Resource Allocation for Multi-cell OFDMA Based Cooperative Relay Network

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STATEMENT OF ORIGIN

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

Cooperative communications is emerging as an important area within the field of wireless communication systems. The fundamental idea is that intermediary nodes, called relay stations (RSs), who are neither the data source nor destination, are used to assist in communication between sender and receiver. In order to maximise their performance, networks which employ RSs require a new resource allocation and optimisation technique, which takes the RSs into account as a new resource.

Several proposals have been presented for the purpose of optimising the distribution of available resources between users. These proposals were developed based on various network scenarios and assumptions. In most cases, impractical assumptions such as; inter-cell interference (ICI) free and full availability of channel state information (CSI) were considered. However, the need for more robust, fair and practical resource allocation algorithms motivated us to study the resource allocation algorithm for OFDMA based cooperative relay networks with more realistic assumptions.

This thesis focuses on the resource allocation for the uplink OFDMA based cooperative relay networks. Multiple cells were considered, each composed of a single base station (destination), multiple amplify and forward (AF) relay stations and multiple subscriber stations (sources). The effects of inter-cell interference (ICI) have been considered to optimise the subcarrier allocation with low complexity. The optimisation problem aims to maximise the sum rate of all sources while maintaining a satisfactory degree of fairness amongst them.

Furthermore, a utility based resource allocation algorithm has been developed

assuming full and partial channel state information for the interference limited OFDMA-based cooperative relay network. In the proposed algorithm, relay selection is initially performed based on the level of ICI. Then, subcarrier allocation is performed on the basis of maximum achieved utility under the assumption of equal power allocation. Finally, based on the amount of ICI, a modified waterfilling power distribution algorithm is proposed and used to optimise the subcarrier power allocation across the allocated set of subcarriers.

This thesis also investigates the impact of the relay-to-destination channel gain on subcarrier allocation for uplink OFDMA based cooperative relay networks using multiple amplify-and- forward (AF) relaying protocols. The closed form outage probability is derived for the system under partial channel state information (PCSI) and considering the presence of inter-cell interference (ICI).

The proposed resource allocation algorithms as well as the mathematical analysis were validated through computer simulations and the results were presented for each chapter. The results show that, compared to conventional algorithms, the proposed algorithms significantly improve system performance in terms of total sum data rate, outage probability, complexity and fairness.

ACKNOWLEDGMENTS

This work would not been accomplished without the help of so many people. In the following lines is a brief account of some but not all who deserve my thanks.

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LIST OF ACRONYMS

1^{st} G	First Generation
2^{nd} G	Second Generation
3^{rd} G	Third Generation
4^{th} G	Fourth Generation
AF	Amplify and Forward
AMPS	Advance Mobile Phone Service
AWGN	Additive White Gaussian Noise
BE	Best Effort
BPA	Binary Power Allocation
BS	Base Station
BTS	Base Transceiver Station
BW	Bandwidth
CDMA	Code Division Multiple Access
CF	Compress and Forward
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
DF	Decode and Forward
EF	Estimate and Forward
ETACS	European Total Access Communication System
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FI	Fairness Index
FM	Frequency Modulation

GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HSDPA	High-Speed Downlink Packet Access
ICI	Inter Cell Interference
ICI-RS	ICI-based Relay Selection
IFFT	Inverse Fast Fourier transform
LTE	Long Term Evolution
MA	Multiple Access
MAC	Medium Access Control
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
MMR	Mobile Multi-hop Relay
MRC	Maximum Ratio Combining
MS	Mobile Station
MUI	Multiuser Interference
NAK	Negative Acknowledgement
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSDMA	Orthogonal Space Division Multiple Access
PA	Power Allocation
PCSI	Partial Channel State Information
PDF	Probability Density Function
PHY	Physical
PSK	Phase-shift Keying
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service

RC	Rate Constraint
RD	Relay To Destination
RRM	Radio Resource Management
R-RS	Random Relay Selection
RS	Relay Station
SCI	Statistical Channel Information
SDMA	Space Division Multiple Access
SER	Symbol Error Rate
SINR	Signal to Interference and Noise Ratio
SMS	Short Message Service
SNR	Signal to Noise Ratio
SR	Source to Relay
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
W-CDMA	Wideband- Code Division Multiple Access
WF	Water-Filling
WiMAX	Worldwide Interoperability for Microwave Access

LIST OF SYMBOLS

P^k	Subcarrier's Power
P_T	Total power
$NC\chi^2$	Non-central Chi-square Distribution with Two Degrees of Freedom
ϵ^k	Estimation Error
$\Gamma(2(n+1))$	Gamma Function
$\gamma(a,b)$	Incomplete Gamma Function
$\gamma_{a,b}$	SNR Ratio Between a and b Channel
$\hat{h}^k_{a,b}$	Estimated Channel Gain between a and b Nodes
$\mathcal{G}_s$	Urgency Factor
ρ	Allocation Index
σ^2	Variance
${}_2F_1$	Hypergeometric Function
$D(.)$	Detrimental Function
FI	Fairness Index
g_r	RS Amplification Factor
$h^k_{a,b}$	Instantaneous Channel Gain between a and b Nodes
I	Interference
I_0	Zeroth-order Modified Bessel Function of the First Kind
$O(.)$	Complexity

P_{out}	Outage Probability
P_r	Probability
R	Data Rate
R_{min}	Minimum Data Rate Requirements
R_T	Total Data Rate
T_s	Time Slot
U	Utility Function
$y_{a,b}$	Received Signal at Node b From Node a

DEDICATION

To my parents and my family

Chapter 1
INTRODUCTION

1.1 Background

The demand for wireless communications services is permanently growing. The number of mobile subscribers being supported and multi-rate users requirements are important issues to be considered with the new wireless communication systems serving heterogeneous users transmitting different media. Regarding multimedia systems requirements, each medium has its own data rate and quality constraints. In order to meet these requirements under the limited frequency spectrum available it is important to use the limited bandwidth spectrum in a more efficient manner.

Generally multiple access techniques enhance the capacity of wireless communication systems by enabling more than one user to utilise the same channel resources simultaneously. Examples of these techniques are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) [1].

Much of the recent research work in the area of wireless communication systems has been primarily focused on OFDMA systems. The OFDMA systems are in fact resistant to frequency-selective multipath fading. This is because OFDMA has the ability to subdivide the total Bandwidth (BW) into a number of sub-channels to be allocated to multiple users. Consequently, OFDMA system becomes the primary and most promising air-interface candidate for the future generations of wireless communication systems [2].

Furthermore, OFDMA has provided the opportunity to enhance the reuse of the available limited frequency resources through the large number of generated subcarriers. However, as the number of subcarriers is limited, excessive reuse of those subcarriers would cause inter-cell interference. Therefore, radio resource management (RRM) should consider the effect of inter-cell interference in order to ensure that the generated inter-cell interference (ICI) is maintained below certain predetermined levels, so that the quality requirements are guaranteed.

1.2 Resource Allocation in A Cooperative Relay Network

The concept of a cooperative relay network has been proposed to increase the system capacity, throughput, communication reliability and network coverage area in wireless communication networks. This is achieved by introducing new network nodes, called relay stations (RSs) [3]. These new RSs resources are meant to be utilised by multiple subscriber stations and base stations, in which they are used to assist the transmission between the source and the destination by relaying the source signal to its destination. In addition to that, the RSs are shared between a number of subscriber stations and base stations [4].

Figure 1.1 depicts a typical cooperative relay network, in which a number of relay stations are being utilised by different base stations and subscriber stations. As shown in the figure, each one of the RSs receives the signal transmitted by both base stations 1 and 2, but the RS discards one of the two received signals while retransmitting the other signal to its destination. The selection of which relay station should serve which signal transmission depends on several factors including the received signal strength, RS availability and target data rate. Con-

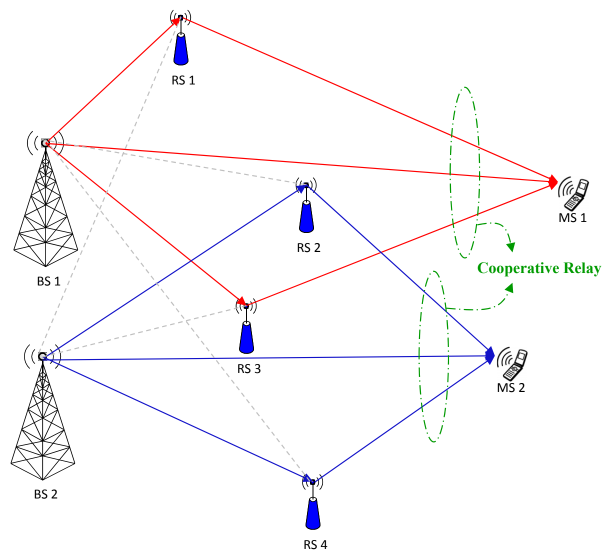


Figure 1.1: Multi-cell cooperative relay network

sequently, other available resources, such as frequency channels and transmit power also need to be carefully allocated to users/relays in such a way that the interference between different nodes is minimised and the objective function (such as maximising the data rate or minimising the transmit power) is achieved.

1.3 Problem Statement and Motivation

The limited bandwidth in wireless communication systems is considered the main challenge that limits the wireless communication capacity. Several researchers have intensively investigated the efficiency of the frequency spectrum utilisation and proposed several methods to improve the resource efficiency for OFDMA based cooperative relay networks by many ways, such as increasing the frequency reuse factor or more efficient allocation of the available resources [5]. However, most of the available algorithms cannot be used in reality because they were designed based on unrealistic assumptions and considerations. These assumptions and considerations include, full knowledge about the channel properties of

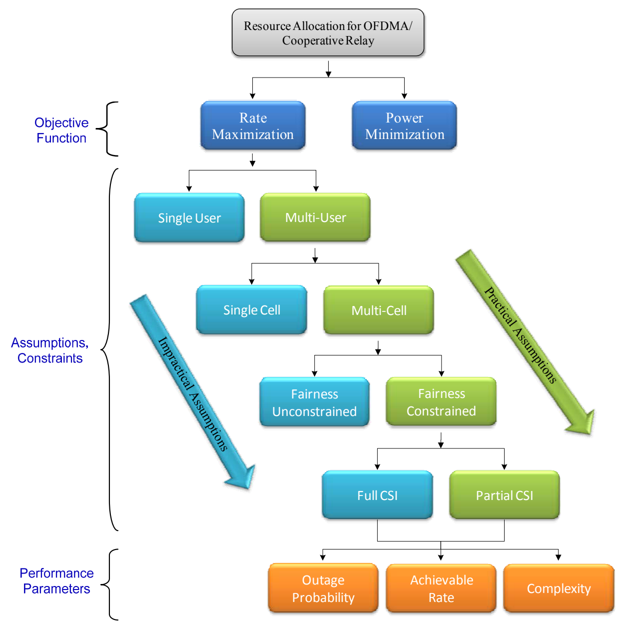


Figure 1.2: Resource allocation for OFDMA possible scinarios

the communication link between the transmitter and the receiver, which is also known as channel state information (CSI) and ignoring the interference effects received from neighbouring cells (called, inter-cell interference (ICI)). Consequently, the lack of practical solutions and the need for more efficient resource utilisation systems motivated this research to closely investigate these topics and address the challenges in resource allocation.

Figure 1.2 classifies the resource allocation problem into two main objective functions (rate maximisation and power minimisation), also the same figure presents various possible network scenarios and assumptions/constraints as well as the major performance parameters. Rate maximisation approach is considered throughout this thesis taking into account various impractical and practical assumptions and considerations (such as full and partial channel state information (CSI)).

The main objective of this thesis is to improve the total data rate that can be achieved in a multi-cell network that employs cooperative relay network through fair and efficient utilisation of the available resources. In addition to that, this thesis aims to investigate the impact of various parameters (for example; channel state information (CSI) and inter-cell interference (ICI)) on the efficiency of resource allocation algorithms.

1.4 Thesis Contributions

This thesis focuses on the resource allocation for the uplink OFDMA-based cooperative relay networks. The main contributions of this thesis are summarised as follows:

- A low complexity subcarrier allocation algorithm has been developed assuming full channel state information for the interference limited OFDMA-based cooperative relay network. The proposed algorithm assumes the channel state information to be fully available at the resource controller. Grouping the subcarriers based on minimum ICI into R significantly reduces the algorithm complexity by a factor of $\approx \frac{1}{R}$ without affecting the other performance metrics (such as total network data rate) for single cell scenario. The total network achievable data rate of the proposed algorithm is improved over the conventional algorithm in the multi-cell scenario.

- A utility-based resource allocation algorithm has been developed assuming full and partial channel state information for the interference limited OFDMA-based cooperative relay network. The proposed algorithm defines two functions, called utility and detrimental functions, and the optimisation problem aims to maximise the first one (i.e., utility) while minimising the second function (detrimental). In addition to that the proposed algorithm imposes fairness constraint to ensure a fair resource allocation. The results showed the system performance (in terms of system complexity, data rate and outage probability) can be significantly improved by including those utility and detrimental functions.

- An ICI-based water-filling power allocation algorithm has been developed, in which the proposed ICI-based WF algorithm allocates the total power across subcarriers based on the amount of ICI affecting each subcarrier. The proposed power allocation algorithm uses the available information on the ICI to optimise the power allocation across subcarriers. This is performed by allocating the power across subcarriers based on the amount of ICI affecting each subcarrier. The results show that the proposed ICI-based water-filling power allocation improves the total sum data rate compared to the equal power allocation algorithm.

- The closed form outage probability has been derived for the interference limited OFDMA-based cooperative relay network assuming only partial channel state information is available. The mathematical framework for such a system is also presented. Furthermore, the impact of the relay-destination link has been investigated. The mathematical findings and simulation results show that the impact of the link between the relay station and the destination is very low when the ICI is high.

The above contributions have been published as follows:

1. Odeh, N.; Abolhasan, M.; Safaei, F.; Franklin, D.R., "On the impact of RD link in resource allocation for multi-cell OFDMA cooperative relay networks with partial CSI," Communications and Information Technologies (ISCIT), 2012 International Symposium on , vol., no., pp.690,695, 2-5 Oct. 2012.

2. Odeh, N.; Abolhasan, M.; Safaei, F., "Low Complexity Interference Aware Distributed Resource Allocation for Multi-Cell OFDMA Cooperative Relay Networks," Wireless Communications and Networking Conference (WCNC), 2010 IEEE , vol., no., pp.1,6, 18-21 April 2010.

3. Odeh, N.; Abolhasan, M.; Safaei, F.; Franklin, D.R., M. Guoqiang, "Utility-based Resource Allocation for Interference Limited OFDMA Cooperative Relay Networks," journal paper ready to be submitted.

4. Odeh, N.; Abolhasan, M.; Safaei, F.; Franklin, D.R., "A Review in Resource Allocation Strategies for OFDMA-based Cooperative Relay Networks," survey paper to be submitted.

1.5 Thesis Organisations

The reminder of this thesis is organised as follows:

In Chapter 2, the mobile communication systems including mobile cellular systems migrations and multiple access techniques are presented and analysed. Then, the concept of the OFDMA-based cooperative relay network is discussed followed by a brief analysis of various cooperative relaying protocols.

In Chapter 3, the resource allocation in an OFDMA network is presented and the two main optimisation objectives (power minimisation and rate maximisation) are analysed. Then, a detailed literature review on the existing and recent resource allocation algorithms is presented considering different network setups and scenarios. Then, the channel state information and inter-cell interference issues are discussed in relation to the resource allocation.

In Chapter 4, the adopted system model is presented, and then the optimisation problem is formulated for the adopted system. Then, the proposed low complexity resource allocation algorithm is presented and analysed. The algorithm complexity has been evaluated and analysed in comparison with conventional algorithms. Finally, simulation results have been provided to validate the performance of the proposed algorithm.

In Chapter 5, the adopted system model is presented. This is followed by a discussion and definition of the utility and detrimental function. Then the problem is formulated based on those functions, followed by the proposed resource allocation and relay selection algorithms. In addition to that, the ICI-water filling algorithm is discussed followed by a presentation of the partial channel state information case. Finally, simulation results are also presented to evaluate the proposed algorithms performance using various performances parameters.

In chapter 6, the impact of the relay-to-destination (RD) link on the resource allocation algorithm has been investigated under the assumption of partial channel state information and an interference limited system. A mathematical framework has been presented and the closed form outage probability has been derived and provided. The system complexity has also been addressed and finally the chapter presents simulation results for validations.

Finally, Chapter 7 concludes the thesis and presents key future research topics.

Chapter 2

REVIEW AND ANALYSIS OF MOBILE COMMUNICATION SYSTEMS

2.1 Overview

During the development of mobile communication systems, several technologies have been emerged in order to support the migration from a certain generation of communication system to a new generation with new attractive features. Concurrently, researchers knocked a lot of doors and intensively study the mobile communication systems in order to achieve the maximum optimisation using the available resources and established technologies. However, it is impossible to go through all of the previous developments on the related literature. In this chapter, the revision and analyses of the mobile communication systems include the followings: mobile cellular systems migrations, Multiple Access (MA) techniques, Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA) conventional systems and finally OFDMA based cooperative relay network with various cooperative relay schemes.

2.2 Mobile Cellular Systems

In cellular mobile systems, the area to be served with mobile communication services is divided into several divisions called cells. Each cell is equipped with a single base station which allows the mobile users within the coverage area of that cell to communicate with each others and with the external world. To do so, multiple access techniques were developed to allow multiple users to access and fairly share the available resources (time, frequency, code, etc.) [1].

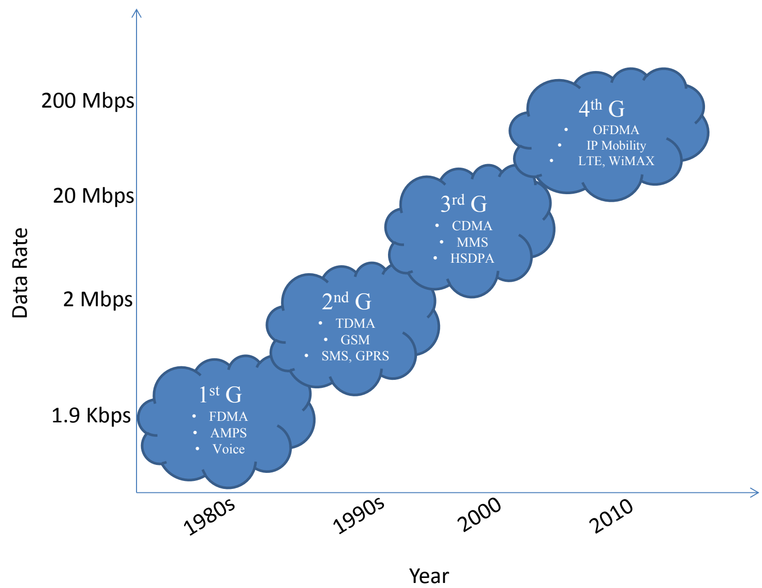


Figure 2.1: Evolutions of mobile communication systems

The development of such multiple access techniques was started in 1980s when the first generation mobile communication system was launched based on dividing the available frequency band among users. As the number of users increased with a limited bandwidth, new multiple access techniques were developed in a subsequent generations.

Figure 2.1, shows the evolution of mobile communications over the past decades starting from the 1^{st} Generation in early 1980s up to 4^{th} generation as of 2010. It can be seen that OFDMA systems are currently leading the mobile communications technology, and they are the best candidates for future mobile communication systems.

The 1^{st} G cellular mobile system was developed to support only telephone service, and it was considered as an analog system since it employs an analog frequency modulation (FM). A typical example of the 1^{st} G cellular mobile system is the Advanced Mobile Phone Services (AMPS), which was established firstly in the US in late of 1983 [1]. Frequency Division Multiple Access/Frequency Division Duplexing (FDMA/FDD) was the multiple access technique that employed in the 1^{st} G.

The limited service provided by the 1^{st} G mobile system and some other technical shortage in system performance and efficiency were the triggers to launch the second generation (2^{nd} G) cellular mobile system that uses digital modulation techniques, hence given the name digital cellular mobile system, and offer large improvement in user capacity and system performance. In addition to the voice communication service, 2^{nd} G provides short message services (SMS) and other technical improvements, such as, compatibility with the existing systems, smooth handover, efficient use of channel resources, and lower power consumption. Several multiple access techniques are used in the 2^{nd} G mobile system, namely, Time Division Multiple Access/Time Division Duplexing (TDMA/FDD) and Code Division Multiple Access CDMA IS-95 [6]. Global System for Mobile Communication (GSM) system is considered as one of the most popular and successful 2^{nd} G cellular mobile system.

In addition to the services provided by 2^{nd} G mobile communication systems, users have demanded new services such as multimedia (such as, data, image, video, websites and other services including Internet). This requires mobile devices to be supported with high speed data transfer. To overcome this requirements, 3^{rd} G mobile systems was developed to provide a data transfer rate of at least 200 kbps. The 3^{rd} G mobile communication system adopted the wideband-CDMA as the multiple access technique which utilises a total bandwidth of 5MHz.

Recently, Fourth Generation 4^{th} G cellular mobile systems has evolved to overcome the 3^{rd} G systems drawbacks and limitations such as, complexity, speed and to provide a new services, such as high quality voice and video and high data rate wireless channels. Unlike 3^{rd} G network, the 4^{th} G systems are completely based on packet switching network; hence low latency data transmission can be achieved. In 4^{th} G systems, backward compatibility is maintained due to the integration of existing technologies such as, GSM, GPRS, CDMA, IMT-2000, Wireless LANs and BlueTooth. Fourth generation networks aim to provide speeds of 100 Mbps with high mobility and up to 1 Gbps for low mobility communication.

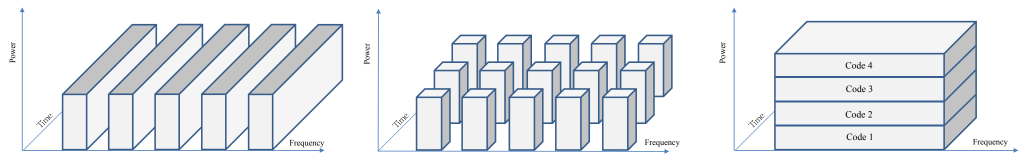
Long Term Evolution (LTE) is the global standard for the fourth generation of mobile broadband. It has been developed to provide a higher speed and capacity over the existing mobile networks in order to satisfy the users requirements of higher users and system capacity. Mobile Worldwide Interoperability for Microwave Access (WiMAX) also uses 4^{th} G term [7].

2.3 Multiple Access Techniques

The idea of multiple access techniques is applied for both wired and wireless channels that allow users to transmit and receive data simultaneously using common transmission channel. Multiple access techniques can be classified as either contentionless multiple access or contention multiple access technique [8]. In contentionless multiple access techniques, no more than one user can use the same channel resource simultaneously, examples of contentionless multiple access techniques are Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). On the other hand, in contention multiple access techniques, users can commonly and simultaneously share the available channel, and if collision is detected the transmitter receives a Negative Acknowledgement (NAK) message to retransmit the collided signal, ALOHA and Carrier Sense Multiple Access (CSMA) are two examples of such a contention multiple access techniques.

