an advantage in cooperative networks if radio resources are used opportunistically according to varying channel conditions [5]. Sixthly, different IEEE working groups and international research forums are working to develop relay-based cooperative communication networks. Relay-based cooperative communication technology has been included in three standards, i.e., IEEE 802.16j; and IEEE 802.16m; for broadband wireless access in metropolitan areas, and the Third Generation Partnership Project (3GPP) long term evolution advanced (LTE-advanced) for next generation mobile networks [1] .

Last, but not the least, efficient allocation of available resources has already been proven effective in improving the performance of different communication systems. Traditional resources include bandwidth, power, time and now antennas in MIMO networks as well. In cooperative communication, resource allocation also includes the selection of relay nodes. Since there are many entities involved to achieve a desired goal in cooperative networks, the resource allocation problem becomes even more important.

1.2.2 Research Challenges

Cooperative communication is a hot research topic currently. Resource allocation is also a key challenge in cooperative networks. There are a number of research challenges in implementing and adopting cooperative networks due to its short history. In a broad sense we can categorize them into the following four classes:

1. Relaying Protocol Design
2. System Optimization
3. Coding
4. Cross-Layer Design Issues

Our research is focused on system optimization and our discussion in this thesis is mainly focused on research challenges regarding resource allocation. In Multi-carrier cooperative communication, relays, subcarriers, power and antennas are the major resources.

Relay Selection: Selection of a suitable relay is a challenging issue in cooperative communication systems. For example, the desired performance cannot be achieved if any of the channel links, such as the source-relay link or relay-destination link, experiences deep fading. Hence, improper selection of relays will result in wastage of limited system resources. The relay selection criterion involves maximizing or minimizing the objective function for each transmission. Possible objective functions include throughput, error rate, signal to noise ratio (SNR) and transmission power. The main purpose of relay selection or allocation is to improve system efficiency. Diversity order can be increased by allowing more than one relay to cooperate as shown in Figure 1.3. But increasing the number of relays can potentially increase the overhead and complexity in the system [6]. A balance in relay selection must be found in order to achieve high efficiency because all relays may not have good channel conditions. Synchronization among participating relays is another potential challenge.

Subcarrier Allocation: In multi-user, multi-carrier systems, different subcarriers experience different and independent channels for different users. Some of the subcarriers may experience deep fading for some users and hence are not suitable at that time instant. Therefore, allocation of subcarriers to different users according to channel conditions, will improve system performance in multipath frequency selective fading environment. Multi-user diversity can also be exploited by adaptive allocation of these subcarriers [7] .

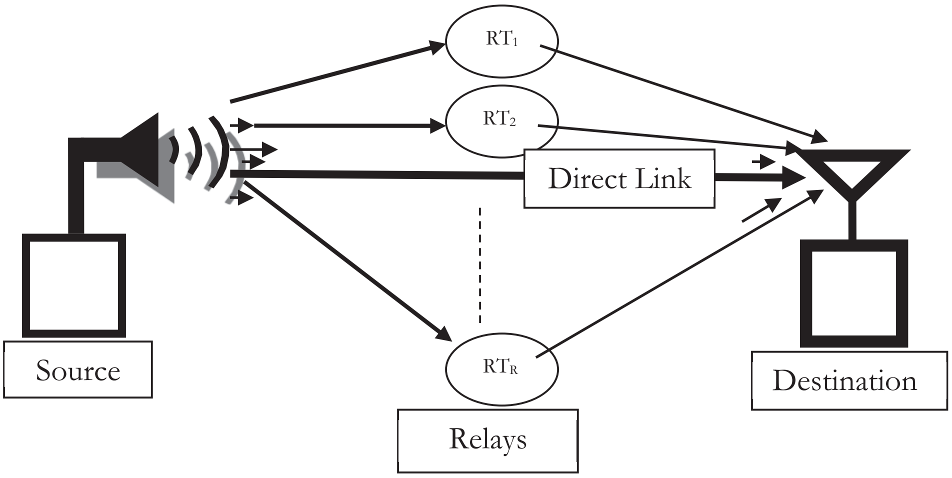


Figure 1.3: Cooperative Communication with Multiple Relays

Power Allocation: Power is always a critical resource in wireless networks. System performance can be improved by efficient use of this resource. Power optimization generally extends the life-time of networks where user's equipment is battery-operated. Power allocation in multi-user multi-carrier cooperative systems becomes a more challenging and important problem due to the increased number of entities involved.

Antenna: The capacity of the cooperative network can be increased by increasing the number of antennas at each relay [8]. But again, increasing the number of antennas increases the complexity of the system. The tradeoff between complexity due to the increased number of antennas and the achievable capacity needs to be analyzed. Power allocation becomes more critical with an increase in the number of antennas in the system. Development of efficient precoding techniques in multi-antenna relay-based cooperative networks is also a potential challenge.

1.3 **Research Problem**

Multi-carrier cooperative communication is a major candidate technology for next generation wireless networks which support higher data rates and better QoS than recent systems. This requires efficient utilization of all the limited radio resources. However, the problem of resource allocation in multi-carrier cooperative systems has not yet been fully addressed. A critical review of the related work done on resource allocation will be presented in the next Chapter.

1.4 **Scope, Aim and Objectives of the Research**

The aim of our research is to optimize the performance of multi-carrier cooperative system in a multi-user environment by an efficient use of limited resources. Although considerable research has been carried out on resource allocation in multi-carrier cooperative networks, there are still many issues that have not been fully addressed. The different objectives of our research are detailed below:

Most of the work on resource allocation in cooperative networks is based on a single source-destination pair. But in practical scenarios, interference due to multiple users also plays a critical role in system performance degradation [9]. In most of the literature, it is also assumed that the same subcarrier is used in both the first and the second hop of cooperative transmission. But due to independent channel fading on the same subcarrier over the two hops, the system performance may not be optimal. The system performance can be enhanced further by subcarrier pairing in the two hops according to their channel conditions [10]. Therefore, our objective is to present subcarrier pairing based low-complexity resource allocation algorithms in multi-user environment in one-way relaying (OWR) networks as proposed for 3GPP LTE-Advanced [11].

Two-way relaying (TWR) has also been proposed for next generation standards along with OWR [12]. The resource allocation problem in TWR needs more attention, as not much work is available in the literature. Our objective is to analyze the performance of TWR networks by proposing low-complexity resource allocation algorithms that aim to enhance system sum-rate while ensuring fairness among users.

By introducing relays in conventional cellular networks, we can extend coverage area, eliminate blind spots in cells and provide high data rates. But this increases processing delays and computational complexity in these networks. Most of the resource allocation techniques reported in the literature does not address this issue. The objective of our research is to design our resource allocation algorithms keeping in mind this issue. The proposed algorithms reduce processing delays by providing load balancing at relays.

In cellular networks, inter-cell interference (ICI) plays a critical role in the system performance. In relay-based wireless networks it becomes more important due to an increase in the number of interfering sources. Our objective is to analyze the relaying network under ICI under different relaying protocols.

The objective of our research is also to provide a comparative analysis of our proposed algorithms. The analysis will elaborate on performance comparison and computational complexity.

1.5 Research Contributions

In this thesis, we solve resource allocation problems by proposing low-complexity resource allocation algorithms in relay networks with different scenarios and assumptions. The resource allocation is formulated into optimization problems with different objectives and constraints.

The main contributions are summarized as follows:

1. A joint optimization problem in single relay network is formulated for the allocation of subcarriers and power. A two-step approach has been introduced to avoid Non-deterministic Polynomial-time (NP)-hard solution of the joint optimization problem.
2. The importance of subcarrier pairing in relay networks has been highlighted.

A joint optimization problem is formulated under the constraints of subcarrier pairing, relay selection, and fairness in multi-user and multi-relay OWR wireless networks. A low-complexity iterative subcarrier pairing and allocation algorithm is proposed.

3. A low-complexity joint load balancing and proportional fairness based resource allocation algorithms in TWR cooperative networks have been established.
4. A theoretical and simulated analysis of relay networks under ICI has been presented with both OWR and TWR networks.

1.5.1 List of Publications

International Journals

[1] **M. Abrar**, X. Gui, A. Punchihewa, "Resource Allocation for Maximizing System Throughput in Multi-User Relay Networks," *International Journal of Advanced Electronics and Communication Systems* vol. 2, Sep-Oct 2012.

[2] **M. Abrar**, X. Gui, A. Punchihewa, "Performance Analysis of Multi-Carrier Two-Way Cooperative Communication with Relay Selection Diversity in *International Journal of Computer Theory and Engineering (IJCTE)* Vol.5, No.5.,2013.

[3] **M. Abrar**, X. Gui, A.Punchihewa, "Radio Resource Allocation in Multi-User Cooperative Relaying Networks with Resource Block Pairing and Fairness Constraints in *International Journal of Wireless Information Networks,*Springer New York, Vol.20, number 2,2013.

[4] **M. Abrar**, X. Gui, A. Punchihewa, "Two-Way Relaying Cooperative Wireless Networks: Resource Allocation and Performance Analysis," *International Journal of Electronics and Telecommunications*. Volume 59, Issue 3, Pages 229–235, Dec. 2013.

International Conference Proceedings

[5] **M. Abrar**, X. Gui.,A. Punchihewa, "Maximizing Sum-Rate for Multi-User Two-Way Relaying Networks with ANC Protocol," *World Academy of Science, Engineering and Technology,* vol. 70, pp. 477-481, 2012.

[6] **M. Abrar**, X. Gui.,A. Punchihewa, "Maximizing system throughput in multi-user cooperative relay networks," in *2nd International Conference on Consumer Electronics, Communications and Networks (CECNet),* 2012, pp. 3310-3314.

[7] **M. Abrar**, X. Gui.,A. Punchihewa, "Performance Analysis of Multi-Carrier Two-Way Cooperative Communication with Relay Selection Diversity," in *International Conference on Intelligent Network and Computing (ICINC)*, 2010, pp. 117-120.

[8] **M. Abrar**, X. Gui.,A. Punchihewa, "Proportional Fairness-Based Resource Allocation in Two-Way Relay Networks," presented at the 7th *International Conference on Broadband and Biomedical Communications (IB2Com)*, 2012.

[9] **M. Abrar**, X. Gui.,A. Punchihewa, "Sub-carrier allocation for downlink multi-user OFDM cooperative cellular networks," in 6th *International Conference on Broadband and Biomedical Communications (IB2Com),* 2011, pp. 63-67.

[10] **M. Abrar**, X. Gui.,A. Punchihewa, et al., "Cooperative diversity versus antenna diversity in wireless communication systems," in *4th International Conference on New Trends in Information Science and Service Science (NISS*), 2010, pp. 260-263.

[11] M. Iqbal, Aziz, T.,Adnan, M., **M. Abrar**, "Relay assisted Slepian-Wolf compression to exploit temporal redundancy," *in 4th International Conference on New Trends in Information Science and Service Science (NISS),* 2010, pp. 390-392.

Book Chapter

[12] **M. Abrar**, X. Gui.,A. Punchihewa, Multi-Carrier Cooperative Wireless Communication in *"4G Wireless Communication Networks: Design Planning and Applications"*: The River Publishers Series in Communications, 2013.

1.6 Organization of the Thesis

This thesis is organized as follows:

Chapter 1 describes the motivation, aim and the objective of the research. It also highlights the research challenges in cooperative networks and contributions of the author during the elaboration of his PhD studies.

Chapter 2 provides some preliminary knowledge on cooperative networks and resource allocation in these networks. This Chapter also includes a literature review about resource allocation in relay networks.

Chapter 3 analyzes the performance of cooperative relay networks in fading environment. A comparative analysis of two basic protocols namely AF and DF is presented with different RB scheduling techniques. A joint optimization problem is formulated and a two-step low-complexity approach is proposed for the allocation of RBs and power. The performance of both protocols is evaluated in terms of the system throughput and individual throughput achieved by users in OWR networks.

Chapter 4 highlights the importance of subcarrier pairing in relay networks. Initially a problem is formulated only to check the performance of subcarrier pairing in relay networks for both AF and DF protocols in OWR networks. To reduce complexity, a joint optimization problem is formulated under the constraints of subcarrier pairing, relay selection and fairness in multi-user and multi-relay wireless networks.

Chapter 5 provides a low-complexity fairness-aware joint load balancing and proportional fairness based resource allocation algorithms in TWR cooperative networks. By considering both TWR-Analog Network Coding (ANC) and TWR- Time Division Broadcast (TDBC) protocols, a binary integer linear programming (BILP) optimization problem is formulated to maximize the overall system sum-rate while maintaining proportional fairness among users. Since the complexity of such a BILP problem is extremely high due to large number of subcarriers and users in real applications, low-complexity algorithms are proposed for practical implementation in this Chapter.

Chapter 6 provides a brief theoretical and simulation analysis on ICI in relay networks.

Chapter 7 concludes the thesis and presents proposals for future enhancement to current work.

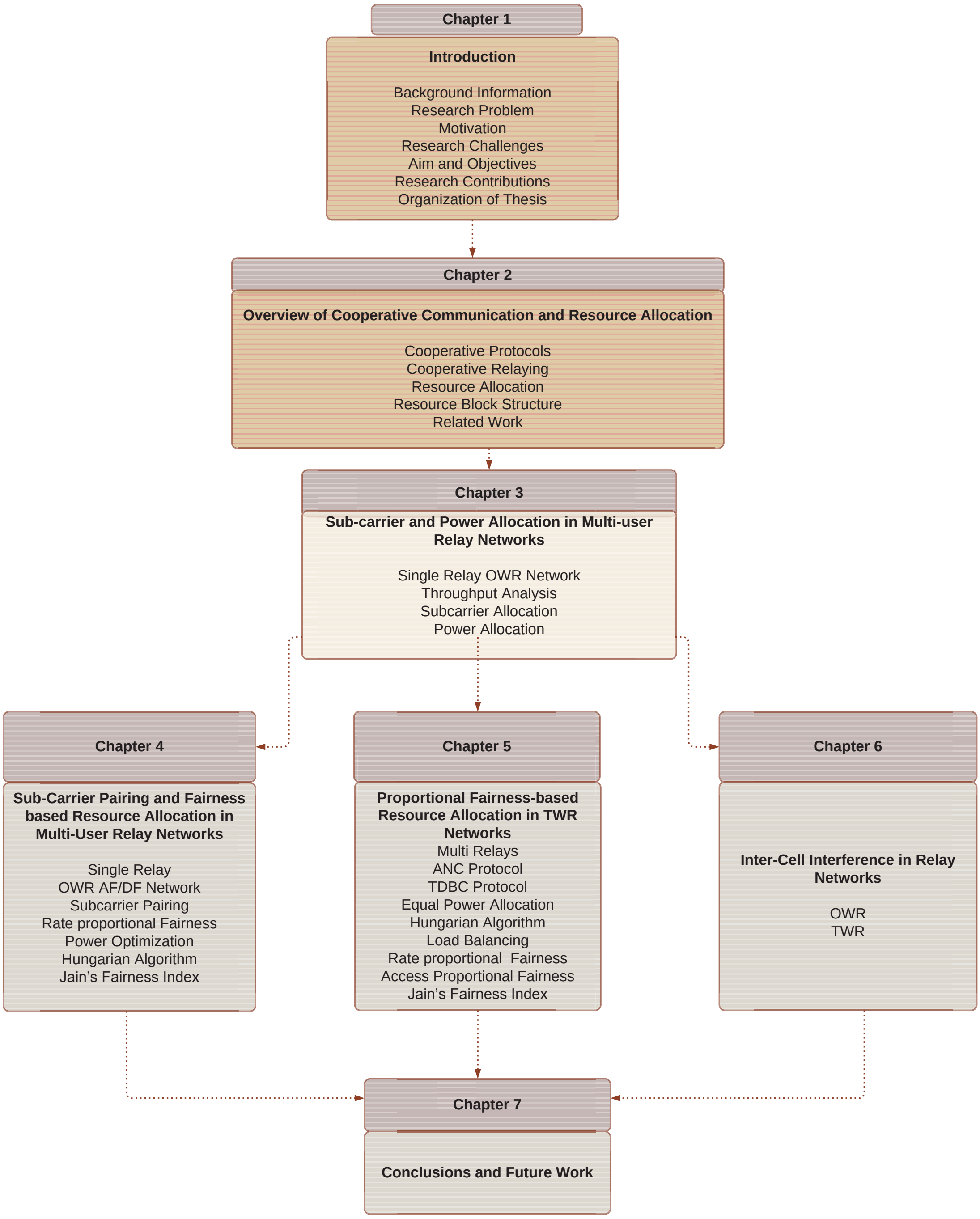


Figure 1.4: Organization of the Thesis

A visualization of the thesis structure is presented in Figure 1.4. The variations of network and optimization variables in different chapters of this thesis are shown in Table 1.1.

			Chapter 3	Chapter 4	Chapter 5	Chapter 6
Network Architecture	Cooperative Protocol	AF	🟩	🟩	🟩	🟩
		DF	🟩	🟩		
	Cooperative Relaying	OWR	🟩	🟩		🟩
		TWR			🟩	🟩
	Relays	Single	🟩	🟩		🟩
		Multiple			🟩	
	Antennas	Single	🟩	🟩	🟩	🟩
		Multiple				
Resource Allocation	RB	No-Pairing	🟩		🟩	
		Pairing		🟩		
	Power Optimization		🟩	🟩		
	Relay Selection			🟩	🟩	
	Antenna Selection					
Fairness	User Fairness	RPF	🟩	🟩	🟩	
		APF			🟩	
	Relay Fairness	LB			🟩	

🟩	Yes
⬜	No

Table 1.1: Variations of Networks and Optimization Variables in Thesis

Chapter 2 Overview of Cooperative Communication and Resource Allocation

An overview of relay-based cooperative communication is presented in this Chapter. Different relaying techniques and relaying protocols are discussed. Some related work on resource allocation is also listed in this Chapter.

2.1 Historical Background

Although the idea of cooperative communication originated from the concept of relaying that was introduced by Van der Meulen [13] in 1971 and Cover and El Gamal [14] in 1979, the early concept of using relays was different from the recent concept of relays being employed in cooperative communication. The authors in [13] and [14] considered AWGN channel only and there was no concept of diversity at that time. In [14], the authors analyzed the capacity of a three-node network consisting of a source, a relay and a destination. They elaborated on different ways that a relay can assist a remote source in extending coverage. In cooperative communication, the relays are used to achieve diversity in fading wireless channels in addition to extending the coverage area. Despite these differences, as far as signal processing at the relay is concerned, they are almost the same. Therefore cooperative communication is interchangeably known as relay communication. Sendonaris et al. were the first to introduce the concept of cooperative diversity in cellular networks [15], while Laneman et al. introduced cooperative communication in ad hoc networks [16]. Since the publication of [15] and [16], in 2003 and 2004, respectively, cooperative communication has become a hot research topic and has received a lot of attention in the research community.

2.2 Cooperative Protocols

Many cooperation techniques known as protocols have been proposed based on the concept of relaying. Some of these are amplify & forward (AF) [17], decode & forward (DF) [16], compress & forward (CF) [18], demodulation & forward [19], adaptive relay protocol [20] and coded cooperation [21]. All of these are somehow variations of the two basic protocols, AF and DF. Here we briefly discuss these two protocols.

2.2.1 Amplify and Forward

AF is the simplest cooperative protocol that was proposed in [17] and more precisely analyzed in [16]. In AF, the amplified version of the received signal at relay is forwarded to the destination. The destination receives two versions of the same signal, one from the source and the other from the relay, thus achieving spatial diversity. The performance of this protocol has been widely investigated. The advantages of this protocol are simplicity and low cost. But the major disadvantage is the noise amplification, as the relay receives a noisy version of the signal and forwards this without any alternation/filtration. Obviously this cooperation highly depends on the condition of channel between the source and the relay. The processing of sampling, amplifying, and retransmitting analogue values is another potential challenge in amplify and forward relaying protocol [22].

2.2.2 Decode and Forward

DF is another commonly used protocol that was also investigated in [15, 16]. In some literature this is also addressed as detect and forward protocol [23]. In this type of protocol, relay attempts to decode the received signal to get the original data bits. After this decoding, the data bits are encoded and transmitted to the destination. This type of protocol looks more practical and also eliminates the noise which is amplified in AF protocol. Thus, this method can considerably outperform AF. But the problem with this protocol is that, if decoding errors occur at the relay due to deep fading in the link from the source to the relay, the relay will transmit these incorrect bits to the destination, leading to error propagation and even worse performance.

2.3 Cooperative Relaying

Due to the practical half-duplex nature of devices, there are two types of cooperative relaying proposed in the literature, namely OWR and TWR.

2.3.1 One-Way Relaying (OWR)

Conventional cooperative networks are known as OWR cooperative systems. In OWR systems, two separate phases of transmission are required for the MT and the BS to exchange information via cooperation due to half-duplex operation of the relays. Hence a total of four time slots are required to complete the exchange of information between the MT and BS.

In the first phase, MT broadcasts its signal and it is received by both the relay and the BS. In the second phase, the relay transmits the signal to the BS. Then, the same two phases are repeated in reverse for the BS to send data back to the MT. In this type of relaying, there is a loss of half of the spectral efficiency as compared to full-duplex relaying. Full-duplex relaying, in which a relay is able to transmit and receive on the same frequency at the same time, is practically more complex. Therefore, from a practical point of view, half-duplex relaying is preferred over full-duplex operation even with this loss of spectral efficiency [24].

2.3.2 Two-Way Relaying (TWR)

To overcome the spectral loss in OWR, two types of TWR have been proposed in the literature [12]. The first type assumes that no direct link is available between MT and BS and only a relay link is available for transmission. Therefore, two time slots are required to complete the exchange of information between the MT and BS. The second type takes into account the direct link, and requires three time slots in order to complete the exchange of information [25]. These two types of AF-based TWR are known as ANC protocol and TDBC protocol, respectively [26].

2.4 Subcarrier and Resource Block

In Long Term Evolution (LTE) system, Resource Block (RB) is the minimal unit to be allocated. A single RB consists of twelve consecutive OFDM subcarriers [27]. OFDM uses a large number of subcarriers having smaller bandwidth for multi-carrier transmission.

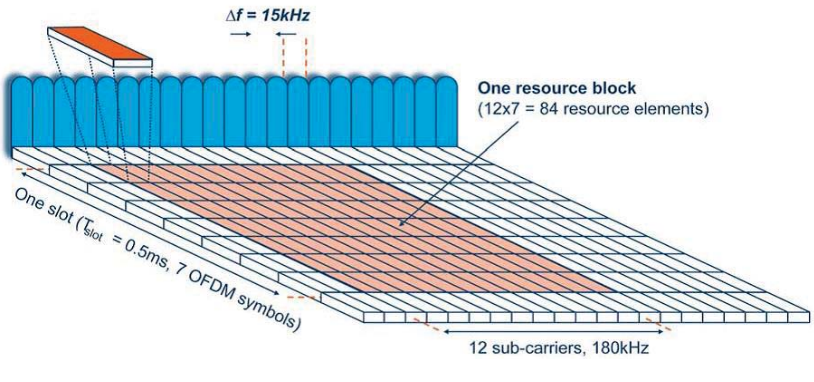


Figure 2.1: The LTE Downlink Physical Resource Based on OFDM [28]

The basic LTE downlink physical resource grid is shown in Figure 2.1. In the frequency domain, the spacing between the subcarriers is 15 kHz. The RBs have a total size of 180 kHz in the frequency domain and 0.5ms in the time domain. Each user is allocated a number of RBs in the time–frequency grid. The allocation of RBs to users depends on the scheduling mechanisms in the frequency and time dimensions [28]. In rest of the thesis the term subcarrier and RB is used alternately.

2.5 Related Work

In recent years there has been an extensive amount of research undertaken and published in the area of cooperative networks. Ranging from protocol design, relaying schemes, to coding and application aspects, the research area of cooperative communication is very broad. Each aspect can also be further sub-categorized due to its rich and diverse content. To make our review concise and focused, we have categorized the literature into three major topic areas, namely: Relaying Protocol Design, MIMO-OFDM Cooperative Systems and Resource Allocation. Since our research is focused on system optimization with resource allocation, a detailed literature review on resource allocation is presented after a brief review of the other two topics.

2.5.1 Relaying Protocol Design

There are several cooperative protocols proposed in the literature with different designs and limitations. In [16], two simple relaying protocols, AF and DF are proposed and Bit Error Rate (BER) performance and outage probability analysis have been presented. It is found that a proper combining technique is required to achieve spatial diversity in the AF protocol while DF may lead to worse performance if error propagation occurs. A closed-form Symbol Error Rate (SER) formulation for the AF protocol is presented in [29]. It is shown that optimum performance of the AF protocol with equal power allocation can be achieved when source and destination nodes are at equal distances from the relay node. The noise amplification problem in AF protocol is discussed in [19] and a new modified version of the AF protocol known as Demodulation and Forward (DemF) is proposed. A simple demodulation process is proposed at the relay to eliminate the noise effect in the AF protocol.

