SPECTRUM SHARING IN WIRELESS CELLULAR NETWORKS

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Contents

Abstract

To support the explosive growth of wireless services, wireless cellular networks are facing escalating spectrum scarcity problem nowadays. Fixed and exclusive allocation of radio spectrum among telecom operators and generations of cellular technologies, which is widely adopted currently, has been proven to be inefficient in utilizing the radio resource. In particular, as cellular technology evolves, the frequency bands allocated to the new generation cellular networks are getting crowded, while those maintained by legacy cellular networks become under-utilized. Thus, by allowing the new generation cellular networks to dynamically access to the licensed bands of legacy cellular networks has attractive capability in improving spectrum utilization and mitigating spectrum scarcity. Such demand of spectrum sharing gives birth to spectrum refarming (SR) technique which is a new paradigm of spectrum sharing of cellular networks. Since Orthogonal-Frequency Division Multiple Access (OFDMA) is the major radio access technique for the new generation cellular networks, the spectrum sharing between OFDMA and Code Division Multiple Access (CDMA) or Global System for Mobile Communications (GSM) systems is of most interest here. In this thesis, we mainly focus on the SR technique for OFDMA/CDMA coexistent system with different types of infrastructure sharing, including active infrastructure sharing, passive infrastructure sharing and non-infrastructure sharing.

First, a fundamental SR model is constructed with active infrastructure sharing where the OFDMA and CDMA systems operate in the common frequency band with sharing of

cell site and base station (BS) antenna. The user signal-to-interference-plus-noise-radio (SINR) is quantified based on which the interference margin provided by CDMA system is predicted by OFDMA system. With the interference margin, the OFDMA system allocates power and subcarrier resource efficiently with protection to the CDMA system. Relying on the CDMA inner power control, the spectral efficiency of the SR system is further improved by exploiting the interaction between OFDMA and CDMA systems.

Next, the fundamental SR model is extended into passive infrastructure sharing model where the OFDMA and CDMA systems share the common cell site but adopt separate antennas at BS. This infrastructure sharing would be popular, as it can achieve higher SR throughput compared with the active infrastructure sharing. A realistic and crucial problem is that the channel power gain from secondary transmitter (STx) to primary receiver (PRx) is hard to know due to the lack of direct communication between the two systems in practice. To solve this problem, we propose a novel resource allocation method for OFDMA system. Somewhat surprisingly, this method can sufficiently protect the CDMA system despite the channel power gain aforementioned is unavailable. Furthermore, utilizing the CDMA inner power control, two innovative resource allocation schemes are proposed for OFDMA system that farthest exploit the sharing opportunity provided by CDMA system. Without direct signalling between the two systems, OFDMA system can compel CDMA system to operate at the optimal status by controlling its own transmission strategy.

Finally, we relax the SR model from infrastructure sharing where the two systems share no infrastructure. This naturally invokes the SR application in the heterogeneous networks where multiple OFDMA small cells share the licensed spectrum of CDMA macrocell network. We quantify the interference between the two systems, based on which the OFDMA resource allocation problem is formulated and solved efficiently. The problem of unavailable channel power gain from STx to PRx is also considered for which solution is proposed.

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List of Abbreviations

2G	second generation
3G	third generation
4G	fourth generation
5G	fifth generation
ARQ	automatic repeat requests
AWGN	additive white Gaussian noise
BS	base station
CCI	cross-channel interference
C-CSI	cross channel state information
CDF	cumulative density function
CDG	CDMA Development Group
CDMA	Code Division Multiple Access
CIPA	channel-inverse power allocation
CP	cyclic-prefix
CR	cognitive radio
CSCG	circularly symmetric complex Gaussian
CSI	channel state information
DSA	dynamic spectrum access
DS-CDMA	direct spreading Code Division Multiple Access
eNodeB	E-UTRAN NodeB

EPA	equal power allocation
FCC	Federal Communications Commission
FDD	frequency-division duplexing
FDMA	Frequency Division Multiple Access
FFT	fast fourier transform
GSM	Global System for Mobile Communications
HetNet	heterogeneous networks
IFFT	inverse fast Fourier transform
IDA	Infocomm Development Authority of Singapore
i.i.d.	independent and identically distributed
ISI	inter-symbol interference
KKT	Karush-Kuhn-Tucker
LLN	law of large number
LTE	long-term evolution
LTE-A	long-term evolution advanced
MBS	macrocell base station
MF	match filter
MIMO	multiple-input and multiple-output
MMSE	minimum mean square error
MUD	multi-user diversity
MUE	macrocell user equipment
Ofcom	Office of Communications
OFDMA	Orthogonal Frequency-Division Multiple Access
OSA	opportunistic spectrum access
PDF	probability density function
PRx	primary receiver
PSD	power spectral density
PTx	primary transmitter

QoS	Quality-of-Service
RMT	random matrix theory
SBS	small cell base station
S-CSI	self channel state information
SINR	signal-to-interference-plus-noise ratio
SISO	single-input and single-output
SNR	signal-to-noise ratio
SR	spectrum refarming
SRx	secondary receiver
STx	secondary transmitter
SUE	small cell user equipment
s.t.	subject to
TDD	time-division duplexing
WCDMA	wideband Code Division Multiple Access
w.r.t.	with respect to
ZTE	Zhongxing Telecommunication Equipment Corporation

List of Notations

$\triangleq$	defined as
$\mathcal{CN}(0, \sigma^2)$	the distribution of a CSCG random variable with zero mean and variance σ^2
$\arg\max f(x)$	the value of x that maximizes the function $f(x)$
$\boldsymbol{X}_{M\times N}$	the matrix of dimension $M \times N$
$\boldsymbol{x}_{1\times N}$	the vector of dimension $1 \times N$
$(\cdot)^T$	transpose of a matrix or a vector
$(\cdot)^H$	conjugate transpose of a matrix or a vector
$\boldsymbol{I}_{N\times N}$	$N \times N$ identity matrix
$\mathrm{diag}(\cdot)$	diagonal matrix
$\mathrm{Tr}\{\boldsymbol{X}\}$	trace of a matrix $\boldsymbol{X}$
$\lvert \cdot \rvert$	absolute value
$\lVert \cdot \rVert$	the Euclidean distance
$\mathbb{E}[\cdot]$	expectation
$(x)^+$	max(x, 0)

Chapter 1

Introduction

When equipped with high-speed processor and bulk storage, the modern mobile terminals, such as mobile phone, laptop and intelligent robot are able to carry out miscellaneous tasks for human beings. A great deal of information that needs to be transmitted via wireless medium motivates various types of wireless network, such as wireless ad-hoc network, wireless mesh network and wireless cellular network. Among them, the wireless cellular network is centralized in nature where the mobile infrastructure known as cell site or base station (BS) will play an important role in organizing and coordinating transmission. The centralized processing enabled by BS offers desirable features for cellular network. The major signal processing and storage are executed by BS, thus low power of mobile terminal is allowed. Moreover, due to the exponential loss of signal power along the distance, radio spectrum can be reused for the coverage of a wide geographical area. Therefore, the wireless cellular network has been widely deployed to reliably provide the worldwide ubiquitous wireless connections.