A multiple access technique is considered a successful one if the power spectral densities of the signals transmitted by users are not overlapping each other, in FDMA, e.g., a certain sub-channel is assigned for only one user and no other users can use the already assigned sub-channel. By this way, two different users signals are said to be orthogonal if they are mutually using the frequency bandwidth and time slot, in FDMA and TDMA, respectively. However, for users to access the channel during transmission and reception process, a full duplex of channel utilisation is required. In order to do so, a MA technique can be combined with a duplex channel either in time domain, Time Division Duplex (TDD) or in frequency domain, Frequency Division Duplex (FDD). In case of TDMA, e.g., the resultant MA technique is TDMA/FDD or TDMA/TDD. To clarify the multiple access technique, a brief description of the major types is considered below (for more details see [8]).

In FDMA multiple access technique, the total frequency bandwidth is divided among many users and each individual user is dynamically assigned an individual frequency channel bandwidth upon his request to communicate over a specific time period and releases the assigned channel to be utilised by other users when finish communication [9]. Unlike FDMA, TDMA system divides the available time into time frames which in turn is divided into timeslots, each timeslot is assigned to a certain user to perform communication. The assigned time unit is handled by a certain user sharing the available bandwidth with other users on a use-and-release fashion [1]. The CDMA system achieves neither the orthog-



(a) FDMA (b) TDMA (c) CDMA

Figure 2.2: Multiple Access Techniques (MAT)

onality between users in frequency nor in time, but different codes (signature sequences) are assigned to different users. The idea of CDMA technique is to multiply the data bit by a spreading code and the resultant wide spread signal modulates a carrier signal to be transmitted. The spreading is achieved by multiplying a data bit of a duration T_b by a spreading code of which the chip duration, T_c , is hundred times less than T_b.

In the previous conventional multiple access techniques, the base station used an omnidirectional antenna to transmit and receive users signals, base station antenna has no knowledge about the users locations, thus, it radiates the power in all directions to cover a specific cell area. Thus, beside the wasted power problem, each user is affected by the generated Multiple Access Interference (MAI) from all of the other users in the cell, moreover, users in neighbouring cells using the same frequency will also be affected by the radiated power. All of these considerations led to the development of Space Division Multiple Access (SDMA), in which, base station antenna use the knowledge of users positions to radiate a specific beam towered each desired user [10], [11]. On the other hand, SDMA provide a spatial orthogonality, unlike FDMA, TDMA and CDMA, SDMA system uses the spatial signature to differentiate between users, even when they use the same physical channel [12]. However, a complex multiple antenna arrays and bream-forming techniques are needed in order to implement the SDMA systems [13], [14].

Finally, OFDMA has been developed to overcome the limitations of the previously mentioned MATs, in which orthogonal sub-channels are allocated to multiple users in order to provide them with the cellular communication services [15], [16]. In this thesis, OFDMA technique is considered as the multiple access technique used to allocate communication channels to multiple users within the cellular communication system. In the following section we review the basic concepts of OFDMA systems.

2.4 Overview of OFDM and OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most promising, and increasingly popular, multicarrier modulation techniques in wireless communication systems. This is mainly due to its high capability of mitigating the impact of frequency selective multipath fading and high spectral efficiency [2], [17], [18]. For this reason, it has been adopted in various recent wireless communication technologies and standards such as, Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX).

The basic concept of OFDM is to divide the available entire bandwidth into orthogonal and overlapping narrow bands, called subcarriers as shown in Figure 2.3 (whereas, in FDMA, the entire bandwidth is divided into non-overlapping bands with a guard interval between adjacent bands as discussed above). Then, the users data is also divided into multiple parallel data streams and modulated over the divided subcarriers using simple Inverse Fast Fourier transform (IFFT). The orthogonality of the subcarriers ensures that the symbols can be demodulated and efficiently separated at the receiver side through the use of IFFT. Thus, the high data rate streams are divided into parallel low rate data streams and carried out using the subcarriers.

Basically, the OFDM base-band signal $x(t)$ is represented by K number of orthogonal subcarriers (indexed as $k = 0, 1, 2, 3, ..., K-1$), each subcarriers is modulated using either quadrature amplitude modulation (QAM) or Phase shift keying (PSK) to generate X_k symbols. The OFDM signal $x(t)$ is written as:

$$x\left(t\right) = \sum_{k=0}^{K-1} X_k e^{j2\pi \frac{k}{T} t} \tag{2.1}$$

Where, $0 \leq t \leq T$, and T is the OFDM symbol duration which is given as $T = KT_s$, T_S is the original symbol duration.

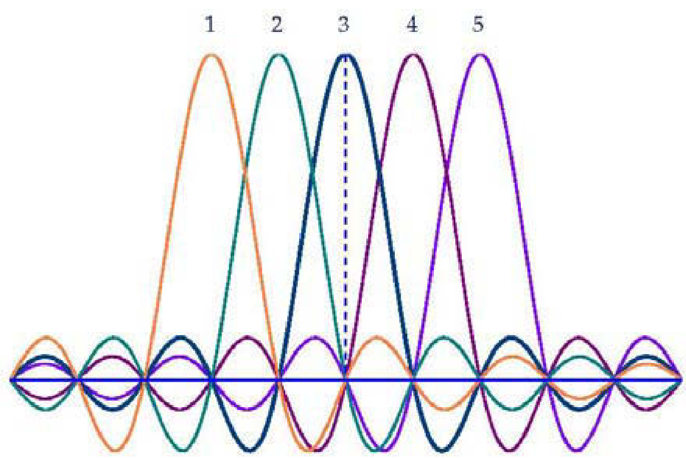


Figure 2.3: Orthogonal subcarriers in OFDM system

Orthogonal Frequency Division Multiple Access (OFDMA) is the multiple access version of OFDM, in which, each user is allocated with a subset of the available subcarriers, and the multiple users signals are distinguished from each other through the use of different subcarriers at different time slots.

Multi-user diversity improves the spectrum efficiency by optimising the subcarriers allocation such that, subcarriers are allocated to users with good channel conditions, thus, the resource utilisation is maximised.

A typical OFDMA system is illustrated in Figure 2.4 for the case of three user, which shows that the users signals are separated both in the time domain, by using different OFDM symbols, and in the frequency domain, by using groups of subcarriers [19]. In this way, both time components and frequency resources are used for multiple user transmission.

As shown in Figure 2.4, the entire bandwidth is subdivided into a number of orthogonal subcarriers, in which, at the centre frequency of each subcarriers, the power of adjacent subcarriers are set to zero, hence, the signal contribution to a certain subcarrier from all other subcarriers is zero. Furthermore, the same figure shows that the subcarriers are further scheduled at different time slots to serve different users. This allows the users to reuse the same subcarriers at different time slots.

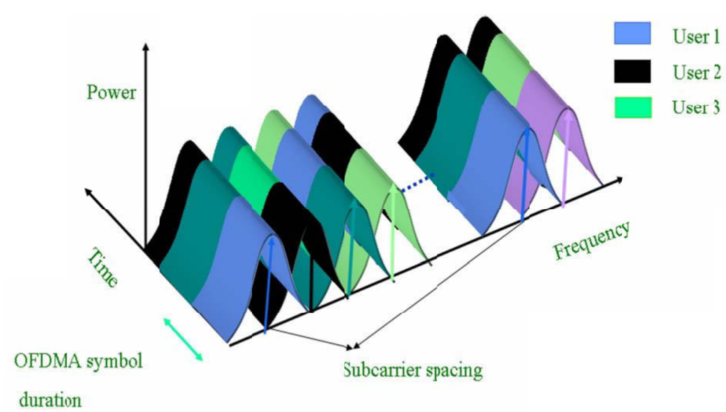


Figure 2.4: Orthogonal Frequency Division Multiple Access (OFDMA)

2.5 OFDMA Based Cooperative Relay Network

As the number of users is continually growing with higher data rate requirements to support various wireless communications applications, the need to increase the system and user capacity as well as to improving the utilisations of the available resource become the main objectives of many researchers [3].

Several proposals have been proposed for the purpose of increasing the user capacity (bps/Hz) over the well-known Shannon capacity formula determined in [20]. Multiple-input multiple-output (MIMO) is considered as one of the most efficient techniques by which the system capacity and the communication link robustness can be enhanced significantly. The MIMO system provides the benefit of spatial diversity and this is achieved by using multiple antenna elements at the transmitter, the receiver or both sides [21]. However, the requirements for installation of multiple antennas at the transmitter or receiver would significantly increase the infrastructure cost. Furthermore, the implementation of multiple antennas at the users devices (such as, mobiles) is technically very challenging due to the small sizes and limited power supply (i.e., short life battery) of these devices [22].

To overcome the aforementioned drawbacks and limitation of the MIMO system, a cooperative relay network has been proposed. In a cooperative relay network, several distributed nodes each with a single antenna cooperate to transmit or receive the required signal to its intended destination node. This is performed by transmitting the original signal by the source node to the destination, and at the same time a relay station receives that signal and re-transmits it to the intended destination. Thus, the destination is able to receive two or more copies of the same signal and combine the received signals, hence enhance the throughput. On the other hand, if the direct link between the source and the destination becomes unavailable, the destination will still be able to receive the relayed signal through the one or more relay stations, hence the communication system is more robust. Figure 2.5 illustrates the idea of a cooperative relay network in its simplest scenario.

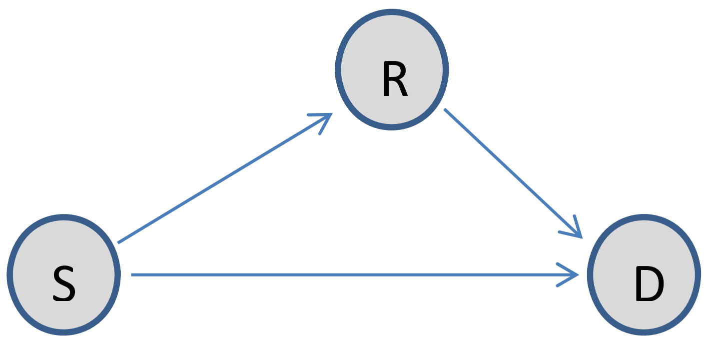


Figure 2.5: Cooperative relay network model

With a cooperative relay network, the MIMO capacity gain is achieved in a distributed manner and without the need to install multiple antenna elements at the communication nodes [23]. Moreover, the use of a relay station allows the cell coverage area to be extended beyond the cell boundary. As a consequence, users located outside the coverage of the source node are still able to communicate through the relay node.

Figure 2.6 presents a more complicated scenario with multiple relay stations (RS_1-RS_4). It can be seen that RS_1 and RS_2 are utilised to assist the BS to communicate with two subscriber stations (SS) located within the BS coverage area but they are either hidden by a building and not able to communicate with the BS directly (SS associated with RS_1) or located at the cell edge with low received signal-to-noise ratio (SNR) from the direct link (SS associated with RS_1). On the other hand, RS_3 and RS_4 are utilised to extend the BS coverage area and hence enable SS located outside the BS original coverage area to communicate with the BS through one or more relay stations; this is called Mobile Multi-hop Relay (MMR) [24].

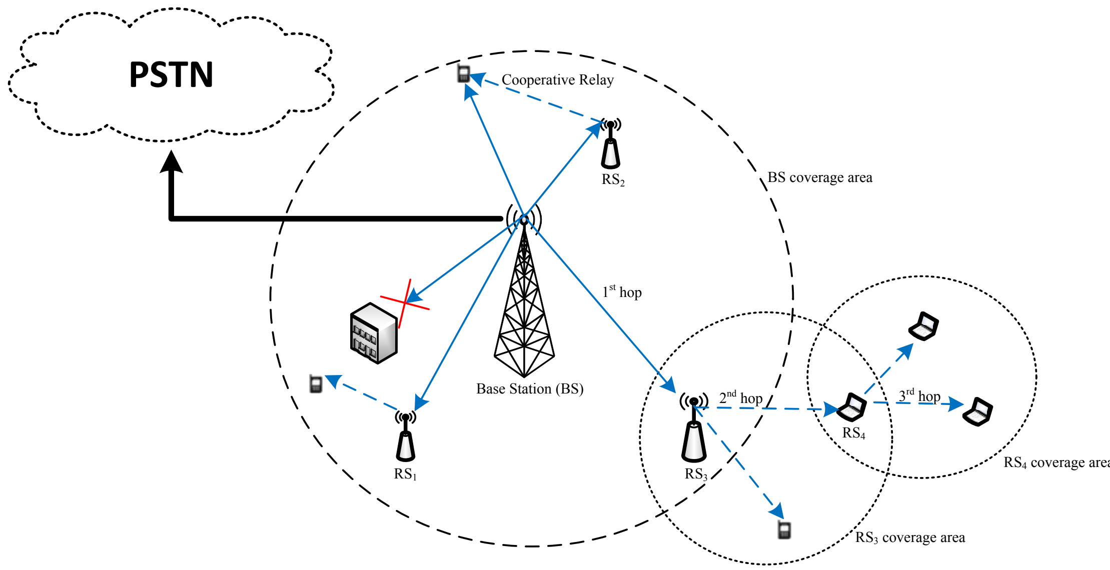


Figure 2.6: Coverage extension using relay station

Furthermore, with a cooperative relay network, the source node can employ either cooperative source or transmit diversity schemes. In the former one, the receiver receives multiple copies of the same originally transmitted signal, i.e., the transmitter transmits the same signal through several relay stations, hence, the communication between the source and destination becomes more robust and reliable. On the other hand, with the cooperative transmit diversity, the receiver receives different signals from different relay stations/antennas, and hence, the data rate is significantly increased. A hybrid scheme is also possible by allowing a subset of the available relay stations to relay the same signal while other signals are being transmitted through other relay stations.

The flexibility with the above diversity schemes allows the transmitter to select the most appropriate scheme based on the current channel conditions and requirements, i.e., to select between reliability and higher data rate.

In addition to that, the role of the relay station can vary according to the relaying protocol employed in that relay station. The three major relaying protocols are called; amplify and forward (AF), decode and forward (DF) and estimate and forward (EF). The selection of a particular relaying protocol would impact several factors such as; achievable data rate, delay and complexity.

2.5.1 Amplify and Forward

In the amplify and forward (AF) relaying protocol, the received signal by the AF relay station is simply amplified and then retransmitted to the final destination. The AF relay station does not need to process the received signal, hence it is considered to be the simplest and most cost effective relaying protocol. However, the drawback of this protocol is that, the noise is also amplified along with the desired signal at the AF relay station.

The channel model of the AF relaying protocol can be analysed as follows: at the first time slot T_{s_1} the source node transmits the signal to the AF relay station and the destination. The received signals at the AF relay station and at the destination are respectively denoted as $y_{s,r}$, $y_{s,d}$ and given as follows:

$$y_{s,r} = H_{s,r}\sqrt{P_s}X_s + w_{s,r} \tag{2.2}$$

$$y_{s,d} = H_{s,d}\sqrt{P_s}X_s + w_{s,d} \tag{2.3}$$

Where, X_s and P_s are the transmitted symbol and the source average transmit power respectively, $H_{a,b}$ represents the channel gain between the node a and node b. $w_{s,r}$ and $w_{s,d}$ are the AWGN noise with zero-mean and variance σ^2 at the relay station and destination respectively.

In the second time slot T_{s_2}, the AF relay station amplifies the received signal and forwards it to the destination node. This is performed by scaling the received signal by an amplification factor denoted by g_r and given by:

$$g_r = \sqrt{\frac{P_r}{P_s \left|H_{s,r}\right|^2 + \sigma_r}} \tag{2.4}$$

During the second time slot (T_{s_2}), the destination receives the amplified copy of the original signal, and the received signal is writen as:

$$y_{r,d} = H_{r,d} g_r y_{s,r} + w_{r,d} \tag{2.5}$$

As a result the destination receives the amplified copy through the AF relay station as well as the original copy by the source node. At the receiver side, a diversity combining technique such as maximum ratio combining (MRC) is used in order to combine the signals received from different channels. MRC technique is selected due to its high capability of maximising the overall SNR [25].

2.5.2 Decode and Forward

Unlike the AF protocol, In Decode and Forward (DF) the relay station demodulates and decodes the received signal, then encodes it and re-transmits the encoded signal to its destination. Hence the noise and interference is minimised at the relay station. However, the process of decoding/encoding at the DF relay station requires more processing time and hardware compared to the AF protocol. It should be noted that the diversity order of this scheme is only one due to the fact that the system performance depends on the channel quality of the source-to-relay (SR) and relay-to-destination (RD) channels [26].

Furthermore, in the DF relaying protocol the overall system performance is highly dependent on the channel quality between the source and the relay station, because when the source-relay channel is in a deep fade, then it is very likely that the relay would erroneously detect the signal and forward that signal to the destination. Thus, the source-to-destination channel capacity is limited by the channel capacity of the worst link between the source-to-relay and the combinations of the source-to-destination and relay-to-destination.

During the first time slot, the received signals at the DF relay station and at the destination are similar to the AF relaying protocol, i.e., equations (2.2) and (2.3). However, the received signal at the destination during the second time slot is written as [26]:

$$Y_{r,d}^{DF} = H_{r,d}\sqrt{P_r}X_s + w_{r,d} \tag{2.6}$$

Similar to AF, the MRC technique can be used in order to combine the received copies of the signal at the destination. The fact that DF is not always reliable and the increased complexity and delay at the relay station limits the DF relaying protocol.

2.5.3 Estimate and Forward

Another relaying protocol is called Estimate and Forward (EF). In this relaying protocol, instead of fully decoding the received signal and performing error correction if an error is detected as in the DF protocol, the EF relay station estimates the received signal and then re-transmits the estimated signal to the destination. The EF relay station does not involve complex signal processing, hence it is simpler than DF and requires simpler software and hardware at the relay station [27].

Similar to previous relaying protocols, the received signals during the first time slot are given in equations (2.2) and (2.3); during the second time slot, the received signal at the destination is given by [28]:

$$Y_{r,d}^{EF} = H_{r,d}\sqrt{P_r}\widehat{X}_s + w_{r,d} \tag{2.7}$$

It was shown in [28], that the performance of both the DF and the EF schemes differs according to the network setup; the DF scheme outperforms the EF scheme when the distance between the source node and the relay node is relatively small, on the other hand, the EF protocol outperforms the DF protocol in terms of achievable rate when the relay station is positioned close to the destination node.

2.6 Summary

In this chapter the migrations of mobile communication systems from the first, second, third, fourth generation and beyond as well as the various types of multiple access techniques were briefly discussed. Furthermore, this chapter analysed the basic concepts of OFDMA multiple access systems and focused on the development of a cooperative relay network. Finally this chapter reviewed the main relaying schemes (i.e., amplify and forward, decode and forward and estimate and forward) that are used in OFDMA based cooperative relay networks.

It is worth mentioning that OFDMA system based on amplify and forward relaying scheme will be considered as the basis system model throughout the work in this thesis.

The next chapter will focus on the resources allocations and optimisation techniques for OFDMA communication systems with and without the utilisations of cooperative relay nodes.

Chapter 3
RESOURCE ALLOCATION FOR OFDMA COOPERATIVE RELAY NETWORKS

3.1 Overview

The resource allocation problems are very sensitive to new technologies (such as, new network setup and parameters, new technologies with new requirements etc). Therefore, the resource allocation algorithms are continuously updated and developed in order to take into account any changes in the network setup or parameters as well as changes related to the users requirements and services. This chapter focuses on the various aspects of resource allocation and optimisation methods for Orthogonal Frequency Division Multiple Access (OFDMA) systems. The earlier sections define the types of resource allocation problems and identify the important factors. Then the various existing and recent resource allocation algorithms are reviewed based on the conventional single-cell and multi-cell OFDMA system, followed by the analysis of resource allocation algorithms for OFDMA based cooperative base stations and relay network. Furthermore, this chapter discusses the availability of the channel state information and its impact on the optimisation process as well as the problem of inter-cell interference (ICI). Finally, the chapter summarises the related literature and highlights the missing gap in the existing work which leads to the impact and importance of the problem statement which is considered in this thesis.

3.2 Resource Allocation for OFDMA Networks

Undeniably, the need for wireless for communication never ceased to grow; in order to meet this need it is necessary to manage the available resources (e.g wireless spectrum) more efficiently. Thus, the OFDMA technique has been put forward for consideration. This technique would allow the division of the available bandwidth into sub-channels, *called Subcarriers*. The subcarriers would, in return, be used by multiple users again.

Efficiency in this level would most probably be evident as one subcarrier may be a failure to one user and be the best to the other due to the nature of wireless communications channels (i.e., frequency selective fading). With this function, the use of subcarriers would reach its highest achievable network performance using modern resource allocation schemes. For this reason, researchers became more interested in maximising the utilisation of the resources at hand by developing several resource allocation and optimisation algorithms.

In line with the optimisation process, the OFDMA resource allocation has two classifications: Firstly, the Power Minimisation which aims to effectively reduce power level at the transmitter while concurrently maintaining a certain level of predetermined data rate. Secondly, the Rate Maximisation which is intended to get the highest possible data rate given that the maximum allowable transmit power is limited [29].

3.2.1 Power Minimisation Problem

As discussed earlier, the power minimisation aims to effectively reduce the power level at the transmitter while concurrently maintaining a certain level of predetermined data rate by optimising the allocated power.

Consider an OFDMA communication system comprising S users and K subcarriers, and assume that the predetermined minimum data rate requirements by the s^{th} user is denoted as R_{min}. Let, h_s^k, p_s^k and $\left(\sigma_s^k\right)^2$ be the channel gain (profile), transmission power and noise spectral density respectively for users over the k^{th} subcarrier. Then, the signal-to-noise ratio (SNR) received by user m over the k^{th} subcarrier is written as [30]:

$$\gamma_s^k = \frac{h_s^k p_s^k}{(\sigma_s^k)^2}, \tag{3.1}$$

And the achievable data rate is:

$$R_s^k = \frac{1}{2} log\left(1 + \gamma_s^k\right) \tag{3.2}$$

The power minimisation problem is formulated to determine the minimum total transmission power subject to minimum data rate requirements, and can be formulated as the following:

$$min \sum_{s=1}^{S} \sum_{k=1}^{K} p_s^k \tag{3.3}$$

subject to

$$\sum_{k=1}^{K} R_s^k \geqslant R_{min}, \forall s \tag{3.4a}$$

$$\sum_{k=1}^{K} p_s^k \leqslant P_T, \forall r \tag{3.4b}$$

$$R_s^k, p_s^k \geqslant 0, \forall s, k \tag{3.4c}$$

Where, (3.3) represents the power minimisation objective function of the optimisation problem. P_T is the total allowable transmit power. Since power is a continuously increasing function of rate, the optimum occurs when the total achieved rate by each user reaches the users minimum rate requirements, i,e., $\sum_{k=1}^{K} R_s^k = R_{min}$. The optimisation problem in 3.3 is non-linear and its computational complexity increases significantly as the number of users increases. Hence, several sub-optimal optimisation methods have been developed with lower complexity compared to an optimal solution.

3.2.2 Rate Maximisation Problem

In contrast to the power minimisation approach, the rate maximisation approach is intended to achieve the highest possible data rate given that the maximum allowable transmit power is limited.