Another protocol known as CF is proposed, where the relay does not decode the received signal completely but quantizes (or compresses) it and then transmits the quantized version of the signal. This protocol increases the complexity at the relay. Adaptive Relay Protocol (ARP) is proposed in [20]. In this protocol, the relay makes a decision as whether to choose AF or DF depending on the decoding result. It is shown that this protocol considerably outperforms both the AF and DF protocols. All these protocols were first proposed in OWR, where the spectral efficiency is reduced by half due to the higher number of time slots required to complete the exchange of information between two users. This loss of spectral efficiency is noticed by Rankov in [12] and bidirectional communication known as TWR was proposed.

2.5.2 MIMO-OFDM Cooperative System

In [30], the authors provide a performance analysis of AF , DF and adaptive protocols in a SIMO-OFDM network. Their analysis shows that adaptive relaying provides better BER performance than both protocols, provided that accurate channel information is available.

In [31], an Alamouti space time coded OFDM system is proposed for cooperative networks. In this paper, both Cyclic Prefix (CP) and ICI self-cancellation scheme are proposed to mitigate the effects of both timing errors and ICI.

The performance of the cooperative system when multiple antennas are used at the relay is investigated in [32]. The coded DF protocol is analyzed with a Maximum Ratio Combining (MRC) and Transmit Beam-forming (TB) techniques at the receiver and transmitter, respectively. It has been shown that the proposed system achieves full diversity when relay antennas are synchronized and no frequency offset is present.

Some work in MIMO-OFDM cooperative network can be found in the literature, e.g., cooperative OFDM system for Wireless Personal Area Network (WPAN) [33], cooperative MIMO-OFDM for downlink multi-cell network [34], and cooperative MIMO-OFDM for uplink Wireless Interactive Broadcasting (WIB) [35].

2.5.3 Resource Allocation

The resource allocation problem for OFDM-based networks without relays has been extensively investigated in the literature. Two individual surveys on uplink and downlink OFDM wireless networks can be found in [36, 37], respectively. The existing open literature on the problem of resource allocation in cooperative networks can be categorized into two groups. The first group focuses on the allocation of individual resources and mainly focuses on relay selection or power allocation, while the second group emphasizes the joint allocation of more than one resource. In next sub-sections we highlight some major contributions from both groups.

2.5.3.1 Power Allocation

A review of different power allocation schemes in relay networks under different network configurations is given in this section.

In [38], three different schemes (Max-min SNR based Allocation, Power minimization based Allocation and Throughput Maximization based Allocation) are investigated for power allocation in multi-user relay networks. The proposed schemes are also reformulated using Geometric Programming (GP). In Max-min SNR based Allocation, worst users are of the major concern, therefore fairness among users is considered. In this scheme the optimization problem is considered which aims at maximize the minimum SNR over all users with source and relay power constraints. This scheme improves the performance of worst user at the cost of loss in network throughput. In Power minimization based Allocation, threshold SNR for users is defined and this threshold SNR is used as a constraint with an objective of minimizing the maximum transmit power for all sources. The third proposed scheme, Throughput Maximization based Allocation is based on maximizing the product of SNRs which is approximately the same as maximizing the overall throughput. Authors proposed that allocation of power to the users with bad channel at low SNR region is better than allocating power to the users with good channel at high SNR region. A joint optimal admission control and power allocation is also investigated in this paper.

In [39], power allocation problem is developed in multi-user cooperative network using single-carrier frequency division multiple-access (SC-FDMA). The use of SC-FDMA in uplink is justified as it offers the same advantages as OFDM but with low peak-to-average power ratio (PAPR) [40]. Two problems were investigated in this paper. In the first problem, the objective function is to minimize the total transmit power while maintaining fairness in terms of minimum SINR for each user. In the second problem, the objective function is maximizing the minimum SINR among all users with a constraint of total relay power. Power allocation algorithm based on min-total relay power and max min SNR for multi-user relay network has been addressed in [41] and [42], respectively, with guarantee of fairness for all user in terms of QoS.

An efficient power allocation scheme based on auction framework is proposed for many-to-one cooperative network in [43]. The network of interest is ad-hoc network in which relay acts as auctioneer and source nodes are bidders. The relay announces a price, the source nodes report back their cooperative power demanded at that price in terms of bidding and power is allocated to source nodes at the current price whenever they are "clinched". The relay then raises the announced price and the process repeats until the total power demand meets the available power supply.

In [44], the power allocation problem for an OWR cooperative network is formulated as an optimization problem to minimize the outage probability. The total power and maximum power per hop are used as two power constraints in this optimization problem. The Lagrange Multiplier method has been used as an optimization tool.

System performance is optimized using power allocation by considering simple AF in a three-node cooperative network in [45]. The power allocation algorithm developed in this paper requires knowledge of the mean channel gains instead of the instantaneous channel gains used in [44].

In [46], the power allocation problem for multi-relay network with single source and destination is considered. The optimization of power allocation by using convex programming has been studied under two different assumptions on the availability of channel state information (CSI) at the relays. In the first assumption, each relay has knowledge of all source-relay links while in the second assumption each relay knows only the CSI of the link between the source and itself. An SER performance comparison with an equal power allocation scheme has been presented. Some other work can be found in the literature, e.g., power allocation problem for downlink cellular network has been addressed in [47], in [48] a lifetime maximization objective is used to allocate power in a two-hop cooperative network and in [49] the performance analysis of a multicast cooperative network with power optimization has been presented.

2.5.3.2 Relay selection

When multiple relays are available for cooperation, selection of suitable single or multiple relays is one of the challenging issues in cooperative networks; In [50], authors for the first time propose an opportunistic relaying scheme for cooperative networks in which the best relay is selected for cooperation between source and destination. The proposed relay selection scheme depends on end-to-end instantaneous channel conditions. It is presented that this selective relaying improves system performance and it also approaches the maximum diversity gain as the number of relays increases.

In [51], authors analyze different relay-selection diversity schemes proposed in the literature and determine their diversity orders. According to their analysis, schemes based on the harmonic mean, SNR and worst link quality can achieve full diversity with the knowledge of full CSI. In this paper, cooperation via multiple relays has also been introduced based on SNR.

In [26, 52, 53], authors propose an AF relay-selection protocol in TWR networks with two sources and a number of relays. In [26], the relay selection schemes for both ANC and TDBC protocols are proposed to minimize the outage probabilities. The max-min criterion is adopted to maximize the mutual information of two opposite directional flows. In the scheme proposed in [52], the two sources first simultaneously transmit to all the relays, and then, a single relay with a minimum SER will be selected to broadcast the received signals back to both sources. To facilitate the selection process, we propose a simple suboptimal min–max criterion for relay selection, where a single relay that minimizes the maximum SER of two source nodes will be selected. While in [53], both single-relay-selection (SRS) and multiple relay-selection (MRS) schemes are discussed. An SRS scheme which chooses the relay that results in the highest worse receive SNR of the two users is proposed. An MRS algorithm is also introduced, by ordering the relays in descending order of the worse end-to-end SNR. Both the SRS and the MRS schemes achieve full diversity, while the latter achieves a larger array gain.

Multi-relay selection scheme for cooperative relaying considering the SNR maximization and power efficiency optimization is proposed in [54]. This work proposes two quantum particle swarm optimization (QPSO) based relay selection schemes with the SNR optimization target and power efficiency target, respectively.

2.5.3.3 Joint Resource Allocation of Multiple Resources

Like MIMO and OFDM systems, efficient use of all available resources is also critical for cooperative networks to cope with fading channel conditions. Now we highlight some of the work related to allocation of multiple resources in multicarrier cooperative networks.

In [55], the authors investigate centralized resource allocation methods for multiuser Orthogonal Frequency Division Multiple Access (OFDMA) cooperative systems. In this paper, their work is limited to multi-source and single destination network with DF protocol and knowledge of full CSI is assumed. Authors assume full-duplex operation of all nodes which appears impractical due to the limitations of practical devices. Primal-dual decomposition optimization approach has been used for joint allocation of subcarrier and relay selection along with power allocation.

Kommate [56] has addressed the resource allocation problem in OFDMA-based multiuser cooperative network using TWR. A Lagrange dual decomposition method is adopted to allocate different resources by decomposing into per subcarrier based sub-problems. The research considers only a single cell of the cellular network. The proposed algorithm has the flexibility of choosing either direct link or relay link and either OWR or TWR.

In [7], a joint resource allocation problem has been formulated for multi-cell OFDMA based cooperative network. To avoid high complexity, resource allocation is carried out in two stages. The resource allocation problem is solved by mixed integer programming. The main focus of this paper is to mitigate ICI and maximize system throughput. The research is limited to the downlink with one-way AF relaying protocol. Although overall system throughput has been increased with the proposed algorithm, it cannot ensure fairness among users in terms of maintaining minimum throughput for each user.

In [57], the relay selection, power allocation and subcarrier assignment problem is formulated as a joint optimization problem with the objective of maximizing system throughput, and is solved by two-level dual decomposition and sub-gradient method. To further reduce the computational complexity, two low-complexity sub-optimal schemes are also proposed. While in [58], the author addresses the problem of resource allocation in TWR-AF networks. The branch-and-bound algorithm is used to solve the optimization problem under power constraints. To reduce computational complexity, a sub-optimal solution is also derived. The work in [59], aims to investigate the downlink performance of general relay-assisted network with optimized system parameters in multi-cell environment. A genetic algorithm (GA) based resource allocation has been proposed. In [60], subcarrier allocation, power allocation and relay selection are examined for OWR-AF relaying networks. An iterative approach has been adopted for the optimization. A joint power and bandwidth allocation with QOS support algorithm is proposed in [61]. A convex optimization technique is used to solve this optimization problem in heterogeneous networks.

Chapter 3 Subcarrier and Power Allocation in Multi-User Relay Networks

This Chapter analyzes the performance of cooperative relay networks in fading environments. A comparative analysis of two basic protocols, namely AF and DF, is presented with different RB scheduling techniques. A joint optimization problem is formulated and a two-step low-complexity approach is proposed for the allocation of RBs and power. The performance of both protocols is evaluated in terms of the system throughput and individual throughput achieved by users in OWR networks.

3.1 Introduction

The demand of higher transmission rate and reliability of data transfer in mobile cellular networks is continuing to grow. To meet these high growing needs, highly spectral-efficient and cost-effective schemes are required. The cooperative relay communication has been proposed to meet these demands in future wireless networks [16]. The deployment of RT between BS and MT is a cost effective solution as compared to deploying more BSs to improve throughput or extend coverage area. On the other hand, implementation of relays increases the contention on the available resources and this may reduce system performance if efficient methods of radio resource management are not implemented. An efficient use of all available resources always provides better performance in wireless communication systems [62].

Multi-carrier transmission such as OFDM is a dominated technology for many wireless communication systems and is also proposed as a key element in the next generation wireless networks. OFDM provides simple equalization solution at receiver by transforming frequency selective channels into frequency flat fading channels [63]. The combination of cooperative relaying with multi-carrier system provides a promising design for the next generation of wireless networks to increase system performance and bandwidth efficiency. In multi-carrier systems, each subcarrier experiences an independent channel for different users. Some of the subcarriers may experience deep fading for some users and hence are not suitable at that time instant [55]. Therefore, allocation of subcarriers to different users according to channel conditions will improve system performance in multipath frequency selective fading environment. On the other hand, power of handheld devices is always a critical resource in wireless networks. System performance can be improved by efficient use of this resource. Power optimization generally extends the life-time of networks where user's equipment is battery-operated. Power allocation in multi-user multi-carrier cooperative systems becomes a more challenging and important problem due to the increased number of entities involved.

Most of the current research on resource allocation focuses either on AF or DF protocols [37, 55, 64, 65]. In [37], the authors address the resource allocation problem in multi-user OFDMA cooperative systems with DF protocols. The authors in [65] provide distributed resource allocation methods for fixed relays in multi-carrier relay systems. The cognitive techniques are applied at relays to enhance the spectral efficiency and fairness among users. In [66], it is proved that the optimum system performance in terms of throughput in multi-user OFDM systems can be achieved only when subcarrier is allocated to a user with best channel conditions for that subcarrier.

In this Chapter we investigate the problem of subcarrier assignment and power allocation in an OFDM-based OWR network with both AF and DF protocols. The optimization problem is formulated as a cell throughput maximization problem with data rate and power constraints.

The rest of the Chapter is organized as follows. Section 3.2 describes the system model and basic assumptions. Brief analysis of the system throughput is described in Section 3.3, while problem formulation and description are presented in Section 3.4. A two-step approach for resource allocation and an introduction to conventional RB allocation techniques are presented in Section 3.5 and Section 3.6, respectively. Furthermore, performance evaluation with simulation results is illustrated in Section 3.7. Finally, summary and conclusion of this Chapter is provided in Section 3.8.

3.2 System Model and Assumptions

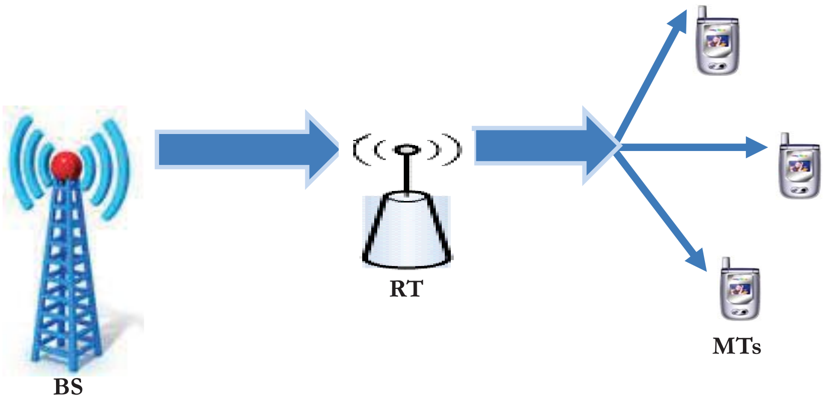


Figure 3.1: A Segment of Cooperative Relay Network

In this Chapter we consider a two-hop multi-user relay-assisted cooperative network as shown in Figure 3.1. From practical scenario we can assume that a relay terminal is located at the roof of a high building and there are M MTs present in that building. All the nodes are equipped with single antenna. The RT is assumed to be operated in half-duplex mode. It means that it cannot transmit and receive at the same time and the same frequency, which is a common assumption in the literature. By considering multi-carrier transmission, it is assumed that there are K RBs; each consists of twelve consecutive subcarriers as described in the previous Chapter.

3.2.1 Protocol Description

A downlink transmission as shown in Figure 3.1 is considered only, where MTs receive information from the BS through the RTs. The uplink transmission can be treated in the same way. In cellular OWR cooperative communication as described in Chapter 2, BS communicates with each MT in two phases. In the first phase, BS transmits its signal to RT. In the second phase, RT amplifies in AF and decode in DF the received signal and re-transmits to the MT.

3.2.2 Propagation Model

The propagation channel is assumed as Rayleigh fading channel and each subcarrier in a single RB experiences the same channel but different RBs experience different channel conditions. It is also assumed that noise power given as σ^2 is identical across all RBs on all the nodes. There is perfect synchronization among the nodes and no inter-carrier interference is considered. For centralized resource allocation it is considered that full CSI is available at the BS.

3.3 Mathematical Formulation

3.3.1 System Throughput

For mathematical analysis of the system throughput, we assume that the same order RB is used in the first and second hops for the m^{th} MT, respectively. Let $P_{B,m}^{k}$ and $P_{R,m}^{k}$ be the transmitted powers of BS and relay for the m^{th} MT using the k^{th} RB, respectively. The terms $h_{\mathrm{BR},m}^{k}$, $h_{\mathrm{B}M,m}^{k}$ and $h_{\mathrm{R}M,m}^{k}$ are the channel coefficients for channels from BS to the RT for the m^{th} MT, BS to the m^{th} MT and from the RT to the m^{th} MT, respectively. The respective noise powers at the RT and the m^{th} MT are denoted as σ_{R}^{2} and σ_{M}^{2}. For the analysis of throughput, we denote the instantaneous SNRs at the m^{th} MT using the RT for AF and DF protocols as $\gamma_{1,m}^{k}$ and $\gamma_{2,m}^{k}$, respectively. Following [2], these SNRs are given in (3.1) and (3.2), when relay link is used only for transmission.

$$\gamma_{1,m}^{k} = \frac{{g_m^k}^2 P_{\mathrm{B},m}^{k} \left|h_{\mathrm{BR},m}^{k}\right|^2 \left|h_{\mathrm{R}M,m}^{k}\right|^2}{\sigma_M^2 + {g_m^k}^2 \left|h_{\mathrm{R}M,m}^{k}\right|^2 \sigma_{\mathrm{R}}^2} \tag{3.1}$$

$$\gamma_{2,m}^{k} = \min\left(\frac{P_{\mathrm{B},m}^{k}\left|h_{\mathrm{BR},m}^{k}\right|^2}{\sigma_{\mathrm{R}}^2}, \frac{P_{\mathrm{R},m}^{k}\left|h_{\mathrm{R}M,m}^{k}\right|^2}{\sigma_M^2}\right) \tag{3.2}$$

Here in (3.1), g_m^k is the amplification factor at the RT on the k^{th} RB for the m^{th} MT and is given in (3.3)

$$g_m^k = \sqrt{\frac{P_{\mathrm{R},m}^{k}}{P_{\mathrm{B},m}^{k}\left|h_{\mathrm{BR},m}^{k}\right|^2 + \sigma_{\mathrm{R}}^2}} \tag{3.3}$$

On the other hand, to get the benefit of multi-path diversity, a direct link transmission between two nodes can also be used along with relay link transmission. Using direct link between BS and MT too, the overall SNRs obtained via MRC can easily be calculated by adding SNRs for the direct link, as shown in (3.4) and (3.5).

$$\gamma_{1,m}^{k} = \frac{{g_m^k}^2 P_{\mathrm{B},m}^{k} \left|h_{\mathrm{BR},m}^{k}\right|^2 \left|h_{\mathrm{R}M,m}^{k}\right|^2}{\sigma_M^2 + {g_m^k}^2 \left|h_{\mathrm{R}M,m}^{k}\right|^2 \sigma_{\mathrm{R}}^2} + \frac{P_{\mathrm{B},m}^{k}\left|h_{\mathrm{B}M,m}^{k}\right|^2}{\sigma_M^2} \tag{3.4}$$

$$\gamma_{2,m}^{k} = \min\ \left(\frac{P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2}}{\sigma_{R}^{2}}, \frac{P_{R,m}^{k}\left|h_{RM,m}^{k}\right|^{2}}{\sigma_{M}^{2}}\right) + \frac{P_{B,m}^{k}\left|h_{BM,m}^{k}\right|^{2}}{\sigma_{M}^{2}} \tag{3.5}$$

Using the Shannon capacity theorem, the instantaneous rate achieved by the m^{th} MT using the RT over the k^{th} RB for AF and DF is given as [2]:

$$r_{m}^{k} = \frac{1}{2}\log_{2}(1+\gamma_{m}^{k}) \tag{3.6}$$

where γ_{m}^{k} is equal to either $\gamma_{1,m}^{k}$ or $\gamma_{2,m}^{k}$ depending on the system protocol. The factor ½ appears here due to the half-duplex operation of relays.

3.4 Resource Allocation

3.4.1 Joint RB and Power Allocation

The instantaneous throughput of one MT over OWR-AF protocol is given in (3.6). The total cell throughput achieved by all MTs can be calculated as:

$$R_{s} = \sum_{m=1}^{M}\sum_{k=1}^{K}\frac{1}{2}\log_{2}(1+a_{m}^{k}\gamma_{m}^{k}) \tag{3.7}$$

where a binary variable a_{m}^{k} is the RB-allocation index. The variable a_{m}^{k} is equal to unity if and only if the k^{th} RB is allocated to the m^{th} MT, otherwise it is equal to zero. In next sub-section, we formulate a joint optimization problem for the optimal allocation of power and RBs for all MTs.

3.4.2 Problem Formulation and Description

Considering joint RB and power allocation, an optimization problem is formulated for Proportional Fairness Scheme (PFS) that considers both fairness in terms of individual performance and overall system performance. The main goal of this optimization problem is to maximize the overall cell throughput, which is given in (3.7) with minimum data rate requirement and power constraints. This optimization problem can be stated as follow:

$$\text{Maximize} \quad \sum_{m=1}^{M} \sum_{k=1}^{K} \frac{1}{2} \log_2 (1 + a_m^k \gamma_m^k) \tag{3.8}$$

Subject to the following constrains:

C1: RB-Allocation Constraint: The RB-Allocation constraint is that each RB can be used only by one MT and hence by one RT to avoid intra-cell interference.

$$\sum_{m=1}^{M} a_m^k \leq 1 \quad , \quad a_m^k \in \{0,1\} \quad \forall k \tag{3.9}$$

C2: Data-Rate Constraint: This constraint ensures that each MT meets its minimum data rate requirement. Let $r_{m,\min}$ be the minimum rate requirement (MRR) for the m^{th} MT.

$$\sum_{k=1}^{K} a_m^k r_m^k \geq r_{m,\min} \qquad \forall m \tag{3.10}$$

C3: Power Constraint: The total maximum transmission power for each RB is optimized by a power constraint:

$$(P_{B,m}^k + P_{R,m}^k) \leq a_m^k \; P_{T,m}^k \qquad \forall k, \forall m \tag{3.11}$$

$$P_{B,m}^k \geq 0, \quad P_{R,m}^k \geq 0 \quad \forall k, \forall m \tag{3.12}$$

where $P_{T,m}^k$ is the total transmission power for two-hop transmission over the k^{th} RB for m^{th} MT.

Since the problem formulated in (3.8) is combinatorial and NP-hard due to both discrete (RB allocation) and continuous (Power allocation) variable values, its computational complexity is too high [55]. To avoid this complexity, the resource allocation is accomplished for PFS in two steps. In the first step, equal power allocation is applied for two-hop transmission over each allocated RB. While in the second step, power optimization is applied to maximize the overall cell throughput.

3.5 Two-Step Approach for PFS

3.5.1 RB Allocation

The optimization problem as described in (3.8) is re-formulated with a two-step approach based on Proportional Fairness, where the RB allocation is made with fixed equal power allocation in the first step. This allocation of RBs is based on MRR of individual MTs. Furthermore this first step is purely based on three principles, namely, Priority, Fairness, and Maximization.

a) **Priority:** The priority of MTs is determined in each round based on their received SNRs over the two hops among all unallocated RBs. There is a total of *K* number of rounds corresponding to the total *K* number of RBs. The MT with the highest received SNR in each round has the highest priority for RB allocation until it meets its own MRR. Due to this process, each MT gets equal chances to use its best channel gains until it meets its MRR.

b) **Fairness:** This principle guarantees that MTs with good channel conditions are not allowed to use all the resources at the expense of others. The MT that meets its MRR is temporary removed from the RB allocation process so that remaining MTs can meet their MRRs. This process continues until either all the MTs meet their MRRs or all the RBs are allocated to MTs.

c) **Maximization:** The RB allocation process continues if there are still unallocated RBs after all the MTs meet their MRRs. This process aims to maximize the overall throughput of the system after meeting MRRs for all the MTs by previously following the fairness principle. The remaining RBs are allocated to the MTs following the priority principle to maximize the overall network throughput.

3.5.2 Power Allocation

After the allocation of all RBs and satisfying MRR, the power is allocated to BS and RT on all assigned RBs by optimizing the objective function under the power constraints.

$$\text{Maximize} \quad \sum_{m=1}^{M} \sum_{k=1}^{K} \frac{1}{2} \log_2 (1 + a_m^k \gamma_m^k) \tag{3.13}$$

Subject to: (3.11) and (3.12)

3.5.2.1 Gradient-based Method

MATLAB optimization toolbox can also be used efficiently to optimize the power in such problems. An optimization tool "FMINCON" which is designed to find the minimum of a given constrained nonlinear multivariable function is applied.

Maximization is achieved by multiplying the objective function with -1 before applying this optimization command. FMINCON is a gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives.

When the problem is infeasible, FMINCON attempts to minimize the maximum constraint value. This built-in function is flexible since it includes both equality and inequality constraints [67]. The flow chart of the algorithm for the two-step approach for resource allocation is given in Figure 3.2.

3.6 Conventional RB Scheduling Algorithms

In this sub-section, different non-cooperative single-hop conventional RB-scheduling algorithms are extended to two-hop cooperative relay networks. These algorithms are round robin and maximum SNR scheme.

3.6.1 Round Robin Scheme

In round robin scheme (RRS), the allocation of RBs is made in cyclic way to each MT. In other words, RBs are equally allocated to all pairs, regardless of the channel conditions.

3.6.2 Maximum SNR Scheme

In maximum SNR scheme (MSS), RBs are allocated to the MTs which have maximum received SNRs. This scheme optimizes the overall system throughput but fairness between MTs is not considered. In this way, any MT which has poor received

SNR due to poor channel conditions may not be allocated any RB.