To accommodate the ever-increasing data-centric bandwidth-demanding wireless services, cellular technology has been evolved from second generation (2G) to third and to fourth generations (3G, 4G). To support the 1000 times growth of wireless traffic in the coming decade, fifth generation (5G) is under preparation [3, 4, 5, 6]. As physical resource such as radio spectrum and mobile infrastructure is the enabler of cellular networks, intelligent resource allocation is essentially important when a new generation of

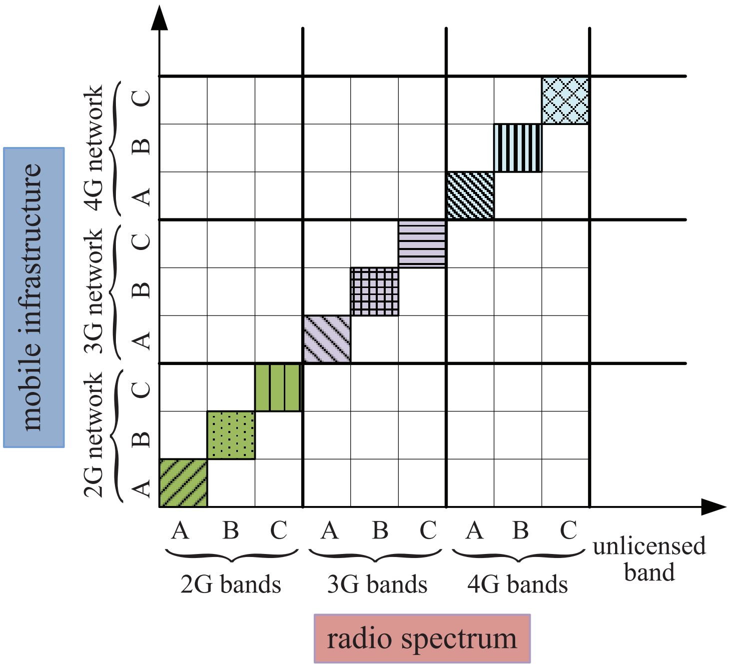


Figure 1.1: Static occupancy of radio resource and mobile infrastructure. A, B and C are dummy telecom operators.

cellular network being deployed on top of older ones. In this thesis, we will focus on the design of advance resource allocation schemes for the next generation cellular networks.

1.1 Static Physical Resource Allocation in Cellular Networks

Two dimensions of physical resource are indispensable for deploying cellular network, which are radio spectrum and mobile infrastructure. As shown in Fig. 1.1, when a telecom operator, such as *operator A* holds a licensed band for 4G cellular operation (horizontal dimension), it installs mobile infrastructures for exclusively used by its own 4G networks (vertical dimension). It is the same with other operators and other generations of cellular networks. Such static allocation of physical resource requires heavy investments from telecom operators when a new generation of cellular network being deployed, including the cost of retaining the licence for exclusively occupying the particular frequency bands and the cost of installing new mobile infrastructures.

1.1.1 Fixed Allocation of Radio Spectrum

Under the management of government agency, each generation of cellular network holds a licence to exclusively occupy specific spectra for its coverage of a geographical area and for a long period of time. This static allocation of spectrum successfully prevents the interference among cellular networks, however, it blocks the available spectra quickly. By 2004, 95% radio frequency has been already allocated to license holders. Due to the severing spectrum scarcity, obtaining a spectrum licence becomes more pricey and competitive. In the end of 2013, Infocomm Development Authority of Singapore (IDA) distributed 4G licences to the three operators with total cost of 360 million Singapore dollars [7]. In the same year, Office of Communications (Ofcom) auctioned a total 250MHz spectrum for 4G operation that costs the five operators in UK over 2.3 billion pounds [8]. It has not accounted for the cost of 2G and 3G licences which have increased by five times since 2010 [9]. With such heavy investment on the spectrum authorization, the operators are keen on maximizing spectrum utilization to offer better services to their subscribers.

1.1.2 Exclusive Usage of Mobile Infrastructure

Besides the investment on spectrum licence, planning and installing the infrastructure for new generation cellular networks is also costly. One of the telecom operators in UK, Vodafone has spent nearly four billion pounds to install its 3G mobile infrastructures. In Germany, Mannesmann invests 10 billion Deutsche Mark to deploying its 3G infrastructures [10]. Due to the faster decay of signal strength at the higher frequency, the coverage of a single 4G BS is smaller than that of 2G and 3G. Thus, to fulfill the first stage coverage, more BSs are needed involving higher investment on the infrastructure deployment.

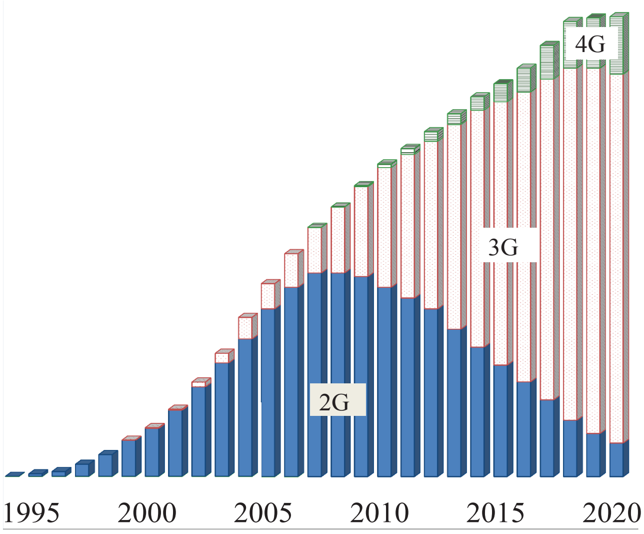


Figure 1.2: Evolution of subscriptions as cellular network technology evolves (Source: CDG, ZTE and [1]).

It is worth noting that when the new generation of cellular network (e.g., 4G) is introduced, the mobile traffic will gradually migrate from the older generation (e.g., 2G/3G) networks towards the new one [11]. Fig. 1.2 illustrates the evolution of subscriptions as cellular technology evolves from one generation to another. As can be seen, the legacy networks will not cease operations immediately after the new one is deployed, and in fact they will have to continue to provide services to the legacy users for a significant period of time before being phased out. During the transition period, the spectrum assigned to the legacy networks will experience low spectral efficiency when the number of legacy users is lower than the designed network capacity. On the other hand, the move of legacy subscribers also reduces the operation burden of mobile infrastructures. For maintaining the legacy services, the infrastructures still have to be in “on” status for cooling down equipments and maintaining the backhaul operation, which are the major electricity consumption. This can be seen as the under-utilization of mobile infrastructures.