Considering a similar communication system as in the previous section, the rate maximisation optimisation problem can be formulated as:

$$max \sum_{s=1}^{S} \sum_{k=1}^{K} \rho_s^k R_s^k \tag{3.5}$$

subject to

$$\rho_s^k \in \{0, 1\}, \forall k, s, R_s^k \tag{3.6a}$$

$$\sum_{s=1}^{S} \rho_s^k = 1, \forall k \tag{3.6b}$$

$$\sum_{k=1}^{K} p_s^k \leq P_T \tag{3.6c}$$

$$p_s^k \geqslant 0, \forall k, s \tag{3.6d}$$

$$\sum_{k=1}^{K} \rho_s^k R_s^k \geqslant R_{min}, \forall s \tag{3.6e}$$

Where, (3.5) represents the rate maximisation objective function of the optimisation problem. ρ_s^k denotes the subcarrier allocation index to determine whether a certain subcarrier is allocated to a certain user.

Various sub-optimal resource allocation algorithms have been proposed to address the optimisation problem in 3.5. The following sections review the recent approaches and proposed methods based on various network settings and scenarios.

3.3 Single-cell and Multi-cell OFDMA Networks

Resource allocation in single-cell OFDMA networks involves designating the subcarriers and power to various users depending on their current Channel State Information (CSI). A dynamic resource allocation algorithm has been proposed to reduce the power being transmitted constrained by a minimum data rate requirements under the assumption of full CSI availability [31], however, the proposed algorithm is unfair to users with bad channel conditions and the complicated means of computation made it impractical.

Another proposition, apparently, came to hand. A non-iterative approach was then introduced to be more lenient with the user's proportionality constraints and requires less computational complexity [32]. The said algorithm follows two stages to perform the resource allocations. Initially, users with a channel in a highest quality condition would be permitted to select the best available subcarriers in their favour. Next, optimisation of power allocation would depend on the already assigned subcarriers.

Unlike the aforementioned resource allocation algorithm, in reference [33], the available resources (i.e., power and subcarriers) are allocated to users jointly.

The proposed joint resource allocation algorithm aims to maximise the total achievable data rate for the OFDMA system in the uplink transmission. In this algorithm, a greedy approach is adopted to allocate the available subcarriers, while the power allocation followed the water filling method. Although the proposed algorithm is much simpler than the optimal resource allocation, the obtained result using this algorithm was relatively close to the optimal one. However, the fairness criterion was once again ignored. Thus, most of the available subcarriers were assigned to users with a high channel gain, while other users with low channel gain were ignored and left behind without resources.

In all of the above proposals, the CSI is assumed to be perfectly known at the resource controller. This assumption is unrealistic due to channel estimation error and the feedback delay.

This problem was addressed in [34] and the optimal resource allocation was proposed based on imperfect CSI. Moreover, the ergodic rate is maximised instead of the instantaneous rate as in most previous research. However, the single cell is considered and the effect of Inter-cell Interference (ICI) was ignored (it was assumed absent or it was simply added to the AWGN.

On the other hand, the work in [35], [36] and [37] consider the multi-cell scenario and the effect of ICI has been considered on the proposed resource allocation algorithms. The proposed algorithms improved the spectral efficiency with less system complexity. However, full knowledge about the CSI at the base station of each cell is considered.

3.4 Cooperative Base Stations

The proposed algorithms in the previous section assume no coordination or cooperation between different nodes on the network. However, in this section the related work is presented which assumes a sort of cooperation between network nodes.

This cooperation seeks to mitigate the interference and make the resources utilisation more efficient within the network to achieve the specific objectives (such as, maximise the rate, minimise the transmit power or any other objective).

In [38], the authors proposed a new power allocation algorithm for the two cell case called Binary Power Allocation (BPA). The proposed algorithm allows the coordination between the two cells given the channel gain information. The BPA means that the BS will chose to be an active or inactive one; in case of an active BS it will transmit with the maximum power, otherwise the BS will not transmit at all. Thus, the ICI is mitigated and the capacity is maximised. Also, during the active period of either one, the base station will schedule the users within that particular cell. This work was extended by the same authors in [39], in which an alternative to the game theory approach was proposed by investigating the distributed forms of iterative multi-cell resource allocation; this is performed by letting every cell independently optimise its own resource allocation according to the provided feedback at that cell. Thus, distributed resource allocation can be achieved. However, both [38] and [39] are based on full CSI knowledge and it is also inefficient for more than two cells. These drawbacks limit the proposed algorithm.

A more generalised multi-cell scenario was investigated in [40], in which, the base station is modelled to act as a relay station and causality constraints were imposed on the relay station for the relay retransmission of the source data. Full CSI is also assumed to be known.

Based on [38] and [39], the authors in [41] extend the BPA algorithm, in which, when the BTS is inactive, it will work as a relay station to relay another BTS signal to its destination. Moreover, this study investigates the impact of the cooperative coupled with complex coding techniques compared to the simple form of power allocation and relaying in interference limited networks. The results show that in a high interference regime, transmits cooperation with complex coding outperform the simple power allocation and relaying system performance. However, at low interference regime, the simple power and relaying system is almost same as the cooperation with complex coding given the CSI information.

3.5 Cooperative Relay Networks

As cooperative communication is becoming more popular with many researchers, new network nodes were introduced to function as a *Relay Stations* (RS). With this new mechanism a new resource and optimisation technique would be necessary. Thus, they have proposed the inclusion of a selection process for Relay Stations to match the best subcarrier and the RS to serve a particular user with a good channel condition.

This new method may have an increased complexity level compared with the conventional OFDMA system, but the performance gain outweighs the latter and this boosted the use of cooperative relay networks.

3.5.1 Single Cell, Single user

This subsection presents the relevant prior art to resource allocation for OFDMA based cooperative relay network taking into account the simplest network scenario, i.e., the algorithm is focused on a single user in a single cell. Therefore, the effect of Inter and Intra-cell interference from other users within the same or neighbouring cells is not taken into consideration; apparently, multi-user diversity gain is also ignored in this case.

The authors in [42] developed an optimal power allocation algorithm under the assumption of single cell and single user OFDMA cooperative relay network. The proposed algorithm is equivalent to the MIMO system, that is to say, the Multiple Input Multiple Output (MIMO) system is achieved in a distributed manner by using multiple relay nodes in which each node uses a single antenna element to transmitreceive data, Thus, the combination of those relay stations simulate the MIMO system. Taking into account the formed distributed MIMO scheme, the singular value decomposition approach is adopted to perform the optimal power allocation algorithm. This algorithm aims to maximise the total achievable data rate while maintaining the transmit power within the predetermined maximum allowable limit. This algorithm, however, is developed only to allocate optimal power for Relay Stations. Furthermore, the proposed algorithm ignores the communication link between the source node and the final destination, which is not applicable in most practical scenarios.

To overcome the shortfall in terms of practical applicability, the authors in [43] have proposed another power allocation algorithm with more practical assumptions. In this scheme, the power is allocated for the source node and the relay node jointly. The power level across subcarriers is allocated based on the full available CSI. The overall allocation process is divided into three steps. Initially, the algorithm aims to optimise the transmit power for the relay stations given that the source transmit power is already decided. Next, the algorithm optimises the transmit power for the source node based on the already allocated transmit power for the relay nodes. Finally, the above steps are repeated in rotation basis until reaching satisfied performance. Please note that there is a trade-off between performance and complexity, i.e., the more optimisation performed, the more time and complexity, but a better system performance can be achieved. However, a better system performance (higher data rate) can be achieved by jointly optimising the transmit power for both the source node and the relay node simultaneously.

The reference [44] developed two power allocation schemes. In the first scheme, the power allocation for source node and relay node is performed successively, taking into account the maximum transmit power level of each node independently, this scheme is comparable to the one proposed in [43]. On the other hand, the second scheme takes the maximum transmit power level for both source and relay nodes jointly in order to perform joint optimisation and power allocated for the source and relay nodes under the assumption of full CSI available at the resource controller.

Another approach was considered in [4], in which the optimisation was performed in three stages. In the first stage the power allocation is performed to minimise the outage probability based on complete CSI and statistical channel information (SCI). Then, the RS with the best performance is chosen to serve the user. Lastly, both solutions are combined (PA and relay selection) to further improve the performance. The results shows that the Symbol Error Rate (SER) can be minimised using the proposed power optimisation. This is achieved by having perfect CSI which will increase the SNR ratio with optimal PA and hence reduce the SER.

The OFDMA cooperative relay network involving two hops has been considered in reference [45]. The proposed resource allocation scheme was developed based on the aforementioned two hops network for the purpose of allocation of the available subcarriers as well as allocation of the available relay stations which are willing to help in relaying the received signal to its destination. Furthermore, in this work, more limitations were involved in the optimisation problem, such as, Quality of Service (QoS) and synchronisation, in order to ensure that the minimum predetermined data rate requirements are achieved and further to ensure that only one relay station is involved in the process of relaying the users signal. Once again, this algorithm assumes that the base station has an access to the full CSI as well as individual users QoS requirements.

Partial CSI (channel amplitude only) is considered in [46] to optimise the resources in a cooperative relay mode with different types of relay stations, such as, amplify and forward (AF), compress and forward (CF) and opportunistic decode and forward (DF). The objective function is to maximise the delay limit capacity (the highest achievable rate that can be sustained independent of the channel state [47]) of the system under long term average total transmitted power constraint.

In [48], two types of feedback were considered; those are complete and partial CSI. The complete CSI is available between the source and RS's and between the RS's and the destination as well. On the other hand, the CSI between the source and destination is partially known (statistical information). The work in [48] focuses on distributed power allocation in AF cooperative relay networks for the TDMA system. The objective here is to minimise the total transmitted power and maintain the targeted outage probability rather than maximising the delay limit capacity as in [46]. The relay is only allowed to forward the signal if the SNR is above a certain threshold (called reliable relay). MRC is used on the receiver to combine signals received from multiple reliable relays.

Under minimum SINR and maximum power constraints, [49] introduced a distributed power control algorithm for the interference limited cooperative relay network. In this algorithm, each source-relay-destination (S-R-D) unit is responsible for optimising its own resources for the purpose of minimising the transmitted power by the source and relay nodes subjected to SINR and power constraints with complete knowledge of the CSI. The interference here is assumed to be within the same cell (i.e., intra-cell interference).

The authors in [50], investigate the factors that affect the resource allocation optimisation in cooperative communications, such as error rate vs. outage probability, modulation type (coherent and differential) and cooperative protocol (AF and DF). The results show that the error rate and the outage probability lead to similar optimisation outcomes. Furthermore, it was shown that the relay protocol is more significant on the overall performance compared to the modulation technique in the case of a small number of RS's. At a high number of RS's, the coherent AF is uniquely different from others.

In [47] and [51], other resource allocation algorithms have been proposed under the assumption of full CSI. The RS's are assumed to be fixed and the optimisation problem involves either the relay selection algorithm [51] or subcarrier pairing between the sources and relays [47].

3.5.2 Single Cell, Multi-user

Multi-user pertains to multiple source nodes competing for the available channel resources needed for them to perform transmission/reception of wireless signals with a predetermined quality level. Hence, it is necessary to consider the problem of fairness between users when designing a resource allocation algorithm. Imposing a fairness constraint would ensure that QoS requirements would be achieved regardless of users individual channel gain condition.

Evidently, fairness issue should be tackled as it is not fair to increase the capacity of only a certain number of users while leaving other users without any resources. Thus, in recent studies, several proposals have been presented to optimise the resources among users for the purpose of increasing the overall capacity without compromising fairness among the users.

In [52], the said proposal aims to give clarifications on two major problems. The first is how to pair a Relay Station to a Mobile Stations in a way that the former would be able to relay the latter's signal to its final destination. The second is how to optimise the subcarrier allocation to these pairs. To address these, a fair centralised resource optimisation algorithm was proposed, assuming that availability of full channel state information at the resource controller.

This resource allocation scheme is focused on the medium access control (MAC) for the purpose of optimising subcarriers and relay stations utilisation in the OFDMA cooperative relay network composed of multiple source nodes, multiple relay station nodes and a single destination base station in a single cell, which is similar to the network topology as in WiMAX 802.16J [53]. Therefore, subcarrier pairing is needed in order to match the best subcarrier in respect of both the source and selected relay.

Furthermore, the proposed subcarrier and power allocation algorithm in [54] aims to maximise the network aggregated throughput under maximum transmit power constraint, while maintaining a fair opportunity for the user with bad channel condition to be assigned with subcarriers. To simplify the matter, the optimisation problem was divided into two steps. Initially the power is assumed to be equally distributed among the available subcarriers, and the subcarriers are allocated to users according to their channel quality. In the second step, the water-filling approach is used to optimise the power allocation across the already allocated subcarriers.

Unlike the proposed subcarrier pairing as in reference [52], this proposal suggests that the user might not use the same subcarrier that is used by the serving relay station for that particular user. The subcarriers allocation for users and relay station is decided according to the individual channel quality of both links (i.e., source to relay and relay to destination). Therefore, the best available subcarrier is utilised to carry the transmitted signal over each hop. However, the drawback of this scheme is the increased level of required synchronisation at the destination end in order to recognize the originally transmitted signal through a number of different subcarriers.

Another resource allocation scheme has been presented in [55], for the uplink signal transmission in the OFDMA system with cooperative relay networks. This algorithm takes the fairness issue into account and involves a fairness constraint in the optimisation problem in order to provide a fair opportunity to all users to achieve their data rate requirements. However, this work assumes that all users have identical data rate requirements. In addition to that, finding the best subcarrier and relay pair to be allocated to a source node becomes tedious as it requires a search over all combinations of subcarriers and relay stations for each individual source node.

Similarly, [56], [57] and [58] investigated the resource optimisation for OFDMA based cooperative relay network with QoS requirements. These algorithms were designed in such a way to optimise the available resources without compromising the predetermined minimum QoS requirements.

With the known limitation of the previous proposal, a lower Complexity Sub-optimal resource allocation algorithm was proposed in [59] with a single relay station. The proposed algorithm considers the single user as well as the multiple user scenarios. In addition, this algorithm assumes multiple services types (i.e., real time and non-real time applications) signal transmission. The proposed algorithm has been developed for the purpose of maximising the spectral efficiency based on adaptive optimal and sub-optimal allocation schemes with predetermined quality and data rate requirements.

Furthermore, reference [60], studied the resource optimisation in an OFDMA based on amplify and forward (AF) and decode and forward (DF) cooperative relay networks considering the presence and absence of diversity. In this manner, this proposal categorises the resource allocation optimisation problem into two: the first one considers that each source node only cooperates with a single relay station using only one subcarrier and the second one deems that the source node cooperate with a single relay station using multiple subcarriers. In order to deal with the above-mentioned optimisation problems, Genetic Algorithms have been adopted given that the CSI is fully available.

Other resource allocation algorithms have been also proposed in which the available resources (relay stations, power and subcarriers) are jointly allocated to the users [61], [62], [63] and [64]. However, the joint allocation requires sophisticated and complex algorithms which may cause time delay. Therefore, this approach may not be suitable for real time applications.

It is clear that the ICI is totally ignored in all of the above proposed techniques. A more realistic assumption is to take the ICI into account because this type of interference severely degrades the system performance and thus it should be treated carefully. Moreover, the complete knowledge of CSI is also an impractical assumption for the reasons stated earlier in this review report.

In the next section, some of the proposed techniques are presented in which the effects of ICI were considered during the resource optimisation process.

3.5.3 Multi-Cell, Multi-user

Multi-cells network is considered in [65]. This paper proposes a resource allocation algorithm for the cooperative relay CDMA system in a multi-cell environment. Two approaches were identified to solve the resource allocation problem in a multi-hop cellular network with the presence of intra and inter cell interference. In the first approach, the interference is measured through the received SINR and thus a minimum SINR value becomes a threshold to determine the selected RS or the allocated power. In the second approach, the resources were jointly allocated with the routing mechanism using graph-theory method, in which, the transmission is only allowed for links that do not interfere with each others at a time. However, in OFDMA the intra-cell interference can be ignored based on the fact that subcarriers are orthogonal.

Another proposal which assumes the interference limited CDMA system with cooperative AF and DF relay networks has been presented in [66]. The optimisation problem was formulated to minimise the total transmitted power subjected to the average transmission rate (minimum SINR requirements). The RS is an ideal MS or BS node, and it will be selected to forward the signal based on its average gain on either best first hop (from MS to RS), best second hop (RS to BS) or best worst(both links are considered).

For the OFDMA networks, Kim *el at*, [67] proposes an optimal resource allocation for multi-hop OFDMA cooperative relay. The objective is to maximise the end-to-end throughput under the routing PHY/MAC constraint. Dual method is used to solve the optimisation problem. Furthermore, Half-duplex is considered and a virtual links is assumed to form the cooperation. The mutual interference between the links is modelled to allow maximum spatial reuse of the spectral resources. The optimisation is performed on the central station at which the channel gain is collected to optimise the resource allocation.

A more general idea was presented in [68]. This paper proposes relay selection schemes considering AF cooperative relay. The effects of multi-user interference was analysed and considered to select the best candidate RS. Moreover, the ICI was considered from the neighbouring cells or clusters in ad hoc network. Furthermore, it was also assumed that the neighbouring cells are based on direct transmission with the users inside these cells while on the intended cell only relay links are active and the direct transmission does not exist. The outage probability analysis is considered to evaluate the system performance with full CSI knowledge.

An intensive study about the interference in cooperative relay was presented in [69]. Unlike other related research papers, this paper considers the large scale cooperative relay network, in which, multiple links interfere with each other. Moreover, it shows that the amount of interference increases as the number of nodes increase. Taking into account the interference effects, [69] proposes a resource allocation algorithm which is able to mitigate the interference. Moreover, it shows that in a large scale cooperative relay the resources consumption will be higher and hence the throughput will be degraded.

The above proposal allocates orthogonal channels to the conflicting links to mitigate the interference between those links; moreover different priorities are assigned to the direct and the relayed links. Two schemes were proposed with a trade-off on the fairness and throughput under the assumption of full CSI knowledge. Finally, different types of performance parameters such as ergodic capacity and outage probability have been discussed and defined.

3.6 Utility-based Resource Allocation

Several utility-based resource allocation algorithms have been proposed for OFDMA network aims to optimise the available resources taking into account the QoS, best effort services and other utility metric (such as, real time, delay, ...etc.) in which the algorithm allocates the resources such that the total benefit (data rate, QoS ..., etc.) of each user is maximised [70], [71] and [72]. This section presents the most recent related work using the utility approach.

The authors in [73] proposed a utility-based resource allocation algorithm for the OFDMA relay network. The proposed algorithm aims to maximise the network capacity (Best Effort (BE) service) and at the same time guarantee the minimum required quality of service (Rate Constraint (RC) service). The proposed algorithm firstly allocates the necessary resources to satisfy the QoS and adjust the allocation based on the allocated power. On the following stage, the remaining subcarriers are allocated to maximise the network capacity.

Recently, the work in [74] proposed a resource allocation scheme with adaptive priority thresholds for a simple OFDMA network without the use of cooperative relay. The proposed algorithm balances the trade-off between the QoS requirement satisfaction and the capacity maximisation objectives. This is performed by adaptively allocating the subcarriers based on the current priority threshold of each user. Then the remaining subcarriers are allocated based on the available channel state information to maximise the network capacity. The priority is adaptively and intelligently adjusted using fuzzy inference by considering the QoS fulfilment with respect to QoS requirements and the channel status with respect to system throughput.

In [75] a utility-based throughput maximisation and complexity-reduction scheduling scheme has been proposed for downlink multi-user Multiple Input Multiple Output (MIMO) OFDMA network. The proposed algorithm allocates subcarriers, antenna sequence, and modulation order to multimedia users for the purpose of maximising the total capacity under QoS requirements as well as reducing the computational complexity. The channel state information and QoS requirements are used to define the utility function of each user and then allocate the resources to maximise the utility. The utility function consists of a QoS monitoring function which indicates the degree of urgency of the user to be allocated with a subcarrier and a radio resource function which shows the spectrum efficiency if it is used by the user.

In [76], [77] and [71] various utility-based resource allocation algorithms are proposed which consider the real time services with a strict delay and rate requirements. The channel conditions and queue information are used to dynamically allocate the available subcarriers and perform the relay selection taking into account the real time and best effort services.

Most of the previous work considers a single cell scenario, in which ICI is ignored. However, in reality ICI severely degrades system performance and hence, for practical systems it should be considered in the allocation process [69].

The effects of ICI have been considered and coordinated through careful frequency reuse [5]. The proposed algorithms aims to maximise the system utilities while satisfying individual users' minimum rate requirements. This paper assumes cooperation between neighbouring Base Stations (BS), therefore, BS's are able to exchange some information, such as, load and other requirements such as QoS and system capacity. Furthermore, the proposed algorithm allows different base stations to access a shared spectrum pool, and then a BS can use the available information to decide what channels to use. However, the information exchange across different cells introduces an overload on the backbone network. Furthermore, the propose algorithm is developed based on simple OFDMA network without the use of cooperative relay.

3.7 Availability of Channel State Information (CSI)

As stated earlier in this chapter, the instantaneous channel state information is considered as the primary metric for optimising the available resources and allocating subcarriers to users with respect to their instantaneous channel conditions. Therefore, the previous resource allocation proposals assumes the availability of perfect channel state information at the transmitter or resource controller, hence the total achievable data rate is maximised accordingly.

In OFDMA, the assumption of full channel state information availability at the transmitter can be realistic in case of a single cell with time division duplex (TDD), due to the channel reciprocity between alternative uplink and downlink transmissions. On the other hand, this assumption is not realistic in the case of frequency division duplex (FDD), where the uplink and downlink channels are expected to be different. Instead, the receiver needs feedback about the channel state information to the transmitter [78].

However, considering the multi-cell scenario with either one of the Time or Frequency division duplexing (TDD or FDD) techniques, the transmitter is not able to estimate perfectly the channel state information due to the interference effects on the receiver side. Therefore, in order to accurately estimate the CSI, the transmitter needs to have a full and up-to-date knowledge about the level of interference affecting each one of the subcarriers allocated to that receiver through the feedback link. This will significantly increase the signalling overhead and increase the system and time complexity required to keep the CSI at the transmitter updated. Therefore, the assumption of full CSI is not valid in a multi-cell scenario.

It should be noted that the efficiency of the dynamic resource allocation algorithm requires an accurate and continuous CSI at the resource controller. Thus, in practice, it is difficult to maintain accurate instantaneous CSI at the resource controller due to insufficient feedback information from the receiver due to channel variations and/or channel estimation error at the transmitter. Thus, the efficiency of the resource allocation is highly affected by the channel feedback.

The fact that perfect CSI cannot be guaranteed at the resource controller motivated the researchers to propose resource allocation algorithms based on imperfect or partial channel state information, such as statistical CSI. Suboptimal resource allocation algorithm can be performed based on imperfect or partial CSI, which still outperforms the fixed resource allocation strategy.