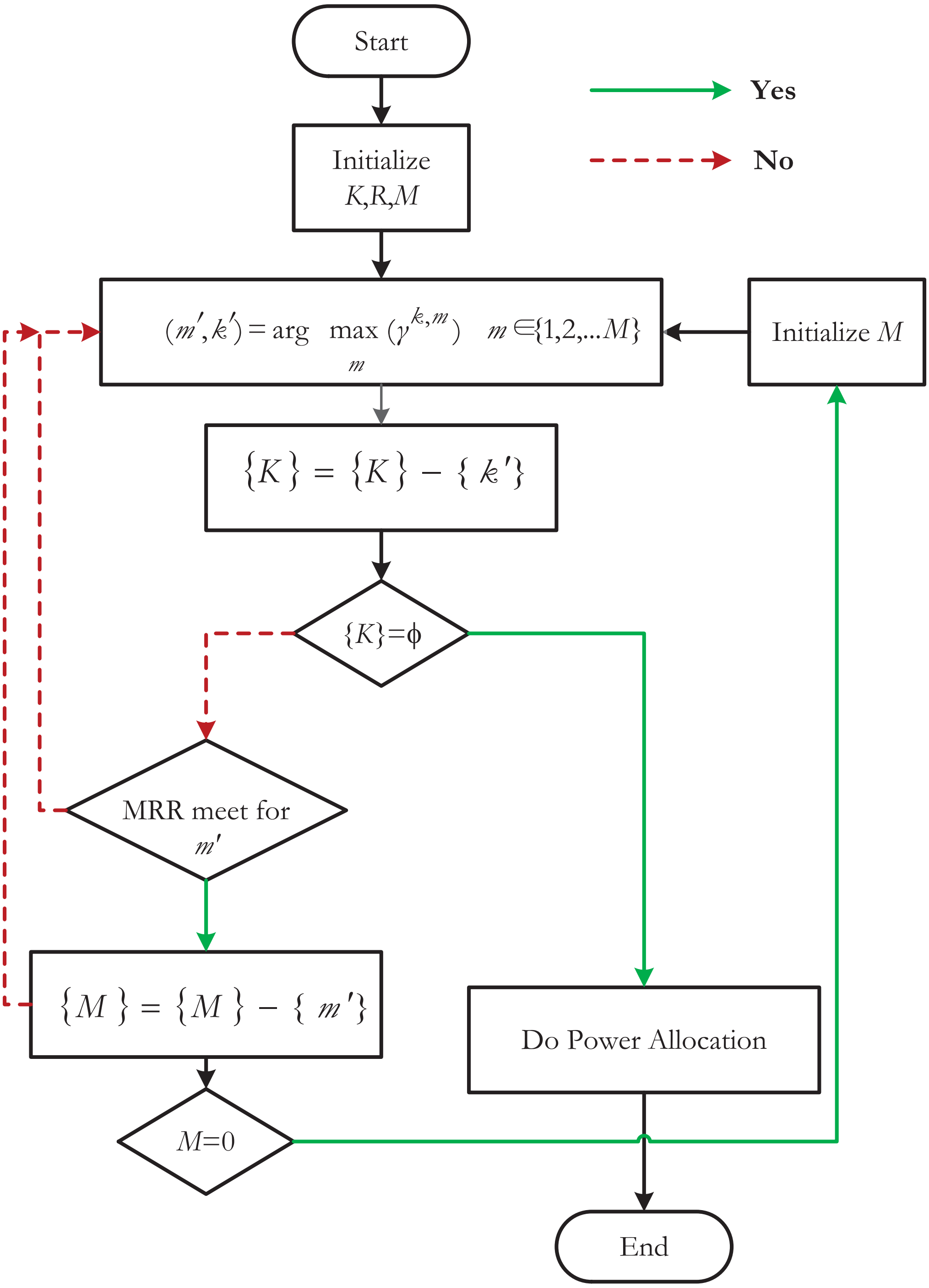


Figure 3.2: Flow Chart of Algorithm for Two-Step PFS

3.7 Performance Evaluation

In this section, we present and compare the numerical results of different RB allocation schemes in two-hop cooperative relay systems with the help of computer simulations. The resource allocation techniques have been evaluated in terms of total achievable system throughput and achievable individual throughput of each MT.

3.7.1 Simulation Setup and Parameters

We use MATLAB environment for all simulations. In these simulations, we assume that relay is located in between BS and each MT and there is no direct link available for transmission.

It is assumed that there are 5 MTs present for our simulation. The MRR = 1 Mb/S for each MT. Only one RT is allowed to cooperate with one MT. To achieve reliable results, all the performances are observed at the average of 1000 random channel realizations by setting the nominal average SNR = P_T^k / σ^2 to 20 dB .

3.7.2 Numerical Results and Discussion

Figure 3.3 shows the overall achievable cell throughput for three RB allocation schemes for AF and DF system at equal power allocation. The RRS scheme aims to provide the equal distribution of resources regardless of their channel conditions. But due to diverse nature of wireless channel, MTs experience different fading at different locations, therefore RRS may not be able to meet the rate requirement for all MTs with even equal distribution of resources and it also affects the cell throughput, which is shown less than that of other schemes in both AF and DF protocols.

On the other hand, MSS provides the maximum cell throughput but without considering individual rates of MTs. The cell throughput is increased as it assigns resources to the MTs with good channel conditions only. The PFS scheme is designed to achieve a tradeoff between cell throughput and individual throughput of MTs. Due to applying three principles given in PFS, it is clear that PFS outperforms RRS and achieves overall system throughput that is very close to MSS.

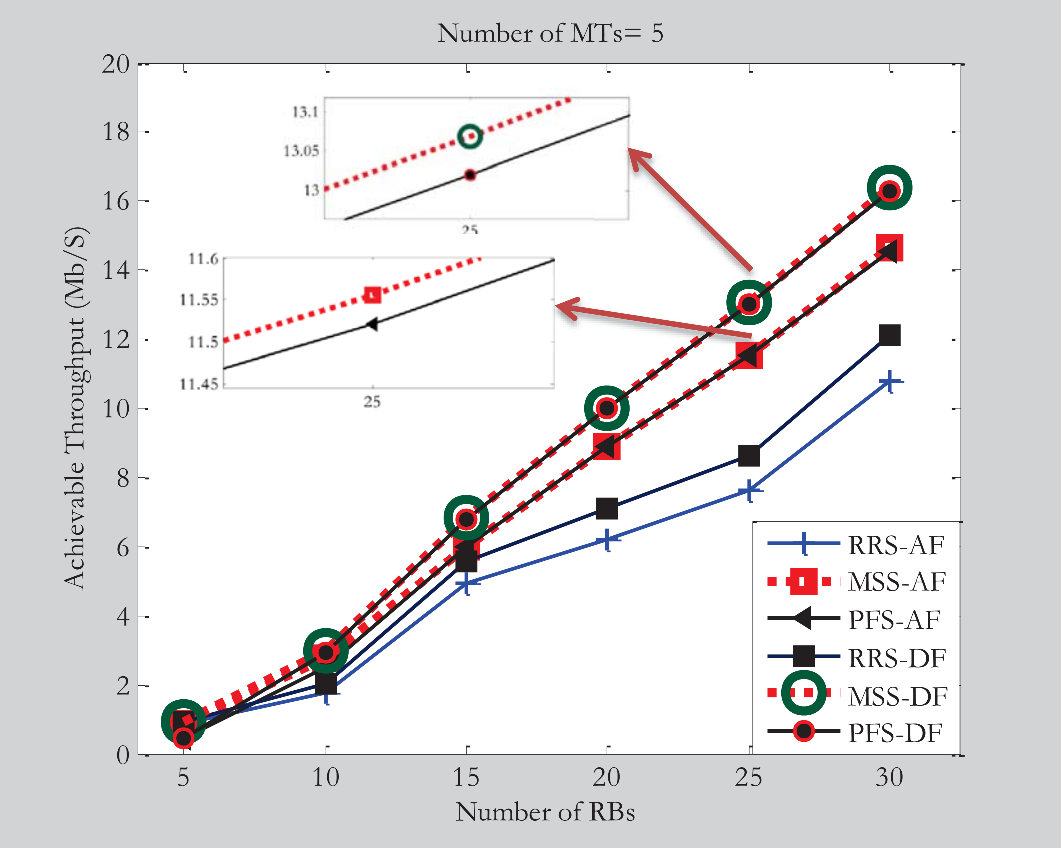
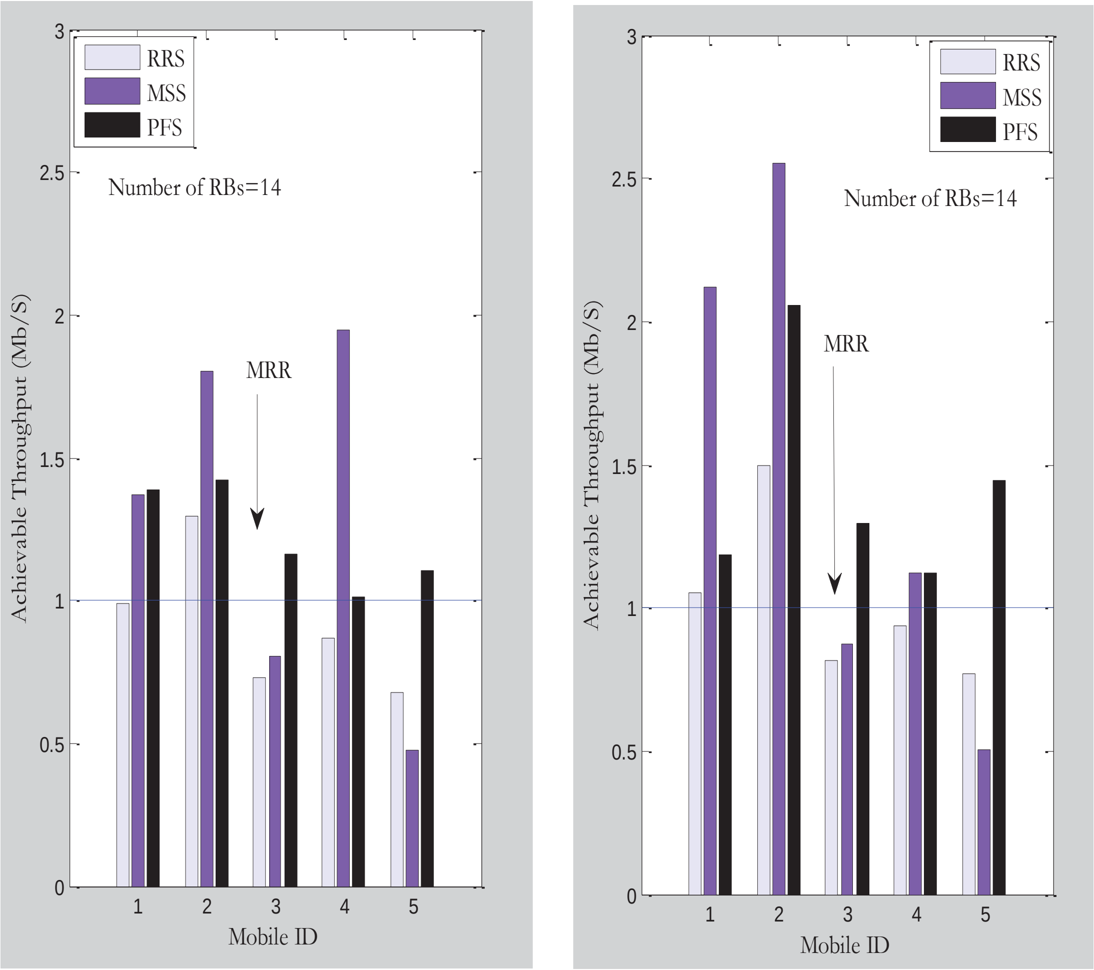


Figure 3.3: System Throughput for AF & DF Protocols

Figure 3.4 shows the individual throughput for AF and DF systems, respectively. In the case of individual throughput, PFS outperform both RRS and MSS. The fairness between all MTs is achieved in PFS, while MSS and RSS are not able to provide fairness for all MTs. For example, some of the MTs in both protocols cannot meet its MRR for both RRS and MMS, while in PFS all the MTs achieve equal or higher rate than MRR. By comparing the results of DF system with AF system it is clear that DF system outperforms AF system in all schemes, in terms of total achievable system throughput and individual achievable throughput.



(a) AF System

(b) DF System

Figure 3.4: Individual Throughput for Each MT

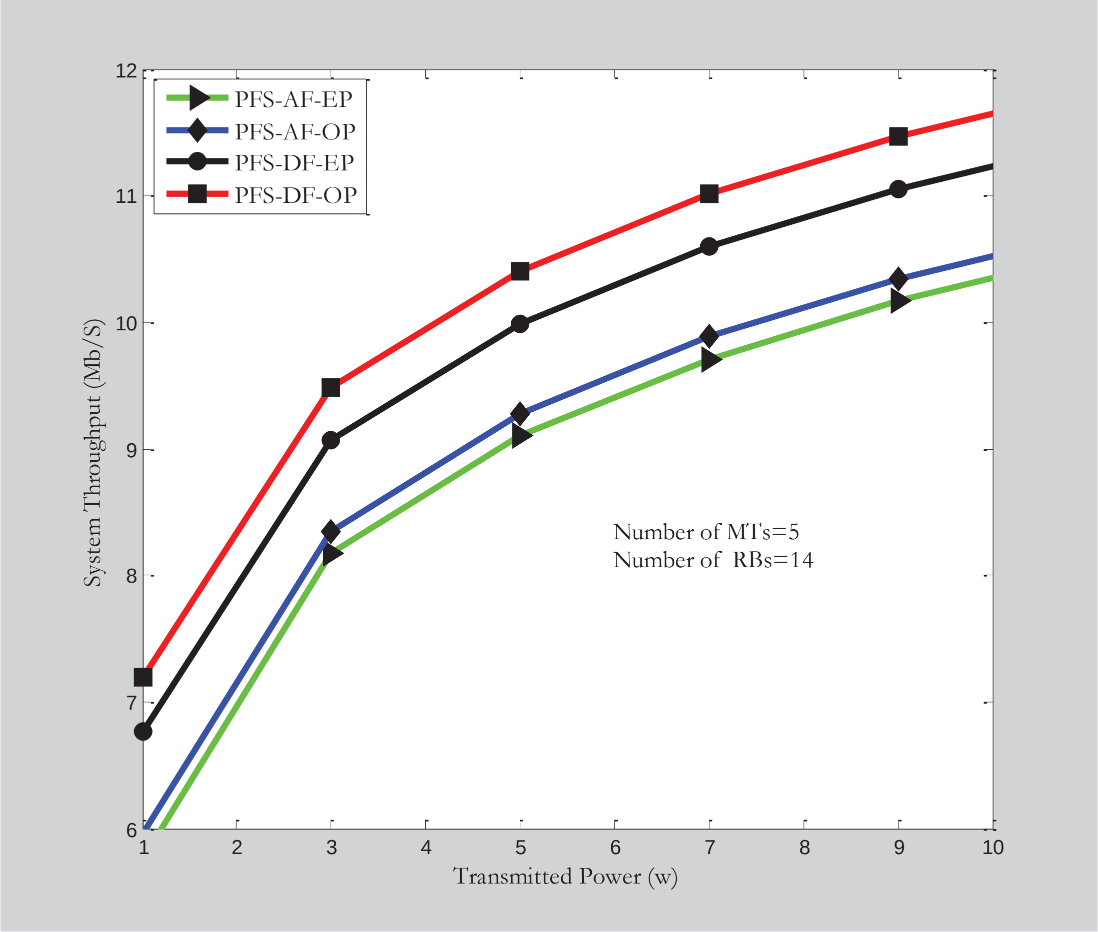


Figure 3.5: Comparison of PFS-EP and PFS-OP for AF and DF Systems

Figure 3.5 presents the result of power optimization in both AF and DF systems. The overall system throughput is observed at different total transmission powers. A sizable throughput gain has been observed by optimizing the power on all RBs. It shows the comparison of PFS scheme with equal power allocation (PFS-EP) and PFS scheme with optimized power allocation (PFS-OP) for both AF and DF systems. All results presented above demonstrate that the PFS shows good tradeoff between total achievable system throughput and individual achievable throughput in multi-user cooperative OFDM systems.

3.8 Summary and Conclusions

The deployment of relay terminal in OFDM-based wireless cellular networks is a promising design to meet high data rates and extended coverage demands in future wireless networks. However, the presence of relay terminals makes the issue of resource allocation more challenging and considerable. In this Chapter, the problem of resource allocation in multi-user relaying networks with AF and DF protocols has been addressed. Three RB scheduling techniques known RRS, MSS and PFS, in OFDM-based wireless networks are investigated and extended to two-hop relay networks.

A joint optimization problem with an objective function of maximizing system throughput has also been formulated under transmission power and data rate fairness constraints. Since the formulated optimization problem is NP-hard due to combination of discrete and continues variables. With time limitation it is difficult to find the optimal resource allocation by extensive search over all possible solutions. To cope with this issue, a two-step proportional fairness resource allocation scheme is investigated in this Chapter.

Simulation results show the effectiveness of PFS over MSS and RSS. Simulation results show that PFS achieves good tradeoff between fairness in terms of MRR for each user and total system throughput. DF protocol outperforms AF protocol. The overall performance of DF-PFS is always better than that of all other schemes in AF and DF systems. Moreover comparing with equal power allocation at BS and RT, optimize power allocation brings sizable throughput gain in both AF and DF protocols.

Chapter 4 Subcarrier Pairing and Fairness Based Resource Allocation in Multi-User Relay Networks

This Chapter highlights the importance of subcarrier pairing in relay networks. In this Chapter the resource allocation is investigated for both AF and DF protocols under the constraints of power, RB-pairing and data rate fairness. To avoid NP-hard solution with high computational complexity, the solution of optimization problem is found in two steps similar to Chapter 3. In the first step, RB-pairing and allocation are conducted jointly at equal transmission power for both the base station and the relay. In the second step, transmission power is further optimized to maximize the system throughput. To further reduce the complexity of the first step, a low-complexity iterative algorithm for RB-pairing and allocation is proposed.

4.1 Introduction

We have already seen in Chapter 3 that the allocation of subcarriers to different users according to channel condition will provide significant gain in system efficiency under fading wireless environment. In most of the literature, it is assumed that the same subcarrier is used in both the first and the second hop of transmission [25, 60] and we also used the same concept in the previous Chapter in formulating the algorithm. But due to independent channel fading on the same subcarrier over the two hops, the system performance may not be optimal. The system performance can be enhanced further by subcarrier pairing in the two hops according to their channel conditions [10]. In [10], subcarrier pairing based resource allocation for cooperative multi-relay networks is addressed for AF protocol. In [68], the concept of subcarrier pairing in relay networks was introduced in the three-node network using the DF protocol. In [69], resource allocation with subcarrier paring is investigated under a joint sum-power constraint for both AF and DF systems. Symbol error performance analysis with subcarrier pairing in OFDM relaying systems is presented in [70]. In all of these papers, the network of interest is a single source-destination pair with either single relay or multiple relays. But in practical scenarios, interference due to multiple users also plays a critical role in system performance degradation [9]. Therefore in this Chapter, we present subcarrier pairing based resource allocation in multi-user environment.

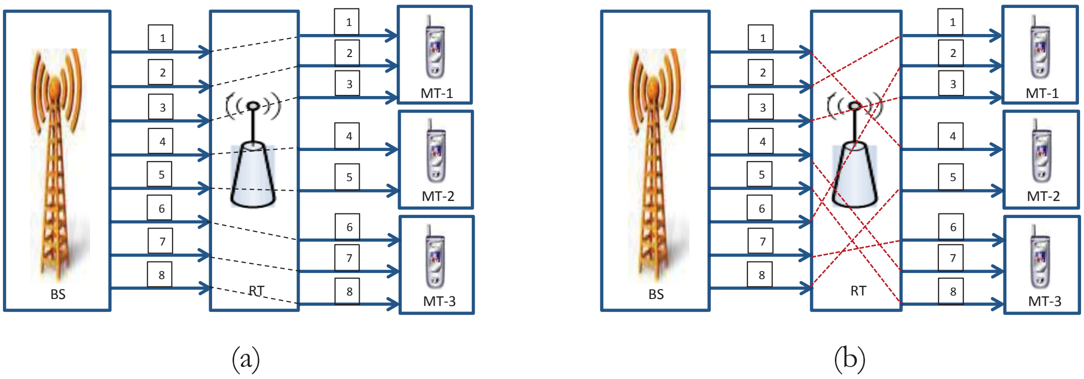
The rest of the Chapter is organized as follows. Section 4.2 briefly introduces the concept of RB-paring in relay networks, while Section 4.3 describes the system model and the optimization problem is also formulated and described here. Subcarrier pairing and fairness based resource allocation is presented in Section 4.4, along with the proposed low-complexity solution for RB-pairing and allocation in multi-user relay networks. The performance evaluation and simulation results are presented in Section 4.5. Finally, summary and conclusion of this Chapter is provided in Section 4.6.

4.2 Resource Block Pairing

In cooperative relay communication, it is commonly assumed that signal transmitted on the k^{th} RB is amplified or decoded at the relay and then retransmitted on the same k^{th} RB towards the destination. But due to independent channel fading on the same RB over the two hops, the system performance would not be optimal. The system performance can be enhanced further by RB-pairing of the two hops according to their channel conditions. At first stage in this Chapter we investigate Selective Order RB-Pairing and compare its performance with Fixed Order RB-Pairing using Exhaustive Search Algorithm (ESA) then we propose a low-complexity RB-pairing and allocation algorithm.

4.2.1 Fixed Order RB-Pairing (FRBP)

It is the most commonly assumed RB-pairing scheme, where the k^{th} RB in the first hop is paired with the same order k^{th} RB in the second hop as shown in Figure 4.1(a). This indicates that the signal transmitted by a source over one RB in the first hop is forwarded by the relay on the same RB in the second hop without considering channel conditions on the second hop.



(a) (b)

Figure 4.1: RB-Pairing Schemes: (a) FRBP (b) SRBP

4.2.2 Selective Order RB-Pairing (SRBP)

In Selective Order RB-Pairing, the RBs in the first hop are paired with RBs of the second hop according to channel conditions as shown in Figure 4.1(b). If we consider that each available RB with the highest channel gain in the first hop is paired with the available RB with the highest channel gain in the second hop for the selected MT, then the RB-pairing decision is made as follow:

$$(k,k') = \arg\left[\max(C_a), \max(C_b)\right] \quad k \in C_a,\ k' \in C_b \tag{4.1}$$

Where C_a and C_b are the set of RBs that are not paired in the first and the second hops, respectively. After pairing k and k', these are removed from C_a and C_b, respectively. This process is repeated until all the available RBs in the first hop are paired with available RBs in the second hop and then these paired RBs are allocated to users. This process can easily be implemented in single source-destination networks and therefore we are not considering fairness in terms of data rate for multiple users. Note that this type of subcarrier pairing and allocation is optimal for single source-destination with single relay networks [10, 69]. But when we consider multi-user environment and fairness constraints, this scheme is not appealing because we need to carry out RB-pairing and allocation jointly to guarantee the fairness among users. Therefore we will focus on multi-user environment in next sections.

4.3 System Model and Problem Formulation

4.3.1 System Model

Here we consider a similar two-hop multi-user relay-assisted OWR cooperative network as described in Chapter 3. Again a downlink transmission is considered only. Let the signal received at RT on the RB with index k is forwarded to MT over the RB with index k'. Here, the RB index k' may not be the same as k and they form a RB-pair (k, k'). Following (3.1) and (3.2) using RB-pairing, the SNRs for AF and DF are given as:

$$\gamma_{1,m}^{k,k'} = \frac{g_m^{k,k'2} P_{\mathrm{B},m}^{k} \left|h_{\mathrm{BR},m}^{k}\right|^2 \left|h_{\mathrm{R}M,m}^{k'}\right|^2}{\sigma_M^2 + g_m^{kk'2} \left|h_{\mathrm{R}M,m}^{k'}\right|^2 \sigma_{\mathrm{R}}^2} \tag{4.2}$$

$$\gamma_{2,m}^{k,k'} = \min\left(\frac{P_{\mathrm{B},m}^{k} \left|h_{\mathrm{BR},m}^{k}\right|^2}{\sigma_{\mathrm{R}}^2}, \frac{P_{\mathrm{R},m}^{k'} \left|h_{\mathrm{R}M,m}^{k'}\right|^2}{\sigma_M^2}\right) \tag{4.3}$$

Using the capacity theorem as in Chapter 3, the instantaneous throughput achieved by the m^{th} MT over the RB-pair (k, k') for AF and DF is given as:

$$r_m^{k,k'}(AF/DF) = \frac{1}{2}\log_2(1+\gamma_m^{k,k'}) \tag{4.4}$$

where $\gamma_m^{k,k'}$ is equal to either $\gamma_{1,m}^{k,k'}$ or $\gamma_{2,m}^{k,k'}$ depending on the system protocol.

4.3.2 Problem Formulation

In this section, we formulate the problem of subcarrier pairing, allocation and power optimization in relay networks. The objective function is to maximize the system throughput with subcarrier pairing under data rate fairness and total power constraints.