In summary, with static and exclusive physical resource occupancy, both the radio spectrum and mobile infrastructure of legacy cellular networks will experience aggravating under-utilization as the new generation cellular networks getting mature. Thus, a new

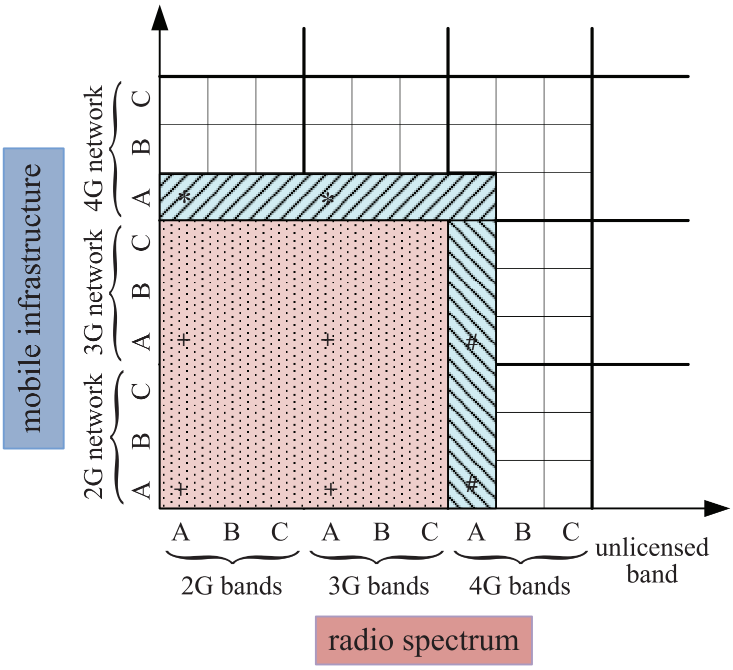


Figure 1.3: Dynamic occupancy of radio resource and mobile infrastructure.

paradigm of physical resource allocation for the new generation network is demanded to mitigate the spectrum tension and monetary investment by improving the physical resource utilization of the legacy cellular networks.

1.2 Dynamic Physical Resource Allocation in Cellular Networks

The utilization of spectrum can be profoundly improved by dynamic spectrum access (DSA) which is enabled by Cognitive Radio (CR) techniques [12, 13]. Due to the underutilization of the licensed spectrum of cellular networks, the application of CR techniques in the cellular scenario becomes attractive. On the other hand, infrastructure sharing is emerging as an appealing technique to improve the utilization of mobile infrastructure [14]. Take *operator A* in Fig. 1.3 that deploys 4G cellular network as an example. The horizontal bar with diagonals shows that the 4G network of *operator A* can operate with its own infrastructure but on the 2G and 3G bands that licensed to all the three operators. This represents a pure dynamic spectrum sharing. The blocks labeled "$*$" indicate the intra-operator spectrum sharing while the remained blocks indicate the inter-operator spectrum sharing. The vertical bar with diagonals shows that all the mobile infrastructures of 2G and 3G can be shared by the 4G cellular networks operated on the bands licensed to *operator A*. This represents a pure infrastructure sharing. Similar with spectrum sharing, the blocks labeled "#" indicate the intra-operator infrastructure sharing while the remained blocks indicate the inter-operator infrastructure sharing. Furthermore, the spectrum sharing and infrastructure sharing can be jointly deployed as indicated by the dotted area, where the blocks with "+" indicate the intra-operator sharing and the remainder indicate the inter-operator sharing. By jointly sharing the spectrum and infrastructure of 2G and 3G belonging to all the operators, the utilizations of the two kinds of physical resource can be simultaneously improved. Technically, this two-dimensional sharing provides us more freedom for designing the resource allocation scheme for next generation cellular networks.

1.2.1 Dynamic Spectrum Access: CR-Enabled Cellular Networks

By allowing the OFDMA-featured 4G cellular network to share the spectrum of legacy cellular networks, the sharing opportunities provided by 2G and 3G cellular networks are different in principle. In 2G GSM system, as the number of subscribers decreases, there are some subbands that sit idle at a given time. Thus, the 4G cellular system can opportunistically access these idle 2G subbands without interfering the 2G users. Such a dynamic spectrum access can be realized by either sensing the idle subbands or dynamically reserving subbands for 2G transmission if the coordination between the two systems is available. Different from 2G system, as the subscribers of 3G CDMA system decreases, the interference among users decreases, meaning that additional interference can be tolerated by the legacy users, which is known as interference margin. When a 4G

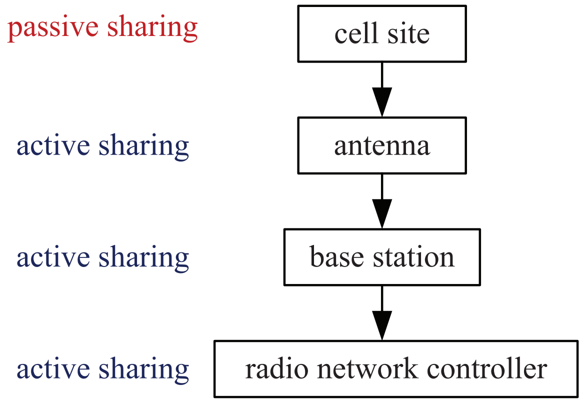


Figure 1.4: Infrastructure sharing scenario [2].

cellular system dynamically access to the 3G spectrum, the interference margin defines the maximal interference power that can be introduced by the 4G system.

The opportunity for the new generation network to dynamically access to 2G and 3G licensed bands gives birth to a new paradigm of spectrum sharing for cellular networks, which is named as spectrum refarming (SR). SR is an innovative spectrum sharing technique which allows different generations of cellular networks to operate in the same radio spectrum. With SR technique, the overall spectral efficiency of cellular networks can be greatly improved. Since radio spectrum is a limited and expensive resource, SR is considered as a promising solution for mobile service operators not only to provide cost effective services to their customers, but also to solve the spectrum scarcity problem faced by them.

1.2.2 Mobile Infrastructure Sharing

Recognizing the paradox of the costly investment for installing new mobile infrastructure and the under-utilization of mobile infrastructures of cellular networks, many countries around the world have proposed to share the mobile infrastructure among generations of cellular networks. Spain, UK, Brazil and Malaysia, etc have promoted the sharing of 3G infrastructures [15]. Considering different degrees of sharing, mobile infrastructure sharing can be mainly divided into two types, i.e., passive sharing and active sharing which is shown in Fig. 1.4. Passive sharing allows operator(s) to share the passive elements in their radio access networks, such as cell sites, building premises, masts, etc, which involves the least sharing of infrastructure elements. In the active sharing, operator(s) can share not only the passive elements, but also the active elements, such as antennas, NodeB, radio network controller, etc [2]. Since the infrastructure elements are deeply shared in the active sharing, stringent regulation is required.