Primolevo et al, [79] investigated the effect of imperfect CSI on the capacity broadcast Orthogonal Space Division Multiple Access (OSDMA)-MIMO systems. This paper considered two types of imperfect CSI, one due to the channel estimation errors and the second source is due to out-dated CSI as a result of quick variations of channel conditions. A similar study has been conducted in [80] for multicarrier systems which considers the same types of errors. Similarly, the work presented in [81] investigates the effects of the imperfections in the CSI required to perform resource allocation,while taking into account the case of asymmetric resource allocation.

Liu et al. [82] proposed a two-slot cooperative relaying scheme for the purpose of maximising the secrecy rate. The network comprises one source node, one destination, one eavesdropper and multiple DF relay nodes. The system performance has been evaluated under the assumption of both full and limited CSI. Reference [83] also address the problem of resource allocation for an OFDMA based cooperative relay network. The proposed algorithm aims to maximise the system throughput based on the estimated CSI available and the distribution of the estimation error. Similarly, [84] investigated the capacity lower bound based on the same CSI assumptions as in [83] and proposed a suboptimal power and subcarrier allocation algorithm.

Liu et al. [85] considered a limited feedback in the proposed dynamic power allocation algorithm for the OFDM system with a single AF relay station. The paper demonstrates that the system performance based on only a few feedback bits is comparable to the one based on full channel state information. The work of [85] has been extended in [86] to include joint power and subcarrier allocation, taking into account both sum and individual power constraints. The performance based on limited feedback is still comparable to that of one with full CSI.

The single cell scenario has been considered in the above research proposals and contributions and the effect of interference has been completely ignored. In practice, the network consists of multiple adjacent cells and the impact of inter-cell interference (ICI) is very significant on the performance of a cellular communication. Therefore, a proper resource allocation and optimisation algorithm cannot be guaranteed without considering the ICI during the optimisation process.

3.8 Inter-cell Interference

Another important factor in wireless cellular systems is the interference caused by users and transmissions within the same cell (called intra-cell interference) and the other source of interference which is caused by other users and transmissions from neighbouring cells (called inter-cell co-channel interference) [87].

However, in OFDMA cellular systems, users within the same cell utilise orthogonal channels (subcarriers), therefore, the problem of Intra-cell interference is overcome by the use of orthogonal channels. However, the OFDMA system performance severely suffers from the effect of ICI received from the neighbouring cells. In fact, ICI is considered as one of the major challenges in the development of mobile cellular communication systems, especially due to the excessive reuse of the limited available bandwidth in order to satisfy users requirements. Several method and techniques have been developed in order to minimise the ICI effect such as cell sectorisation, dynamic frequency reuse as well as interference cancellation receivers [88, 89]. However, the problem of ICI still persists.

For the above reasons, a proper and practical resource allocation algorithm should consider the effects of ICI during the allocation process in order to optimise the resources utilisation and hopefully minimise the impact of the ICI on the overall multi-cell network.

3.9 Summary

This chapter presented different types of resource allocation and optimisation problems for OFDMA systems. Various types of already developed resource allocation algorithms have been discussed and analysed taking into account different network setup and scenarios. It is evident from the discussion in this chapter that the optimisation problem becomes more complex when practical assumptions are incorporated and considered in the optimisation process (such as; multiple users and multiple cells as well as using multiple relay stations). Furthermore, this chapter shows that the availability of full channel state information cannot be guaranteed, and hence a more realistic assumption is to consider partial channel state information. In addition to that, this chapter discussed the impact of inter-cell interference on the process of resource optimisation. To the best of our knowledge, most of the previous research proposals were developed based on one or more impractical assumptions (such as, Full CSI, ICI-free, single user, ...etc.). Taking into account the literature review as presented in this chapter, this thesis is intended to fill the gap and focuses on the resource allocation problem taking into account practical assumptions and network scenarios. Inter-cell interference system is considered throughout the following chapters. While the following chapter assumes full CSI knowledge to be available at the resource controller, partial CSI is considered in the subsequent chapters.

Chapter 4

ICI AWARE RESOURCE ALLOCATION ALGORITHM FOR OFDMA BASED COOPERATIVE RELAY NETWORK WITH FULL CSI

4.1 Overview

This chapter focuses on the subcarrier allocation for the uplink OFDMA based cooperative relay networks. Multiple cells were considered, each composed of a single base station (destination), multiple amplify and forward (AF) relay stations and multiple subscriber stations (sources). The effects of inter-cell interference (ICI) have been considered to optimise the subcarrier allocation with low complexity. The optimisation problem aims to maximise the sum rate of all sources and at the same time maintain the fairness among them. Full channel state information (CSI) is assumed to be available at the base station. In the proposed algorithm the subcarrier allocation is performed in three steps; firstly the subcarriers are allocated to the Relay Stations (RSs) by which the received ICI on each RS is minimised. Then, the pre-allocated subcarriers are allocated to subscribers to achieve their individual rate requirements. Finally the remaining subcarriers are allocated to subscribers with the best channel condition to maximise the total sum of their data rates. Grouping the subcarriers based on minimum ICI into R significantly reduces the algorithm complexity by a factor of $\approx \frac{1}{R}$ without affecting the other performance metrics (such as total network data rate) for single cell scenario. The total network achievable data rate of the proposed algorithm is improved over the conventional algorithm in the multi-cell scenario.

In this chapter, the ICI is modelled to take into account the effects on the relay stations as well as the destination. It is also assumed that the destination receives from the relay stations as well as directly from the source. Moreover, the CSI of all communication links within each cell is completely known by the serving BS of that cell. This knowledge is obtained through the feedback links between the communication nodes within the cell and the destination (BS). Under the above assumptions, this chapter suggests a new subcarrier allocation algorithm which is able to maximise the total sum rate with low complexity compared to the existing algorithms and able to further increase the total network achievable rate in a multi-cell scenario.

4.2 System Model

Figure 4.1, illustrates the adopted system model, in which the proposed network comprises of multiple cells with multiple source nodes (S), multiple relay nodes (R) and a single destination (D). One cell is considered and the rest of the neighbouring cells are assumed to be interference sources (I). Moreover, a number of subcarriers (K) are assumed to be available at the destination base station to be assigned to different sources and relay stations. Denote the set of source nodes, relay nodes, interference nodes and subcarriers as $\mathcal{S} = \{1, ..., s, ..., S\}$, $\mathcal{R} = \{1, ..., r, ..., R\}$, $\mathcal{I} = \{1, ..., i, ..., I\}$ and $\mathcal{K} = \{1, ..., k, ..., K\}$ respectively.

Here, it is also assumed that the ICI is generated due to the transmission with equal transmit power from the RSs which are located within and close to the cell boundary of the neighbour cells. Thus, the serving BS has a knowledge about the transmitted power by all other RS's, i.e., P_i is known for all i and the transmitted power across each subcarrier P_i^k is averaged and given by $P_i^k = P_i/K$.

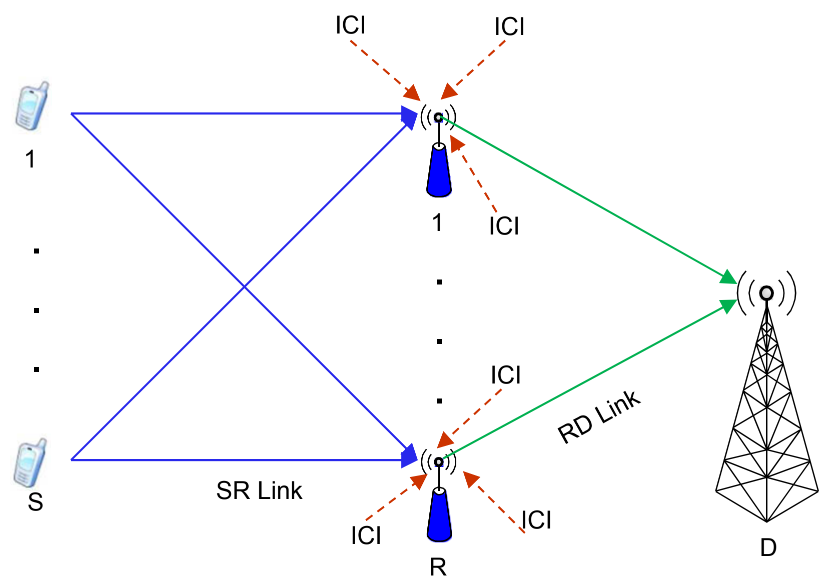


Figure 4.1: Multi-cell cooperative relay system model

The destination receives the transmitted signal by the source through a direct link between the source and the destination L_{SD} and through the AF relay station links L_{SRD} as shown in Fig. 4.1, where the straight lines represent the desired signal and the dashed lines represent the interference from neighbouring cells.

During the first time slot (T_{s_1}), the source s transmits the signal and both the relays $r, r = 1, 2, .., R$ and the destination D receives the transmitted signal, and on the second time slot T_{s_2} the RS's forward the amplified copy of the received signal to the destination using different subcarriers.

Assuming that the interference only affects the relays and the destination during the first time slot, mathematically, the received signal by the r^{th} relay station and the destination (D) during T_{s_1} over the k^{th} subcarrier can be respectively written as:

$$y_{s,r}^{k} = h_{s,r}^{k}\sqrt{P_s^k}X_s + \sum_{i=1}^{I} h_{i,r}^{k}\sqrt{P_i^k}X_i + w_r \tag{4.1}$$

$$y_{s,d}^{k} = h_{s,d}^{k}\sqrt{P_s^k}X_s + \sum_{i=1}^{I} h_{i,d}^{k}\sqrt{P_i^k}X_i + w_d \tag{4.2}$$

where,

- $h_{a,b}^{c}$ Denotes the channel gain between nodes a and b over subcarrier c.
- $y_{a,b}^{c}$ Denotes the received signal at node b from node a over subcarrier c.
- P_a Denotes the transmitted power from node a.
- X_a Denotes the transmitted signal from node a.
- w_a Denotes the AWGN at node a.

During T_{s_2}, the received signal at each relay station is amplified and forwarded to the destination. Thus, the received signal at the destination from all RSs is given by:

$$y_{R,d}^{k} = \sum_{r=1}^{R} h_{r,d}^{k} g_r y_{s,r}^{k} + w_d \tag{4.3}$$

g_r is the RS amplification factor given by [90]:

$$g_r = \sqrt{\frac{P_r^k}{P_s^k \left|h_{s,r}^{k}\right|^2 + \sum_{i=1}^{I} \left|h_{r,i}^{k}\right|^2 P_i + w_{rs}}} \tag{4.4}$$

By substituting (4.1) in (4.3), we have

$$y^k_{R,d} = \sum_{r=1}^{R} h^k_{r,d} g_r h^k_{s,r} \sqrt{P^k_s} X_s + \sum_{r=1}^{R} \sum_{i=1}^{I} h^k_{r,d} g_r h^k_{i,r} \sqrt{P^k_i} X_i + \sum_{r=1}^{R} h^k_{r,d} g_r w_r + w_d \tag{4.5}$$

The signal to interference and noise ratio (SINR) at the r^{th} relay station and at the destination from the direct link are respectively

$$SINR^k_r = \frac{\left|h^k_{s,r}\right|^2 P^k_s}{\sigma^2_r + \sum_{i=1}^{I} \left|h^k_{r,i}\right|^2 P^k_i} \tag{4.6}$$

$$SINR^k_{s,d} = \frac{\left|h^k_{s,d}\right|^2 P^k_s}{\sigma^2_d + \sum_{i=1}^{I} \left|h^k_{i,d}\right|^2 P^k_i} \tag{4.7}$$

Considering the r^{th} RS, the SINR at the destination from the forwarded signal in (4.5) is given by:

$$SINR^k_{r,d} = \frac{\left|h^k_{r,d}\right|^2 g_r \left|h^k_{s,r}\right|^2 P^k_s}{\sum_{i=1}^{I} \left|h^k_{r,d}\right|^2 g_r \left|h^k_{i,r}\right|^2 P^k_i + \left|h^k_{r,d}\right|^2 g_r \sigma^2_r + \sigma^2_d} \tag{4.8}$$

Let, $\gamma_{s,r} = \left|h^k_{s,r}\right|^2 p^k_s/\sigma^2$, $\gamma_{r,d} = \left|h^k_{r,d}\right|^2 p^k_r/\sigma^2$, $\gamma_{s,d} = \left|h^k_{s,d}\right|^2 p^k_s/\sigma^2$, $I_{I,r} = \sum_{i=1}^{I} \left|h^k_{i,r}\right|^2 p^k_i/\sigma^2$, $I_{I,d} = \sum_{i=1}^{I} \left|h^k_{i,d}\right|^2 p^k_i/\sigma^2$ and $\sigma^2_r = \sigma^2_d = \sigma^2$, then by substituting (4.4) in (4.8) and considering that the r^{th} relay station is utilised to forward the original signal to its destination, then the received SINR at the MRC receiver [91] is written as:

$$\begin{aligned} SINR^k_{MRC,r} &= SINR^k_{r,d} + SINR^k_{s,d} \\ &= \frac{\gamma_{s,r}\gamma_{r,d}}{I_{I,r}\left(\gamma_{r,d}+1\right) + \gamma_{s,r} + \gamma_{r,d} + 1} + \frac{\gamma_{s,d}}{1 + I_{I,d}} \end{aligned} \tag{4.9}$$

Also, it could be noted here that only the ICI is considered and it is assumed that intra-cell interference is zero due to orthogonal subcarriers and perfect synchronisation in OFDMA system [37]. However, in case of imperfect synchronisation, the multi-user interference (MUI) may occur due to the different carrier frequency offsets between different users. This MUI can be mitigated using some cancellation techniques such as the one proposed in [92].

4.3 Problem Formulation

This section formulates the optimisation problem with an objective function to maximise the sum of the source's achievable data rates by imposing fairness (every source receives their minimum rate requirements) and power constraints. The instantaneous rate achieved by the s^{th} source over the k^{th} subcarrier with the assistance of the r^{th} Relay is given by [55]:

$$R_{s,r}^{k} = \frac{1}{2}\log\left(1 + SINR_{MRC,r}^{k}\right) \tag{4.10}$$

Assuming all subcarriers are allocated to the source s , the total sum rate achieved by the source is given by

$$R_s = \sum_{r=1}^{R}\sum_{k=1}^{K}\rho_{s,r}^{k}R_{s,r}^{k} \tag{4.11}$$

and the total achieved rate by all sources and subcarriers is given by

$$R = \sum_{s=1}^{S}\sum_{r=1}^{R}\sum_{k=1}^{K}\rho_{s,r}^{k}R_{s,r}^{k} \tag{4.12}$$

where, $\rho_{s,r}^{k}$ denotes the subcarrier allocation index, given by:

$$\rho_{s,r}^{k} = \begin{cases} 1 & \text{if subcarrier } k \text{ allocated to source } s \text{ and relay } r; \\ 0 & \text{otherwise.} \end{cases} \tag{4.13}$$

The resource allocation optimisation problem is then formulated as follows

$$\max \sum_{s=1}^{S} \sum_{r=1}^{R} \sum_{k=1}^{K} \rho_{s,r}^{k} R_{s,r}^{k} \tag{4.14}$$

subject to:

$$\rho_{s,r}^{k} \in \{0,1\} \, \forall k, s, R_{s}^{k} \tag{4.15a}$$

$$\sum_{s=1}^{S} \sum_{r=1}^{R} \rho_{s,r}^{k} = 1, \forall k \tag{4.15b}$$

$$\sum_{k=1}^{K} P_{s}^{k} \leq p_{s}, \forall s \tag{4.15c}$$

$$\sum_{k=1}^{K} P_{r}^{k} \leq p_{r}, \forall r \tag{4.15d}$$

$$P_{s}^{k} \geq 0, \forall k, s \tag{4.15e}$$

$$P_{r}^{k} \geq 0, \forall k, r \tag{4.15f}$$

$$\sum_{k=1}^{K} \sum_{r=1}^{R} \rho_{s,r}^{k} R_{s,r}^{k} \geq R_{min}, \forall s \tag{4.15g}$$

Where, (4.14) represents the rate maximisation objective function of the optimisation problem. The constraints (4.15a) and (4.15b) indicate that subcarriers are exclusively allocated to one source-relay pair to avoid intra-cell interference. Constraints (4.15c)-(4.15f) are the maximum and the minimum transmission power by each source and relay respectively and constraints (4.15g) are the minimum rate requirements of each source.

It could be seen that the optimisation problem in (4.14) contains both integer (such as, $\rho_{s,r}^{k}$) and continuous (such as, P_{s}^{k} and P_{r}^{k}) decision variables. Thus, the problem is computationally complex. In order to simplify the matter, this chapter focuses on the subcarrier allocation rather than power allocation. This simplification reduces the computational complexity significantly while maintaining a comparable performance to the optimal algorithm. At this stage equal power allocation is assumed across subcarriers, i.e., $P_s^k = P_r^k = P_T/K, \forall s, r$. Power allocation can be optimised once the subcarriers re efficiently allocated.

4.4 Proposed Subcarrier Allocation Algorithm

The optimal allocation can be obtained by joint subcarrier and power allocation for the optimisation problem in (4.14) using binary integer programming. However, this would incur significant computational complexity which makes it impractical for real time processing. Therefore, in our proposed heuristic approach, equal power allocation is assumed across all subcarriers. Thus, the power allocation constraints are ignored and the original problem is simplified to:

$$\max \sum_{s=1}^{S} \sum_{r=1}^{R} \sum_{k=1}^{K} \rho_{s,r}^k R_{s,r}^k \tag{4.16}$$

subject to:

$$\rho_{s,r}^k \in \{0,1\}\, \forall k, s, R_s^k \tag{4.17a}$$

$$\sum_{s=1}^{S} \sum_{r=1}^{R} \rho_{s,r}^k = 1 \forall k \tag{4.17b}$$

$$\sum_{k=1}^{K} \sum_{r=1}^{R} \rho_{s,r}^k R_{s,r}^k \geq R_{min_s}, \forall s \tag{4.17c}$$

Where, (4.16) represents the rate maximisation objective function of the simplified optimisation problem. Taking into account the objective function in (4.16) and its constraints (4.17a)-(4.17c), the proposed subcarrier allocation algorithm is depicted in **Algorithm 1**. This algorithm consists of four main steps to be performed sequentially at the base station. These steps are described in more detail as follows:

Variable initialisation: in this step the sets of variables such as the number of users, relay stations, subcarriers, interference nodes ..etc. are initialised.

Algorithm 1 Proposed Subcarrier Allocation

Step 1: Variables Initialisation
Set $\mathcal{S} = \{1, 2, \cdots, S\}$, $\mathcal{R} = \{1, 2, \cdots, R\}$, $\mathcal{K} = \{1, 2, \cdots, K\}$, $\mathcal{I} = \{1, 2, \cdots, I\}$, $R_s = 0, \forall s \in \mathcal{S}$, $\mathcal{K}^r = \phi, \forall r \in \mathcal{R}$

Step 2:Subcarriers grouping
while $\mathcal{K} \neq \phi$ **do**
  $k \leftarrow random\,(\mathcal{K})$
  $(r^*) = \underset{r}{\arg\min} \sum_i^I (h_{i,r}^k P_i), r \in \{\mathcal{R}\}, i \in \{\mathcal{I}\}$
  $\mathcal{K}^{r^*} \leftarrow \mathcal{K}^{r^*} \cup \{k^*\}, \mathcal{K}^r \subseteq \mathcal{K}$
end while

Step 3:Rate satisfaction
while $\min\,[R_S - R_{min}] < 0$ **do**
  $(s^*) = \underset{s}{\arg\min}\,[R_S - R_{min}]$
  $(r^*, k^*) = \underset{r,k}{\arg\max}\, R_{s^*,r}^k,\ r \in \{\mathcal{R}\}, k \in \left\{\mathcal{K}^{r^*}\right\}$
  $\mathcal{K}^{r^*} \leftarrow \mathcal{K}^{r^*} - \{k^*\}$
  update R_S
end while

Step 4:Rate maximisation
while $sum(\mathcal{K}^r \neq \phi, \forall r)$ **do**
  $k^* \leftarrow random\,(\mathcal{K}^r), r \in \{\mathcal{R}\}$
  $(s^*) = \underset{s}{\arg\max}\, R_{s,r^*}^{k^*}, s \in \{\mathcal{S}\}$
  $\mathcal{K}^{r^*} \leftarrow \mathcal{K}^{r^*} - \{k^*\}$
  update R_S
end while

Subcarrier grouping: This is the main step, in which the subcarriers are grouped into R groups. Each group is assigned to a single RS, by which subcarriers with a high interference on a certain relay station are avoided for that RS. This grouping is performed by the resource controller (base station) in which, the BS distributes the available subcarriers among the relay stations such that the ICI effects is minimised. The subcarrier selection for each group (relay) is performed to minimise the ICI on that RS, as the following:

$$(r^*) = \arg_r \min \sum_i^I (h_{i,r}^{(k)} P_i), r \in \{\mathcal{R}\}, i \in \{\mathcal{I}\}$$

Note that by doing this grouping, the BS will reduce the amount of ICI on the neighbouring BSs. This is achieved by avoiding subcarriers which have a high negative impact on the neighbouring cells.

Moreover, the distributed allocation allows the coordination between neighbouring BS without any extra signalling between these BSs, and the global objective of maximising overall network capacity is obtained in a distributed manner.

The process of assigning the subcarriers to the different groups will continue until every subcarrier joins one of the groups.

The output of this step is R groups, each containing a subset of $\mathcal{K}^r$ subcarriers. These subsets of subcarriers (groups) are then used in the following step to be allocated to different sources.

Rate satisfaction: in this step, the subcarriers are allocated to different sources to satisfy their individual data rate requirements according to their subscribed service. The fairness between sources is enforced by calculating the difference between the achieved rate and the required rate for each source. The priority of selecting the best subcarrier is given to the one that minimises this difference, i.e., $(s^*) = \arg\min_{s} \, [R_S - R_{min}]$.

Thus, if the number of subcarriers is not enough to satisfy all sources, this constraint will ensure that all sources will still be able to achieve a rate close to their requirements. This means, sources with high rate requirements will not be allowed to use all the subcarriers at the expense of others.

The source with the highest priority (i.e.,s^*) is allowed to select the best subcarrier from any group which maximises its rate. Note that selecting a certain subcarrier also means selecting the RS to be utilised by that source.
$(r^*, k^*) = \arg\max_{r,k} \, R^k_{s^*,r}, \; r \in \{\mathcal{R}\}, \mathcal{K}^r \subseteq \mathcal{K}$

These processes will continue till either the required rates by all sources are achieved or the subcarriers are all allocated. This step is considered as user oriented, because the best subcarriers and relays are assigned to a user based on their requirements.

Rate maximisation: In this step we assume that the number of available resources (subcarriers) is big enough to ensure that the minimum rate requirements have been achieved for all sources during the resource allocation of the previous step (i.e., rate satisfaction). Thus, this part of the algorithm aims to maximise the total sum rate, and hence this step is considered as subcarrier oriented because the algorithm here tries to find the best user for a certain subcarrier.

It is expected that most of the remaining subcarriers will be allocated to a small subset from the complete set of sources. This is because there should be a group of users having good channel conditions compared to the rest of the users. However, if the sources are mobile users, then this set will continuously change and the users will have a similar probability of having the best channel conditions. Thus, the fairness is also valid here for the long-term for all sources to achieve a maximum data rate. These processes will continue till all of the remaining subcarriers are allocated.