First of all we define two binary variables $\delta^{k,k'}$ and $\alpha_m^{k,k'}$ as the RB-pairing index and RB-allocation index, respectively.

$$\delta^{k,k'} = \begin{cases} 1 & \text{If RB } k \text{ is paired with RB } k' \\ 0 & \text{Otherwise} \end{cases}$$

$$\alpha_m^{k,k'} = \begin{cases} 1 & \text{If RB pair } (k,k') \text{ is allocated to MT } m \\ 0 & \text{Otherwise} \end{cases} \tag{4.5}$$

The total achieved network throughput (R_s) over all RBs and MTs can be expressed as:

$$R_s = \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{k'=1}^{K}\frac{1}{2}\log_2(1+\delta^{k,k'}\alpha_m^{k,k'}\gamma_m^{k,k'}) \tag{4.6}$$

4.3.2.1 RB-Pairing-Based Joint RB and Power Allocation

Considering joint RB and power allocation with RB-pairing, an optimization problem is formulated in this subsection. The main goal of this optimization problem is to maximize the overall system throughput, which is given by

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{k'=1}^{K}\frac{1}{2}\log_2(1+\delta^{k,k'}\alpha_m^{k,k'}\gamma_m^{k,k'}) \tag{4.7}$$

Subject to the following constrains:

C1: RB-Pairing Constraint: The RB-Pairing constraint is that each RB in the first hop can be paired with only one RB in the second hop.

$$\sum_{k=1}^{K} \delta^{k,k'} = 1 \qquad \forall\, k' \text{ and } \sum_{k'=1}^{K} \delta^{k,k'} = 1 \qquad \forall\, k \tag{4.8}$$

C2: RB-Allocation Constraint: The RB-Allocation constraint is that each RB-pair can be used only by one MT to avoid intra-cell interference.

$$\sum_{m=1}^{M} a_m^{k,k'} \le 1 \quad , \quad a_m^{k,k'} \in \{0,1\} \qquad \forall k, \forall k' \tag{4.9}$$

C3: Data-Rate Constraint: This constraint ensures that each MT meets its MRR. Let $r_{m,\min}$ be the same MRR as described in Chapter 3.

$$\sum_{k=1}^{K} \sum_{k'=1}^{K} \delta^{k,k'} \alpha_m^{k,k'} r_m^{k,k'} \ge r_{m,\min} \qquad \forall m \tag{4.10}$$

C4: Power Constraint: The maximum transmission power on each RB sets the power constraint:

$$(P_{B,m}^{k} + P_{R,m}^{k'}) \le \delta^{k,k'} P_{T,m}^{k,k'} \qquad \forall k, \forall k' \tag{4.11}$$

$$P_{B,m}^{k} \ge 0, \quad P_{R,m}^{k'} \ge 0 \quad \forall k, \forall m \tag{4.12}$$

where $P_{T,m}^{k,k'}$ is the total transmission power for two-hop transmission over RB-pair (k, k'). The variables in the optimization problem defined by (4.7) are: RB-pairing, RB allocation, and power allocation. The solution to (4.7) is based on the joint optimization of these variables subject to the constraints listed in (4.8)-(4.11). This type of joint optimization problem may be solved by implementing centralized control system, which will require separate channel for information exchange. However, the solution of such an optimization problem is NP-hard due to extremely high computation complexity [71].

4.4 RB-Pairing-Based Two-Step RB and Power Allocation

In order to reduce complexity, the same principle as that of the two-step resource allocation technique proposed in Chapter 3 can be applied here. The only difference is regarding RB-pairing which can be carried out in the first step along with RB-allocation; while in the second step, power allocation is made to optimize the objective function under power limitations only.

4.4.1 RB-Pairing and Allocation Scheme (RBPA)

In the RB-Pairing and Allocation step, we optimize the overall system throughput by ensuring rate fairness among all users. The total available transmission power (P_T) on each RB (P_T/K) is equally divided between BS and RT at each RB for RB-pairing and allocation.

The optimization problem as described in (4.7) is developed and the RB-pairing and allocation is made using the following criteria:

1: In each round, the MT with the highest received SNR over two hops has priority to use that RB-pair. This is possible by assuming known channel condition at BS or using feedback link from RT and MT to BS.

2: The MT that has achieved MRR is excluded from this process. This step provides guarantee that any MT with the best channel could not use all the resources at the expense of other MTs.

3: If the MRR for all MTs have been achieved and still there are un-allocated RBs, then these RBs are to be assigned to the MTs with the highest received SNR over two hops. This step aims to maximize the overall throughput.

4.4.2 Power Allocation

After the allocation of all RBs and providing MRR to each MT, the power is re-allocated to the BS and RT on all assigned RBs by optimizing the system throughput under the power constraint only.

For any RB-pair (k, k') using (4.2) we have expression for AF as:

Algorithm-4.1

```
1: Initialize
   $MTs = \{1,2,.....M\}, C_a = \{1,2,...K\}, C_b = \{1,2,...K\}$
2: for rounds =1: $K$
3:     Do $(m,(k,k')) = \arg\max_{m,(k,k')} (\gamma_m^{k,k'})$   $m \in MTs, k \in C_a, k' \in C_b$
4:     $\alpha_m^{k,k'} = 1, \delta^{k,k`} = 1$
5:     Do $C_a = C_a - \{k\}$ ,   $C_b = C_b - \{k'\}$
6:     if $\sum_{k=1}^{K} \sum_{k'=1}^{K} a_m^{k,k'} \delta^{k,k'} r_m^{k,k'} \geq r_{m,\min}$
7:         Do $MTs = MTs - \{m\}$
8:     end if
9:     if $MTs = \varphi$
10:        go to 13
11:    end if
12: end for
13: Do for all remaining RBs
14: for rounds= 1: length of remaining RBs
15:     Do $(m,(k,k')) = \arg\max_{m,(k,k')} (\gamma_m^{k,k'})$   $m \in MTs, k \in C_a, k' \in C_b$
16:     $\alpha_m^{k,k'} = 1, \delta^{k,k'} = 1$
17:     $C_a = C_a - \{k\}$ ,   $C_b = C_b - \{k'\}$
18: end for
19: Do Power Allocation
20: Exit
```

$$\text{Maximize } \sum_{m=1}^{M} \frac{1}{2}\log_2\left(1+\frac{P^{k}_{B,m}\gamma^{k}_{BR}P^{k'}_{R,m}\gamma^{k'}_{RM}}{P^{k}_{B,m}\gamma^{k}_{BR}+P^{k'}_{R,m}\gamma^{k'}_{RM}+1}\right) \tag{4.13}$$

Subject to: (4.11) and (4.12)

Here $\gamma^{k}_{BR}=\left|h^{k}_{BR,m}\right|^{2}/\sigma^{2}_{R}$, $\gamma^{k'}_{RM}=\left|h^{k'}_{RM,m}\right|^{2}/\sigma^{2}_{M}$, $\sigma^{2}_{M}=\sigma^{2}_{R}=\sigma^{2}$ and $\alpha^{k,m}=1$ for all assigned RBs. This simplified optimization problem has now only continuous variable values and can be solved by using convex optimization techniques [71]. The optimal power allocation can be obtained by using Lagrange Multiplier techniques. By using Lagrange Multiplier technique, the optimal power allocations are obtained for AF [69] and given in (4.14) and (4.15) for any MT *m*.

$$P^{k}_{B}=\begin{cases}\dfrac{-\gamma^{k'}_{RM}+\sqrt{\gamma^{k}_{BR}\cdot\gamma^{k'}_{RM}}}{\gamma^{k}_{BR}\quad\gamma^{k'}_{RM}}.P^{k,k'}_{T} & \text{if } \gamma^{k}_{BR}\neq\gamma^{k'}_{RM}\\ P^{k,k'}_{T}/2 & \text{if } \gamma^{k}_{BR}=\gamma^{k'}_{RM}\end{cases} \tag{4.14}$$

$$P^{k'}_{R}=\begin{cases}\dfrac{\gamma^{k}_{BR}-\sqrt{\gamma^{k}_{BR}\cdot\gamma^{k'}_{RM}}}{\gamma^{k}_{BR}-\gamma^{k'}_{RM}}.P^{k,k'}_{T} & \text{if } \gamma^{k}_{BR}\neq\gamma^{k'}_{RM}\\ P^{k,k'}_{T}/2 & \text{if } \gamma^{k}_{BR}=\gamma^{k'}_{RM}\end{cases} \tag{4.15}$$

Similarly for DF, the maximization can be achieved when the SNRs of both hops are equal [69], i.e., $P^{k,k'}_{B}\gamma^{k}_{BR}=P^{k,k'}_{R}\gamma^{k'}_{RM}$.

The optimal power allocation for DF is therefore given as

$$P^{k,k'}_{B}=\frac{\gamma^{k'}_{RM}}{\gamma^{k}_{BR}+\gamma^{k'}_{RM}}.P^{k,k'}_{T} \tag{4.16}$$

$$P_R^{k,k'} = \frac{\gamma_{BR}^{k}}{\gamma_{BR}^{k} + \gamma_{RM}^{k'}} . P_T^{k,k'} \tag{4.17}$$

The process of RB and power allocation based on RB-pairing is depicted in Algorithm 4.1.

4.4.3 Computational Complexity

The computational complexity of the RB-pairing in this proposed algorithm is $O(M \times K^K)$. With increasing number of MTs and RBs the complexity becomes too high which need to be avoided in practical applications. Therefore in the next section we will propose a new low-complexity Iterative RB-Pairing and Allocation (LIRBPA) algorithm.

4.4.4 The Low-Complexity Iterative RB-Pairing and Allocation (LIRBPA)

To reduce the complexity, we solve the RB-pairing problem by using a one-to-one optimization solver known as Hungarian Algorithm (HA). The HA [72] is a one-to-one optimization solver for assignment problems with polynomial complexity. It has already been used in different resource allocation algorithms in non-relaying networks [73, 74] . For a description on how HA works please refer to Appendix-1.

The following steps are involved in LIRBPA.

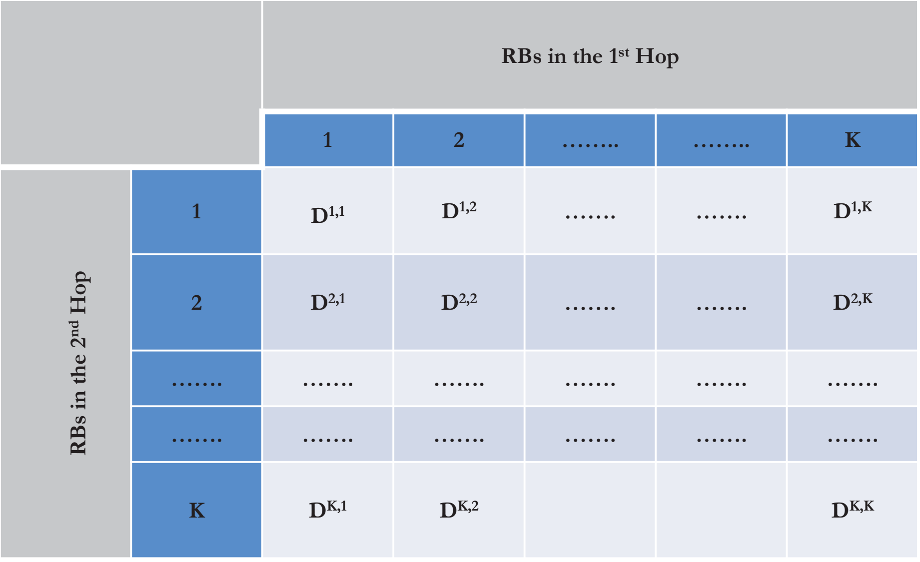
1. The *K* X *K* matrix is established in such a way that the demand metric ($D^{k,k'}$) on each RB-pair is calculated as the maximum of *M* links.

$$D^{k,k'} = \max_{m} \{ r_m^{k,k'} \} \qquad m \in \{1,2,....M\} \tag{4.18}$$

Here $r_m^{k,k'}$ indicates the rate achieved by *m*th MT on RB-pair (k,k').

2. By applying HA on each $K \times K$ matrix the best RB-pairing is achieved here.
3. The allocation of these RB-pairs is made iteratively to MTs by implementing the constraint given in (4.10).

4. The rows and the columns with assigned RB-pairs are eliminated.
5. The MTs satisfying MRR are removed temporarily.
6. 1-5 are repeated until all RBs are assigned or all MTs have achieved MRR.
7. If RBs are still available the steps 1-2 is done once to assign RBs to the best users to maximize the system throughput.
8. The power allocation is then made using methods described in 4.4.2.



		RBs in the 1st Hop				
		1	**2**	**……..**	**……..**	**K**
RBs in the 2nd Hop	**1**	**$D^{1,1}$**	**$D^{1,2}$**	**…….**	**…….**	**$D^{1,K}$**
	2	**$D^{2,1}$**	**$D^{2,2}$**	**…….**	**…….**	**$D^{2,K}$**
	…….	**…….**	**…….**	**…….**	**…….**	**…….**
	…….	**…….**	**…….**	**…….**	**…….**	**…….**
	K	**$D^{K,1}$**	**$D^{K,2}$**			**$D^{K,K}$**

Figure 4.2: Snapshot of HA-Matrix for RB-Pairing

The Computational Complexity has been reduced significantly as compared to the previous solution. The total complexity of step 1 is $O(M\times K\times K)$ while the polynomial complexity of one iteration of HA is $O(K_n^3)$ [15, 21], where K_n is the number of unassigned RBs. We need maximum of K iterations to implement RB-pairing and fairness in terms of data rate among all MTs, therefore the maximum complexity of step 1 is $O(M\times K^2)$ and applying HA with ensuring fairness is $O(K^4)$. While the complexity of 7th step is $O(K^3)$. Then complexity of the whole LIRBPA algorithm is loosely upper-bounded as $O(M\times K^6+K^3)$, comparing with the RBPA algorithm there is a significant reduction in the computational complexity with the same optimization performance.

4.5 Performance Evaluation

In this section we evaluate the performance of the proposed resource allocation algorithm with some simulation results. The same channel model and parameters as described in Chapter 3 are used.

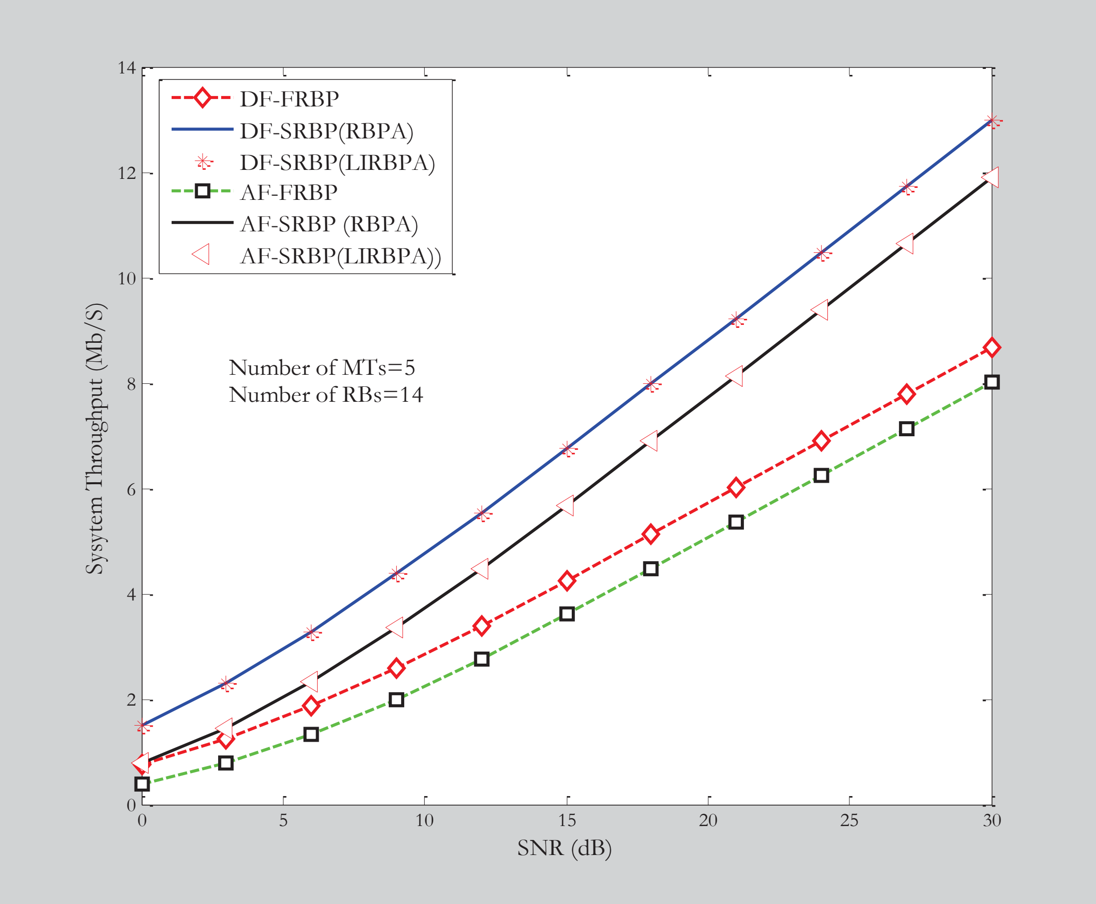


Figure 4.3: Achieved System Throughput versus SNR

The performance of system throughput against average received SNR is depicted in Figure 4.3. We simulate both RBPA and LIRBPA techniques for RB-pairing and allocation. It produces the same result but with different computation complexity as described in Sub-Section 4.4.3 and Sub-Section 4.4.4 respectively. The selective RB-pairing provides significant gain in system throughput over fixed RB-pairing in both AF and DF systems. It can also be observed that the difference between SRBP and FRBP increases with the SNR.

The result presented in Figure 4.3 clearly confirms that RB-pairing provides significant gain in system throughput as compared to the system throughput when there is no RB-pairing used and data is transmitted on the same order RB in the 1st and 2nd hop, respectively. The figure shows the performance of system throughput at different nominal average SNR= $P_T^{k,k'}/\sigma^2$ values.

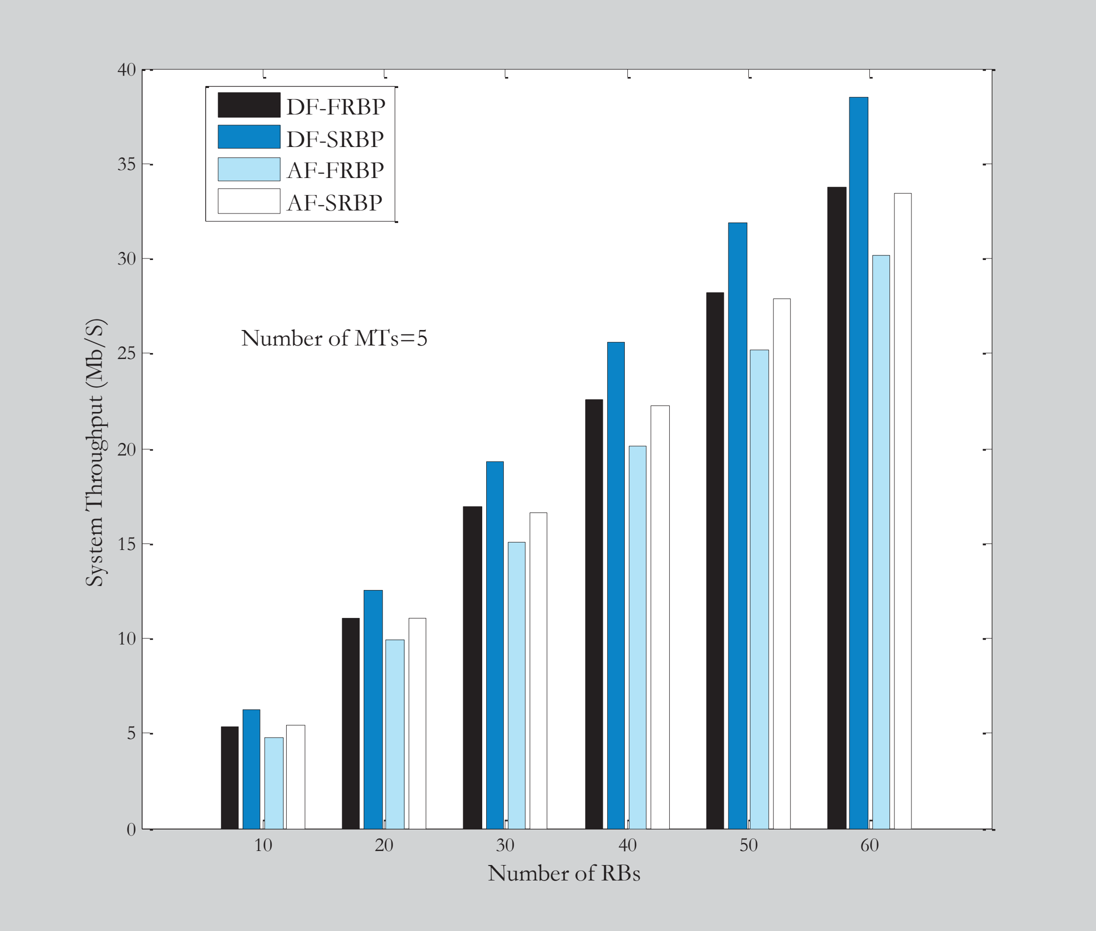
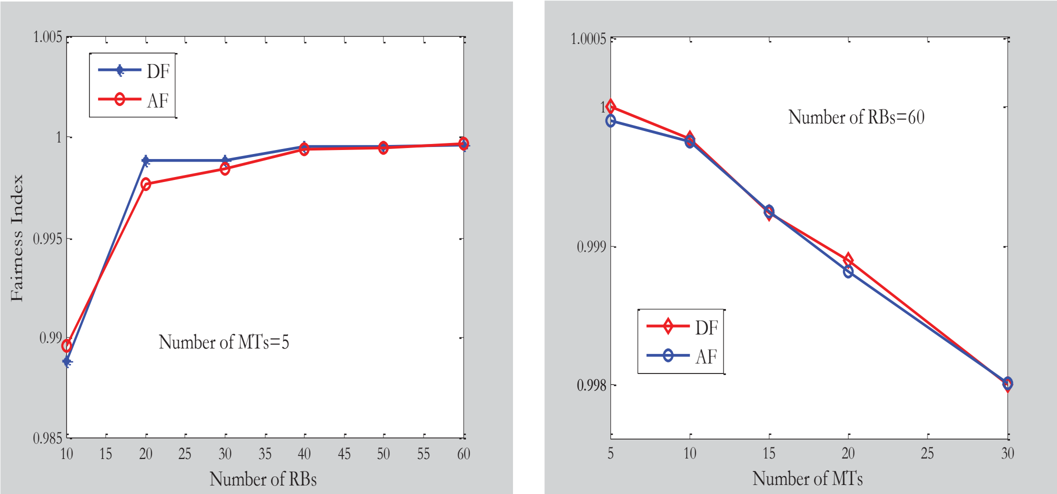


Figure 4.4: Achieved System Throughput versus the Number of RBs

Figure 4.4 shows the total achieved throughput for AF and DF systems with SRBP and FRBP against increasing number of available RBs. In both AF and DF systems, MRR constraint is implemented. The better performance in term of throughput is achieved with SRBP than FRBP RB-pairing. It is also noticeable that the gain in performance with RB-pairing increases as the number of available RBs increases. Because the more RBs, the more flexibility that the system has in exploiting the channel diversity gains.