1.3 Objectives

Since the SR technique and mobile infrastructure sharing can respectively improve the spectrum and infrastructure utilization, the variant combinations of them becomes attractive for efficiently designing the next generation of cellular networks. This thesis target to propose SR models with different types of mobile infrastructure sharing. Resource allocation problems in the proposed models are formulated and solved. In particular, the coexistence of OFDMA-based 4G and CDMA-based 3G cellular networks is under consideration. The objectives of the thesis can be summarized as follows.

(i) To gain the fundamental insight in the SR between OFDMA and CDMA system, an uplink OFDMA/CDMA synchronized system with active infrastructure sharing, i.e., the cell site and BS antenna are both shared by the two systems, is considered. The signal-to-interference-plus-noise ratio (SINR) of CDMA user accounting for the interference from OFDMA users are quantified for the first time, based on which the interference margin provided by CDMA system can be determined. Then, the OFDMA system allocates the user resource to maximize its throughout while guaranteeing the interference to CDMA users below the interference margin.

(ii) Next, the SR model with active mobile infrastructure sharing is extended to the passive mobile infrastructure sharing where only cell site is shared while the BS antennas of two systems are separated. When compared with active infrastructure sharing, such sharing offers more flexibility in negotiation and regulation between cellular networks to implement SR techniques. A critical information that facilitates the OFDMA system to share the CDMA spectrum is the channel power gains from OFDMA users (secondary transmitter) to CDMA receiver at BS (primary receiver). However, since the CDMA system is reluctant to be upgraded and the direct communication between the primary and secondary systems is unavailable, the required channel power gains are very difficult to obtain. Faced with this realistic problem, the second objective in this thesis is thus to facilitate the SR technique with passive infrastructure sharing despite the interference channel power gains are unavailable. Moreover, to farther exploit the sharing potential, advanced resource allocation schemes are needed to be designed for OFDMA system.

(iii) The final objective of the thesis is to apply the SR technique for heterogeneous networks, where there is no infrastructure sharing. In this scenario, the OFDMA small cells can share the spectrum of CDMA macrocell with intelligent resource allocation. To control the interference from small cells to macrocell users, the problem that the interference channel power gains are unavailability is also considered.

1.4 Major Contributions of the Thesis

The SR between OFDMA and CDMA systems is developed based on the conventional CR techniques. But there are still many practical difficulties that have not been solved in the literatures, including

- **System model and interference margin.**

  The infrastructure sharing has not taken into consideration in the system modeling of the conventional spectrum sharing studies. In fact, the type of infrastructure sharing affects the sharing protocol and interference analysis. For example, when

BS antenna is shared, the secondary uplink transmission can only share the spectrum of primary uplink transmission. However, when BS antenna is not shared, the secondary uplink can share the spectrum of primary of downlink transmission if the interference cancelation is enabled. In the literatures, interference margin is either a given value, or a function of primary system instantaneous parameters, such as S-CSI. The former one is lack of justification on its protection to the primary system, and the latter one requires the instantaneous information sharing between primary and secondary systems, which is unavailable in practice. For CDMA primary system, the interference margin is also related to the spreading codes adopted by each CDMA user, which are independently random. Therefore, using the conventional method to evaluate the interference margin is infeasible for the SR system for OFDMA and CDMA coexistence.

The thesis, for the first time, proposes to model the SR system by considering different kinds of infrastructure sharing, based on which the interference margin without instantaneous primary system information is evaluated by asymptotic analysis with large-dimensional *random matrix theory* (RMT) and *law of large number* (LLN). With the proposed interference margin evaluation method, the normal service CDMA system can be protected.

- **Interference prediction without C-CSI.**

  Another critical problem in the SR system is the unavailability of C-CSI which makes the interference prediction difficult for the secondary system. The schemes proposed in the existing literatures either requires the re-design of the transmission frame, i.e., a probing phase is added before the data transmission phase, or special signal waveform and fast-converged power control are needed.

  To solve the problem aforementioned, the thesis analyzes the structure and property of the solution provided by convex optimization theory. Then, a simple robust scheme is proposed to predict the interference without C-CSI. The thesis further proposes iterative-based resource allocation schemes to exploit the sharing opportunity provided by the primary system to improve the secondary system performance.

- **Accurate and efficient resource allocation.**

  In the literatures, the resource allocation schemes for spectrum sharing system assumed the fixed operation parameter of the primary system. Thus, the they are the secondary system resource allocation schemes. In fact, when the primary system adopts inner power control, the secondary system resource allocation will affect the primary operation status, which in turn affect the interference margin that constraints the secondary system resource allocation. This means that, the resource allocations of primary and secondary system are coupled by the primary system inner power control. Therefore, the secondary system resource allocation by assuming fix primary operation is inaccurate and inefficient.

  The thesis formulates the problem for jointly allocating the OFDMA and CDMA resource, and high efficient optimization solution and algorithm are proposed. Although the resources of OFDMA and CDMA systems are joint optimized in mathematics, in practice, the algorithm is only executed by the OFDMA system, and the CDMA system can operate in the optimal status with the help of inner power control.

The main contribution of the thesis can be summarized as follows.

SR with Active Mobile Infrastructure Sharing

The thesis first proposes an SR model for OFDMA/CDMA coexistent system where the OFDMA and CDMA systems share the same cell site and same BS antenna. This sharing could be possible for both CDMA and OFDMA networks belonging to the same operator or not. Since the BS antenna is shared, the interference channel power gain equals the channel power gain of the secondary signal channel (OFDMA user to the BS antenna), thus can be easily known by OFDMA channel state estimation mechanism. This is an interesting and fundamental model for the proposed SR system, from which various studies could be made. The signal model of the proposed SR system is established. Then the asymptotic SINR of the CDMA and OFDMA users in the proposed SR system is quantified by using the RMT and the LLN, from which the interference margin tolerable by CDMA system is derived. Different from the majority of the existing literatures, the interference from CDMA system to the OFDMA system is also taken into consideration for evaluating the SINR of OFDMA users. Finally, by using the interference margin together with the transmission power constraints, the resource allocation problem of the OFDMA system is formulated and solved through dual decomposition method. Despite the infrastructure sharing that the proposed SR system adopts, it can be seen that the evaluation of CDMA SINR and interference margin are applicable to any other kinds of infrastructure sharing. Therefore, this study is can be regarded as a fundamental for the following studies.