From the last two steps, it can be seen that the algorithm is only focused on allocating the available subcarriers to different sources rather than to RSs and the search is performed only once for each subcarrier to be assigned to a certain source. This is because the subcarriers are pre-allocated to RSs, and hence sources do not have the choice of selecting a subcarrier from the r^{th} group and selecting the j^{th} relay when $j \neq r$, i.e., the RS selection is performed when the source selects the best subcarrier. This significantly reduces the complexity, which will be discussed in the following section.

4.5 Complexity Analysis

In a conventional approach to allocate the best subcarrier to each source, the algorithm needs to check the maximum achievable rate of that source over all combinations of the available relay stations and subcarriers, hence the complexity associated with each source is equivalent to $\mathcal{O}(RK)$, and for all sources this become $\mathcal{O}(SRK)$. Since K and S are expected to be large compared to the number of relay stations R, i.e., $K >> S >> R$, then this will significantly increase the system overall complexity [55].

In the proposed algorithm, the allocation process is divided into two main steps. The first one is to group the subcarriers into R subsets based on minimum ICI with a complexity of $\mathcal{O}(RK)$ which is similar to the conventional algorithm for one source, and then the sources will select a subcarrier from those subsets with a complexity of $\mathcal{O}\Big(\sum_{r=1}^{R} K^r\Big)$, for each source, where K^r denotes the number of subcarriers in the subset $\mathcal{K}^r$ and $\mathcal{K}^r \subseteq \mathcal{K}$. Now considering all sources, and taking into account the grouping complexity, the complexity associated with the overall process becomes $\mathcal{O}\Big(RK + \sum_{r=1}^{R} SK^r\Big)$.

The number of elements in $\mathcal{K}^r$ is approximately equal to $(\frac{K}{R})$. Thus, although the grouping complexity will increase as the number of relay station increases, this will be compensated during the second step and the complexity is reduced by a factor of $\approx \frac{1}{R}$.

4.6 Numerical Results

This section presents the numerical results of the proposed distributed subcarrier allocation algorithm. The proposed algorithm has been evaluated in terms of total achievable sum rate of a single cell and multi-cell cases in free space environment with path loss exponent value equal to 2 [93]. The results were compared to the conventional algorithm which is a modified version of Jeong algorithm in [55]. The proposed algorithm in [55] involves a fairness constraint in the optimisation problem and requires a search over all combinations of subcarriers and relay stations for each individual source node. Furthermore, this algorithm assumes equal rate requirements and consider a single cell without ICI. In order to make a fair comparison, the algorithm in [55] was modified by including ICI and assuming different rate requirements for different sources. The sources and relays are distributed randomly within the cell in all cases.

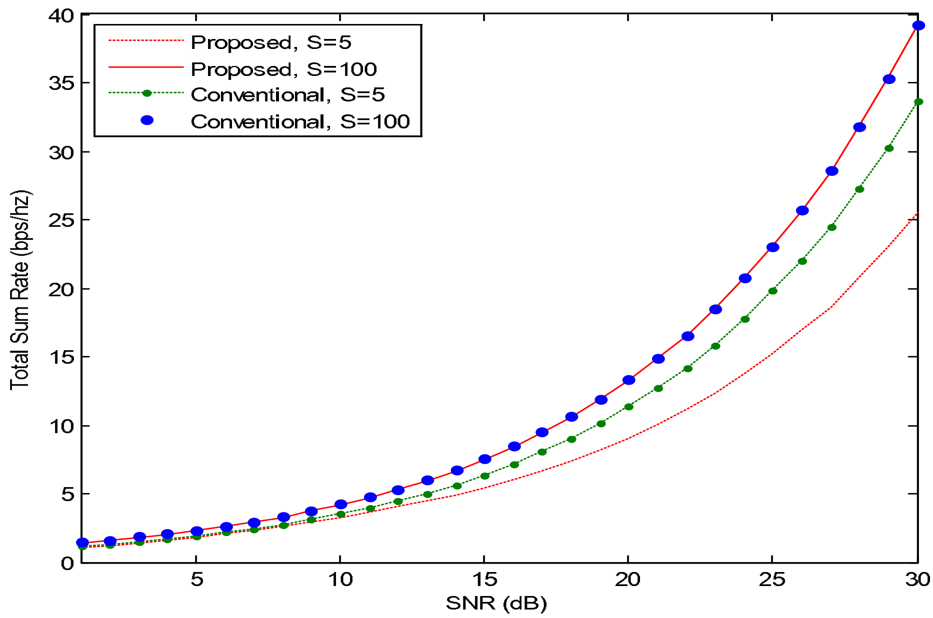


Figure 4.2: Total achieved sum rate of the proposed algorithm compared to conventional algorithm with K=256 and R=6

4.6.1 Single Cell case

Figure 4.2 shows the sum rate of the proposed algorithm compared to the conventional algorithm. Here, the sum rate indicates the achievable sum rate of all sources within the cell under consideration. In the case of five sources, it can be seen from the figure that the conventional algorithm outperforms the proposed algorithm especially at high SNR. On the other hand, in the case of a large number of sources (one hundred in this case), we can see that the proposed algorithm behaves exactly the same as the conventional one at any arbitrary SNR value. Thus, the same rate can be achieved with a much simpler algorithm compared to the conventional algorithm. Algorithm complexity is an important measure in real time mobile communication systems because the resources needs to be continuously optimised as the channel conditions changes in order to maintain efficient utilisation of the resources.

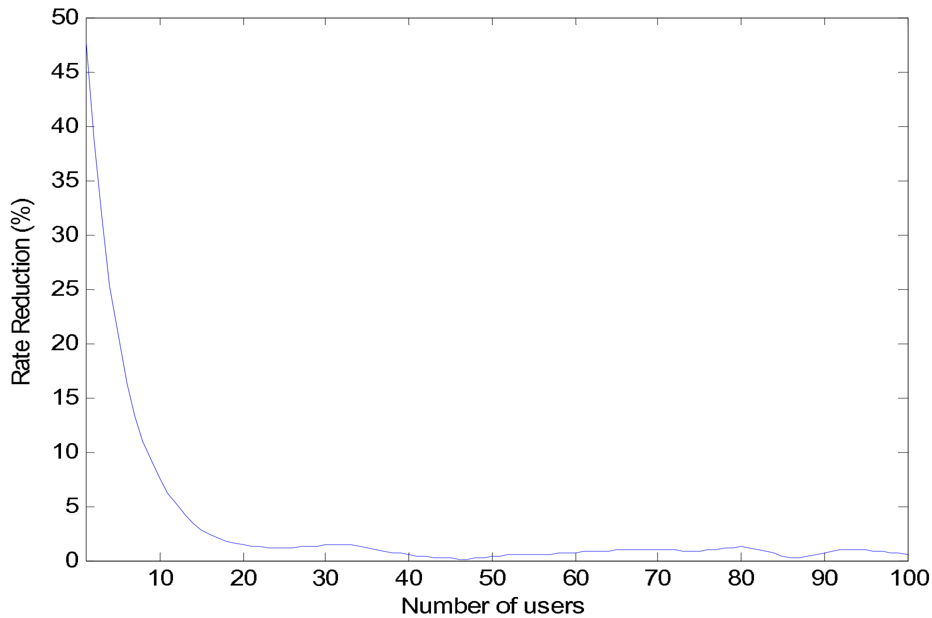


Figure 4.3: The rate reduction ratio when adopting the proposed algorithm compared to the conventional one for SNR=20 dB, K=256 and R=6

Moreover, a practical cellular system is very unlikely to have a small number of sources in a cell equipped with four relay stations. Hence the case of five sources is unlikely to happen in a practical cellular system.

To further validate the proposed algorithm, the same simulation was repeated with a different number of sources (users) as shown in Figure 4.3. Here, the curve presents the difference between the achieved rate of the proposed and the conventional algorithms. It can be seen from the figure that the difference converges to zero as the number of users increases. Moreover, we can see that this difference sharply drops from 45% to less than 5% with less than 20 users. Since practical cellular systems accommodate a number of users, in the order of tens or hundreds, it can be said that the proposed algorithm is low in complexity and without any penalty on the sum rate performance.

Taking into account the total network sum rate, Figure 4.4 shows the total

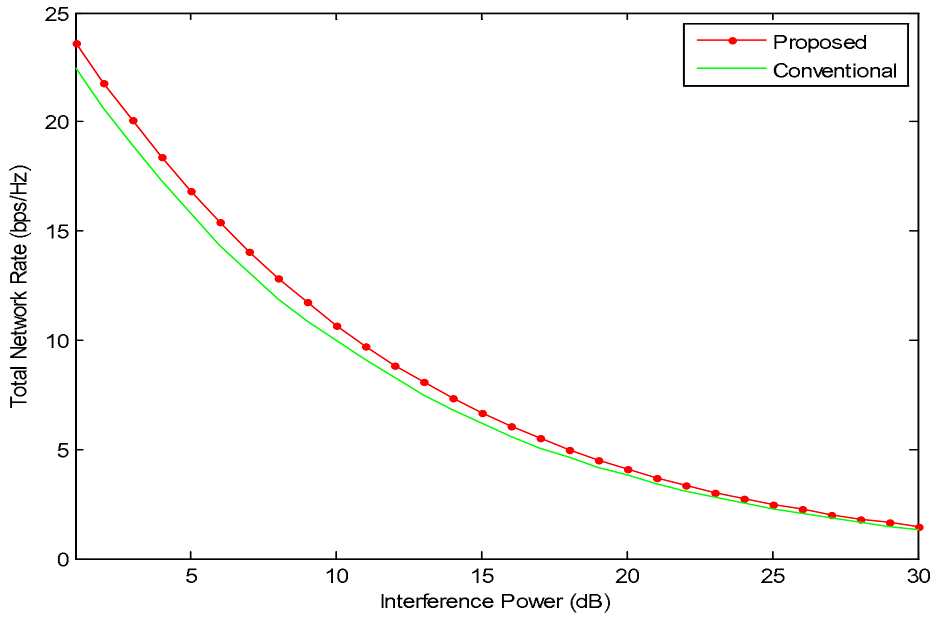


Figure 4.4: Total network sum rate, K=256, S=40, 2 cells each with 4 RSs

achievable rate of the overall network which consists of two cells, each equipped with four relay stations and 40 randomly distributed sources. The same 256 subcarriers are stored in each BS of both cells to be allocated to the relays and sources.

Although the proposed algorithm achieves a similar performance as the conventional one in the single cell case, the key result is that it outperforms the conventional algorithm in the multi-cell scenario. This validates our claims earlier in this chapter that in spite of the distributed nature of the proposed algorithm, the ICI is coordinated and minimised in each cell which results in better performance. For the sake of accuracy and reliability, the monte carlo simulation method has been adopted by repeating the same simulation one hundred times using different seed values and the results were averaged out.

Furthermore, it can be seen that the gap between the proposed and the conventional algorithm is getting smaller as the interference power increases. This

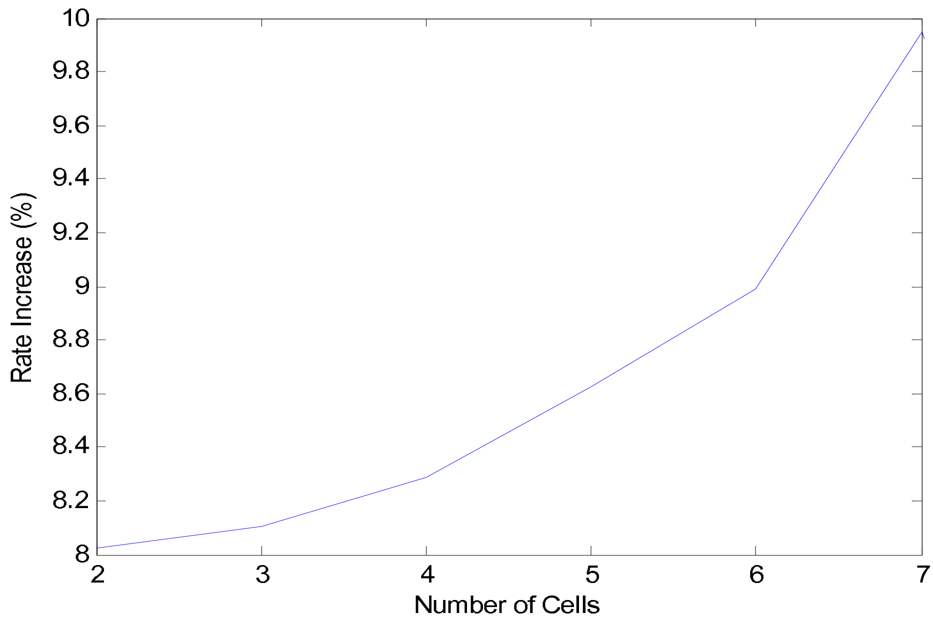


Figure 4.5: Total network sum rate with different number of cells, K=256, S=40 and R=4

is because at high interference power, the available subcarriers to be allocated to different sources are severely affected by the high interference power. However, the proposed algorithm still outperforms the conventional one.

4.6.2 Multi-cell case

Finally, Figure 4.5 depicts the percentage improvement of the proposed algorithm compared to the conventional one. Different network sizes (i.e., 2 to 7 cells) were considered with the same parameters as in Figure 4.4 (i.e., K=256, S=40 and R=4). It is clear that the proposed algorithm achieves higher data rate over the conventional algorithm for all network sizes. Furthermore, the figure shows that the increment on the total network rate increases as the number of cells increase. This is because, at high number of cells the coordination becomes more significant to achieve a better rate and hence, the proposed algorithm becomes more efficient.

4.7 Summary

This chapter proposes a new subcarrier allocation algorithm taking into account the ICI in multi-cell environment. The proposed algorithm operates in a distributed manner. The results show that the proposed algorithm's performance is similar to the conventional one in case of single cell. However, the proposed algorithm demonstrates a significant improvement over the conventional one in terms of complexity and required processing time. Moreover, in the multi-cell scenario, the proposed algorithm outperforms the conventional one when measuring the total network achievable rate as well as significantly reducing the overall network complexity.

Chapter 5

UTILITY-BASED RESOURCE ALLOCATION WITH FULL AND PARTIAL CSI

5.1 Overview

As discussed earlier in section 3.6, most of the previous work considers the QoS and capacity trade-off and aims to balance this trade off sequentially. i.e., the proposed algorithms perform the resource allocation to guarantee the QoS requirements first and then the remaining subcarriers are allocated to maximise the capacity. This framework shows a significant improvement over the conventional greedy algorithms. However, this methodology implies that, a user with high rate requirements compared to other users will get the highest priority to select the best subcarrier to satisfy his QoS requirements regardless to his channel conditions; therefore, a user may select the best subcarrier from his perspective which has a small impact on that user capacity and at the same time this particular subcarrier may has a higher impact on other users with less rate requirements. This will cause degradation on the total network capacity.

For this reason, this chapter proposes a utility-based resource allocation, in which the current QoS requirements of every user and the impact of every subcarrier on the total capacity will be jointly considered to dynamically update the selection priority.

This chapter proposes a new utility-based resource (relay stations, subcarriers and power) allocation algorithm for the uplink OFDMA cooperative relay network. The network composed of multiple cells, in each cell multiple users are communicating with a single base station through one or multiple amplify-and-forward (AF) relay stations. The effects of inter-cell interference (ICI) have been considered and mitigated during the resource allocation processes. The proposed algorithm aims to maximise the total system utility and at the same time satisfy the individual user's minimum quality of service (QoS). The CSI of each cell is assumed to be completely known by the serving BS of that cell. This knowledge is obtained through the feedback links between the SSs/relay stations and the destination (BS). In the proposed algorithm the subcarrier allocation is performed first based on the maximum achieved utility under the assumption of equal power allocation. Then an updated Water-filling algorithm (ICI-based WF) is used to optimise the power allocation across pre-allocated subcarriers. In addition to that, the proposed utility-based resource allocation algorithm is extended to consider the case of partial channel state information (PCSI), in which, only statistical information about the CSI is available at the serving BS of each cell.

The ICI is modelled to take into account the effects on the relay stations during the first time slot. It is also assumed that the destination only receives through the AF relay stations, hence, no direct transmission between Subscriber Stations and destination is allowed.

5.2 System Model

This chapter considers a multiple cell scenario as shown in Figure 5.1. The subscriber stations, amplify and forward (AF) relay stations and destination are denoted as S, R, and D respectively. The cell under consideration receives an ICI from the interference sources I of the neighbouring cells. Moreover, the available bandwidth is divided into (K) subcarriers and are available at the destination.

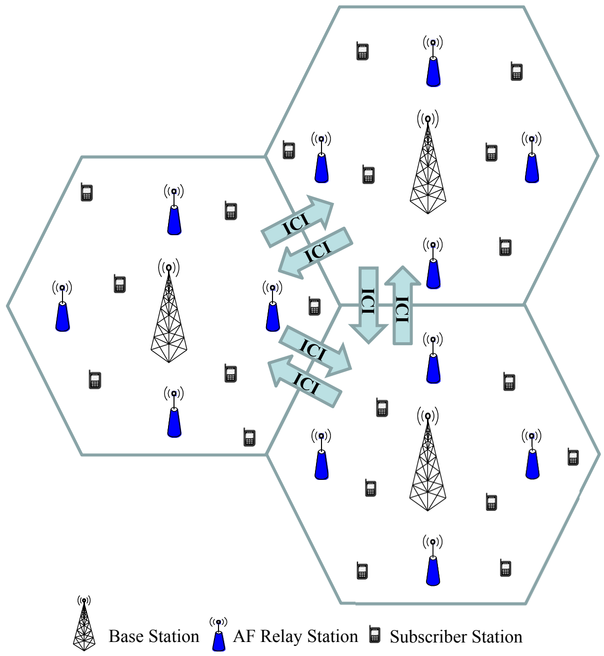


Figure 5.1: Multi-cell interference limited OFDMA-based cooperative relay system model

Furthermore, we assume that the RS of the neighbouring cells transmits data with equal transmission power and the serving BS has knowledge about the transmit power of the i^{th} interference source (P_i). Therefore, the average power across each subcarrier is given by $p_i^k = P_i/K, i = 1, \ldots, I$

In previous chapter, the received SINR at the MRC receiver with the help of the r^{th} relay station is written as:

$$SINR_{MRC,r}^{k} = \frac{\gamma_{s,r}\gamma_{r,d}}{I_{I,r}\left(\gamma_{r,d}+1\right)+\gamma_{s,r}+\gamma_{r,d}+1} + \frac{\gamma_{s,d}}{1+I_{I,d}} \tag{5.1}$$

In this chapter, a new approach based on utility and detrimental function is proposed for the purpose of optimising the available resources (subcarriers as well as power) in the system.

5.3 Utility and Detrimental Functions Modelling and Definition

This section models the utility function based on the system model described in Section 5.2 and defines the objectives of this utility-based resource allocation.

The term *Utility* here indicates the degree of user satisfaction in terms of data rates and fairness. In fact, this chapter focuses on two main objectives: guaranteeing the minimum QoS requirements and maximising the total achievable data rate. This is achieved through relay selection, subcarrier allocation and power allocation algorithms.

Figure 5.2(a,b) depicts the utility function of the minimum rate satisfaction and total rate maximisation objectives. In the case of minimum rate satisfaction ($U_{R_{min}}$), the utility is represented by a unit step function, in which a certain subscriber (the s^{th} user) is considered to be satisfied when its minimum required data rate is achieved (i.e., $R_s \geq R_{s_{min}}$). This is referred to as a *hard threshold.*

However, the total rate maximisation utility (U_{R_T}) has no hard threshold to reach. Instead, the objective is to maximise the total sum rate. The minimum total sum data rate is the sum of the minimum rate requirements by all subscribers ($\sum_{s=1}^{S} U_{R_{min}(s)}$), as shown in Figure 5.2(b). Note that this is only valid when the system has a sufficient number of resource channels to satisfy all the subscribers' minimum rate requirements.

By contrast, inter-cell interference is considered to be a detrimental factor, and the effects of ICI over the r^{th} relay station is denoted $D(r)$. In this case, the objective is to *minimise* this detrimental effect over the relay stations through ICI-based relay selection. As shown in figure 5.2(c), the r^{th} relay station will receive the maximum ICI when it uses the maximum number of subcarriers (i.e.,

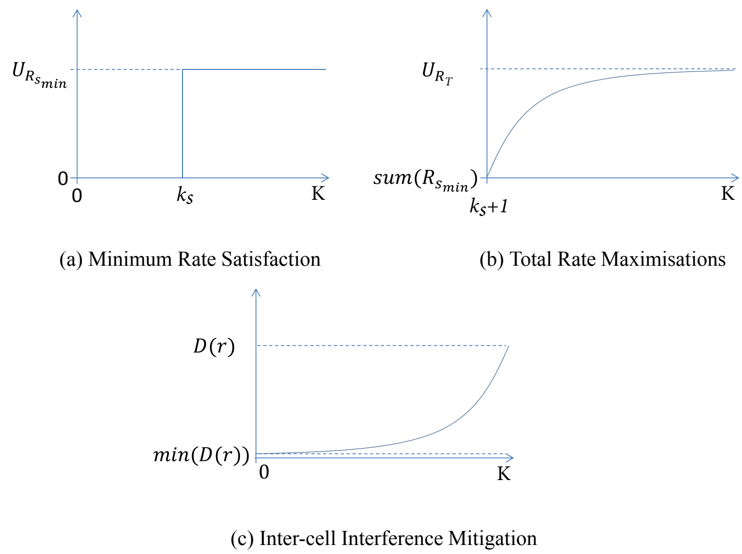


Figure 5.2: Utility and detrimental functions

K). This is due to the fact that every subcarrier will carry a fraction of the total ICI. However, since a total number of K subcarriers need to be utilised by R relay stations, then every relay station will only be able to use some of the available subcarriers. Thus, the minimisation of $D(r)$ here refers to carefully selecting the subcarriers to be used by each relay station, such that $D(r)$ is minimised.

5.4 Problem Formulation

In this section, the optimisation problem is formulated for the purpose of maximising the utility function associated with the total sum data rate (Figure 5.2(b)), subject to fairness and maximum power constraints. The fairness constraint is imposed to guarantee the minimum rate utility function (Figure 5.2(a)) to be satisfied for as many subscribers as the available resources can accommodate.