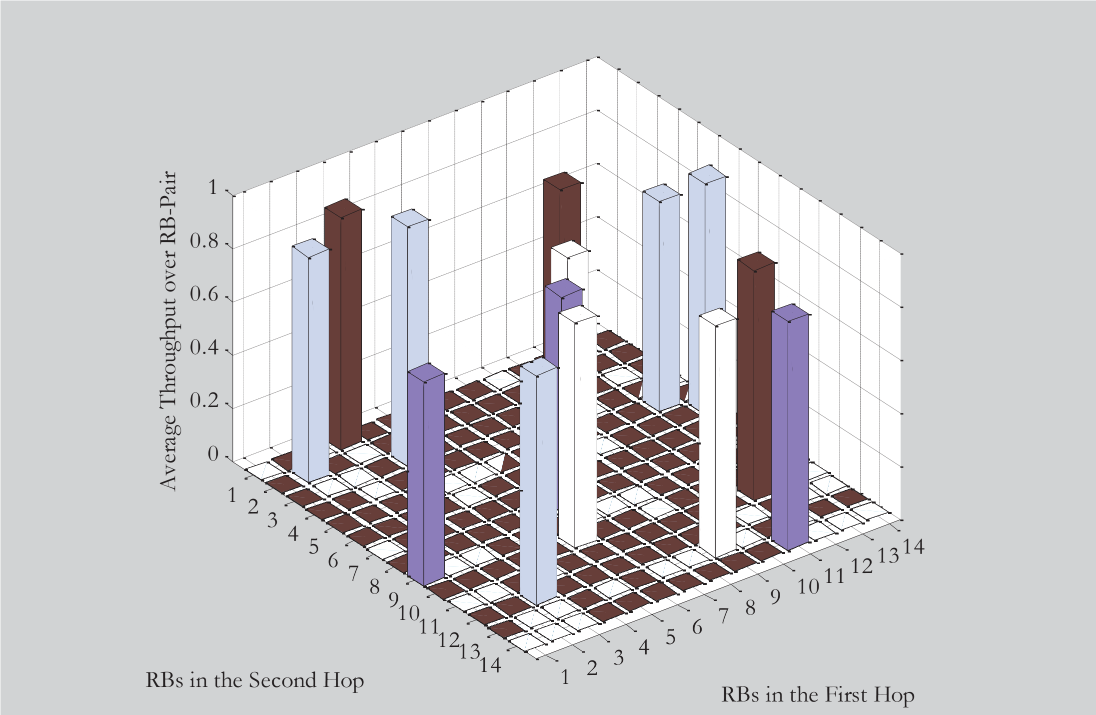
(a) (b)

Figure 4.5: Variations of the Fairness Index against the Number of RBs and MTs

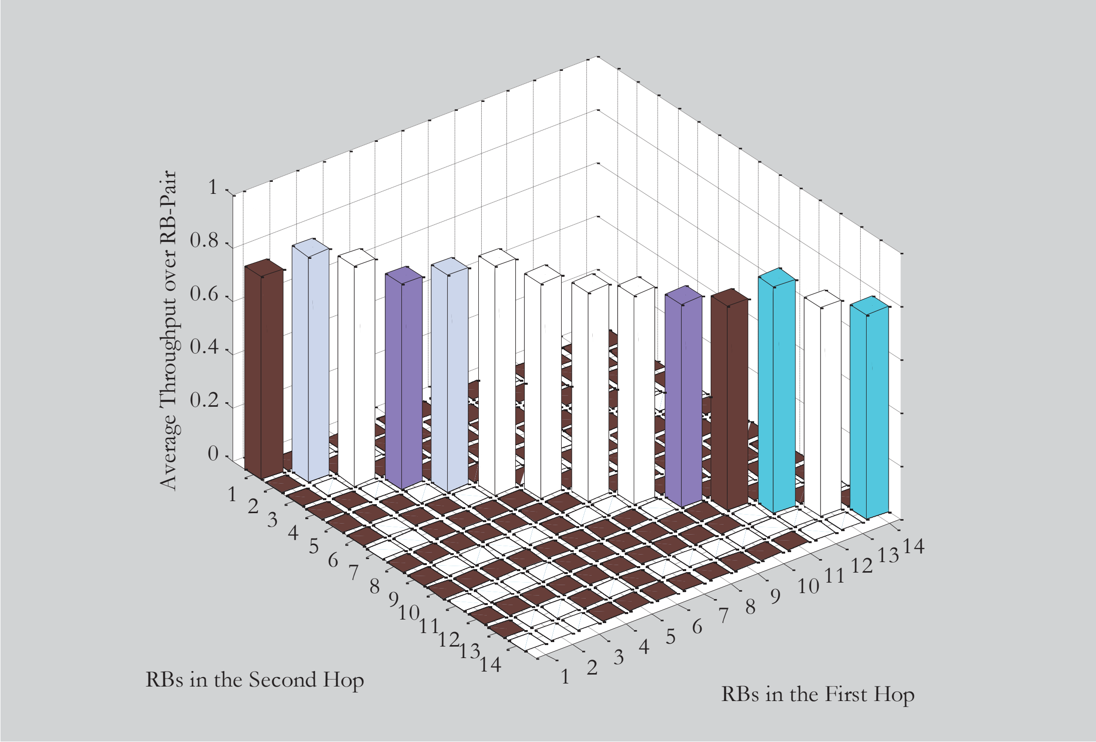
We also employ Jain's fairness index [75] to assess the performance of our proposed algorithms. Jain's fairness index has already been widely used to determine the proportional fairness among users [76, 77]. It is given by

$$f = \frac{\left[\sum_{i=1}^{M} r_i \right]^2}{M \sum_{i=1}^{M} r_i^2} \tag{4.19}$$

where r_i is the normalized sum-rate for the i^{th} user. The value of this index ranges from 0 (worst case) to 1 (best case).

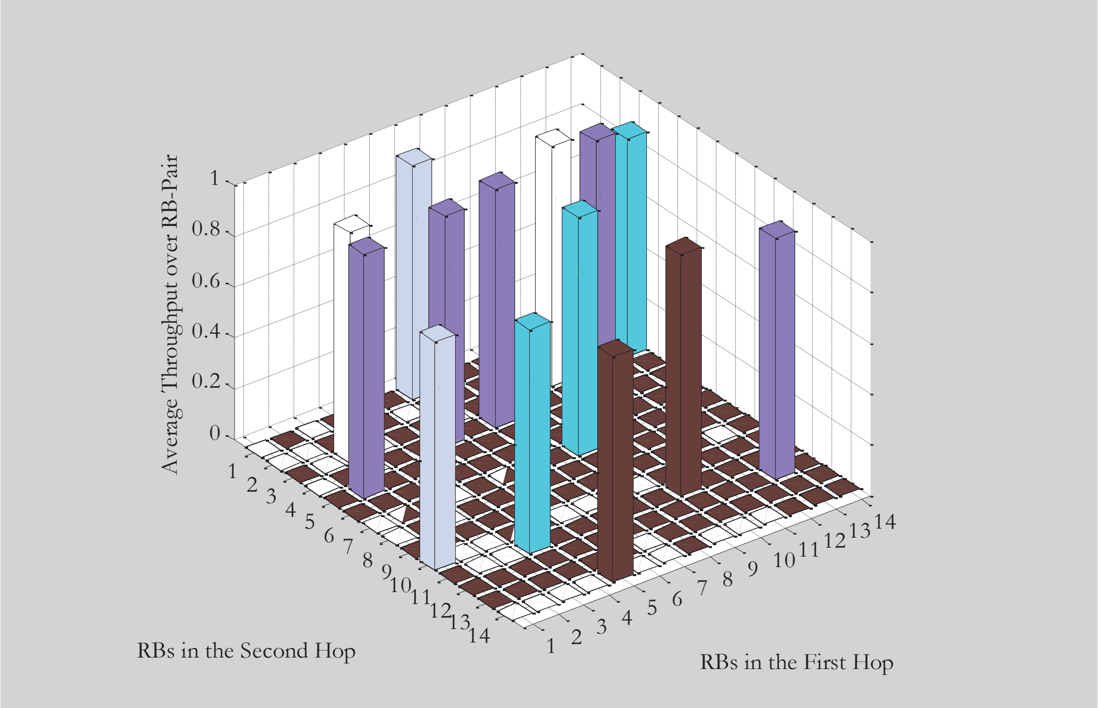


(a)

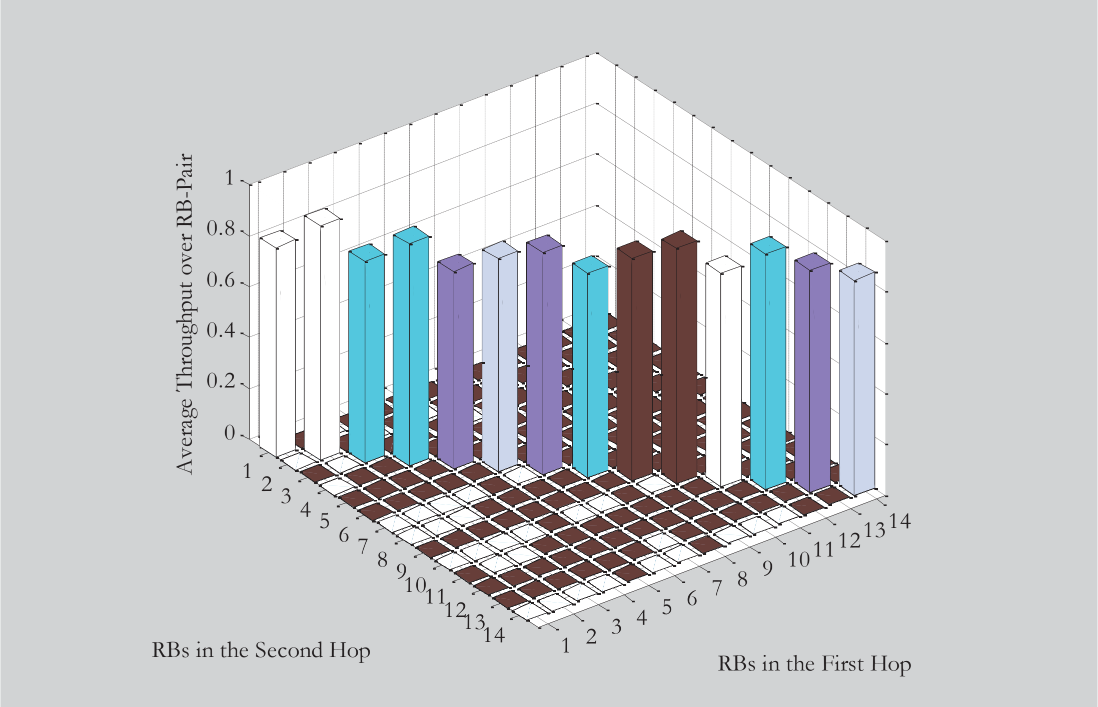


(b)

Figure 4.6: Snapshot of Simulated RB-Pairing for AF (a) SRBP (b) FRBP



(a)



(b)

Figure 4.7: Snapshot of Simulated RB-Pairing for DF (a) SRBP (b) FRBP

It is clear from Figure 4.5 that the fairness index remains around 1 in both cases with different number of available RBs having fixed number of MTs and with different number of MTs having fixed number of RBs, respectively. This means that we are achieving maximum fairness among users in both cases.

Figure 4.6 and Figure 4.7 show the bar graphs of RBs which are assigned to different MTs using SRBP and FRBP in AF and DF protocols, respectively. Each bar position shows that how different RBs are paired in the 1st and 2nd hops in different schemes. The SRBP is clearly shown in Figure 4.6(a) and Figure 4.7 (a), in which the 1st hop RBs are, paired with different order RBs in the 2nd hop, while Figure 4.6(b) and Figure 4.7 (b) indicated that RB in the 1st hop is paired with the same order RB in the 2nd hop. The different color of bars indicates the different MTs.

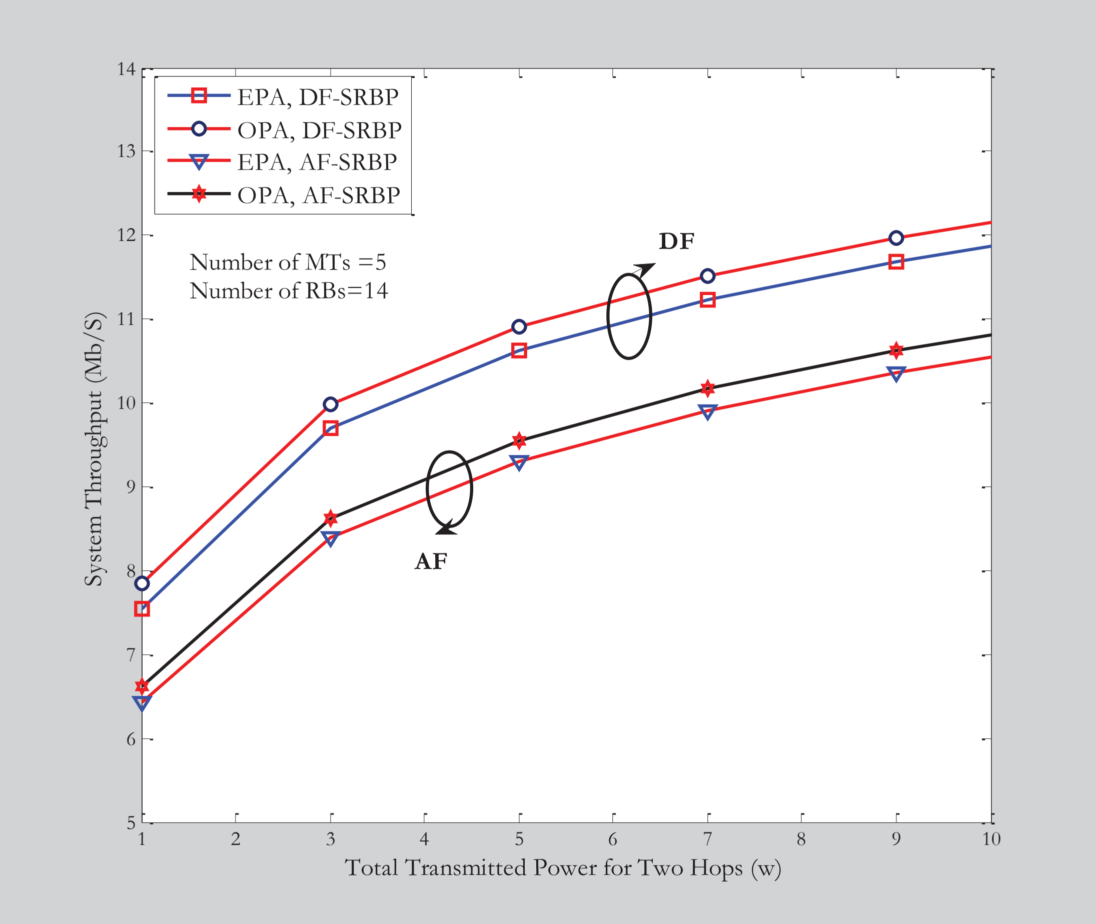


Figure 4.8: Achieved System Throughput versus Transmitted Power

Figure 4.8 presents the result of power optimization in both AF and DF systems. The overall system throughput is observed at different total transmission powers. A sizeable throughput performance gain has been observed by Optimal Power Allocation (OPA) on all RBs over equal power Allocation (EPA). It is clear that selective order RB-pairing itself provide higher data rates than conventional same order RB-pairing, but more system throughput gain can be achieved by optimizing the power for all allocated RB-pairs.

4.6 Summary and Conclusions

Multi-carrier cooperative relaying communication is of particular interest in future wireless networks. In this Chapter we focus on subcarrier pairing in dual-hop relay networks. We present resource allocation algorithm in which subcarrier pairing is implemented along with fairness constraint in multi-user networks.

We propose two techniques for RB-pairing and allocation. The first one which is similar to the scheme presented in the previous Chapter. In this two-step approach, NP-hard optimization problem is solved in two steps. But we see that the computational complexity of the first step on RB-paring and allocation ensuring fairness among users is still too high to be applicable in practical applications. Therefore we propose a new low-complexity iterative RB-pairing and allocation scheme which has much less computational complexity with same optimization performance.

Simulation results demonstrate that RB-pairing proposed in these algorithms provides significant gain in system throughput. The proposed algorithms are also capable to provide maximum fairness in terms of data rate among all users. The simple model and low computational complexity make these proposed algorithms suitable for solving such optimization problems in relay networks.

Chapter 5 Proportional Fairness-Based Resource Allocation in Two-Way Relaying Networks

Relay-based cooperative wireless network has been widely considered one of the cost-effective solutions to meet the demands in future wireless networks. In this Chapter we will focus on TWR networks. In order to maximize the overall sum-rate while maintaining proportional fairness among users, we investigate different resource allocation algorithms in TWR networks with both ANC protocol and TDBC protocol. These investigated algorithms are different from traditional PFS in terms of fairness and computational complexity as we have applied Access Proportional Fairness (APF) and Minimum Rate Proportional Fairness (MRPF) along with load balancing at the relays. A MATLAB simulation has been performed and simulation results show the effectiveness of these algorithms.

5.1 Introduction

As described in Chapter 2, two types of TWR have been proposed in the literature to overcome the spectral loss in OWR. These two types of AF-based TWR are ANC protocol and TDBC protocol, respectively.

In recent years there has been an extensive amount of research undertaken and published in the area of cooperative networks. The initial work on cooperative networks was focused on OWR only; but now TWR has attracted a lot of interest from researchers due to its high spectral efficiency. In [26] authors have addressed the relay selection problem for TWR networks. The closed-form expression for outage probability is derived. A single-pair network is considered, therefore there is no multi-user interference (MUI). A similar network configuration is used in [78] to address the relay selection problem in bidirectional relaying with unknown CSI. The problem of resource allocation in TWR has been addressed in [79] for a two-terminal network with multiple relays. A fairness constraint is imposed on relays with maximum sum capacity as an objective function. In [56], a hierarchical protocol for OWR and TWR is proposed. The transmission mode of each MT as well as relay is already assigned, either direct or relaying. The joint resource allocation problem is formulated under total power constraints. Power allocation with data rate fairness is studied in [80] for AF and DF protocols. In [81], a joint optimization problem of subcarrier assignment and relay selection in multiple-user-pair bidirectional relaying communication is addressed. A graph theoretical approach is applied to solve this problem. In [82] resource allocation problem with subcarrier pairing in OFDM-based TWR relay network is formulated as a mixed integer programming problem. The optimization problem is solved efficiently by using the dual method.

By introducing relays in conventional cellular networks, we can extend coverage area, eliminate blind spots in cells and provide high data rates. But to achieve these goals we need to reduce processing delay and computational complexity in relay networks. Since relays are low-power nodes, congestion can occur if many mobile stations make use of a single relay while other relays remain unused. This problem can be solved by introducing load balancing on relays in each cell. On the contrary, an uneven load distribution could drain out the relay system resources quickly and lead to low system resource utilization [83].

In a general resource allocation problem as addressed in the literature, the main focus resides in resource allocation without any traffic or load balancing consideration. In conventional non-cooperative cellular networks, several load balancing aware algorithms have been reported [61,84,85]. However, these algorithms cannot be used directly for relay-based networks due to dual-hop or multi-hop transmission in relay networks [76]. In [76], authors provide fairness-aware joint routing and scheduling technique for downlink OWR networks; while in [83], an optimal mobile association and load balancing has been introduced in downlink OWR cooperative networks. Some other individual work on load balancing can be found in [86-88].

In Chapter 3 and Chapter 4 we have formulated and investigated different resource allocation techniques in single relay based OWR networks. However, these techniques do not consider any load balancing operation at any node in these networks. Therefore, in this Chapter a fairness-aware joint load balancing and proportional fairness based resource allocation is investigated in multi-relay based TWR cooperative networks. The objective function is to maximize overall sum-rate under the load balancing and fairness constraints. We investigate load balancing with access proportional fairness (LB-APF) and load balancing with minimum rate proportional fairness (LB-MRPF) in TWR with both ANC and TDBC protocols. The optimization problem is formulated as a sum-rate maximization problem with fairness constraints.

The rest of the Chapter is organized as follows. Section 5.2 describes the system model and basic assumptions. A brief introduction to both ANC and TDBC protocols is also presented. The mathematical analysis of the system sum-rate and problem formulation and description are described in Section 5.3. In this section a low-complexity resource allocation technique is also presented. Furthermore, performance evaluation with simulation results is illustrated in Section 5.4. Finally, summary and conclusion of this Chapter is provided in Section 5.5.

5.2 System Model and Protocol Descriptions

A multi-user cellular network is considered with TWR transmission. Time Division Duplex (TDD) is used to achieve separation between uplink and downlink transmission to and from RT respectively and RTs are assumed to be operated in half-duplex mode with AF protocol only. The BS serves *M* MTs through *R* RTs. There are *K* RBs available in the cell. It is also considered that the bandwidth of a RB which consists of number of subcarriers is less than the expected coherence bandwidth of the channel. Therefore, the channel is assumed time-invariant within a single RB but is time-variant for different RBs.

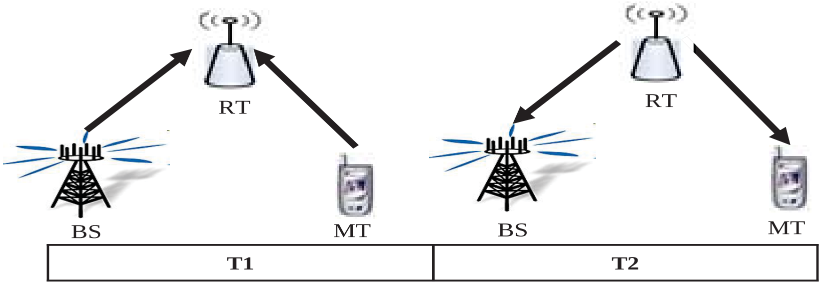


Figure 5.1: TWR-ANC Assisted Transmission Model

5.2.1 Protocol Description

5.2.1.1 ANC Protocol

In ANC protocol as shown in Figure 5.1, both MT and BS transmit their signal to the relay during the first time slot. The relay receives the combined signal of MT and BS due to the broadcast nature of wireless channel. The relay amplifies this combined signal and then retransmits to both MT and BS in the second time slot.

5.2.1.2 TDBC Protocol

In TDBC protocol as shown in Figure 5.2, BS transmits its signal to both MT and relay during the first time slot, while MT transmits its signal to both BS and relay in the second time slot. In the third time slot the relay amplifies the combined signal of BS and

MT and retransmits to both MT and BS.

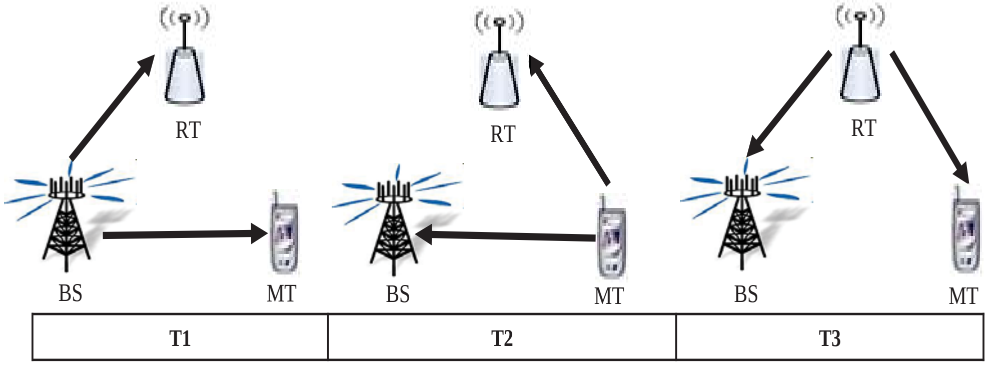


Figure 5.2: TWR-TDBC Assisted Transmission Model

In both protocols, the received signal at MT and BS consists of their own transmitted signal known as the self-interference. With the knowledge of the channel and its own signal, this self-interference can be subtracted from the received signal [2].

5.2.2 Mathematical Description

The achievable rates from BS to MT and from MT to BS in ANC protocol of the m^{th} MT via the r^{th} relay on the k^{th} RB is given by (5.1) and (5.2) respectively as in [24]:

$$R_{m,r}^{k}(ANC) = \frac{1}{2}\log_2(1+\gamma_{m,r}^{k}(ANC)) \tag{5.1}$$

$$R_{b,r}^{k}(ANC) = \frac{1}{2}\log_2(1+\gamma_{b,r}^{k}(ANC)) \tag{5.2}$$

The factor ½ appears here again due to the half-duplex operation of relays. It means relays transmit and receive in two different time slots. The $\gamma_{m,r}^{k}(ANC)$ and $\gamma_{b,r}^{k}(ANC)$ are the received SNRs at the MT and the BS, respectively; and given in (5.3) and (5.4) assuming identical noise variance at all nodes and complete self-interference cancellation.

$$\gamma_{m,r}^{k}(ANC) = \frac{P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2} P_{R,m}^{k}\left|h_{RM,m}^{k}\right|^{2}}{P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2} + (P_{R,m}^{k} + P_{M,m}^{k})\left|h_{RM,m}^{k}\right|^{2} + \sigma^{2}} \tag{5.3}$$

$$\gamma_{b,r}^{k}(ANC) = \frac{P_{M,m}^{k}\left|h_{MR,m}^{k}\right|^{2} P_{R,m}^{k}\left|h_{RB,m}^{k}\right|^{2}}{(P_{B,m}^{k} + P_{R,m}^{k})\left|h_{RB,m}^{k}\right|^{2} + P_{M,m}^{k}\left|h_{MR,m}^{k}\right|^{2} + \sigma^{2}} \tag{5.4}$$

The instantaneous sum-rate is then given by (5.5)

$$R_{m,r}^{k}(ANC) = \frac{1}{2}\log_2(1+\gamma_{m,r}^{k}(ANC)) + \frac{1}{2}\log_2(1+\gamma_{b,r}^{k}(ANC)) \tag{5.5}$$

Let $\gamma_{m,r}^{k}(TDBC)$ and $\gamma_{b,r}^{k}(TDBC)$ represent the SNRs at MT and BS respectively for TDBC protocol and given by [26]:

$$\gamma_{m,r}^{k}(TDBC) = \frac{P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2} P_{R,m}^{k}\left|h_{RM,m}^{k}\right|^{2}}{P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2} + (P_{R,m}^{k} + P_{M,m}^{k})\left|h_{RM,m}^{k}\right|^{2} + \sigma^{2}} + \frac{P_{B,m}^{k}\left|h_{BM,m}^{k}\right|^{2}}{\sigma^{2}} \tag{5.6}$$

$$\gamma_{b,r}^{k}(TDBC) = \frac{P_{M,m}^{k}\left|h_{MR,m}^{k}\right|^{2} P_{R,m}^{k}\left|h_{RB,m}^{k}\right|^{2}}{(P_{B,m}^{k} + P_{R,m}^{k})\left|h_{RB,m}^{k}\right|^{2} + P_{M,m}^{k}\left|h_{MR,m}^{k}\right|^{2} + \sigma^{2}} + \frac{P_{M,m}^{k}\left|h_{MB,m}^{k}\right|^{2}}{\sigma^{2}} \tag{5.7}$$

The instantaneous sum-rate of TWR-TDBC protocol is given as:

$$R_{m,r}^{k}(TDBC) = \frac{1}{3}\log_2(1+\gamma_{m,r}^{k}(TDBC)) + \frac{1}{3}\log_2(1+\gamma_{b,r}^{k}(TDBC)) \tag{5.8}$$

The factor 1/3 shows that the transfer of information between two nodes is completed in three time slots. The achievable sum-rate of the network over all MTs and RBs using any protocol is given as:

$$r = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{k=1}^{K} \delta_{m,r}^{k} R_{m,r}^{k} \tag{5.9}$$

where $\delta_{m,r}^{k}$ is used as the binary integer RB assignment indicator variable. If the k^{th} RB is assigned to the mth MT on the rth RT, then $\delta_{m,r}^{k}$ is equal to one, otherwise it is equal to zero. The term $R_{m,r}^{k}$ is equal to $R_{m,r}^{k}(ANC)$ or $R_{m,r}^{k}(TDBC)$ depending on the system protocol.