SR with Passive Mobile infrastructure Sharing

With the minimum sharing of infrastructure elements, passive mobile infrastructure sharing provides the SR techniques with more flexibility. The thesis first proposes an SR model for the uplink OFDMA/CDMA coexistent system, where the cell site is shared and different receive antennas at BS are exclusively used by the two systems. Given the interference margin evaluated by the OFDMA system, the OFDMA resource allocation problem is formulated to maximizes the OFDMA throughput while protecting the CDMA services. Since the two systems adopts separate receive antennas at the BS, the OFDMA system needs the channel power gains from its users to the CDMA receiver at BS, which is rarely available in practice. This is particularly true for the proposed system, as the CDMA system is reluctant to be upgraded as legacy it is. To deal with this realistic problem, the thesis proposes to use the signal channel power gains in stead of the required interference channel power gains for OFDMA system to predict the interference power introduced to CDMA users during the resource allocation. Via rigorous theoretical proof, it is shown that the proposed scheme can provide sufficient protection to CDMA users. This shows that without interference channel power gain, the OFDMA system still be able to share the CDMA spectrum with enough protection to CDMA users. By observing that there is a gap between the predicted interference and actual interference suffered by CDMA users with the proposed scheme, the thesis further propose an iterative resource allocation scheme executed by OFDMA system to exploit the gap, with a given fixed CDMA target receive power. This scheme iteratively exploits the CDMA inner power control which is novel and rarely studied by the literatures. The thesis further proposes a resource allocation scheme which considers an adaptive CDMA target receive power which can vary within a feasible region. This scheme is executed by OFDMA system and pushes the CDMA system to response, and eventually makes the two systems operate at the optimal status, which helps the OFDMA system to farthest exploit the spectrum sharing opportunity provided by the CDMA system. This interaction between the primary and secondary systems is novel and interesting compared with the existing CR literatures.

SR in Heterogeneous Networks

The thesis proposes an SR model in which a legacy CDMA macrocell networks is overlaid with multiple OFDMA small cells. In order to control the interference from OFDMA small cells to CDMA macrocell users and to predict the interference margin tolerable by the CDMA macrocell network, the downlink transmissions of OFDMA small cells are synchronized with the uplink transmission of the CDMA macrocell. In this scenario, the interference margin determination is still the same with the previous scenarios. The difference lies in the quantification of the interference between the OFDMA and CDMA systems. For the interference from the OFDMA to CDMA system, the interference will be significantly different among the small cells due to the variant distance-based path loss. For the interference from the CDMA users to the OFDMA users in each small cell coverage, it is also different among the small cells but is uniform within a small cell. The resource allocation problem for OFDMA small cells is formulated and transformed for achieving a highly efficient algorithm. By noticing that the small-scale fading of the channel from small cell BS to the macrocell BS is difficult to obtain, the thesis further investigates the resource allocation problem for the OFDMA small cells without such channel state information.

1.5 Organization of the Thesis

The remainder of the thesis is organized as follows. In Chapter 2, an elaborative literature review on spectrum sharing techniques and infrastructure sharing is presented. In Chapter 3, the thesis introduces and solves the fundamental SR model for cellular networks with active mobile infrastructure sharing and formulate the resource allocation problem. In Chapter 4, the thesis studies the SR for cellular networks with passive mobile infrastructure sharing. The realistic problem that the interference channel power gains is unavailable is addressed. In Chapter 5, the thesis investigates the SR technique applied for heterogeneous networks where there is no infrastructure sharing. Finally, thesis is concluded in Chapter 6 where future research potential of this topic is discussed.

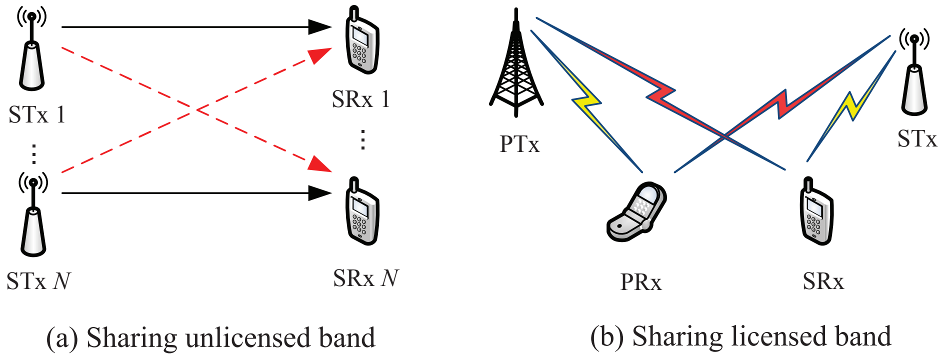
Chapter 2

Literature Review

In this chapter, we first present a literature review in Section 2.1 on the spectrum sharing in cognitive radio networks and its development in the cellular scenario. Then, identifying the spectrum sharing between different generations of cellular networks, we present an overview in Section 2.2 on SR which is of our main concern throughout this thesis. Finally in Section 2.3, we present a literature review on the joint implementation of SR with various types of infrastructure sharing.

2.1 Spectrum Sharing

There are two kinds of spectrum band that can be shared by different wireless networks, which are licensed band and unlicensed band. When multiple wireless networks share



(a) Sharing unlicensed band (b) Sharing licensed band

Figure 2.1: Spectrum sharing scenario.

an unlicensed band which is illustrated as in Fig. 2.1(a), there is no interference cap for protecting the primary system and each network behaves selfishly with equal priority. The key problem in such spectrum sharing is how to schedule the access among multiple networks. The random access protocol with power control taken by the multiple networks has been proposed in [16] where each network is modeled as a player in a game. Different from [16] where frequency-flat fading interference channel is considered, [17] studies frequency-selective fading interference channel where Pareto optimal rate region is derived. In [18], a distributive power control for the multiple sharing systems is proposed which aims to maximize the total sharing throughput of all systems. For spectrum sharing on licensed band, one or multiple secondary systems can share the licensed band of primary system which is shown in Fig. 2.1(b). The spectrum sharing on licensed band can be implemented in opportunistic or concurrent manner, where in opportunistic spectrum sharing the secondary system can transmit on a frequency band only when the primary system is silent on it. On the contrary, concurrent spectrum sharing allows the secondary and primary systems to transmit simultaneously provided the interference to primary system not exceeding a tolerable level which is called as interference margin. It is noted that the opportunistic spectrum sharing and concurrent spectrum sharing are also referred to as overlay spectrum sharing and underlay spectrum sharing, respectively [19]. In the remainder of the thesis, only spectrum sharing on licensed band is considered and the term "spectrum sharing" only refers to the spectrum sharing on licensed band.

2.1.1 Opportunistic Spectrum Sharing

Opportunistic spectrum sharing allows secondary system to access the primary spectrum band only when primary system is silent on that band which is called as spectrum hole. Thus, the key issue in this kind of spectrum sharing is the detection of spectrum hole via spectrum-sensing techniques. There are mainly two kinds of spectrum sensing technique that are *local spectrum sensing* and *cooperative spectrum sensing*. In *local spectrum sensing*, STx is required to detect the affected PRx or PTx which are respectively referred to as direct spectrum sensing and indirect spectrum sensing. Direct spectrum sensing can be realized by detecting the local oscillator of PRx or sending a probing signal then detecting the response of the PRx [20, 21]. On the other hand, in indirect spectrum sensing, various schemes were developed such as match filter detection [22], energy detection [23], cyclostationary detection [24] and covariance-based detection [25]. If multiple antennas are equipped, eigenvalue-based detection can be used [26]. Due to the limitation of sensing performance provided by local spectrum sensing, *cooperative spectrum sensing* in which multiple STx's cooperatively sense spectrum hole was proposed to reduce detection error by using spatial diversity [27] among the STx's. A thorough overview on spectrum sensing techniques in CR networks has been provided in [28].