From (5.1), the instantaneous sum data rate utility of the s^{th} subscriber on the subcarrier k is given by:

$$U_{R_s^k} = \frac{1}{2}\log\left(1 + SINR_{MRC,r}^k\right) \tag{5.2}$$

Taking into account all possible allocated subcarriers, then using (5.2), the total sum data rate utility of all subscribers can be written as:

$$U_{R_T} = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{k=1}^{K}\rho_{s,r}^k U_{R_s^k} \tag{5.3}$$

where $\rho_{s,r}^k$ denotes the subcarrier allocation index, as defined in (4.13)

The data rate utility-based resource allocation optimisation problem can be formulated as:

$$max\ \ (U_{R_T}) \tag{5.4}$$

subject to:

$$\rho_{s,r}^k \in \{0,1\}, \forall k, s, r \quad (5.5a)$$

$$\sum_{s=1}^{S}\sum_{r=1}^{R} \rho_{s,r}^k = 1, \forall k \quad (5.5b)$$

$$\sum_{k=1}^{K} U_{R_s^k} \geq U_{R_{min(s)}}, \forall s \quad (5.5c)$$

$$\sum_{k=1}^{K}\sum_{s=1}^{S} p_s^k \leq P_T \quad (5.5d)$$

$$\sum_{k=1}^{K}\sum_{r=1}^{R} p_r^k \leq P_T \quad (5.5e)$$

$$p_s^k \geq 0, \forall k, s \quad (5.5f)$$

$$p_r^k \geq 0, \forall k, r \quad (5.5g)$$

Where, (5.4) represents the utility maximisation objective function of the optimisation problem. The constraints (5.5a) and (5.5b) indicate that each subcarrier is only allocated to a single subscriber-relay pair. Constraints (5.5c) guarantee the satisfaction of the minimum rate utility for all subscribers. Constraints (5.5d) and (5.5e) ensures that the transmitted power by subscribers and relay stations should not exceed the total power constraint P_T. Finally, constraints (5.5f) and (5.5g) limit the subscribers and relay stations minimum transmitted power.

The optimisation problem in (5.4) contains both discrete and continuous variables ($\rho_{s,r}^k$ and p^k). This makes the problem intractable and computationally complex.

Conversely, the second optimisation problem is to minimise the ICI effects on each relay station. This optimisation problem may be formulated as:

$$min \ (D(r)) \tag{5.6}$$

subject to:

$$\rho_r^k \in \{0, 1\}, \forall k, r \tag{5.7a}$$

$$\sum_{r=1}^{R} \rho_r^k = 1, \forall k \tag{5.7b}$$

$$\sum_{r=1}^{R} \sum_{k=1}^{K} \rho_r^k = K, \tag{5.7c}$$

Where, (5.6) represents the detrimental minimisation objective function of the optimisation problem. Constraints (5.7a) and (5.7b) are similar to those in (5.5a) and (5.5b) respectively, and constraint (5.7c) indicates that the available subcarriers need to be distributed among the available relay stations. In fact, this constraint will force the relay stations to accept the use of subcarriers carrying some amount of ICI.

In the following section, a heuristic utility-based resource allocation algorithm is proposed in which the objective functions in (5.4) and (5.6) with their constraints are taken into account.

5.5 Proposed Resource Allocation Algorithms

Taking the above optimisation problems into account, the following sections present the proposed resource allocation algorithms.

5.5.1 ICI Mitigation Through Relay Selection

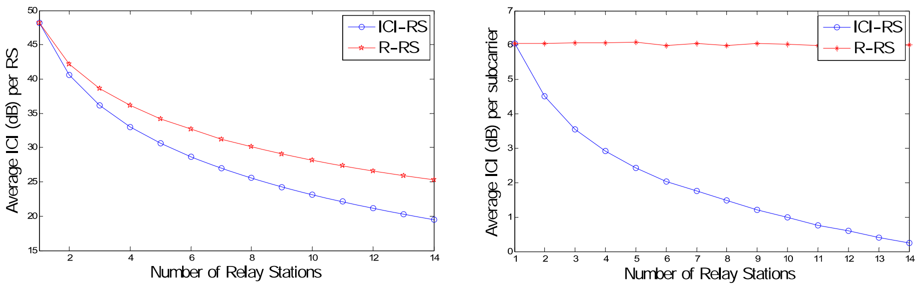
This section presents the proposed algorithm in which relay stations will be selected to be the serving RS for certain subcarriers.

Different RSs experience different ICI levels on each subcarrier. Thus, the resource controller (base station) distributes the available subcarriers among the relay stations such that the ICI effects is minimised. By doing so for all subcarriers, the total number of subcarriers K will be divided between the R relay stations. Thus, every RS has a subset of the total number of subcarriers K allocated to it.

Figure 5.3 illustrates the outcome of the proposed ICI-based relay selection (ICI-RS) compared to random relay selection (R-RS). It can be seen in Figure 5.3(a) that the proposed relay selection algorithm significantly reduces the average ICI per relay station over the random selection algorithm. In fact, for random selection, the average ICI per RS is reduced due to the random division of the total available ICI between the available relay stations. However, in the proposed algorithm the new relay selection scheme contributes in further minimising the average ICI per RS.

Figure 5.3(b) illustrates the average ICI per subcarrier. Again, the proposed algorithm performs significantly better than the random selection algorithm. This is because increasing the number of RSs means that every subcarrier has more allocation options, increasing the likelihood that it can be be allocated to the RS by which the ICI effects can be minimised.

A relay station r^* will be selected to serve a given subcarrier k that satisfies the following condition [94]:



(a) ICI Mitigation / RS (b) ICI Mitigation / Subcarrier

Figure 5.3: ICI mitigation using the proposed ICI-based RS selection algorithm

$$(r^*) = \underset{r}{\arg}\ min \left(\sum_{i}^{I} (h_{i,r}^{k} p_i) \right), r \in \{\mathcal{R}\}, i \in \{\mathcal{I}\} \tag{5.8}$$

Applying this condition on all available subcarriers produces a subset of subcarriers R which will be allocated to subscribers in the following section.

5.5.2 Subcarrier Allocation

At this point, it is assumed that the total power is equally distributed over K subcarriers, to simplify the subcarrier allocation process; that is, $p_s^k = p_r^k = P_T/K, \forall s, r$. Thus, constraints (5.5d) , (5.5f) and (5.5g) can be removed and the optimisation problem in (5.4) is simplified to:

$$max\ (U_{R_T}) \tag{5.9}$$

subject to:

$$\rho_{s,r}^{k} \in \{0,1\}, \forall k,s,r \tag{5.10a}$$

$$\sum_{s=1}^{S}\sum_{r=1}^{R}\rho_{s,r}^{k} = 1, \forall k \tag{5.10b}$$

$$\sum_{k=1}^{K} U_{R_s^k} \geq U_{R_{min(s)}}, \forall s \tag{5.10c}$$

Where, (5.9) represents the utility maximisation objective function of the simplified optimisation problem. A subcarrier allocation algorithm which implement the objective function in (5.9) subject to its constraints (5.10a)-(5.10c) is depicted in **Algorithm 2**.

The *urgency*, $\mathcal{G}_s$ is defined as the necessity of a certain subscriber to be allocated with a subcarrier to meet its minimum rate requirements and is calculated as the difference between the current achieved data rate (R_s) and the minimum data rate requirements ($R_{s_{min}}$) by each subscriber as follows:

$$\mathcal{G}_s = \{R_s - R_{s_{min}}\} \tag{5.11}$$

The subscriber which minimises (5.11) has the highest priority with respect to subcarrier allocation; that is, this subscriber will be allocated the best subcarrier. However, this will allow a certain subscriber who is subject to deep fading over all subcarriers to excessively use most of the available subcarriers, degrading the total achieved rate and disadvantaging the other subscribers. To avoid this problem, the urgency factor is jointly used with the impact of each subcarrier on each subscriber in terms of achievable data rate. This means that the subcarrier will be assigned to subscriber who most urgently needs resources and whose data rate will be significantly increased with the use of this particular subcarrier compared to other subscribers.

This is performed by identifying the subscriber with highest priority (s^*) according to (5.11). This subscriber will then be able to select the relay-subcarrier set r^*, k^* by which its instantaneous rate is maximised:

$$(r^*, k^*) = \underset{r,k}{\arg} \; max \; \left(R^k_{s^*,r}\right), \; r \in \{\mathcal{R}\}, \; k \in \left\{\mathcal{K}^{r^*}\right\} \tag{5.12}$$

Next, the selected relay/subcarrier pair will be used to check the achievable data rate of this pair over the other subscribers, i.e. calculate $R^{k^*}_{s,r^*}, \forall s \in \mathcal{S}$.

Finally, the negative of the urgency factor $\mathcal{G}_s$ in (5.11) is multiplied by the instantaneous rate $R^{k^*}_{s,r^*}$ to obtain the utility that each subscriber can achieve through the selected relay (r^*) and subcarrier (k^*):

$$U^{k^*}_{s,r^*} = -\mathcal{G}_s R^{k^*}_{s,r^*} \tag{5.13}$$

Therefore, the constraint (5.10c) is now incorporated in the utility function (5.13), which means that this constraint can be removed and the objective function in (5.9) is modified to:

$$max \; (U_s) \tag{5.14}$$

The other constraints ((5.10a) and (5.10b)) remain the same. This procedure will continue until the rate requirements of all users are achieved; at this point the remaining subcarriers will be allocated to maximise the total sum data rate, and the objective function is similar to (5.9), but in this case constraint (5.10c) is omitted. The entire procedure is described in **Algorithm 2**.

Algorithm 2 Utility-based subcarrier allocation algorithm

1) Initialisation

a) Initialise the sets of S, R, K and I as $\mathcal{S}, \mathcal{R}, \mathcal{K}$ and $\mathcal{I}$

b) $p_s^k = p_r^k = P_T/K, \forall s, r,\ R_s = 0, \forall s \in \mathcal{S}$,

c) $\mathcal{K}^r = \phi, \forall r \in \mathcal{R}$

2) Minimum Data Rate Satisfaction Utility

$\mathcal{G}_s = \{R_s - R_{s_{min}}\}$

while $min\ (\mathcal{G}_s) < 0$ **do**

$(s^*) = \arg\underset{s}{min}\ (\mathcal{G}_s)$

$(r^*, k^*) = \arg\underset{r,k}{max}\ \left(R^k_{s^*,r}\right),\ r \in \{\mathcal{R}\}, k \in \left\{\mathcal{K}^{r^*}\right\}$

$U^{k^*}_{s,r^*} = -\mathcal{G}_s R^{k^*}_{s,r^*}\ s \in \{\mathcal{S}\},$

$(s^{**}) = \arg\underset{s}{max}\ \left(U^{k^*}_{s,r^*}\right)$

$\mathcal{K}^{r^*} \leftarrow \mathcal{K}^{r^*} - \{k^*\}$

update R_S

end while

3) Data Rate Maximisation Utility

a) Allocate the remaining subcarriers based on (5.9) without the constraint (5.10c).

5.6 ICI-based Water-Filling Algorithm

In the previous section, equal distribution of power across subcarriers is considered. However, further performance enhancements may be achieved by distributing the available power resource in a more efficient manner. This section proposes a power allocation algorithm based on the water-filling (WF) approach.

In OFDMA networks, it is very common to use the WF power allocation algorithm based on the CSI (i.e., subcarriers with superior channel conditions will be allocated more power compared to those with poor channel conditions). However, if the cooperative relays are taken into account, this procedure must be extended to include the CSI between the subscriber and relay stations as well as between the relays and the destination (i.e., two hops), which will increase the algorithm complexity. In spite of the increased complexity, the algorithm is still worth considering due to the potential performance improvement.

Applying the adopted system model, it can be seen that system performance is dominated by the ICI effects on the relay stations. Thus, the level of ICI may be used as an input to the WF algorithm.

In fact, the proposed ICI-based WF algorithm allocates the total power across subcarriers based on the amount of ICI affecting each subcarrier. Therefore, the proposed power allocation scheme only considers the channel between the interfering sources and relay stations (one hop), simplifying the power allocation process to a level similar to a simple OFDMA network.

As shown in Figure 5.4, more power is allocated to subcarriers with minimal ICI interference (such as; subcarrier number 4), while the ones with relatively high interference are allocated with minimum amount of power (such as subcarrier number 3) or no power at all if the amount of interference exceeds the predetermined water level (such as subcarriers 2 has no power due to high ICI level). With this scheme, the good subcarriers with low ICI are able to get more power and hence utilised efficiently, at the same time, the system avoids using the highly impacted subcarriers by allocating zero power to them (i.e., not using them).

Again, let $I_{I,r} = \sum_{i=1}^{I} \left|h_{i,r}^{k}\right|^2 p_i^k/\sigma^2$, represents the aggregated inter-cell interference at certain r^{th} relay station, then the power allocation across subcarriers utilised by that relay station is given by [95]:

$$p_r^k = max\left(\left(\frac{1}{\lambda} - I_{I,r}\right), 0\right) \tag{5.15}$$

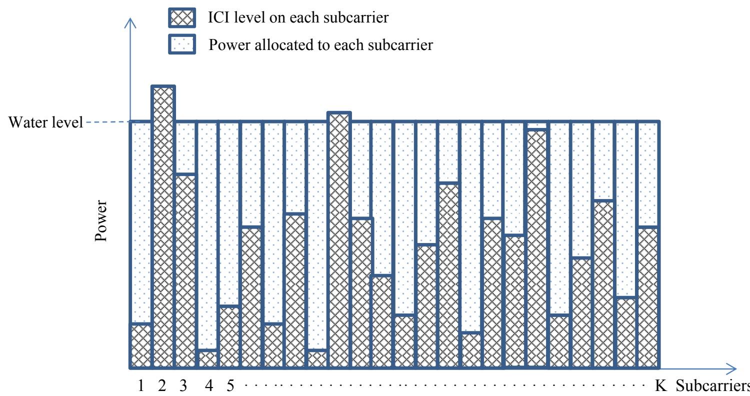


Figure 5.4: ICI based water-filling algorithm

Where, $\left(\frac{1}{\lambda}\right)$ is chosen such that the power constrain (water level) is satisfied. The total available power is derived from (5.15) and given by:

$$P_T = \sum_{k=1}^{K} \left(\frac{1}{\lambda} - I_{I,r} \right)^+ \tag{5.16}$$

Where, $(x)^+ = max(x, 0)$.

As previously discussed, equal power allocation across subcarriers was initially assumed in order to optimise the subcarriers allocation (see algorithm 1). However, once the subcarrier allocation algorithm allocates the subcarriers, the algorithm will proceed to the next step, in which the power across subcarriers is allocated based on the proposed ICI based water-filling power allocation algorithm (5.15).

5.7 Partial Channel State Information

So far, in previous section, it was assumed that the channel state information (CSI) is perfectly known at the resource controller. In reality, perfect knowledge about the CSI requires a huge amount of feedback and cannot be quarantined due to feedback estimation error. However, some statistical information about the

CSI could be easily available at the resource controller, this is called partial CSI. In this section, we will investigate the proposed allocation performance assuming only partial CSI is available. Equations (4.6), (4.7) and (4.8) describe the SINR rations at the relay station from the direct link and at the destination from the direct and forwarded links respectively. Note here in equations (4.6) to (4.9) and (5.1), the channel gain is assumed to be imperfect due to estimation error, thus the channel gain can be written in terms of estimated value ($\hat{h}_{a,b}$) and estimation error ($\epsilon^k_{a,b}$) as the following:

$$h_{a,b} = \hat{h}_{a,b} + \epsilon^k_{a,b} \tag{5.17}$$

In the actual gain (i.e., $h_{a,b}$) is modeled as $\mathcal{CN}(\hat{h}_{a,b}, \sigma^2_{a,b})$ and its square (i.e., $|h_{a,b}|^2$) follow the noncentral Chi-square distribution with a pdf given as [96,97]:

$$f_{\left|h^k_{a,b}\right|^2}(\mathcal{V}) = \frac{1}{(\sigma^k_{a,b})^2} e^{-\frac{\left(\left|\hat{h}^k_{a,b}\right|^2 + \mathcal{V}\right)}{(\sigma^k_{a,b})^2}} I_0 \left(2\sqrt{\frac{\left|\hat{h}^k_{a,b}\right|^2 \mathcal{V}}{\left(\sigma^k_{a,b}\right)^4}} \right) \tag{5.18}$$

Where, I_0 is the zeroth-order modified Bessel function of the first kind. Assuming that the AWGN effect is small enough to be ignored in (4.7), then the signal to interference ratio (SIR) at the destination from the direct link is the ratio of two Chi-square distributions given as:

$$g(\alpha) = \frac{e^{-\left[\frac{B_1^2}{2\sigma_1^2} + \frac{B_2^2}{2\sigma_2^2}\right]} \left(\frac{1}{4\sigma_1^2\sigma_2^2}\right)}{\left(\frac{\alpha}{2\sigma_1^2} + \frac{1}{2\sigma_2^2}\right)^2} \sum_{j=0}^{\infty} \left(\frac{B_2}{2\sigma_2^2}\right)^{2j} \frac{\Gamma(2+j)}{\left(\frac{\alpha}{2\sigma_1^2} + \frac{1}{2\sigma_2^2}\right)^j}$$
$$\sum_{i=0}^{j} \left(\frac{2B_1\sigma_2^2}{2B_2\sigma_1^2}\right)^{2i} \frac{\alpha^i}{i!\,(j-i)!\,\Gamma(i+1)\,\Gamma(j-i+1)} \tag{5.19}$$

Where $\Gamma(2(n+1))$ represents the gamma function. Under the same assumptions of zero AWGN, the SIR at the destination from the relay link in (4.8) can be written as:

$$SIR_{r,d}^{k} = \frac{P_s^k g_r \mathcal{X}}{P_i^k g_r \mathcal{Y} + g_r \mathcal{Z}} \tag{5.20}$$

where, $\mathcal{X}$ and $\mathcal{Y}$ are i.i.d random variables which follow the pdf given by:

$$g(\beta) = 2e^{-\left[\frac{B_1^2}{2\sigma_1^2}+\frac{B_2^2}{2\sigma_2^2}\right]} \times \left(\frac{1}{4\sigma_1^2\sigma_2^2}\right)$$
$$\sum_{j=0}^{\infty}\left(\frac{\beta\sigma_2^2}{\sigma_1^2}\right)^{j/2}\left(\frac{B_2}{2\sigma_2^2}\right)^{2j}\sum_{i=0}^{j}\frac{\left(\frac{B_1\sigma_2}{B_2\sigma_1}\right)^{2i}K_{2i-j}\left(2\sqrt{\frac{\beta}{4\sigma_1^2\sigma_2^2 f}}\right)}{i!\,(j-i)!\Gamma(i+1)\,\Gamma(j-i+1)} \tag{5.21}$$

Where B_1 and B_2 represents $\left|h_{r,d}^k\right|^2$ and $\left|h_{s,r}^k\right|^2$ for the random variable $\mathcal{X}$ and $\left|h_{r,d}^k\right|^2$ and $\sum_{i=1}^{I}\left|\hat{h}_{I,r}^k\right|^2$ for the random variable $\mathcal{Y}$. $K_n(x)$ is the n^{th} order modified Bessel function of the second kind [98]. The random variable $\mathcal{Z}$ follows the chi-square distribution given in (5.18) with a non-centrality parameter of $\left|h_{r,d}^k\right|^2$. Thus, the received SIR at the output of the MRC receiver under the assumption of partial CSI is written as

$$SIR_{MRC,r}^{k} = \sum_{j=1}^{J} SIR_{j,d}^{k} = \frac{P_s^k g_r \mathcal{X}}{P_i^k g_r \mathcal{Y} + g_r \mathcal{Z}} + \mathcal{M} \tag{5.22}$$

where $\mathcal{M}$ represents the Pdf of the direct SIR which follows the distribution in (5.19).

5.8 Numerical Results

This section evaluates the system performance of the proposed utility-based resource allocation algorithms. Multi-cell mobile network is considered with multiple users and relay stations in each cell, the cell under consideration receives inter-cell interference from neighbouring cells. The achievable aggregate data rate, outage probability and fairness are considered as the main performance metric evaluation. The results were compared to the greedy resource allocation

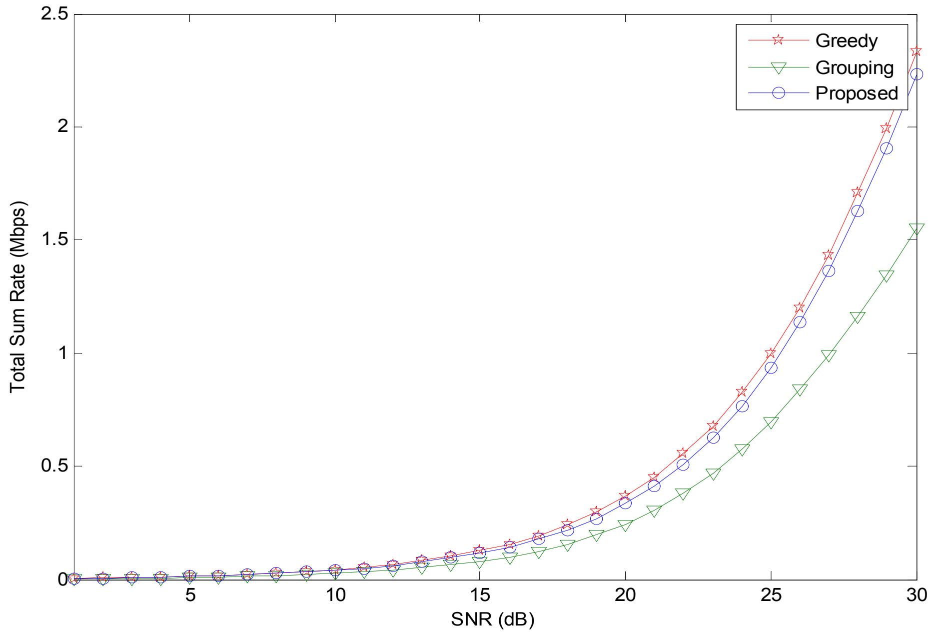


Figure 5.5: Total sum data rate as a function of SNR; $K = 256$, $I = 4$, $R = 4$ and $S = 20$

algorithm (in which the subcarriers are selfishly allocated to users with best channel conditions regardless of the QoS requirements [99]) and with the algorithm proposed in [94], which is referred to as the *grouping algorithm* here. In the grouping algorithm, subcarriers are allocated to sources such that the total achievable data rate is maximised. Sources with data rates below their minimum data rate requirements are given the absolute priority to be allocated with more resources. This proposed utility based algorithm is compared with the grouping algorithm in order to evaluate the significance of considering utility function rather than only minimum data rate threshold.

Figure 5.5 shows the total achieved sum data rate of the proposed resource allocation algorithm compared to the greedy and grouping algorithms. As expected, the total sum rate increases with SNR in all cases. However, the greedy algorithm outperforms the proposed and grouping algorithms in terms of total

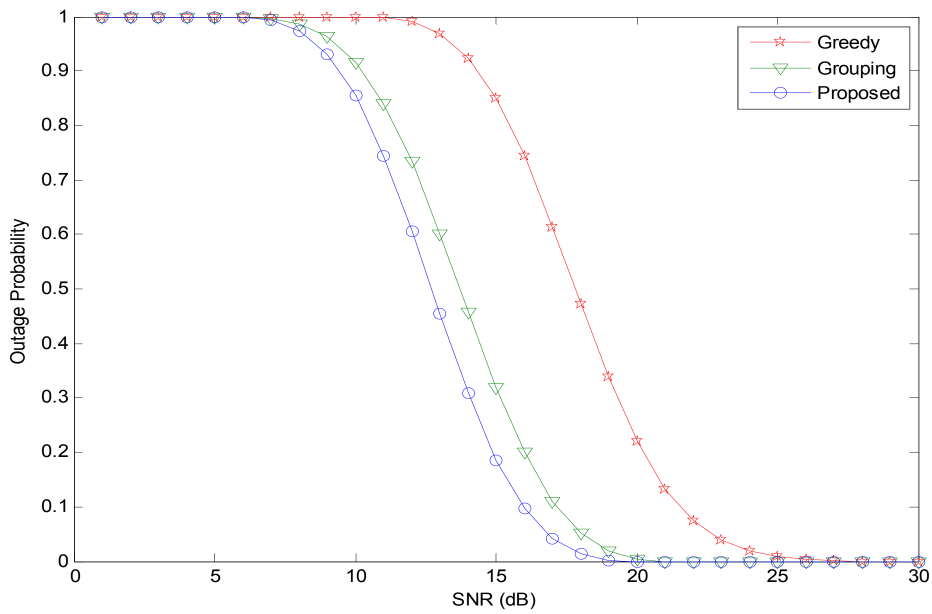


Figure 5.6: Outage probability as a function of SNR; $K = 256$, $I = 4$, $R = 4$ and $S = 20$

sum rate. This is expected because the greedy algorithm is 'selfish' and therefore results in optimal performance with respect to total sum rate. However, the proposed utility-based algorithm provides a significant improvement over the grouping algorithm and achieves a total sum data rate which approaches that of the greedy algorithm.