5.3 Problem Formulation and Description

In order to maximize the system sum-rate while maintaining load balancing at relays and proportional fairness among users, a BILP optimization problem is formulated as

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{k=1}^{K} \delta_{m,r}^{k} R_{m,r}^{k} \tag{5.10}$$

Subject to the following constraints:

C1: RB-Allocation Constraint: The RB-Allocation constraint is that each RB can be used only by one RT to avoid intra-cell interference.

$$\begin{aligned} &\sum_{m=1}^{M}\sum_{r=1}^{R} \delta_{m,r}^{k} \leq 1, \ \forall k, \\ &\delta_{m,r}^{k} \in \{0,1\}, \ \forall (m,r,k) \end{aligned} \tag{5.11}$$

C2: Load-Balancing Constraint: The load-balancing constraint is that RBs are equally distributed among all relays.

$$\sum_{m=1}^{M} \sum_{k=1}^{K} \delta_{m,r}^{k} \geq \mu, \quad \forall r \tag{5.12}$$

where $\mu = K/R$ is the minimum number of RBs to be allocated to any RT. If K mod R =0, each RT will be assigned exactly K/R RBs.

C3: MRPF Constraint: This constraint ensures that each MT meets the minimum date rate requirement. Let $r_{m,\min}$ be the MRR for each MT, then

$$\sum_{r=1}^{R} \sum_{k=1}^{K} \delta_{m,r}^{k} \mathrm{R}_{m}^{k} \geq r_{m,\min}, \quad \forall m \tag{5.13}$$

C4: APF Constraint: This constraint is applied when we need to distribute the all RBs equally among all MTs.

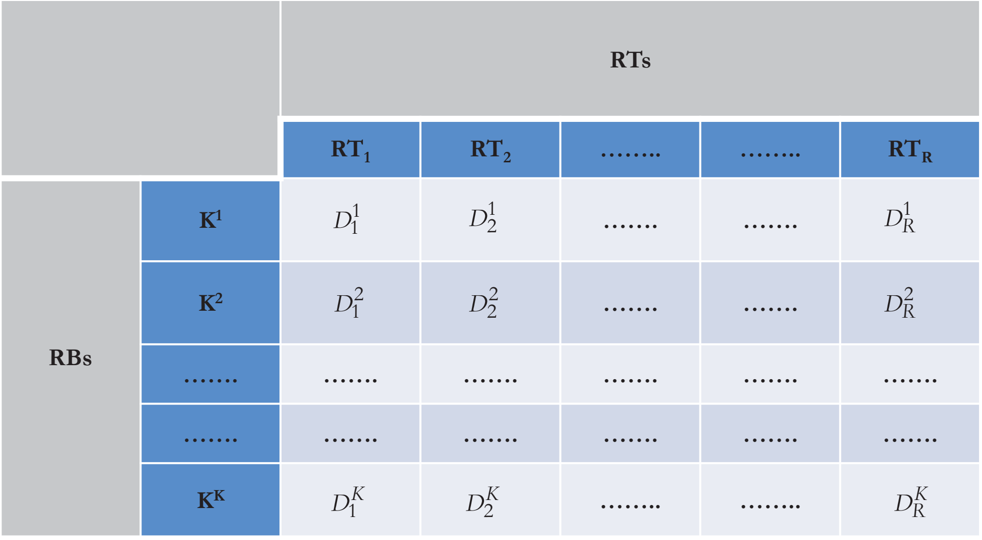
$$\sum_{r=1}^{R} \sum_{k=1}^{K} \lambda_{m,r}^{k} \geq \lambda, \quad \forall m \tag{5.14}$$

where λ is the minimum number of RBs to be allocated to any MT. If K mod M =0, each MT will be assigned exactly K/M RBs.

This BILP optimization problem is non-polynomial in time and the computational complexity of such problem can be expressed as $O(R \times M)^{K}$. With increasing number of R, M and K, the computational complexity might reach prohibitive limits in practical systems. Therefore, a low-complexity algorithm is necessary to solve this type of optimization problem.

5.3.1 Hungarian Algorithm (HA) Based Resource Allocation

In this sub-section, we solve our BILP optimization problem described above by using HA. We have already explained that HA is a one-to-one optimization solver for assignment problems with polynomial complexity. The other main reason of using this algorithm is that load balancing at relays is achieved inherently with this algorithm.



		RTs				
		RT_1	**RT_2**	**……..**	**……..**	**RT_R**
RBs	**K^1**	D_1^1	D_2^1	…….	…….	D_R^1
	K^2	D_1^2	D_2^2	…….	…….	D_R^2
	…….	…….	…….	…….	…….	…….
	…….	…….	…….	…….	…….	…….
	K^K	D_1^K	D_2^K	……..	……..	D_R^K

Figure 5.3: Snapshot of HA-Demand Matrix

Let us first define a demand metric for any BS-MT link on the k^{th} RB for each RT as the product of the achievable sum-rate on that link and the proportional fairness index (PFI) for that MT, as follow

$$D_{m,r}^{k} = \omega_{m,r}^{k}\, r_{m,r}^{k} \qquad ,\forall m,\ \forall r \tag{5.15}$$

where ω_{m}^{k} is the binary integer variable as PFI for the m^{th} MT on the k^{th} RB. The binary indicator PFI ω_{m}^{k} is equal to zero for all MTs satisfying constraints (5.13) or (5.14), otherwise it is equal to unity. Here $r_{m,r}^{k}$ is the achievable sum-rate for the m^{th} MT on the k^{th} RB for the r^{th} RT. This sum-rate is calculated, without loss of generality, using the equations (5.5) or (5.8) depending on the protocol types.

The following sub-steps are involved in applying HA to our BILP problem.

1) The demand metric on each RB for every RT is calculated as the maximum of M links as

$$D_r^k = \max_m \{\omega_m^k r_m^k\} \qquad m \in \{1,2,....M\} \tag{5.16}$$

2) The total R demand metrics on each RB has been calculated. By applying HA to the demand matrix as shown in Figure 5.3, the algorithm solves a one-to-one optimization problem to maximize the total demand. In each iteration, R RBs are allocated, therefore total K/R iterations are needed to allocate all the K RBs.

3) The rows with assigned RBs are eliminated and MTs are marked with assigned RBs.

4) The constraint (5.13) or (5.14) is checked for LB-MRPF and LB-APF, respectively. The PFI of MTs satisfying these constraints are set to zero.

5) The steps 1-4 are repeated until all RBs are assigned or all MTs have achieved MRR.

6) If RBs are still available in LB-MRPF, the process is repeated except step 4 until all RBS are assigned.

5.3.1.1 Computational Complexity

By using HA, the computational complexity has been significantly reduced. Referring to the previous Chapter, the polynomial complexity of one iteration of HA is $O(K_n^3)$, where K_n is the number of unassigned RBs. With K/R iterations, the complexity of the whole algorithm is $O(K^4 / R)$.

The pseudo-code for the HA-based resource allocation algorithm is given in Algorithm-5.1.

Algorithm-5.1

```
1: Set
$\mathrm{MTs}=\{1,2,3,....M\}, \mathrm{RTs}=\{1,2,3,.....R\}, \mathrm{RBs}=\{1,2,3,.....K\}$
$R'=$ Size of RTs
$K'=$ Size of RBs
2: for $k=1:K'$
3: for $r=1:R'$
4: $D_r^k=\max_m\{\omega_m^k r_m^k\}$        $m\in\{1,2,....M\}$
5: end for
6: end for
7: D = $\{D_r^k\}, r=1,2,..R', k=1,2,..K'$ }, as shown in Figure 5.3
8: for rounds = $1:K'/R'$
9: Hungarian (D) $\Rightarrow$ ARBs=Set of assigned RBs
10: Do RBs = RBs-ARBs
11: $K'=$ Size of RBs
12: Do for LB-APF
13: AMTs1=Set of MTs Satisfying $\sum_{r=1}^{R}\sum_{k=1}^{K}\lambda_{m,r}^{k}\geq\lambda,\quad\forall m\in\mathrm{MTs}$
14: Do MTs = MTs}-AMTs1
15: Do for LB-MRPF
16: AMTs2=Set of MTs satisfying $\sum_{r=1}^{R}\sum_{k=1}^{K}\delta_{m,r}^{k}\,\mathrm{R}_m^k\geq r_{m,\min},\quad\forall m\in\mathrm{MTs}$
17: Do MTs = MTs-AMTs2
18: MTs = $\phi$ and $K'\neq 0$ go to 22
19: if $K'=0$ go to 23
20: end if; end if
21: end for
22: Repeat only 3-11until $K'=0$
23: Exit
```

5.4 Numerical Results and Performance Analysis

In this section, we present and compare numerical results with the help of computer simulations to evaluate the performance of resource allocation algorithms described in Section-5.3.1. MATLAB-based simulations have been conducted.

5.4.1 Simulation Models and Parameters

In these simulations we assume random distribution of all RTs and MTs. We consider that all channels remain constant for one complete transmission while all noise variances are identical and respective channel gains are reciprocals. To establish centralized resource allocation techniques it is assumed that CSI is known to the BS.

Parameters	Value
Cell Radius	1 Km
Carrier Frequency	2 GHz
OFDM Subcarrier Bandwidth	15 KHz
Number of Subcarrier per RB	12
Nominal Average SNR	20 dB

Table 5.1: Simulation Parameters

The Line- of-sight (LOS) path loss model is used for BS-RT link as we assume that relays are in LOS of BS which has directional antennas for transmission. The Non line-of-Sight (NLOS) Path loss model is used for RT-MT links. Both path loss models follow those defined for the Urban Micro (UMi) environment for the evaluation of 4G mobile wireless systems [89] and are given as

$$\begin{aligned} \mathrm{PL\_LOS} &= 36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c) \ \ \mathrm{dB} \\ \mathrm{PL\_NLOS} &= 22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c) \ \ \mathrm{dB} \end{aligned} \tag{5.17}$$

where *d* is the distance between transmitter and receiver in meters and f_c is the carrier frequency. No shadowing loss is considered here. Other simulation parameters are given in Table 5.1.

The proposed algorithms have been evaluated in terms of total achievable system sum-rate and achievable individual sum-rate of each pair. To compare the performance of the both proposed algorithms LB-APF and LB-MRPF, the Load Balancing with No Fairness (LB-NF) algorithm is also investigated. In LB-NF, we only consider the load balancing at relays without any fairness constraints.

5.4.2 Simulation Results and Discussions

Figure 5.4 and Figure 5.5 demonstrate the load balancing at relays of the low-complexity algorithm proposed in this Chapter. Figures show the assignment of RBs to each RT in three different algorithms for ANC and TDBC protocols, respectively. It can be observed that each relay can occupy 5 RBs which is equal to K/R, with K=15 and R=3.

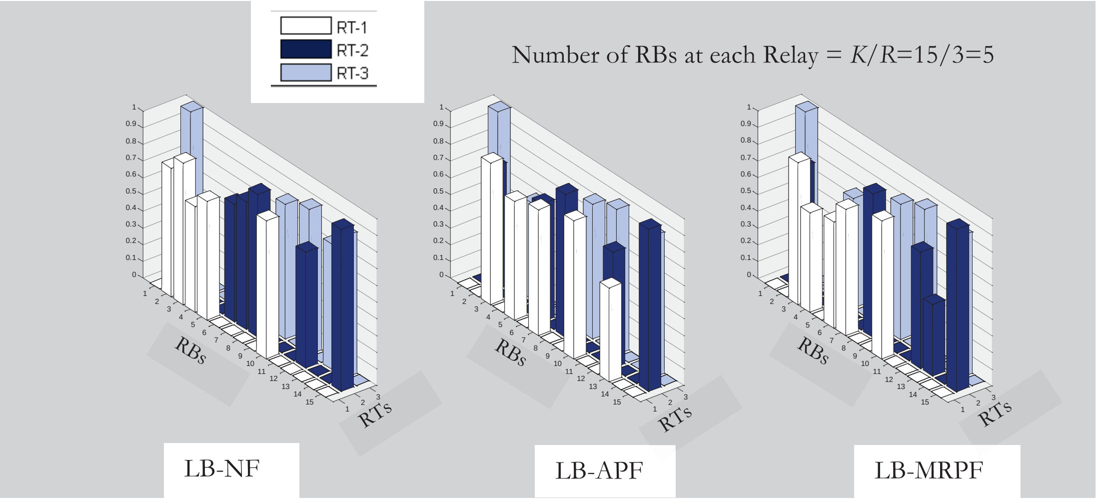


Figure 5.4: Load Balancing at Relays in TWR-ANC Protocol

Each bar in these plots represents the magnitude of the sum-rate on respective RB using different algorithms in both protocols. The difference can be observed in both protocols in term of allocation of RBs to different RTs and also in terms of sum-rate achieved on each RB. The sum-rate has been dropped in TDBC protocol due to the factor 1/3 instead of 1/2 in ANC protocol even though there are some additional gains due to the direct transmission between BS and MTs in TDBC protocol as described in Section 5.2.2. These results also indicate that load distribution at relays also affects the allocation of RBs due to the presence of constraints. By distributing the traffic load among relays, we not only reduce the processing delays at relays but also make sure the use of all resources efficiently, noting that efficient relay selection has been already made.

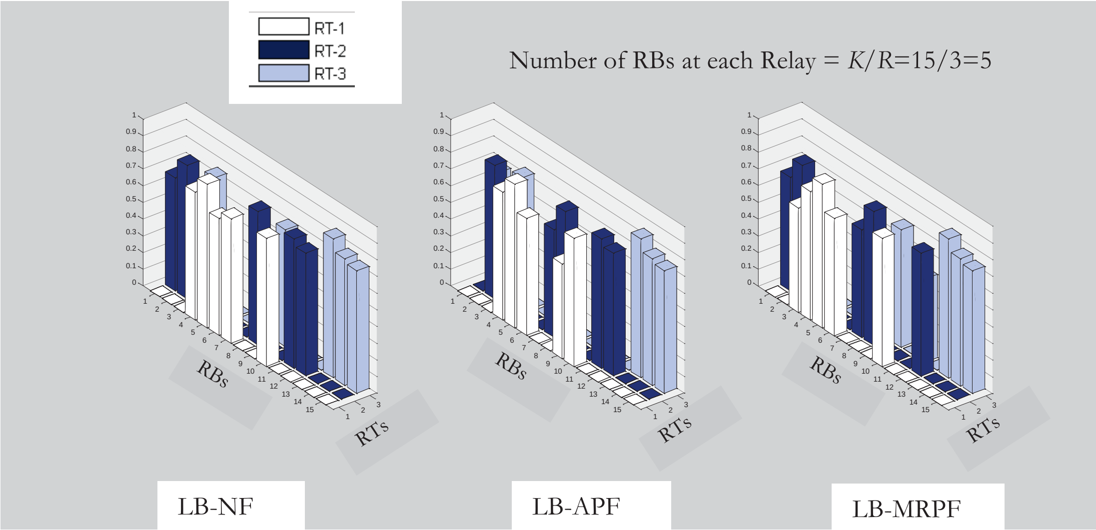
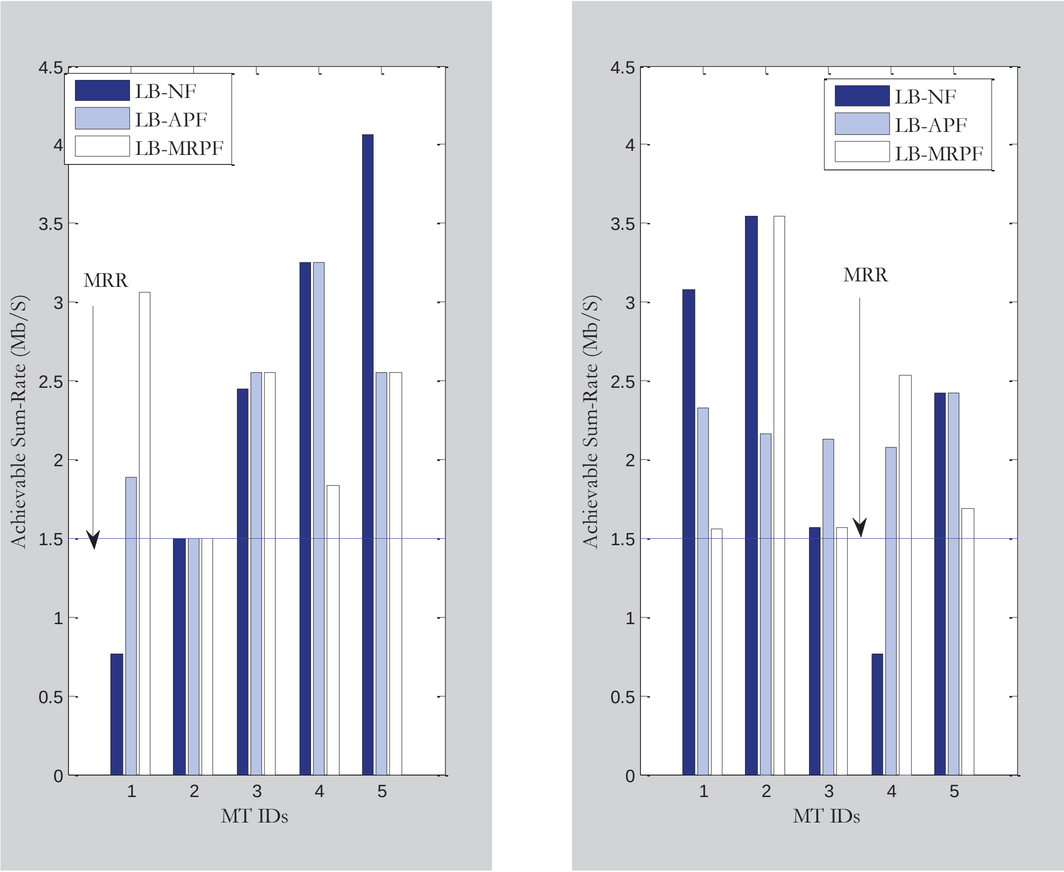


Figure 5.5: Load Balancing at Relays in TWR-TDBC Protocol

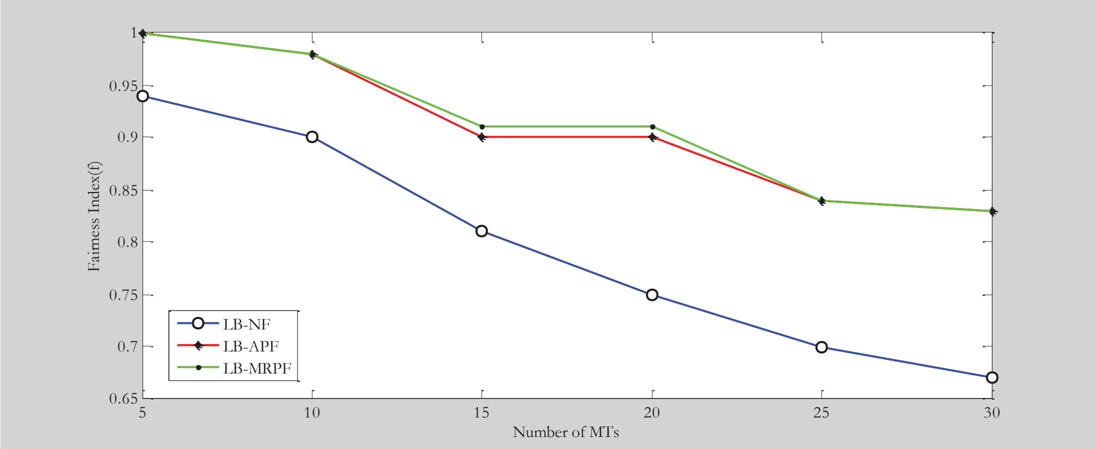
Figure 5.6 shows the individual achievable sum-rate for each pair in ANC and TDBC protocols. In this case of individual sum-rate, LB-MRPF outperforms LB-NF. The MRR for all MTs is achieved in LB-MRPF and LB-APF, while LB-NF is not able to meet MRR for all MTs in both protocols. This plot only indicates one snapshot of achievable sum-rate for 5 MTs. It can be observed that in the LB-NF algorithm, some MTs get much higher sum-rate than others. Even worse there are some MTs which could not meet their MRR in both protocols. In Figure 5.6(a), it can be observed that the sum-rate of MT-1 with LB-NF algorithm is less than the required MRR while it is also clear in Figure 5.6(b) that MT-4 cannot achieve MRR with the LB-NF algorithm.

Even though the MRR for all MTs is achieved in LB-APF, but on the other hand the overall sum-rate of LB-APF is lower than that of the LB-MRPF scheme shown as Figure 5.8 and Figure 5.9.

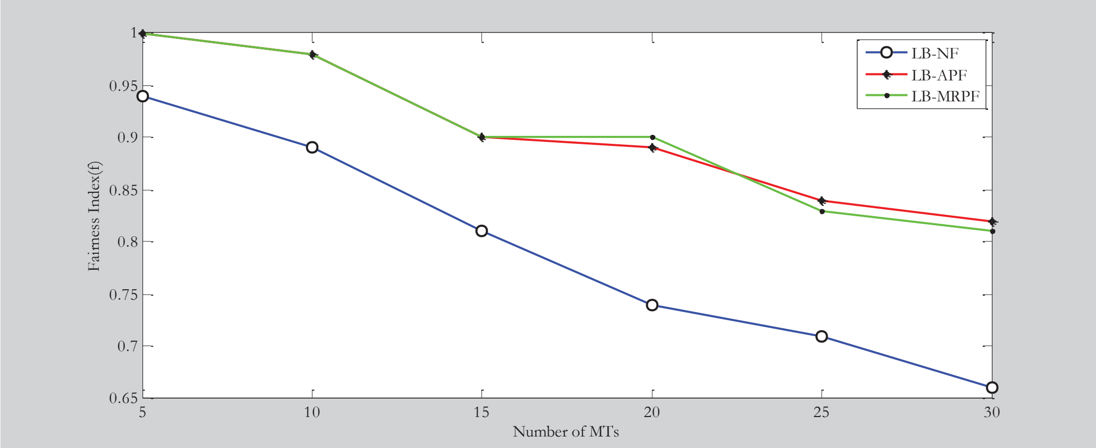


(a) TWR-ANC (b) TWR-TDBC

Figure 5.6: Individual Sum-Rate for Each MT-BS Pair in TWR (*K*=15, *R*=3)



(a) TWR-ANC



(b) TWR-TDBC

Figure 5.7: Jain's Fairness Index with different number of MTs (*K*=60, *R*=3)

We again employ Jain's fairness index to check the fairness performance of our proposed algorithms. Jain's fairness index is given by (4.19) in the previous Chapter.

Figure 5.7 (a) and Figure 5.7(b) show that fairness index remains around 90% in both LB-MRPF and LB-APF while it drops significantly in LB-NF with increasing number of users in both ANC and TDBC protocols, respectively. We can observe that it becomes difficult to maintain fairness as the number of MTs increases, due to the fixed number of RBs. But still it can be noticed that there is less degradation in fairness in both proposed schemes as compared to LB-NF scheme.