2.1.2 Concurrent Spectrum Sharing

Concurrent spectrum sharing allows secondary system to co-transmit with primary system on the same frequency band. The concurrent transmission of secondary system inevitably introduces interference to the primary system and thus degrades the primary system performance. Primarily, the secondary transmission has to be controlled so that the primary transmission will not be violated. Then, to achieve as much as sharing capacity, the secondary system needs efficient resource allocation scheme to make a good use of the interference margin provided by primary system. To achieve these two goals, some critical information is required by secondary system, which includes the interference margin provided by primary system and the interference actually introduced to primary system.

2.1.2.1 Determination of Interference Margin

In the majority of the related literatures, the interference margin which defines the maximum interference power that can be tolerated by PTx is given as a predefined value, such as [29, 30, 31, 32]. To justify the determination of interference margin, we first review the typical resource allocation of secondary system which is formulated as

$$\max_{\boldsymbol{P}} \; U(\boldsymbol{P}) \tag{2.1}$$

$$s.t. \; < \text{interference power constraint} > \tag{2.2}$$

$$< \text{transmission power constraint} > \tag{2.3}$$

where $U(\boldsymbol{P})$ is the utility function of transmission strategy $\boldsymbol{P}$ of secondary system, which can be interpreted as weighted (sum) rate, total transmission power, etc. Then, the interference margin can be derived from the interference power constraint which is related to primary QoS requirement, such as

$$R_p \geq R_{\min} \text{ or } \gamma_p \geq \gamma_{\min}, \tag{2.4}$$

where R_p and $R_{\min}$ represent the primary rate and its minimum requirement, and γ_p and $\gamma_{\min}$ denote the primary SINR and it minimum requirement.

Which is more beneficial, peak or average interference power constraint?

Consider a fundamental point-to-point spectrum sharing system with fading channels. When each transmitter and receiver in the system is equipped with single antenna that comprises a single-input single-output (SISO) system, the power control of secondary system was extensively investigated in [33, 34] where various combination of peak/average interference power constraint and peak/average transmission power constraint are considered. It was shown that with average interference power constraint the secondary system can achieve higher throughput than that achieved with peak interference power constraint. This is because the former constraint is less stringent, and in some fading states it allows the interference to exceed the maximum level. The author in [35] further proved that the average interference constraint is superior over the peak interference constraint in terms of primary and secondary ergodic capacities due to the so called *interference diversity*. For example, when multiple channels are shared by a single STx, the STx can allocate more power resource on the channel which gives a better secondary receive quality but least degradation to primary performance. Furthermore, if there are multiple secondary users, the secondary system can exploit the multiuser diversity (MUD) to improve secondary capacity by choosing the secondary user with best receive quality and least interference to primary system to be active for transmitting or receiving. The MUD of sharing a single frequency band was carefully studied in [36, 37, 38, 39, 40]. To benefit from the interference diversity or MUD, channel power gains of STx-SRx, STx-PRx and PTx-PRx are needed to be known by the secondary system.

Exploiting primary system information to gain more sharing opportunity

In [41], a new primary protection criteria which is called rate loss constraint was proposed to upper bound the rate loss of primary system due to secondary transmission. By finding the relationship between the interference power constraint and the rate loss constraint, the benefit of the new criteria is revealed. With the rate loss constraint, the proposed scheme allows higher transmission power from secondary system by exploiting primary system information to search more sharing potential. Compared with the traditional interference power constraint, exploiting primary system information can achieve better secondary performance where the knowledge of the primary system information involves the communication between primary and secondary systems. Generally speaking, the primary system information that can be utilized by secondary system includes the channel power gain of PTx-PRx and the transmission power of PTx. Knowing the channel state of PTx-PRx can help the resource allocation of secondary system to exploit the interference diversity [42]. Detecting the transmission power of PTx can help the secondary system improve the sensing quality in opportunistic spectrum sharing system or improve the quality of the channel state estimation of STx-PRx in concurrent spectrum sharing system [43, 44]. To detect the transmission power of PTx, STx sends a probe signal with strong power. To race with the strong interference, PTx will increase its transmission power which can be heard by SRx. Then, the secondary system manage to determine the interference margin provided by primary system and estimate the channel power gain of STx-PRx which are the critical information for secondary system to successfully share the primary spectrum.

2.1.2.2 Prediction of Interference Introduced to Primary System

In most practical scenarios, due to the lack of cooperation from primary system, accurately acquiring the channel power gain of STx-PTx is extremely difficult. Taking into account the imperfectness of channel power gain of STx-PTx, the author in [45] proposed a chance constraint to restrict the interference power from secondary transmission. Due to the non-convexity of the new constraint, the work adopted a conservative convex approximation to solve the resource allocation problem for secondary system. Other papers considering the interference channel uncertainty include [46, 47, 48], where robust optimization method were employed. It must be noted that, in the practical spectrum sharing system, the interference channel status is normally unavailable. Without this information, at a glance, the spectrum cannot be shared by secondary system, since the imposed interference power cannot be predicted and controlled. Despite the essentiality of this problem, there is rare study that solves this problem. In fact, the solution is extremely valuable for the spectrum sharing technique to be widely implemented in practical.

2.1.3 Spectrum Sharing Enabled Cellular Networks

To implement spectrum sharing technique in cellular networks is by no mean a trivial task [49]. Although the resource allocation for the cellular networks has been extensively investigated both in single-cell scenario, such as [50, 51, 52, 53], and multi-cell scenarios, such as [54, 55, 56, 57], the spectrum sharing in cellular scenario could be challenging due to the additional interference power constraint. Spectrum sharing in the cellular networks is characterized by the multiple users to be simultaneously served in the primary and secondary systems. Uplink multiple access and downlink broadcasting transmissions can be considered and sometimes can be treated as duality.

2.1.3.1 Spectrum Sharing in Single-cell Scenario

In [58], a CDMA-based secondary system is designed which can adaptively choose either opportunistic manner or concurrent manner to share the spectrum. As the OFDMA becomes the major radio access technique for the next generation cellular network, there are lots of works that have studied the spectrum sharing between OFDMA cellular networks. Authors in [59, 60, 61] considered an OFDMA-based point-to-multi-point secondary system that opportunistically accesses the primary subchannels and the cross-channel interference (CCI) was controlled. Considering the difficulty in acquiring the information of primary user activity and limit cognitive capability of user terminal, the author of [62] proposed a novel resource allocation scheme which uses power-bandwidth product as the objective function to be minimized, by which the power and spectrum can be efficiently utilized. In [63], the author proposed a resource allocation scheme for the OFDMA secondary system by jointly adopting opportunistic and concurrent spectrum sharing.