On the other hand, Figure 5.6 shows the performance of the same three algorithms in terms of outage probability. In this Figure, an outage probability event will occur when at least one source node is not able to achieve its minimum data rate requirements, in other words the outage probability is defined as the probability that the mutual information is less than the given threshold. Since the greedy algorithm is selfish, it does not take the QoS requirements into account; therefore, it has the worst performance in terms of outage probability. The proposed algorithm significantly outperforms the grouping and greedy algorithms in terms of outage probability.

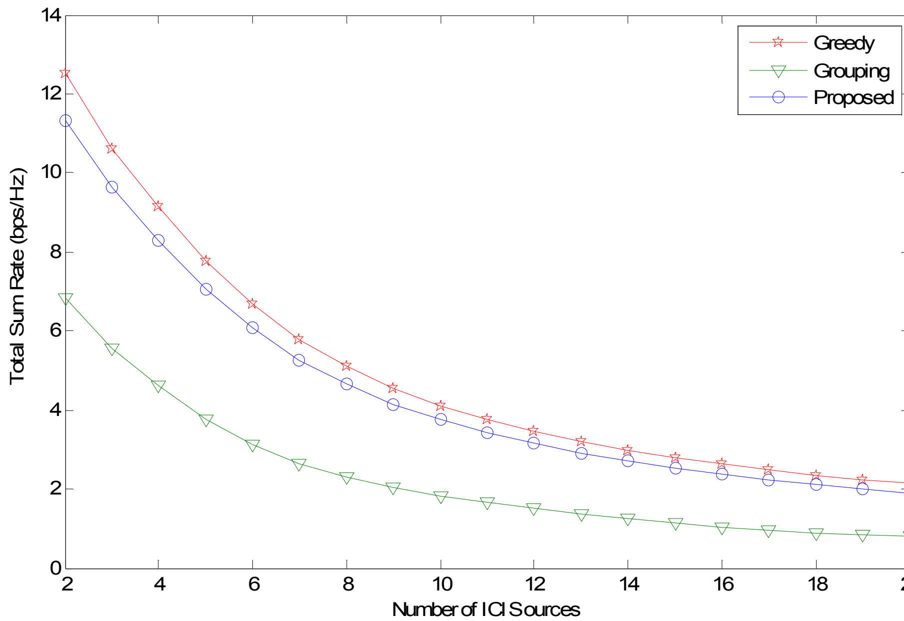


Figure 5.7: Total sum data rate as a function of number of ICI sources; $K = 256$, $R = 6$ and $S = 10$

The three algorithms were also evaluated in terms of total sum data rate versus the number of ICI sources as shown in Figure 5.7. The figure shows that the proposed algorithm significantly outperforms the grouping algorithm for all levels of ICI, although it has slightly lower performance compared to the greedy algorithm.

Jain's fairness index (FI) [100] has been widely adopted to test the fairness capabilities of resource allocation algorithms. Based on this index, an algorithm that allocates similar average data rates to all users is considered to be fair. However, in a situation when there are different data rate requirements for subscribers, this definition of fairness becomes inappropriate. Therefore, in this chapter we have modified Jain's FI by incorporating the minimum data rate requirements ($R_{s_{min}}$) into the formula as follows: $FI = \frac{\left(\sum_{s=1}^{S} \alpha_s\right)^2}{S \sum_{s=1}^{S} \alpha_s^2}$, where,

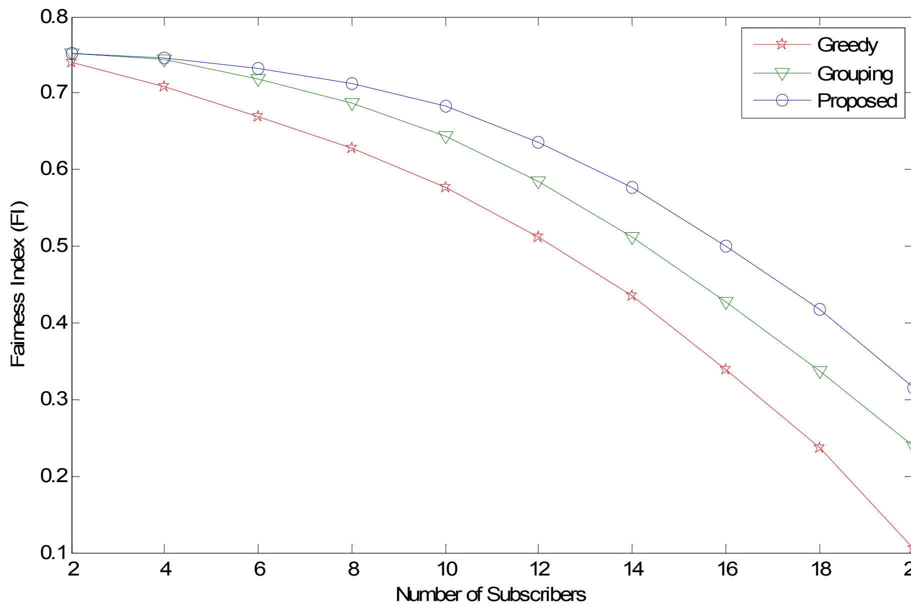


Figure 5.8: Fairness index as a function of number of subscribers, $K = 256$, $I = 4$ and $R = 4$

$\alpha_s = \frac{\bar{R_s}}{R_{s_{min}}}$, $\bar{R_s}$ is the s^{th} subscriber's average achieved data rate. FI takes a value between '0' and '1', and the higher FI value indicates that the system is fairer.

Figure 5.8 depicts the fairness performance of the aforementioned three algorithms. It can be seen that the proposed utility-based algorithm achieves the highest performance in terms of fairness compared to the other two with various number of subscribers. This indicates that the proposed algorithm results in a fair balance between the achieved data rates and outage taking the individual's minimum data rate requirements into account. As the number of subscribers increases, it becomes harder to maintain the same level of fairness in all algorithms.

The preceding results assume that power allocation is equal across all subcarriers. By contrast, the performance of the proposed interference-based water filling power allocation algorithm is evaluated in terms of total sum data rate

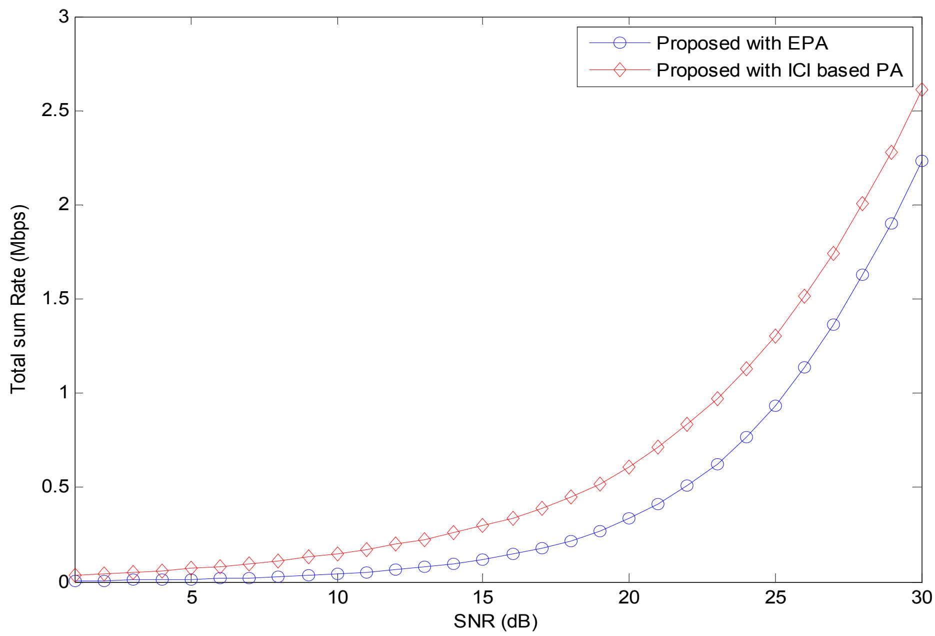


Figure 5.9: Total sum data rate as a function of SNR, $K = 256$, $I = 4$, $R = 4$ and $S = 20$

versus SNR in Figure 5.9. The proposed utility-based subcarrier allocation was utilised with both equal-power and ICI-based power allocation algorithms. It can be seen that the proposed ICI-based water filling approach improves the total sum data rate compared to the equal power allocation algorithm.

Figure 5.10 depicts the system performance in terms of total sum data rates considering full availability of CSI as well as partial channel state information (PCSI).

In this figure, the system performance was predicted assuming that the estimation error (ϵ) is zero, hence the available CSI are full and accurate. Then, the actual achieved system performance was obtained assuming that the estimation error is larger than zero (i.e., $\epsilon = 0.01$ and 0.1) hence the available CSI are partial.

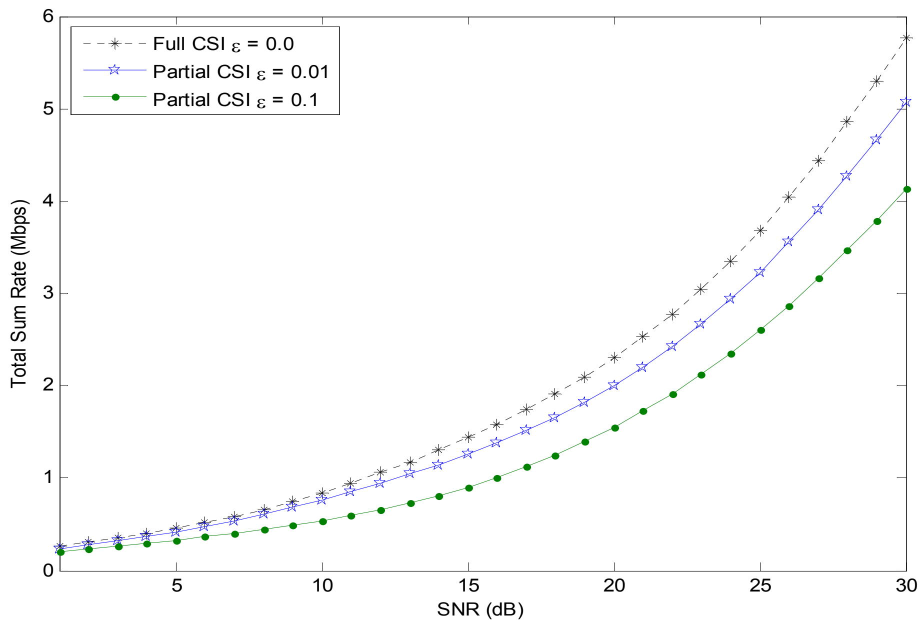


Figure 5.10: Total achieved sum rate of the proposed algorithm with Full (estimation error (ϵ)=0.0) and partial (estimation error (ϵ)=0.01 and 0.1) CSI, K=20, K=256 and R=4

It can be seen from the figure that the system performance when considering full CSI is in fact inaccurate. This is expected because the estimation error was not taken into account during the resource allocation process, therefore the allocation outcome is not efficient for this network. The figure also shows that the actual performance is less than the predicted performance when taking PCSI into account with some estimation error. In spite of the performance reduction based on PCSI compared to the predicted performance based on full CSI, the fact that the system performance based on PCSI reflects the actual achieved performance cannot be ignored. Therefore, it is worth considering PCSI in order to obtain accurate results, hence more efficient resource allocation can be designed.

Furthermore, it can be seen that the performance is reduced as the estimation error value increases. This is because the resource allocation depends highly on the available channel information; therefore, the algorithm becomes less efficient when the channel information is estimated with high estimation error.

5.9 Summary

This chapter proposes a utility-based resource allocation algorithm which takes the ICI in a multiple cell environment into account. The results show that the proposed utility-based algorithm outperforms the grouping algorithm in terms of total achievable data rate, outage probability and fairness. On the other hand, the proposed algorithm achieves an aggregate data rate which is slightly lower than that of the greedy algorithm. However, the proposed algorithm significantly reduces the outage probability and enhances the fairness compared to the greedy algorithm. Furthermore, the proposed ICI-based WF algorithm further enhances the total sum data rate of the proposed algorithm. In addition to that, partial channel state information (PCSI) model was introduced and considered in this chapter, the result with respect to PCSI shows that an accurate prediction of the achievable data rate can be obtained when partial CSI is considered. A comprehensive analysis and investigation about the partial channel state information case will be presented in the following chapter.

Chapter 6

OUTAGE PROBABILITY ANALYSIS WITH PARTIAL CSI

6.1 Overview

This chapter investigates the impact of the relay-to-destination channel gain on subcarrier allocation for uplink OFDMA based cooperative relay networks using multiple amplify and forward (AF) relaying protocols. The closed form outage probability is derived for the system under partial channel state information (PCSI) and considering the presence of inter-cell interference (ICI). This chapter proves that the impact of the relay-destination (RD) link on overall network performance decreases as the ICI increases. Moreover, the closed form outage probability for the system based on a single link (without RD link) is derived, taking into account the availability of partial CSI only.

6.2 System Model

Recall the SINR at the destination from the forwarded signal as given by (4.8)

$$SINR_{r,d}^{k} = \frac{\left|h_{r,d}^{k}\right|^{2} g_r \left|h_{s,r}^{k}\right|^{2} P_s^k}{\sum_{i=1}^{I} \left|h_{r,d}^{k}\right|^{2} g_r \left|h_{i,r}^{k}\right|^{2} P_i^k + \left|h_{r,d}^{k}\right|^{2} g_r \sigma_r^2 + \sigma_d^2} \tag{6.1}$$

Assuming that the noise power is much less significant than the interference (i.e., a large number of ICI sources are present), then the noise can be neglected [101], [102], [103] and hence the first term of the denominator of (6.1) becomes significantly higher than the sum of the other two terms. Furthermore, assume that all signal transmission has to go through at least one relay station. Then, from (6.1) the received SIR at the destination from the r^{th} relay station may be approximated as:

$$SINR_{r,d}^{k} = \frac{\left|h_{s,r}^{k}\right|^{2} P_{s}^{k}}{\sum_{i=1}^{I} \left|h_{i,r}^{k}\right|^{2} P_{i}^{k}} \tag{6.2}$$

It can be seen that the signal to interference ratio in (6.2) is independent of the link quality between the relay station and the destination - that is, the relay-destination channel gain $h_{r,d}^{k}$ does not affect the system performance and hence the channel information of this particular link is not required. Hence, the amount of information which needs to be transferred back to the base station through the feedback link can be considerably reduced.

It is also important to note that in (4.6) and (6.2), the channel gain is assumed to be imperfect due to estimation error, thus the channel gain between any two nodes over the k^{th} subcarrier can be written in terms of estimated value $\hat{h}^{k}$ and estimation error ϵ^{k}:

$$h_{s,r}^{k} = \hat{h}_{s,r}^{k} + \epsilon_{sr}^{k} \tag{6.3}$$

$$h_{i,r}^{k} = \hat{h}_{i,r}^{k} + \epsilon_{ir}^{k} \tag{6.4}$$

In (6.3) and (6.4), the actual gains ($h_{s,r}^{k}$ and $h_{i,r}^{k}$) are modelled as non-zero mean complex Gaussian random variable $h_{s,r}^{k} \sim \mathcal{CN}(\hat{h}_{s,r}^{k}, {\sigma_{s,r}^{k}}^{2})$, where $\hat{h}_{s,r}^{k}$ is the mean of the estimated channel gain and ${\sigma_{s,r}^{k}}^{2}$ is the estimation error variance; similarly, $h_{i,r}^{k} \sim \mathcal{CN}(\hat{h}_{i,r}^{k}, {\sigma_{i,r}^{k}}^{2})$. Therefore, their squares follows the non-central Chi-square ($NC\chi^{2}$) distribution with two degrees of freedom, with PDFs given by [96, 97]:

$$f_X(x) = \frac{1}{\alpha(\sigma_{s,r}^k)^2} e^{-\frac{\left(\left|\hat{h}_{s,r}^k\right|^2 + \left(\frac{x}{\alpha}\right)\right)}{(\sigma_{s,r}^k)^2}} I_0 \left(2\sqrt{\frac{\left|\hat{h}_{s,r}^k\right|^2 x}{\alpha\left(\sigma_{s,r}^k\right)^4}} \right) \tag{6.5}$$

and

$$f_Y(y) = \frac{1}{\sum_{i=1}^I (\sigma_{i,r}^k)^2} e^{-\frac{\left(\mathcal{I}^2 + y\right)}{\sum_{i=1}^I (\sigma_{i,r}^k)^2}} .I_0 \left(2\sqrt{\frac{\mathcal{I}^2 y}{\left(\sum_{i=1}^I \left(\sigma_{i,r}^k\right)^2\right)^2}} \right) \tag{6.6}$$

where $X = \alpha S$, $Y = \sum_{i=1}^I \left|h_{i,r}^k\right|^2$, $\alpha = \frac{P_s^k}{P_i^k}$ and $S = \left|h_{s,r}^k\right|^2$. I_0 is the zeroth-order modified Bessel function of the first kind, and $\mathcal{I}^2$ represents the sum of interference channel gain, given by $\mathcal{I}^2 = \sum_{i=1}^I \left|\hat{h}_{i,r}^k\right|^2$.

Note that the PDF in (6.6) represents the sum of I non-central chi-square independent random variables (i.r.v.'s) with parameters $(\sigma_{i,r}^k)^2$ and $\left|\hat{h}_{i,r}^k\right|^2, i = 1, 2, ..., I$, which also follows the non-central chi-square distribution with parameters $\sum_{i=1}^I (\sigma_{i,r}^k)^2$ and $\sum_{i=1}^I \left|\hat{h}_{i,r}^k\right|^2$ [104].

6.3 Total Achievable Data Rate

From (6.2), the instantaneous rate achieved by the s^{th} source over the k^{th} subcarrier with the assistance of the r^{th} relay is given by

$$R_{s,r}^k = \frac{1}{2} \log\left(1 + SINR_{r,d}^k\right) \tag{6.7}$$

Taking into account all available subcarriers and relay stations, and with the use of maximum ratio combining (MRC), the total sum rate achieved by the s^{th} source is given by

$$R_s = \sum_{r=1}^{R} \sum_{k=1}^{K} \rho_{s,r}^{k} R_{s,r}^{k} \tag{6.8}$$

The total network rate achieved by all sources and subcarriers is given by

$$R = \sum_{s=1}^{S} R_s \tag{6.9}$$

where $\rho_{s,r}^{k}$ denotes the subcarrier allocation index, given in (4.13):

The algorithm proposed in [94] is used to optimise the subcarrier allocation (without consideration of the relay-destination link). Equal power allocation is assumed across subcarriers, i.e., $P_s^k = P_{s,T}/K_s$ and $P_r^k = P_{r,T}/K_r$ $\forall s, r$, where $P_{s,T}, P_{r,T}$ represent the total transmit power for each source/relay and K_s, K_r represent the total number of subcarriers allocated to each source/relay.

6.4 Outage Probability

Outage probability is defined as the probability that the received SINR falls below a threshold Z. From (6.2), the outage probability (P_{out}) can be represented as:

$$P_{out} = P_r \left\{ \frac{X}{Y} \leq Z \right\} = P_r \left\{ X \leq YZ \right\} \tag{6.10}$$

Equation (6.10) can be written as [105]:

$$P_{out} = \int_0^{\infty} f_Y\left(y\right) \int_0^{yZ} f_X\left(x\right) dx dy \tag{6.11}$$

Let $a = \frac{\left|\hat{h}_{s,r}^{k}\right|^2}{\left(\sigma_{s,r}^{k}\right)^2}$, $b = \frac{1}{\alpha\left(\sigma_{s,r}^{k}\right)^2}$. Then, using (6.5) and (6.6), the outage probability in (6.11) becomes:

$$P_{out} = \int_0^\infty f_Y\left(y\right) \int_0^{yZ} be^{-a-bx} \sum_{n=0}^{\infty} \frac{(-1)^n}{(n!)^2} \left(\frac{2\sqrt{abx}}{2}\right)^{2n} dxdy$$
$$= \int_0^\infty f_Y\left(y\right) be^{-a} \sum_{n=0}^{\infty} \frac{(-1)^n (ab)^n}{(n!)^2} \int_0^{yZ} e^{-bx} x^n dxdy \tag{6.12}$$

Using 3.351(1) in [106], the second integration in (6.12) can be solved, resulting in

$$P_{out} = Bbe^{-a} \sum_{n=0}^{\infty} \frac{(ABab)^n}{(n!)^4} b^{-n-1} B^{-n-1}$$
$$\int_0^\infty y^n e^{-A-By} \gamma(n+1, bZy) dy \tag{6.13}$$

where $A = \frac{\mathcal{I}^2}{\sum_{i=1}^{I}\left(\sigma_{i,r}^k\right)^2}$, $B = \frac{1}{\sum_{i=1}^{I}\left(\sigma_{i,r}^k\right)^2}$ and $\gamma(n+1, byZ)$ represents the incomplete gamma function.

The integration in (6.13) can be solved using 6.455(2) from [106], then after performing some mathematical manipulations, the closed form outage probability is obtained:

$$P_{out} = Be^{-A-a} \sum_{n=0}^{\infty} \frac{(ABa)^n (bz)^{n+1} \Gamma(2(n+1))}{(n!)^4 (bz+B)^{2(n+1)}}$$
$${}_2F_1\left(1, 2(n+1), n+1; \frac{bz}{bz+B}\right) \tag{6.14}$$

where $\Gamma(2(n+1))$ represents the gamma function and ${}_2F_1$ represent the hypergeometric function. Again, the outage probability is independent of the relay-destination channel information. This means that the system performance can be evaluated without requiring knowledge about the relay-destination channel gain.

6.5 Complexity Analysis

This section discusses the resource allocation complexity based on the conventional and proposed schemes. In the conventional scheme, the resource allocation unit needs to know the channel quality between the source and the relay (SR link) as well as the channel between the relay and the destination (RD link); the achievable data rate is then calculated using (6.1). However, the proposed scheme requires the SR link information to perform the resource allocations and the achievable data rate is calculated using (6.2).