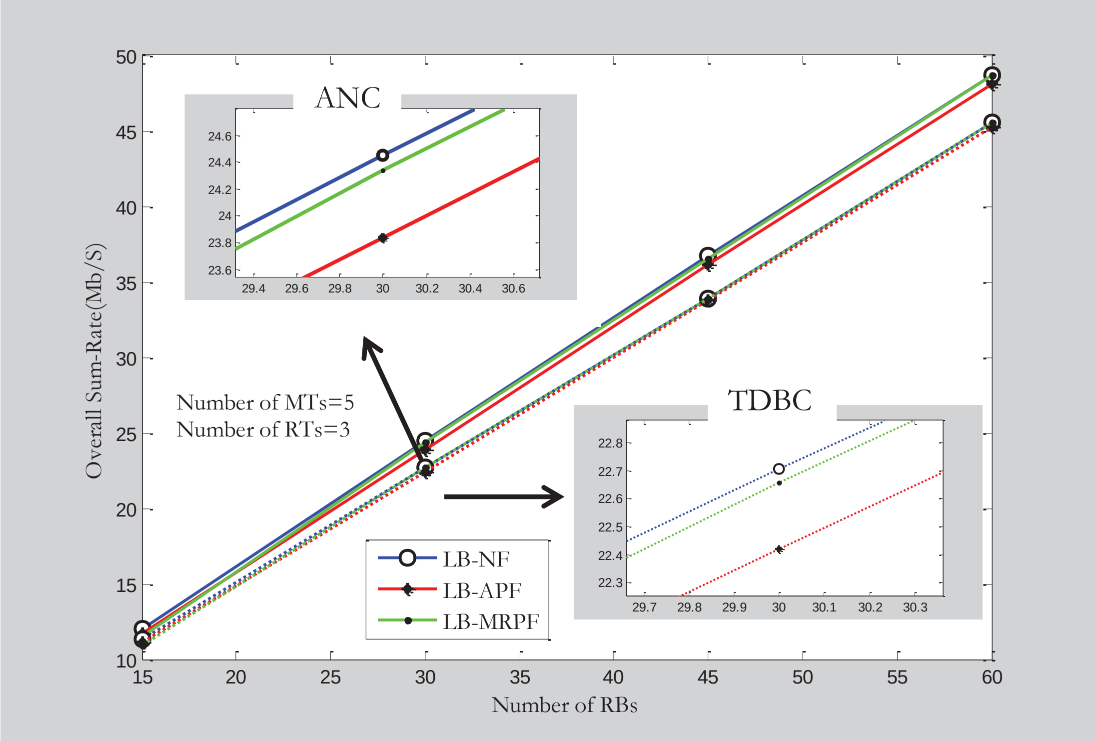


Figure 5.8: Overall Sum-Rate versus the Number of RBs

The system sum-rate performance against different number of RBs and MTs for both protocols can be observed in Figure 5.8 and Figure 5.9, respectively. It can easily be observed that the overall sum-rate of LB-NF is always the highest against different number of RBs or MTs. This is due to the fact that this algorithm assigns RBs to MTs with the best channel gains, hence increasing overall sum-rate at the expense of proportional fairness among MTs. While LB-APF gives lower sum-rate than others because it ensures APF among MTs by ensuring assignment of equal number of RBs, which may compromise on overall and individual sum-rates. A compromise between sum-rate and fairness has also been made in LB-MRPF and a good tradeoff between overall sum-rate and individual sum-rate can be observed.

In Figure 5.9 we can observe that cell throughput is increasing with an increase in number of MTs in all schemes. This indicates that RBs are assigned to available MTs with best channel gains on those RBs in all schemes with or without proportional constraints.

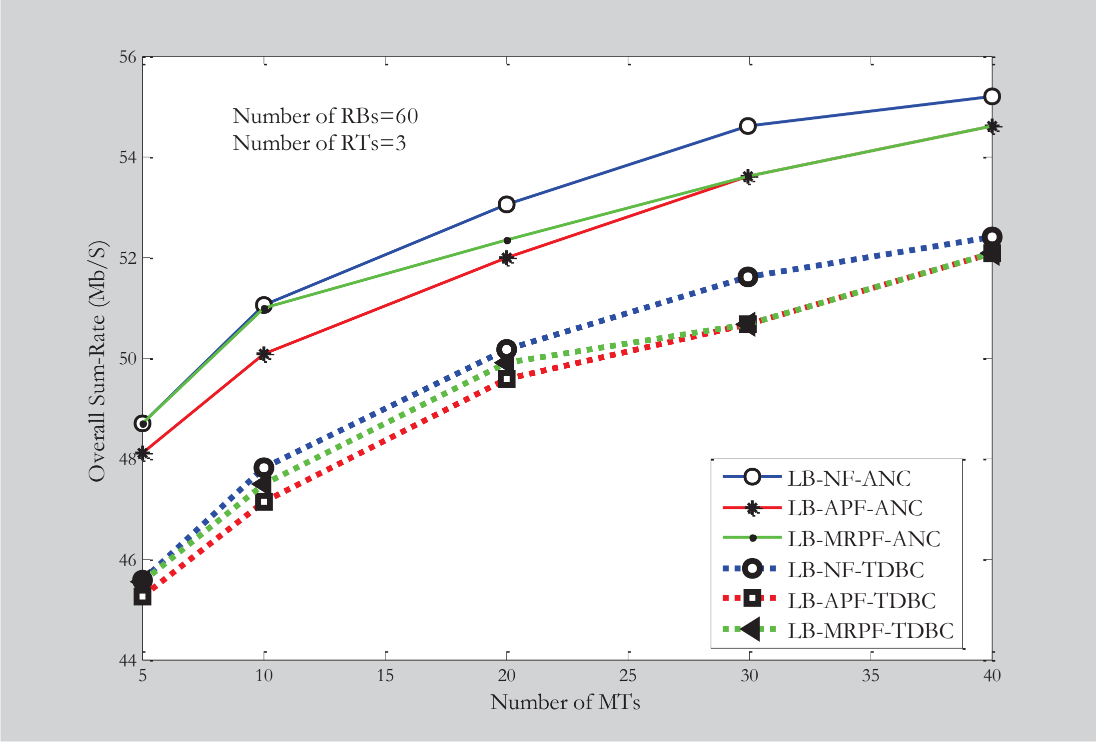


Figure 5.9: Overall Sum-Rate versus the Number of MTs

5.5 Summary and Conclusions

Efficient resource allocation algorithms are required to meet the demands of future relay-based wireless networks. This Chapter provides a fairness-aware joint load balancing and proportional fairness based resource allocation algorithms in TWR cooperative cellular networks. By considering both TWR-ANC and TWR-TDBC protocols, a BILP optimization problem is formulated to maximize the overall system sum-rate while maintaining proportional fairness among users. Since the complexity of such a BILP problem is extremely high due to large number of subcarriers and users in real applications, therefore low-complexity algorithms are required for practical implementation.

To reduce computational complexity, HA-based different resource allocation algorithms have been investigated in this Chapter. Considering the proportional fairness among users, an efficient allocation of subcarriers is proposed. These algorithms also exploit the inherent feature of load balancing in HA. Therefore, these proposed algorithms not only provide the use of all the available subcarriers in efficient manners but also help to reduce the processing delays at relays, increasing the efficiency of the system.

Chapter 6 Inter-Cell Interference in Relay Networks

ICI in multi-cell wireless networks is a major limitation in the performance of these networks. The number of sources of ICI increases in the relay-based wireless networks due to an increase in the number of transmitting nodes in the form of relays. In this Chapter, we highlight and briefly describe the effects of ICI in relay networks.

6.1 Introduction

Resource management in wireless systems is crucial to achieve the best system performance. Most of the initial work on OFDM-based relay network is focused on a single-cell scenario to provide the basic ideas of allocating resources to maximize the local performance gain. There are few works on multi-cell interference in relay networks [90-93].

In [90], inter-cell relay cooperation in forming the uplink precoders to maximize the SINR is investigated and its transmission rate is evaluated for a linear 3 cell topology. The authors in [91] have proposed a user pairing control method for multi-cell shared multi-user MIMO relay system. In their method, the RT is set on the cell boundary and multiple users located on the adjacent cells make pair for relay transmission. In [92] authors try to transform the non-convex optimization problem to a convex problem by relaxing the multi-cell interference to a limited Interference threshold and, then solving the relaxed convex problem which leads to a suboptimal solution. In [93] authors tried to solve the same problem in [92] but in a multi-cell relayed network which by relaxing the instant interference to a limited interference.

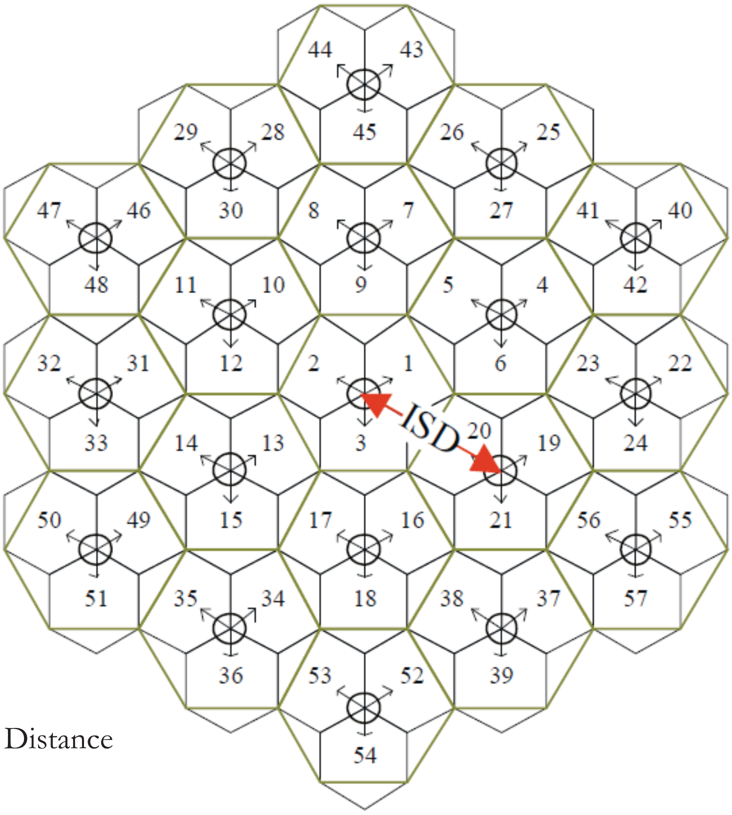
In previous Chapters we also focus on the single-cell scenario where Intra-cell interference and MUI are of our interest. However, in next generation wireless networks, a high frequency reuse factor and small cell size will be necessary in order to achieve higher data rate; and these lead to severe ICI. In reality, ICI severely degrades the system performance and hence should be considered in the resource allocation process.

6.2 ICI Analysis in Relaying Networks

Consider a fixed relay based multi-cell OFDM wireless network. Base stations are placed in a regular grid, following the hexagonal layout as described in [89]. A basic hexagonal layout with three cells per site is shown in Figure 6.1.

The ICI typically involves MTs in neighboring cells or sectors being scheduled on the same RBs. The transmission rate of MTs can be degraded due to ICI, especially the

MTs present at the edges of cells.



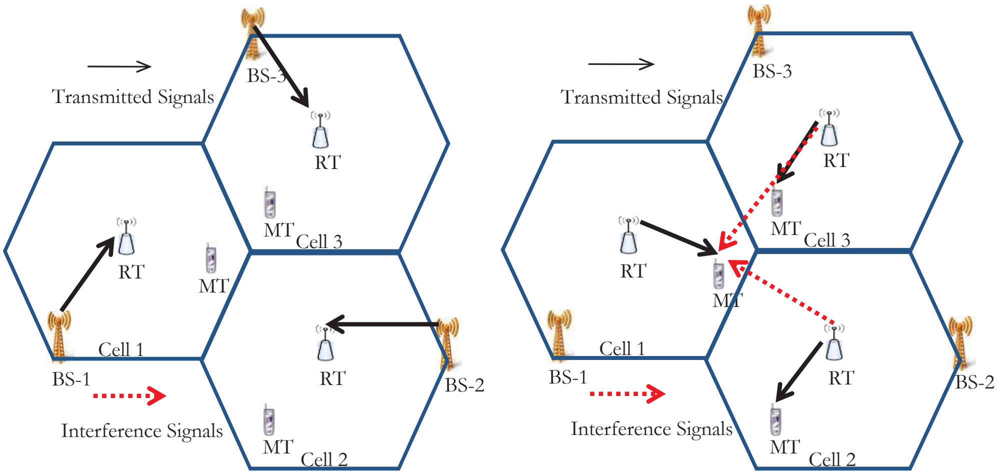
ISD= Inter-Site Distance

Figure 6.1: Sketch of Base Coverage Cell Layout without Relay Nodes [89]

Let us consider an example of three adjacent cells of three sites. By considering Cell 1 as the target cell, we investigate the interference signals from other two neighboring cells in both OWR and TWR networks.

6.2.1 ICI in OWR Networks

Usually it is assumed that a dedicated link can be established between a BS and a fixed RT. Thus ICI can be avoided in this link in the multi-cell scenario. Therefore, there will be no ICI in the first phase if only the relay link is being used for transmission, as shown in Figure 6.2. On the contrary, there will be ICI in the first phase if the direct link between BS and MT is being used as shown in Figure 6.3.



(a) The First Phase (b) The Second Phase

Figure 6.2: Multi-Cell OWR Downlink Transmission without the Direct Link

Keeping in view the ICI signals in the first and second phases, mathematically, the SINR for the first case when there is no direct communication can be written as:

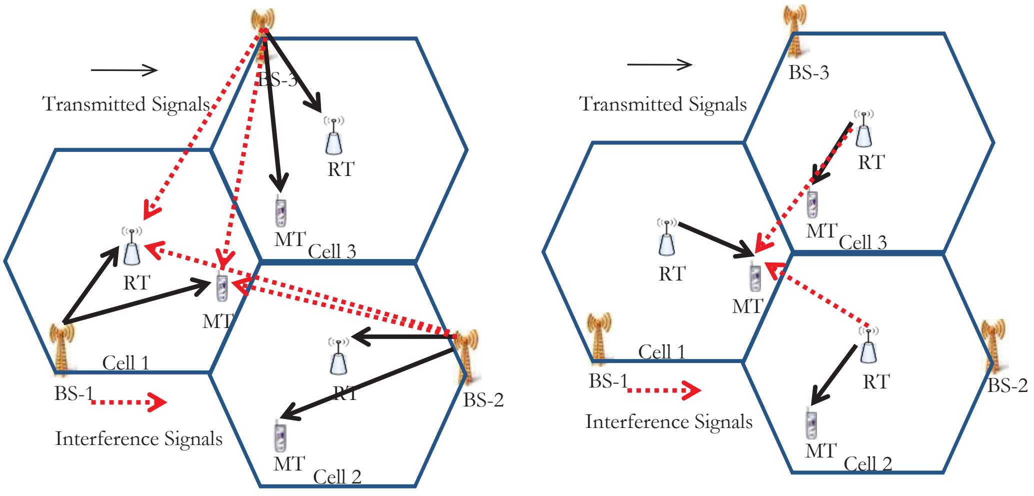
$$SINR_1^k = \frac{{g_m^k}^2 P_{B,m}^k \left|h_{BR,m}^k\right|^2 \left|h_{RM,m}^k\right|^2}{\sigma_M^2 + {g_r^k}^2 \left|h_{RM,m}^k\right|^2 \sigma_R^2 + \sum_{i=1}^{I} P_{R,i}^k \left|h_{RM,i}^k\right|^2} \tag{6.1}$$

where g_m^k is the scaling factor as given in (3.3) and $\sum_{i=1}^{I} P_{R,i}^k \left|h_{RM,i}^k\right|^2$ represents the interference signals in the second phase from all I neighboring cells. The $P_{R,i}^k$ is the transmission power of RT in i^{th} neighboring cell while $h_{RM,i}^k$ is the channel gain between RT in the i^{th} cell and the MT in target cell.

From Figure 6.3, it is clear that to include the direct link transmission; we also need to consider ICI signals on both RT and MT in the first phase of transmission.

Using $\sum_{i=1}^{I} P_{B,i}^{k}\left|h_{BR,i}^{k}\right|^{2}$ and $\sum_{i=1}^{I} P_{B,i}^{k}\left|h_{BM,i}^{k}\right|^{2}$ are the interference signals in the first the phase from BS to RT and MT in the target cell respectively, the SINR for this transmission can be calculated as:

$$SINR_{2}^{k}=\frac{{g_{m}^{k}}^{2}P_{B,m}^{k}\left|h_{BR,m}^{k}\right|^{2}\left|h_{RM,m}^{k}\right|^{2}}{\sigma_{M}^{2}+{g_{r}^{k}}^{2}\left|h_{RM,m}^{k}\right|^{2}\sigma_{R}^{2}+{g_{r}^{k}}^{2}\sum_{i=1}^{I}P_{B,i}^{k}\left|h_{BR,i}^{k}\right|^{2}\left|h_{RM,m}^{k}\right|^{2}+\sum_{i=1}^{I}P_{R,i}^{k}\left|h_{RM,i}^{k}\right|^{2}}+\frac{P_{B,m}^{k}\left|h_{BM,m}^{k}\right|^{2}}{\sigma_{M}^{2}+\sum_{i=1}^{I}P_{B,i}^{k}\left|h_{BM,i}^{k}\right|^{2}} \tag{6.2}$$



(a) The First Phase (b) The Second Phase

Figure 6.3: Multi-Cell OWR Downlink Transmission with the Direct Link

The $P_{B,i}^{k}$ represents the transmission power of BS in i^{th} neighboring cell. The $h_{BR,i}^{k}$ is the channel gains between BS in the i^{th} cell and the RT in target cell while

$h_{BM,i}^{k}$ is the channel gains between BS in the i^{th} cell and the MT in target cell. The amplification factor g_m^k with interference signals received at RT for m^{th} MT is given as:

$$g_m^k = \sqrt{\frac{P_{\mathrm{R},m}^k}{P_{\mathrm{B},m}^k \left|h_{\mathrm{BR},m}^k\right|^2 + \sum_{i=1}^{I} P_{\mathrm{B},i}^k \left|h_{\mathrm{BR},i}^k\right|^2 + \sigma_{\mathrm{R}}^2}} \tag{6.3}$$

6.2.2 ICI in TWR Networks

The uplink and downlink transmissions occur simultaneously in TWR. Therefore, unlikely OWR, the ICI from neighboring cells occurs in both hops of transmission even if we consider a dedicated link between BS and RTs.

During the first phase in TWR-ANC, the ICI is received from MTs of others cells scheduled on the same RBs. There will be no ICI signal from BSs of other cell as the transmission between BSs and RTs are over dedicated links as shown in Figure 6.4(a). While in the second phase, ICI signals are received by both BS and MT in the target cell due to the broadcast nature of the signal from RTs as shown in Figure 6.4(b).

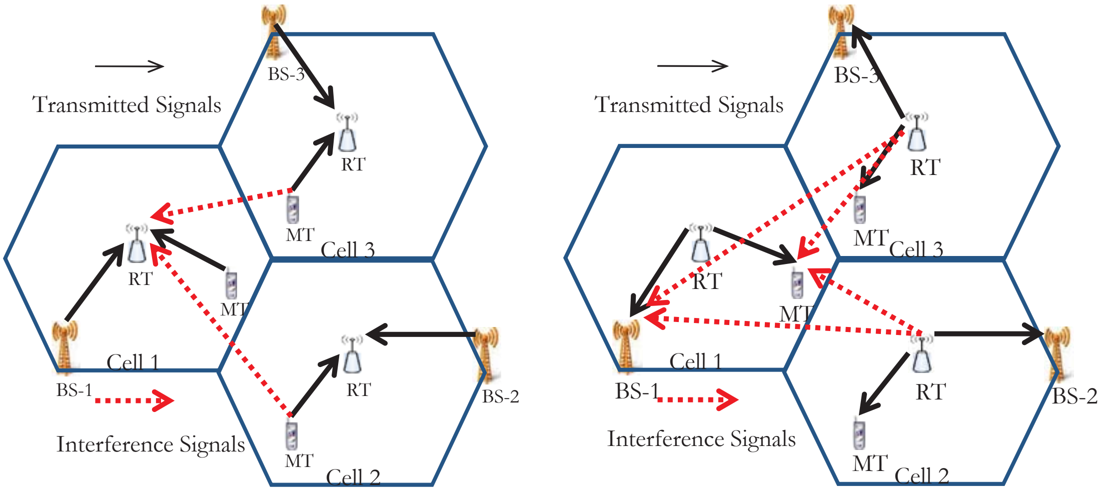
Therefore, the SINRs at MT and BS in the target cell can be written as:

$$\gamma_m^k(ANC) = \frac{{g_m^k}^2 P_{\mathrm{B},m}^k \left|h_{\mathrm{BR},m}^k\right|^2 \left|h_{\mathrm{RM},m}^k\right|^2}{\sigma_M^2 + {g_r^k}^2 \left|h_{\mathrm{RM},m}^k\right|^2 \sigma_{\mathrm{R}}^2 + {g_r^k}^2 \sum_{i=1}^{I} P_{\mathrm{M},i}^k \left|h_{\mathrm{MR},i}^k\right|^2 \left|h_{\mathrm{RM},m}^k\right|^2 + \sum_{i=1}^{I} P_{\mathrm{R},i}^k \left|h_{\mathrm{RM},m}^k\right|^2} \tag{6.4}$$

$$\gamma_b^k(ANC) = \frac{{g_m^k}^2 P_{\mathrm{M},m}^k \left|h_{\mathrm{RB},m}^k\right|^2 \left|h_{\mathrm{MR},m}^k\right|^2}{\sigma_{\mathrm{B}}^2 + {g_r^k}^2 \left|h_{\mathrm{RB},m}^k\right|^2 \sigma_{\mathrm{R}}^2 + {g_r^k}^2 \sum_{i=1}^{I} P_{\mathrm{M},i}^k \left|h_{\mathrm{MR},i}^k\right|^2 \left|h_{\mathrm{RB},m}^k\right|^2 + \sum_{i=1}^{I} P_{\mathrm{RB}}^k \left|h_{\mathrm{RB},i}^k\right|^2} \tag{6.5}$$

The amplification factor g_m^k with interference signals received at RT is given as:

$$g_m^k = \sqrt{\frac{P_{R,m}^k}{P_{B,m}^k \left|h_{BR,m}^k\right|^2 + P_{M,m}^k \left|h_{MR,m}^k\right|^2 + \sum_{i=1}^{I} P_{i,m}^k \left|h_{i,r}^k\right|^2 + \sigma_R^2}} \tag{6.6}$$

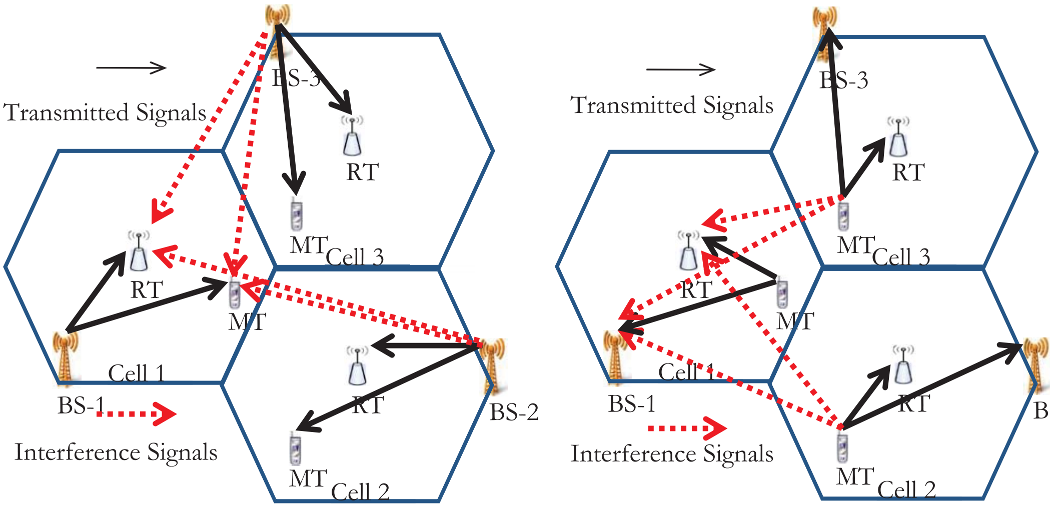


(a) The First Phase (b) The Second Phase

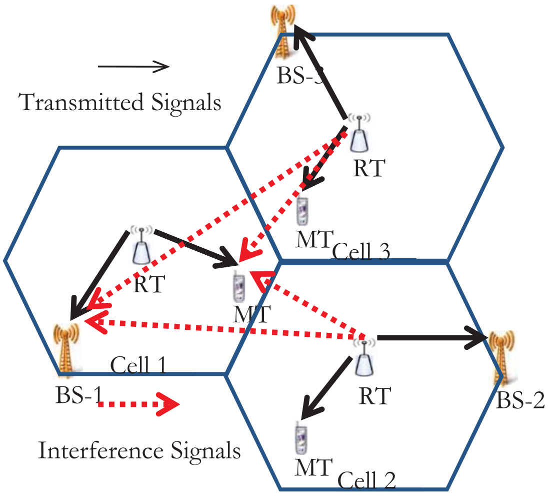
Figure 6.4: Multi-Cell TWR-ANC Transmission

On the other hand, in TWR-TDBC networks, there is more ICI present as shown in Figure 6.5. As we know, the TDBC transmission takes three time slots to complete the information transfer from source to destination; and the ICI presents in each time slot.

During the first phase, ICI arises from neighboring BSs to target RT and target MT, while in the second phase neighboring MTs scheduled on the same RBs produce ICI signal toward both target BS and target RT. In the third phase, when RTs are broadcasting the amplified signals, the neighboring RTs produce ICI in target cell on both BS and MT.