2.1.3.2 Spectrum Sharing in Multi-cell Scenario

At the same time, there are some studies addressing the spectrum sharing in multi-cell scenario. In [64], the author studied the subcarrier and power allocation problem for the multicell CR-OFDMA networks by using distributive decomposition method, where the primary system is an ad-hoc network with multiple transmission pairs. When a secondary multicell networks coexisting with a primary multicell network and both of them adopt OFDMA technique, the author in [65] proposed a spectrum sharing model where secondary BSs are collocated with primary BSs and the secondary uplink transmission is synchronized with the downlink transmission of primary networks. This work is an important step towards the implementation of CR technique in the cellular networks that promotes the cognitive cellular networks.

2.1.3.3 Spectrum Sharing in Heterogeneous Networks

To provide high throughput and seamless coverage for wireless communications, small cells have been proposed to overlay the conventional cellular networks [66, 67]. According to [68], 11 million small cells have been deployed by 47 operators around the world in residential, enterprise and public area by 2013. Conventionally, small cells are deployed by sharing the same spectrum bands and adopting the same radio access scheme with the macrocell networks. For example, in [69] and [70], CDMA-based small cells coexisting with CDMA macrocell was investigated; while in [71] and [72] the OFDMA-based small cells overlaying OFDMA macrocell were considered. The small cells can offload the macrocell traffic directly, however, they will introduce interference to the users in the macrocell and thus degrade their performance. From the CR perspective, the interference existing in the heterogeneous system can be solved by various techniques from CR networks. For example, the interference among small cells can be managed by the schemes proposed for spectrum sharing on the unlicensed bands, while the interference between the macrocell and small cells can be managed by the solutions proposed for spectrum sharing on the licensed bands.

2.2 Spectrum Refarming (SR)

It is worth noting that almost all the existing literatures have investigated the spectrum sharing between systems with same radio access technique [73]. For example, an OFDMA secondary system shares the spectrum of an OFDMA primary system, or both of them are CDMA-based. In fact, spectrum sharing among OFDMA systems will be increasingly difficult as the spectrum licensed to OFDMA systems are accelerating crowded, due to the explosive growth of the 4G traffic. Since the 4G technique outperforms the 2G and 3G techniques in terms of peak data rate, latency and throughput, 2G and 3G subscribers gradually move to the 4G cellular networks as 4G networks being deployed. Looking back the legacy systems, such as GSM and CDMA with their exclusive licensed

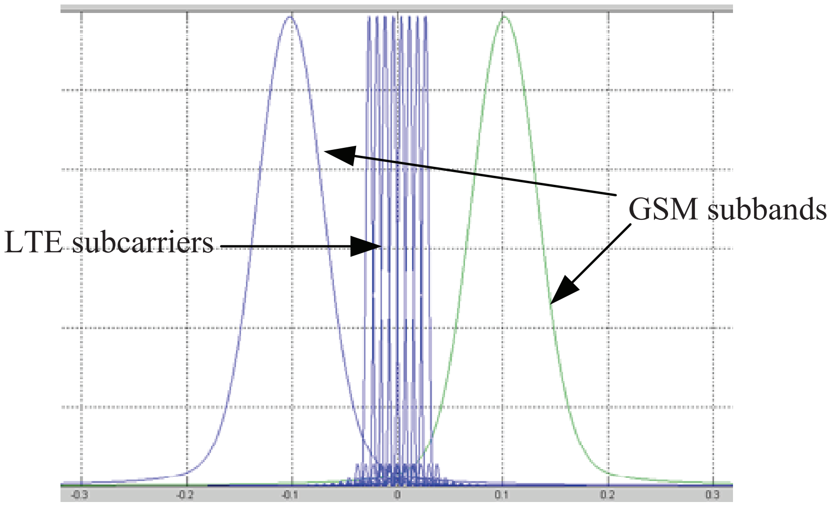


Figure 2.2: LTE/GSM opportunistic SR.

bands, out-moving of their subscribers decreases the spectrum utilization which implies the spectrum sharing can be happened between the OFDMA system and legacy systems. By doing this, the utilization of legacy licensed bands can be improved, meanwhile, the spectrum tension faced by 4G wireless can be mitigated. Spectrum refarming (SR) is such a radio resource management technique that enables the spectrum sharing between different generations of cellular networks, which becomes a new paradigm of spectrum sharing. As discussed above, the spectrum sharing can be implemented in two ways [28]: opportunistic spectrum sharing which allows the secondary users to utilize the vacant frequency band of primary system, and concurrent spectrum sharing which allows secondary and primary system co-transmit at the same band. Similarly, there are two types of SR models: opportunistic SR and concurrent SR. As the OFDMA will be the major radio access technique for the next generation cellular networks, it is more interest to let the OFDMA cellular network refarm the licensed bands of GSM and CDMA-based 3G cellular networks.

2.2.1 Opportunistic SR

In the opportunistic SR model, the OFDMA system dynamically accesses the frequency band of legacy system that is temporally idle. Due to the narrowband nature of GSM system, the SR for long-term evolution (LTE) and GSM coexistence belongs to opportunistic SR model whose operation principle can be stated as follows. Suppose the GSM network is initially designed to be able to support U users. As shown in Fig. 2.2, when U decreases, there exist idle subbands that can be opportunistically accessed by the OFDMA system. In an other word, *the sharing opportunity for LTE/GSM coexistent system comes from the existence of idle subbands due to the decrement of GSM users.* In [74], the author proposed an LTE/GSM SR system for an OFDMA system to dynamically refarm the GSM band by utilizing the subbands that are not occupied by the GSM system. Noted that in [74], the LTE system reserves partial subbands for GSM transmission and controls the transmission power for both GSM and LTE to constraint the inter-technology interference. The symbol containing GSM and LTE information is transmitted by the LTE transmitter. When reserving subbands for GSM system, the subbands that carry the important control information of OFDMA system were protected. This SR model was further extended to the heterogeneous cellular system where OFDMA small cells refarm the spectrum of the GSM macrocell [75].

2.2.2 Concurrent SR

Concurrent SR allows different generations of networks co-transmit at the same band, provided the primary system can be protected. When OFDMA system shares the spectrum of CDMA system, the SR system has to operate in the concurrent manner due to the wideband nature for both systems. The operating principle of OFDMA/CDMA SR system can be described as follows.