From (6.2), it is clear that the proposed scheme significantly reduces the complexity of resource allocation. Furthermore, it can be seen that the proposed scheme also reduces the load on the feedback channel since RD link CSI is ignored. The next section shows the reduction in algorithm complexity in terms of time required to perform the resource allocation based on the proposed and conventional scheme.

6.6 Numerical Results

This section presents the numerical results of the conventional and proposed single link (i.e., with and without the RD link) schemes. The proposed scheme has been evaluated in terms of total achievable data rate, outage probability and the Hamming distance between the outcomes of the proposed and the conventional algorithms. The sources and relays are distributed randomly within the cell in all cases. The conventional scheme considers both links in its subcarrier allocation algorithm (as described in [94]), while the proposed scheme ignores RD CSI. although the analysis and the numerical results of this chapter were made for the

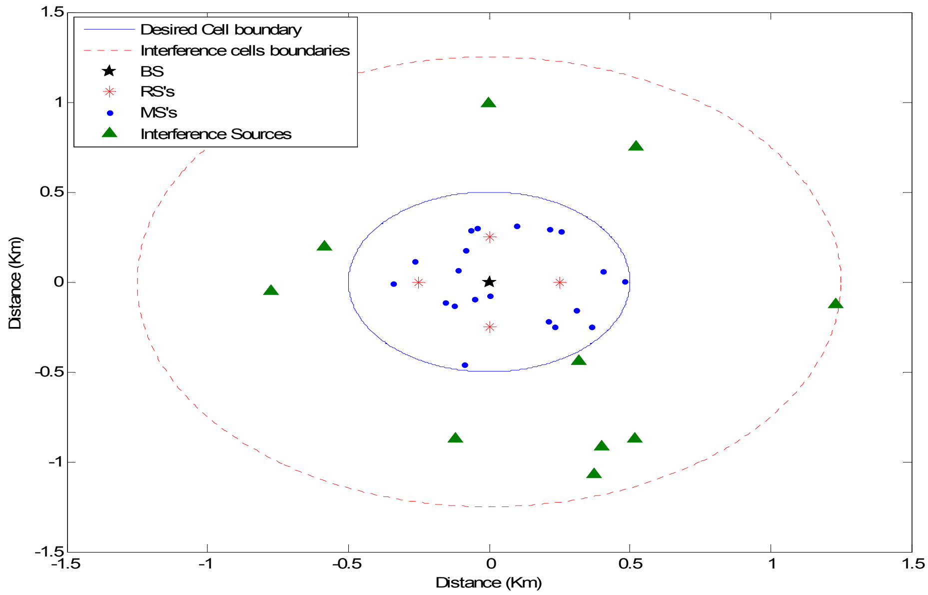


Figure 6.1: Network setup example, $S = 20$, $I = 10$ and $R = 4$

gaussian channel, the same procedures can be applied to derive the closed form outage probability for other channels as well such as Rayleigh fading channels.

Figure 6.1 shows an example of the network configuration used for simulation. In this example, a cell with a radius of 0.5 km is used (the inner circle in Figure 6.1). Four relay stations are fixed at 0.25 km from the BS and 20 users are randomly distributed within the cell. The ICI is received from the neighbouring cells (the area between the inner and the outer circles in this figure). In this example, ten ICI sources are assumed to be randomly distributed within the interference area. Note that this is a snapshot example; in the actual simulation, the users and ICI sources are generated and placed randomly in each iteration, and the simulation was repeated thousands of times to obtain reliable results.

The number of ICI sources is the parameter which has the greatest effect on performance. Therefore, system performance is shown as a function of the num-

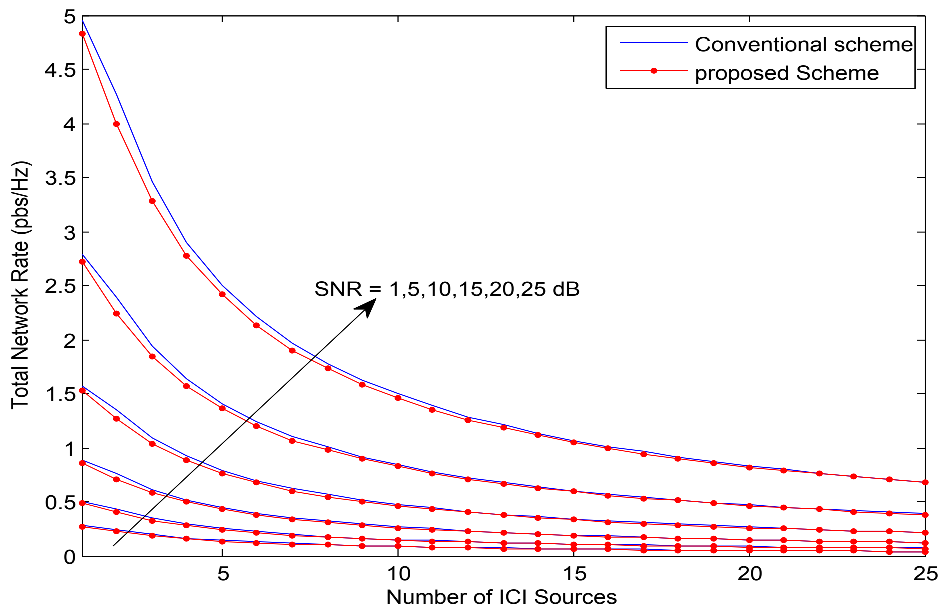


Figure 6.2: Total network rate vs. number of ICI sources for the conventional and proposed schemes, $S = 25$, $K = 128$ and $R = 4$

ber of interference sources. The number of users, number of relay stations and available subcarriers are set to 25, 4 and 128 respectively. While other values for these parameters may be used, simulation results consistently exhibit the same relative performance.

Figure 6.2 shows the total achieved data rate of the proposed resource allocation algorithm with and without considering the RD link. It can be seen that the total achieved data rate decreases as the number of ICI sources increases in both cases. As expected, the total network rate based on conventional scheme outperforms the proposed scheme at low levels of ICI. However, as the number of ICI sources increases, the achieved data rate for the proposed scheme approaches that of the conventional method. Hence, ignoring the RD link does not significantly affect the total achieved rate for high values of ICI.

Figure 6.2 shows that the difference between the performance of the conven-

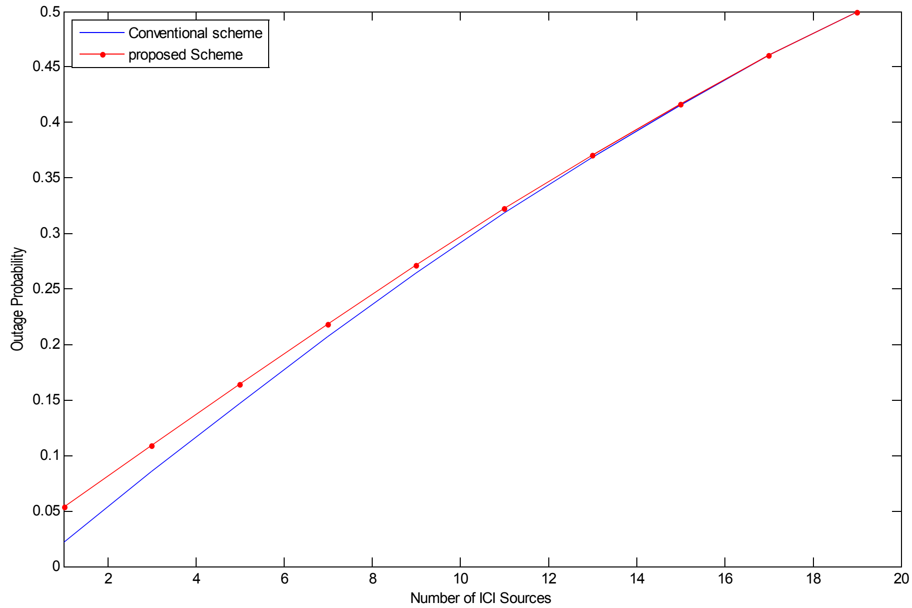


Figure 6.3: Outage probability vs. number of ICI sources for the conventional and proposed schemes, $S = 25$, $K = 128$ and $R = 4$

tional and proposed scheme is also affected by the SNR; specifically, the difference increases as SNR increases. This is because at high SNR, the channel gain between different nodes is high and hence the impact of the RD link increases compared to the low SNR case.

Figure 6.3 shows the outage probability of the proposed resource allocation algorithm with and without consideration of the RD link. It can be seen that the probability of outage increases as the number of ICI sources increased in both cases. As expected, in terms of the outage probability, the conventional scheme outperforms the proposed scheme at low levels of ICI. Once again, as the number of ICI sources increases, the outage probability of the proposed scheme approaches that of the conventional scheme. Hence, the RD link can be ignored at high level of ICI.

Figure 6.4 illustrates the normalised Hamming distance between the alloca-

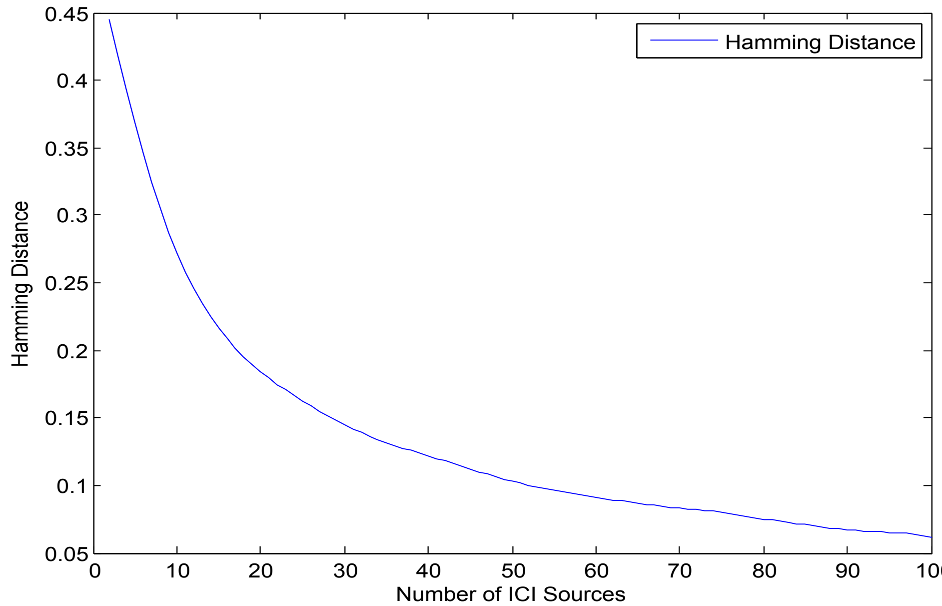


Figure 6.4: Hamming distance between the allocation vectors based on the conventional and proposed schemes, $SS = 25$, $K = 128$ and $R = 4$

tion matrix based on the conventional scheme (with RD link) and the proposed scheme (without RD link). It can be seen that the distance is large (about 40%) when the number of ICI sources is low (<5). This means that 40% of the allocation matrices resulting from the proposed scheme differ from those obtained from the conventional scheme. This distance decreases as the number of ICI sources is increased; that is, as the amount of ICI increases, the allocation matrix of the two schemes converges. This also supports the claim that the RD link can be ignored at high values of ICI.

Figure 6.5 illustrates the outage probability versus the number of users for different ICI levels. The conventional and proposed schemes exhibit near-identical behaviour, especially when the number of ICI sources is high. Regardless of network size, increasing the number of users will result in an increased outage probability, even if the RD link CSI is completely ignored. Thus, the impact of the RD link on overall network performance is independent of the number of

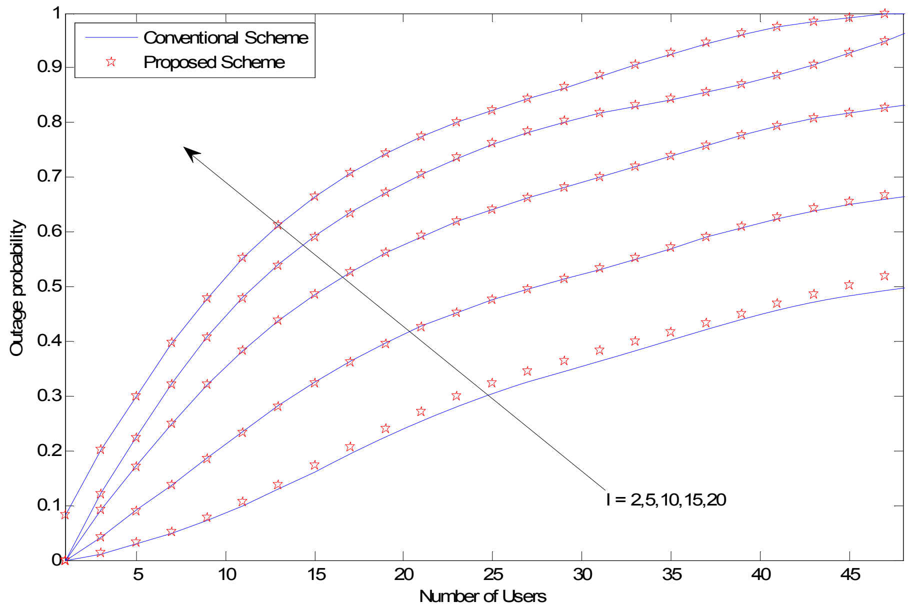


Figure 6.5: Outage probability vs. number of users for different number of ICI, $K = 128$ and $R = 4$

users.

Finally, Figure 6.6 demonstrates the percentage of the time complexity reduction (in seconds) using the proposed scheme over the conventional scheme in percentage. The two algorithms were implemented using MATLAB on the same machine with exactly similar input parameters. The CPU time required to perform the resource allocation using each scheme was recorded, with the result averaged over several thousand trials. It can be seen from Figure 6.6 that the proposed scheme significantly reduces the required execution time over the conventional scheme for different numbers of users. As the number of users increases, the complexity of both algorithms also increase, hence the execution time difference between the two algorithms becomes insignificant compared to the high complexity (execution time) of each algorithm. Therefore, beyond a certain number of users (approximately 43 in this example) the time complexity reduction percentage saturates. On average, the proposed scheme outperforms

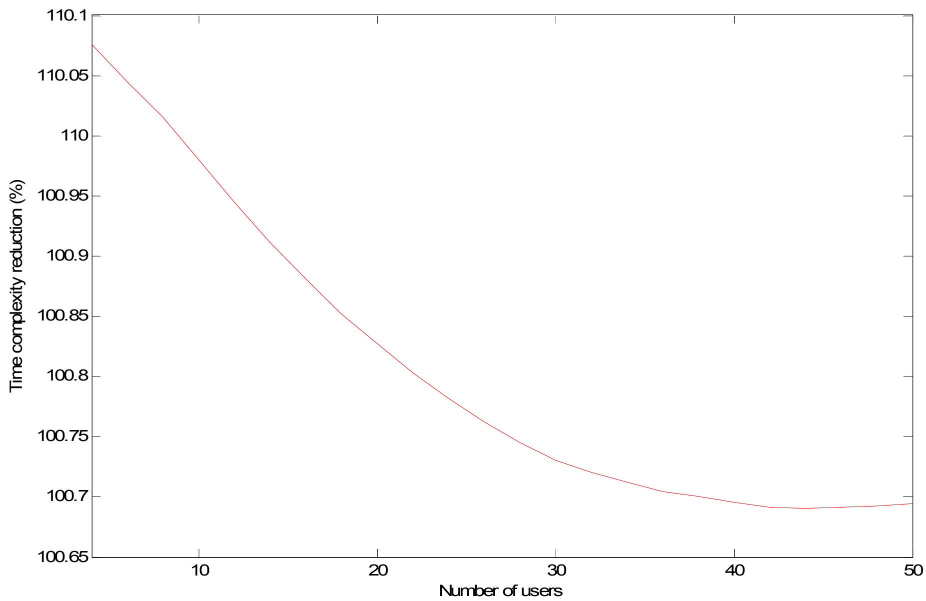


Figure 6.6: Average execution time reduction using the proposed scheme over the conventional scheme, $K = 128$, $I = 4$ and $R = 4$

the conventional approach in terms of execution of about 108.176%.

6.7 Summary

This chapter investigates the impact of the RD link, taking into account the ICI in multi-cell environment and assuming the availability of partial channel state information only. The closed form outage probability has been derived for the proposed scheme. The mathematical findings and simulation results show that the impact of the link between the relay station and the destination is very low when the ICI is high. Thus, the system performance can be evaluated independently of the RD channel in these situations. Moreover, the proposed scheme is significantly simpler and greatly reduces overall execution time compared with the conventional approach.

Chapter 7
CONCLUSION AND FUTURE RESEARCH

7.1 Overview

In this thesis, resource allocation algorithms were developed for interference limited OFDMA based cooperative relay networks. Furthermore, mathematical frameworks for performance metrics, such as the outage probability and data rate were developed assuming only partial channel state information is available at the resource controller.

Cooperative relay networks are used to maximise the total network channel capacity by exploiting the spatial diversity. A conventional point-to-point OFDMA-based receiver would decode the information received directly from the source node and would regard other received signals as interference, whereas in the case of cooperative relay networks, the receiver combines the received signal through the direct link as well as the received signals through one or more relayed links. Hence, the system throughput is increased. However, the overall system complexity is increased by introducing these relay stations. In particular, the resource distribution and management becomes more challenging as the available bandwidth is limited by nature and the excessive reuse of the available frequency band increases the interference effects.

In Chapters 4, 5 new resource allocation algorithms were developed to increase the system capacity in terms of total achievable data rate while maintaining a satisfactory degree of fairness among users. In chapter 6, mathematical performance models of cooperative relay networks were developed based on partial channel state information to assess cooperative relay system performance using different physical network parameters. A brief summary and conclusion remarks are presented in the following section.

7.2 Conclusion Remarks

In Chapter 4, a low complexity distributed resource allocation algorithm has been proposed for the multi-cell OFDMA-based cooperative relay network.

The proposed algorithm assumes the channel state information to be fully available at the resource controller. Grouping the subcarriers based on minimum ICI into R significantly reduces the algorithm complexity by a factor of $\approx \frac{1}{R}$. Obviously, the proposed resource allocation algorithm requires less processing time to allocate the resources; consequently it can effectively operate in real time mobile communication systems.

Furthermore, the results show that this significant complexity reduction did not affect the other performance metrics (such as total network data rate) in the single cell scenario. On the contrary, the total network achievable data rate of the proposed algorithm is improved over the conventional algorithm in the multi-cell scenario. In additional to that, the impact of the proposed algorithm is higher as the number of cells is increased.

In Chapter 5, the proposed algorithm in Chapter 4 has been extended to include new constraints in the optimisation problem by which the resource allocation algorithm is designed to take into account the necessity of a certain user to be allocated resources.

Chapter 5 defines two functions, called utility and detrimental functions, and the optimisation problem aims to maximise the first one (i.e., utility) while minimising the second function (detrimental). As in Chapter 4, CSI was assumed to be fully known by the resource controllers at the beginning of this chapter, and then the performance of the algorithm was evaluated based on the availability of only partial channel state information (PCSI).

In addition to the complexity reduction and data rate improvements as discussed in the previous chapter, this chapter also showed the system performance can be further improved by including those utility and detrimental functions. Furthermore, the proposed algorithm in this chapter achieves another important performance metric which is fairness. Thus, the total network data rate is not maximised at the expense of one or more users with weak channel conditions. This is also important because users who subscribe to the same mobile system services should not be disadvantaged when the resource controller tries to improve the overall network data rate if their channel gain is low. Furthermore, the proposed power allocation algorithm uses the available information on the ICI to optimise the power allocation across subcarriers.

Taking PCSI into account, it was shown that more accurate prediction of the network achievable data rate can be obtained when considering PCSI. The result shows that the accuracy of the predicted network data rate is highly dependent on the estimation error. Thus, it is more realistic to consider PCSI when allocating the resources so that the actual minimum achievable data rate is guaranteed.

Chapter 6 extended the analysis of the multi-cell OFDMA based cooperative relay network with PCSI and investigates the impact of the relay-to-destination (RD) link. A mathematical framework has been developed and the closed form outage probability has been derived.

The mathematical findings and simulation results show that the impact of the link between the relay station and the destination is very low when the ICI is high. The provided mathematical model and framework can be used to quantify the level of interference by which the RD link can be totally ignored. It should be noted that ignoring the RD link means less feedback traffic on the backhaul network, consequently the overload on the backhaul network will be reduced significantly and the resources can be used to carry information data instead of feedback data. Thus the data rate can be further improved.

In conclusion, the system performance of the OFDMA-based cooperative relay network can be significantly improved by implementing the proposed algorithms. Furthermore, the proposed algorithms and mathematical framework can be used to evaluate/analyse the system performance of similar network scenarios.

7.3 Future Research Directions

In this thesis, resource allocation algorithms have been developed for the multi-cell OFDMA with the assistance of amplify and forward relay stations. Moreover, a mathematical framework for the aforementioned system with partial channel state information has been also developed. Various system and design parameters have been considered for the purpose of obtaining accurate and practical results. However, the research in the area of resource allocation cannot be covered in a single thesis. Therefore, more related research issues are to be considered in the future, the work in this thesis can be extended to cover many related research issues including but not limited to the following key points:

- **Cooperative Base Stations**: In this thesis the cooperation was only limited to relay stations, while each one of the base stations has no knowledge about the neighbouring BSs performance and load, hence the BS will not take into account other BSs performance when it maximises its own system performance (i.e., fully distributed system). However, nowadays it becomes possible to share some information between the neighbouring base stations through a wireless or wired link. Therefore, the base stations can exchange information regarding the load, the utilised RS's and the requirement (e.g., data rate, SNR). Based on this information each BS will select the most suitable RS(s) in which the overall system performance can be enhanced. It would be interesting to investigate the impact of this cooperative base station on the system performance when performing resource allocation. Furthermore, it is interesting to study the trade-off between the data rate gain versus the added complexity to the resource allocation algorithms.

- **Other relaying protocols**: The Amplify and Forward relaying protocol has been considered throughout this thesis. However, the proposed algorithms can be modified to work with different relaying protocols (such as, decode and forward, estimate and forward, etc.), so it is an interesting issue to investigate the system performance of the proposed algorithms using different relaying protocols and to make a comparison between them in order to determine which relaying protocol works better in which circumstance. Furthermore, the mathematical framework was developed taking into account the AF relaying protocol; this mathematical framework can be obtained for the other relaying protocols by following the same steps as presented in this thesis.

- **Resource Allocation in Cognitive Radio**: Recently, the resource allocation for cognitive radio has attracted the attention of many researchers. The idea is to utilise the licensed radio frequency by unlicensed users when these frequency channels are not in use by the licensed users. In this case, the priority will be always given to the ones who own the frequency channels. However, the unlicensed users may be allowed to use the channel under certain conditions (such as, channels are not in use or no interference will be caused by allocating the channels to other unlicensed users or any other condition). Therefore, different constraints have to be considered for such resource allocation problems. Thus, the proposed resource allocation algorithms can be extended to include those parameters and constraints in order to evaluate the algorithms for the cognitive radio technology.

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