(a)The First Phase (b) The Second Phase



(c) The Third Phase

Figure 6.5: Multi-Cell TWR-TDBC Transmission

Keeping in view all these interferences, the received SINR at MT in target cell can be expressed as:

$$\gamma_{m,r}^{k}(\text{TDBC})=\frac{{g_m^k}^2 P_{\text{B},m}^k \left|h_{\text{BR},m}^k\right|^2 \left|h_{\text{RM},m}^k\right|^2}{\sigma_M^2+{g_r^k}^2\left|h_{\text{RM},m}^k\right|^2\sigma_{\text{R}}^2+{g_r^k}^2\sum_{i=1}^{I}P_{\text{BR},i}^k\left|h_{\text{BR},i}^k\right|^2\left|h_{\text{BR},m}^k\right|^2+{g_r^k}^2\sum_{i=1}^{I}P_{\text{M},i}^k\left|h_{\text{MR},i}^k\right|^2\left|h_{\text{RM},m}^k\right|^2+\sum_{i=1}^{I}P_{\text{R},i}^k\left|h_{\text{RM}}^k\right|^2} + \frac{P_{\text{B},m}^k Z}{1+I_{BM,i}} \tag{6.7}$$

The amplification factor here is given as:

$$g_m^k=\sqrt{\frac{P_{\text{R},m}^k}{P_{\text{B},m}^k\left|h_{\text{BR},m}^k\right|^2+P_{\text{M},m}^k\left|h_{\text{MR},m}^k\right|^2+{g_r^k}^2\sum_{i=1}^{I}P_{\text{BR},i}^k\left|h_{\text{BR},i}^k\right|^2+\sum_{i=1}^{I}P_{i,m}^k\left|h_{i,r}^k\right|^2+\sigma_{\text{R}}^2}} \tag{6.8}$$

The received SINR at BS in target cell can be calculated in the same way.

6.3 Simulation Setup and Parameters

6.3.1 Cellular Architecture

The cellular network consisting of 7 sites is considered for simulation. Each site consists of three hexagonal cells and a RT is added to each cell as shown in Figure 6.6. The relays are placed at the middle of each cell. The distance between two BSs is 1 KM.

6.3.2 Propagation Models

The shadowing and path losses are considered separately. The LOS path loss model is used for BS-RT link as we assume that relays are in LOS of BS which has directional antennas for transmission. The NLOS path loss model is used for RT-MT links. Both path loss models are given in (5.17) in the previous Chapter. The simplified model given in (6.9) is adopted for shadowing loss.

$$L_{\text{shadow}}(m)=\begin{cases}\rho\,\text{dB}, & \text{if } m \text{ is in a shadowed area}\\ 0\,\text{dB} & \text{otherwise}\end{cases} \tag{6.9}$$

where ρ is the standard deviation. While shadowing loss is considered at both MT-RT and RT-MT links, no shadowing loss is imposed for the dedicated BS-RT link.

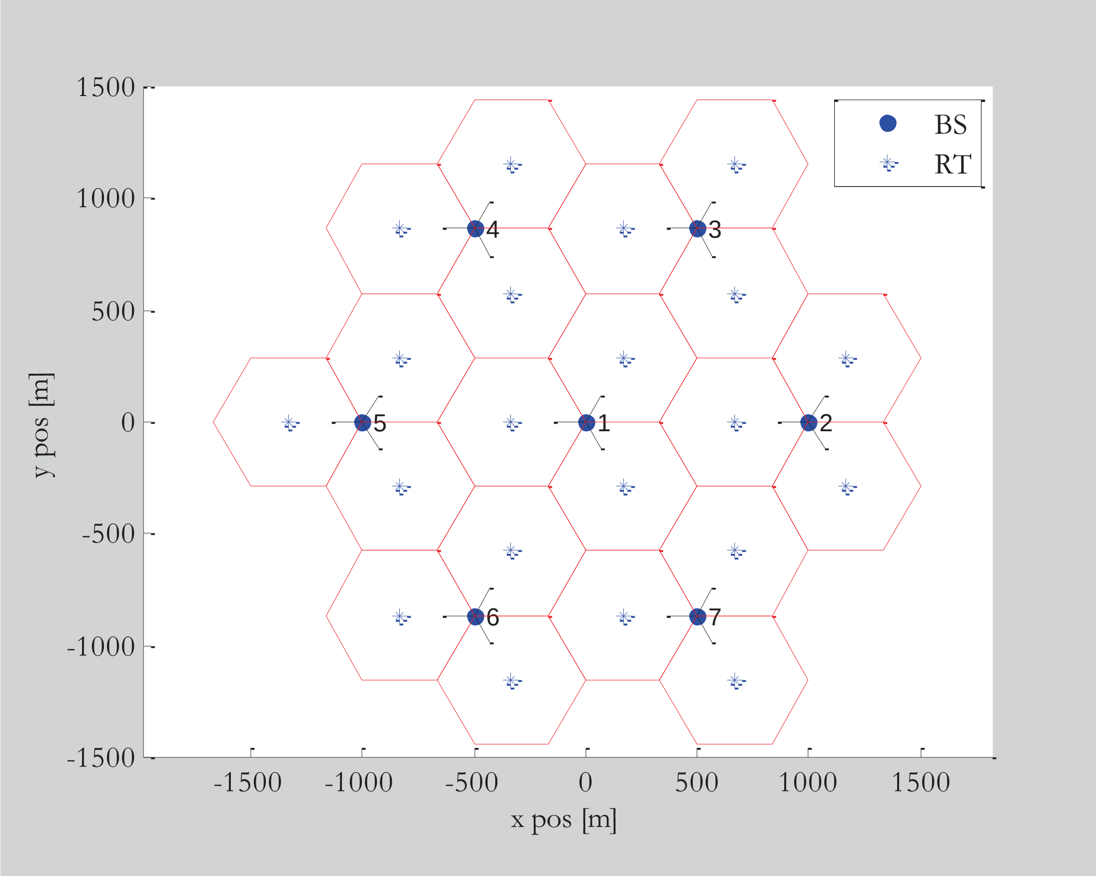


Figure 6.6: Simulation Setup for Multi-Cellular Layout with Relays

6.3.3 Antenna Configuration

To take into account the ICI, the antenna pattern for all nodes should be considered. Here we assume that all BSs are equipped with both sectored directional antennas to support LOS transmission between BSs and RTs and omnidirectional antennas for direct transmission between BSs and MTs, while all RTs and MTs are equipped with a single omnidirectional antenna, respectively. Figure 6.7 shows the BS antenna pattern for 3-sector cells.

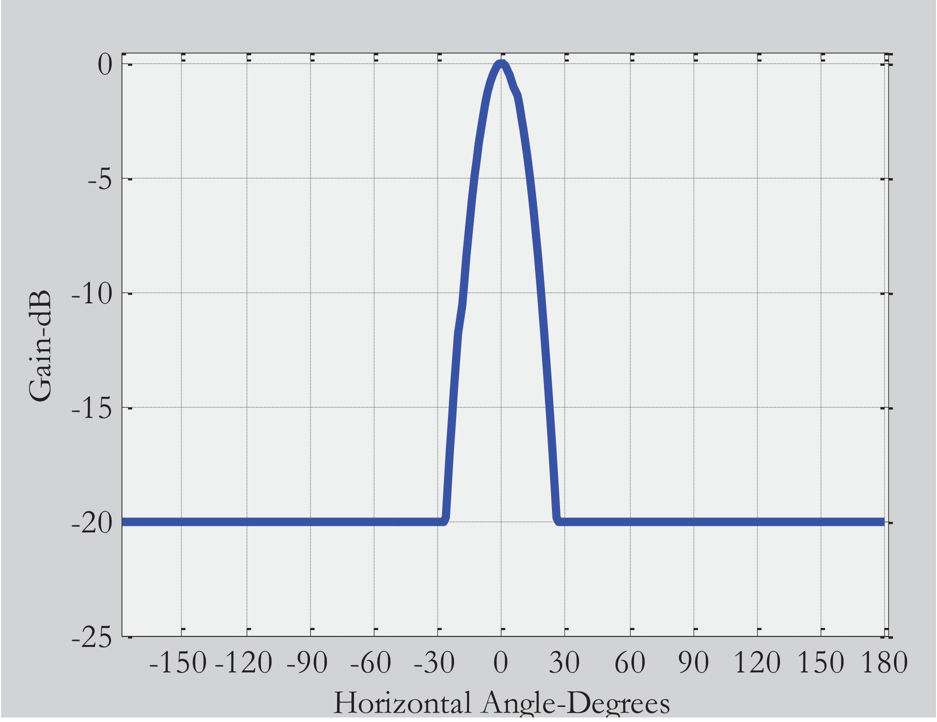


Figure 6.7: BS Antenna Pattern [89]

The antenna pattern for sectored antennas as proposed in [89] is given as:

$$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right] \tag{6.10}$$

where

$A(\theta)$ = Relative antenna gain(dB) in the direction θ;

$-180^\circ \leq \theta \leq 180^\circ$ is the angle between the direction of interest and the bearing direction of the antenna;

min [.], denotes the minimum function;

θ_{3dB} is the 3 dB beamwidth and $\theta_{3dB} = 70^\circ$;

A_m = 20 dB is the maximum attenuation;

Parameters	Value
Number of Sites	7
Number of Cells per Site	3
BS-BS Distance	1 Km
Number of RTs per Cell	1
RT-BS Distance	0.5 x Cell Radius
Carrier Frequency	2 GHz
Shadowing for NLOS Link	8.9 dB
OFDM Subcarrier Bandwidth	15 KHz
Number of Subcarrier per RB	12
Noise Power Density	-170 dBm/Hz
BS Max. Tx. Power	46 dBm
RT Max. Tx. Power	37 dBm
MT Max. Tx. Power	15 dBm

Table 6.1: Simulation Parameters

6.4 Numerical Results

This section presents the simulation analysis on ICI in both OWR and TWR networks. For OWR we consider only downlink transmission while for TWR both uplink and downlink transmissions are considered simultaneously. Cell 1 of Site 1 is considered as target cell and all other neighboring cells are assumed as interfering cells. A single MT is placed in each cell at the same position for simplicity. Other simulation parameters are given in Table 6.1.

Figure 6.8 shows the ICI analysis on OWR with and without the presence of the direct link between BS and MT during transmission. It is clearly shown that higher transmission rate is achieved with the direct link due to the diversity gain.

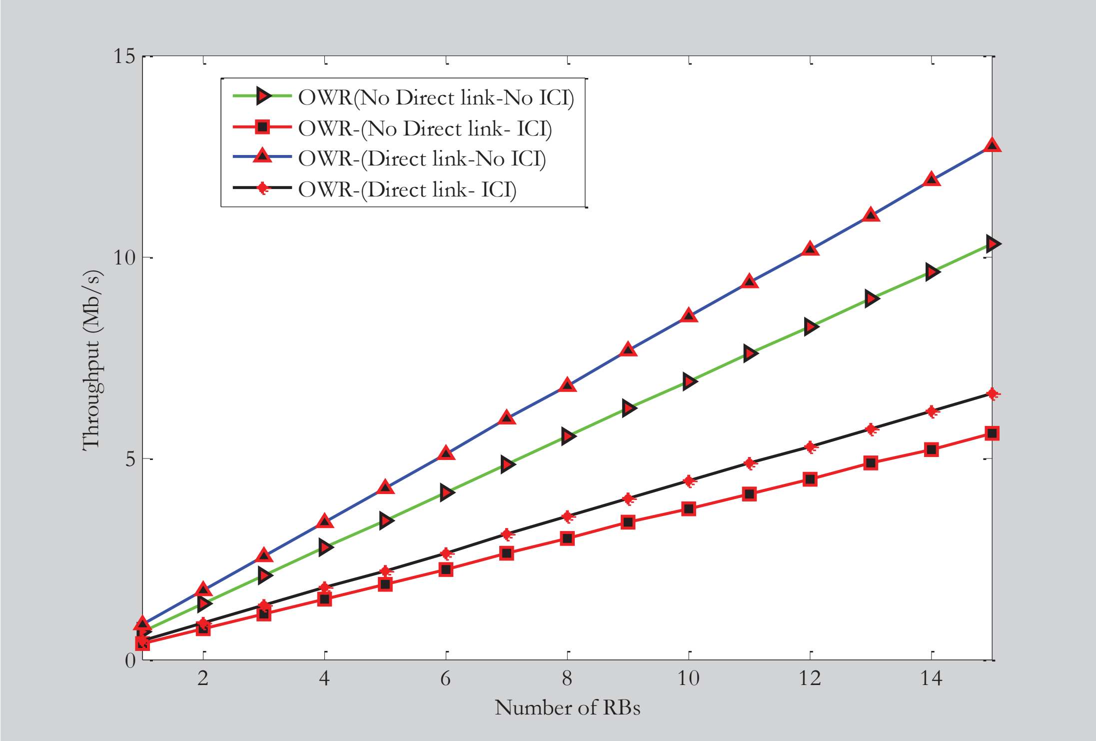


Figure 6.8: ICI Analysis on OWR Networks with and without the Direct Link

There are two points to be noted here. The first point is that transmission rate is much degraded due to the presence of ICI, and therefore ICI cannot be neglected in any practical scenario. The second point is that the difference in transmission rate between the case with direct link and that without direct link widens as the number of RBs increases, when ICI is not considered. However, this difference shrinks notably once ICI is taken into account. This is because of the presence of the ICI signals in the first phase of transmission when the direct link is also being used for transmission along with the relay links.

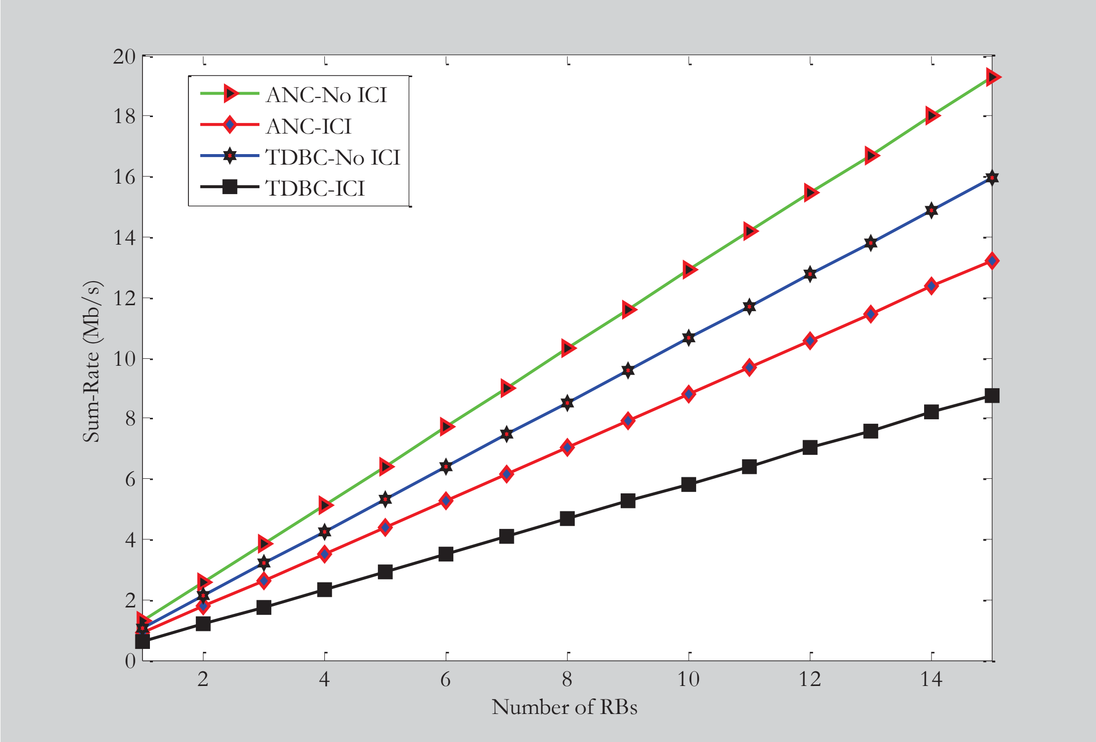


Figure 6.9: ICI Analysis on TWR Networks with ANC and TDBC Protocols

Figure 6.9 presents an analysis of ICI on TWR network. Both ANC and TDBC protocols are considered. Like in OWR, the ICI degrades the sum-rate in TWR as well. As discussed in the previous Chapter, ANC is an efficient protocol than TDBC in terms of spectral efficiency due to the less number of time slots required to complete the exchange of information between source and destination, and here the same is again verified with and without the presence of ICI. As shown in Figure 6.5, TDBC protocol experiences more interference than ANC protocol. Therefore the sum-rate difference between ANC and TDBC protocols increases when ICI is taken into account in TWR networks.

6.5 Resource Allocation with ICI Consideration

The resource allocation problems presented in Chapter 3 to Chapter 5 for OWR and TWR respectively can easily be extended to multi-cell scenario by using SINRs instead of SNRs and summation over all cells.

6.6 Signaling Feedback, Delays and Implementation Issues

In this section we will briefly discuss some key implementation factors for applying resource allocation algorithms.

6.6.1 CSI Measurement

For centralized resource allocation, CSI measurement should be taken before the start of the cooperative transmission. For CSI measurement, BSs acquire the CSI for all links in the networks. This can be achieved by broadcasting the pilot packets for channel estimation. After receiving the packet, every RT and MT within the cell returns the measurements results by dedicated feedback uplink channels.

In order to exploit the multi-user and frequency diversities, the resource allocation process should be conducted periodically with the period not greater than coherence time for the highest user mobility supported [76]. Since the resource allocation presented in this thesis should be operated for each OFDM frame, the CSI is required frequently for maximum mobility, such as 100 Km/hr as per the LTE-advanced [27]. However for lower mobility, the CSI can be acquired less frequently depending on the coherence time of the channel but it should be less than the coherence time of the channel for that user.

6.6.2 Timing and Frequency Offsets

In relay-based wireless communication networks, a receiver experiences time delays between signals from its own cell and from neighboring cells. Therefore, multi-cell frame-level synchronization is a key implementation issue. Different OFDM frame synchronization schemes are given in the literature. For example in [94] the cyclic prefix is used to synchronize the timing offset in different frames. Due to the imperfect synchronization, the MUI may also occur because of different frequency offsets between different users. This MUI can be mitigated using some MUI cancellation techniques such as proposed in [95].

6.7 Summary and Conclusions

In this Chapter, the different ICI cases of relay networks are analyzed. Simulation results show that the throughput degrades significantly due to the presence of ICI. The degradation differs slightly with different network relaying techniques and protocols.

The performance degradation due to ICI may be reduced by extending the scheduling algorithms presented in previous Chapters to multi-cell scenarios.

Chapter 7 Conclusions and Possible Future Extensions

In this Chapter, we summarize our conclusions and discuss some open issues that can be addressed in future research.

7.1 Thesis Conclusions

Future wireless communication systems require the use of advanced technologies to effectively enhance the utilization of radio resources, which motivates the research on relay-based cooperative wireless commination in this thesis. We have studied the resource allocation and performance analysis of OFDMA relay enhanced cellular networks. Efficient and intelligent resource allocation schemes are necessary to harness the opportunities in future relay-based OFDM wireless networks where conventional techniques are not adequate. With the deployment of relay stations in traditional OFDMA cellular networks, how to allocate resources efficiently and feasibly becomes a more complicated and crucial problem to be addressed to materialize the diversity gain of cooperative relaying.

In this thesis, firstly, we focused on OWR and formulated a joint optimization problem for resource allocation in relay networks using both AF and DF protocols in Chapter 3. The objective function of our optimization was system throughput under the constraints of power and data rate fairness. A two-step approach was proposed for the allocation of subcarriers and power. Three RB scheduling techniques known RRS, MSS and PFS, in OFDM-based wireless networks was investigated and extended into two-hop relay networks. The main focus of Chapter 4 was on subcarrier pairing and we studied resource allocation in OWR considering on subcarrier pairing, and fairness in terms of minimum data rate requirement for each user. A new low-complexity iterative RB-pairing and allocation algorithm was investigated along with the previously described two step approach in Chapter 3.

Secondly, TWR was brought into attention in Chapter 5, in which we provided a proportional fairness based resource allocation in TWR networks. The algorithms investigated in this Chapter also addressed the issue of load balancing in relay networks. To reduce computational complexity, three different HA-based resource allocation algorithms investigated in this Chapter. Considering the proportional fairness among users an efficient allocation of subcarriers was proposed. Beside this, these algorithms also exploited the inherent feature of load balancing in HA. Therefore, these proposed algorithms not only provided the use of all the available subcarriers in efficient manners, but also helped to reduce the processing delays at relays, which resulted in increased efficiency of the system. Finally, we considered multi-cell scenario and investigated various ICI signals present in relay-based networks in Chapter 6.

In conclusion, we studied resource allocation in relay-based wireless networks under different protocols and relaying techniques. We formulated the optimal resource allocation problem under different assumptions and constraints. Simulation results proved that our algorithms provided a good trade-off between network throughput and fairness among users in multi-user networks.

7.2 Proposed Future Work

Although relaying for coverage extension in wireless networks is an old concept, using relays in OFDMA cellular networks has become an important research topic over the past half-decade. We have studied the resource allocation in OFDMA relay enhanced cellular networks. However, to provide ubiquitous high-data-rate coverage by using multi-hop relaying in practical networks, there are several remaining issues for investigation.

7.2.1 Resource Allocations in Relaying Networks with Partial or Imperfect CSI

We have developed different resource allocation algorithms in relay-based wireless networks where we have assumed that the central controller or BS knows the perfect CSI. However, in reality there always exists some uncertainty in CSI due to the time-varying nature of the wireless channel and limited capacity and reliability of feedback channels. Therefore, it would be interesting to extend the proposed resource allocation algorithms to multi-user relay networks with partial or imperfect CSI.

7.2.2 Resource Allocation in Multi-Hop Relaying Networks

In our work, we have focused only on two-hop relaying networks. A possible extension would be to consider multi-hop networks such as sensor networks.

7.2.3 Distributed Resource Allocation for OFDMA Based Cooperative Relaying Systems

Another interesting extension of the proposed work is the distributed resource allocation in multi-cell relay-based cooperative systems. Relays in cooperative networks extend the coverage area; however at the same time these relays also create another source of interference in multi-cell networks as described in Chapter 6. In centralized systems, all the information is transmitted to and from the central unit, where ICI signals are properly managed and control information is then sent back to each cell and relays therein. However, the overhead introduced will also be overwhelming. Therefore, distributed or semi-centralized approach in which resource allocation can be done in distributed manner would be an extending future research area to current work.

7.2.4 MIMO Relay Networks

The work presented in this thesis is focused on single-antenna systems and can be extended to multiple-antenna systems, where beamforming, precoding and antenna selection in relay-based wireless networks would also be interesting topics for future research.

APPENDIX-I

How to Use the Hungarian Algorithm (HA)

The Hungarian Algorithm allows a "minimum matching" to be found, but can be used for "maximum matching" by multiplying each number by -1 in step-1. Let us consider an example to understand how it works:

Example: There are four activities (A, B, C, D) that need to be assigned to four persons (P1, P2, P3, P4). The estimated costs assigning a particular activity to particular person are given in table below. The assignment is to be made so that the total cost is a minimum.

	A	B	C	D
P1	80	40	50	46
P2	40	70	20	25
P3	30	10	20	30
P4	35	20	25	30

Steps:

1. Arrange the information in a matrix as shown above. Ensure that the matrix is square by adding of dummy rows/columns. Conventionally, each element in the dummy row/column is the same as the largest number in the matrix.
2. Reduce the costs in each row by subtracting the minimum value of each row from that row.

	A	B	C	D	
P1	40	0	10	6	-40
P2	20	50	0	5	-20
P3	20	0	10	20	-10
P4	15	0	5	10	-20

3. Reduce the costs in each column by subtracting from each element of a column the least element in that column.

	A	B	C	D
P1	25	0	10	1
P2	5	50	0	0
P3	5	0	10	15
P4	0	0	5	5
	-15	0	0	-5

4. Now cover all zeros with minimum number of vertical or horizontal lines or both. (If the number of lines is equal to the number of rows then go step-8)

	A	B	C	D
P1	25	~~0~~	10	1
P2	~~5~~	~~50~~	~~0~~	~~0~~
P3	5	~~0~~	10	15
P4	~~0~~	~~0~~	~~5~~	~~5~~

5. Add the minimum uncovered element to every covered element. (If an element is covered twice, add the minimum element to it twice).

	A	B	C	D
P1	25	1	10	1
P2	6	52	1	1
P3	5	1	10	15
P4	1	2	6	6

6. Subtract the minimum element from every element in the matrix.

	A	B	C	D
P1	24	0	9	0
P2	5	51	0	0
P3	4	0	9	14
P4	0	1	5	5

7. Now again cover all zeros with minimum number of vertical or horizontal lines or both. (If the number of lines is not equal to the number of rows then return to step-5).

	A	B	C	D
P1	~~24~~	~~0~~	~~9~~	~~0~~
P2	~~5~~	~~51~~	~~0~~	~~0~~
P3	~~4~~	~~0~~	~~9~~	~~14~~
P4	~~0~~	~~1~~	~~5~~	~~5~~

8. Select a matching by choosing a set of zeros so that each row or column has only one selected. This can be easily sorted by giving priority to rows with single zero element.

	A	B	C	D
P1	24	0	9	⓪
P2	5	51	⓪	0
P3	4	⓪	9	14
P4	⓪	1	5	5

9. Apply the matching to the original matrix. This shows who should do which activity to give overall minimum cost.

	A	B	C	D
P1	80	40	50	㊻
P2	40	70	⑳	25
P3	30	⑩	20	30
P4	㉟	20	25	30

For more details on HA, please refer to

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