Let us consider a single-cell direct sequence CDMA (DS-CDMA) uplink in which the CDMA users are assigned with random spreading codes. When the receiver is applied,

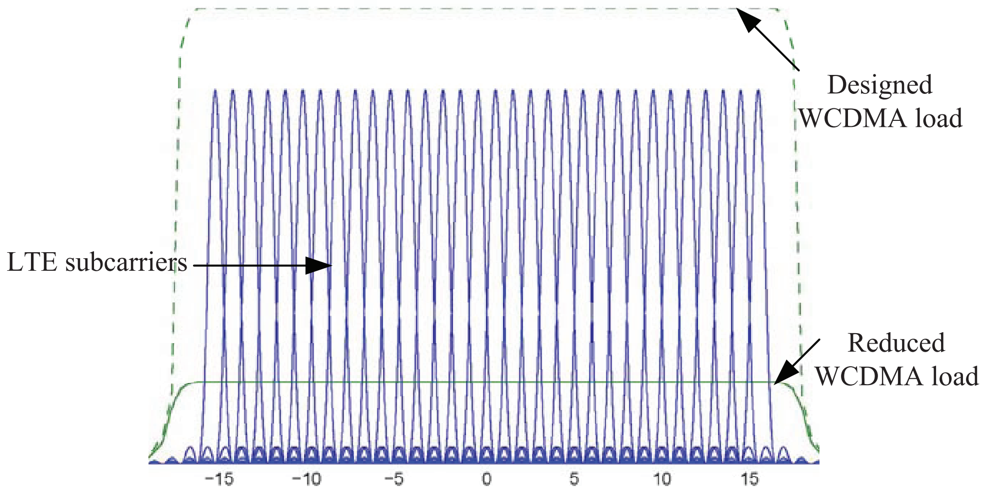


Figure 2.3: LTE/WCDMA concurrent SR.

such as match filter (MF) or linear minimum mean-square-error (MMSE) receiver, there exists inter-user interference, which is related to the CDMA system load defined as the ratio of total number of CDMA users to the spreading gain [76]. It has been proven that, when the spreading gain and number of users are both large, the signal-to-interference-plus-noise-ratio (SINR) of the receiver output will converge to a limiting SINR, which is independent of the specific spreading codes [76]. Thus, for a given receive power, the maximum CDMA system load only depends on the target SINR. In another word, when the CDMA system is operating with lower system load, the CDMA users will experience less interference. Thus, there exists an interference margin that can be tolerated by CDMA users whose target SINR can be maintained. This interference margin in fact defines the maximum interference power that can be introduced by the OFDMA system to the CDMA system in the OFDMA/CDMA SR system. The relationship between the designed CDMA system load, reduced CDMA system load and interference margin is shown in Fig. 2.3. Thus, we can see that different from GSM system, *the sharing opportunity provided by CDMA system comes from the decrement of inter-user interference due to CDMA traffic reduction.*

To successfully implement the OFDMA/CDMA SR system, several key challenges can be described in the following. First and foremost, the interference margin provided by the CDMA system has to be predicted. In conventional spectrum sharing studies, the primary and secondary systems usually operate with the same access scheme, where the interference margin is given as a predefined threshold [30, 31, 33, 60]. The spectrum sharing between the CDMA and OFDMA systems was considered in [77], but there was no justification on how to determine the interference margin. To this end, the evaluation of interference margin based on CDMA SINR analysis for the proposed SR system is of our concern. Although there are extensive investigations on CDMA SINR in single/multi-cell and flat/frequency-selective fading scenarios [76, 78, 79, 80], few effort have addressed SINR performance when CDMA users are interfered by a system with a different radio access scheme, such as OFDMA. During evaluating the SINR of CDMA users, it is required to know the specific spreading codes assigned to users and the channel state information (CSI) between users and the base station (BS). This could be impractical for the SR system, due to limited information exchange between the two systems. Motivated by [76], [78] that the CDMA SINR converges in probability to a deterministic value when the system dimensions get large, we resort to the asymptotic analysis to predict the interference margin for our SR system. Thus, several questions need to be answered. *How can the asymptotic SINR of CDMA user accommodate the interference from OFDMA system, since the interference here is colored in spectrum? When the CDMA system adopts different receive filters, such as MF and MMSE filter, is the effect of OFDMA interference identical? What will be the impact of the CDMA system to the OFDMA system?* By answering these questions will reveal the essential benefits of FDMA/CDMA SR system.

When the CDMA interference margin is obtained, this margin should be effectively used by the OFDMA system to perform resource allocation. Again, in conventional spectrum sharing studies, to keep the interference to primary receiver below the interference margin, the channel power gains between OFDMA users and CDMA receiver has to be known [30, 31, 33, 60] or partially known [45]. In the following section, we can see that the required channel power gains will not be always available in practice. We notice that, this thesis focuses on the concurrent SR for OFDMA/CDMA coexistence, thus the remained chapters will always talk about the concurrent OFDMA/CDMA SR system.

2.3 Spectrum Refarming (SR) with Mobile Infrastructure Sharing

Since the SR technique and infrastructure sharing can respectively improve the spectrum and infrastructure utilization, their joint implementation becomes attractive for efficiently designing the next generation of cellular networks. In the following parts, different combinations of SR and mobile infrastructure sharing are reviewed.

2.3.1 SR with Active Infrastructure Sharing

With active infrastructure sharing, the OFDMA system shares the legacy spectrum, legacy cell site and legacy BS antenna. Such an SR model requires less cost for installing the hardware in infrastructure, but needs stringent negotiation between the new and legacy systems.

Consider an uplink SR system. By sharing the cell cite and BS antenna, the channel power gain from secondary users to primary receiver is identical with that from secondary users to secondary receiver. Since the channel power gain within a system can be easily estimated by hearing its own pilot signal, the interference channel power gain is readily known. Thus, the interference introduced by OFDMA system to legacy system can be predicted by OFDMA system. Thus, only interference margin prediction and resource allocation of OFDMA system are needed to be addressed in this scenario. Importantly, as shown in Chapter 3, the interference margin prediction for active infrastructure sharing can be easily extended to the passive infrastructure sharing or without infrastructure sharing; thus, it should be treated as the fundamental for the other variations of SR model.

We highlight the differences between our work and the existing studies [77] and [81]. In terms of system model, [77] and [81] considered that OFDM transmission pair(s) shares the spectrum of CDMA cellular system and the receivers of the two systems are non-collocated. In our work, however, the primary and secondary systems are both cellular-based, and the cell site and BS antenna are shared. Consequently, the C-CSI in our work is naturally available; and thus, the interference from ST to PR is predictable. In terms of interference margin, [77] gave the interference margin as a predefined value without justification, and [81] evaluated it based on the outage of CDMA SINR by approximating the CDMA inter-user interference as additive white Gaussian noise (AWGN). Unfortunately, the interference margin evaluated in [81] is only applicable when CDMA system adopts MF receiver. In our work, the interference margin is evaluated based on instantaneous CDMA SINR using RMT and LLN, and different types of CDMA receivers, i.e., MF and MMSE receivers are considered. As to be shown in theoretical analysis and simulation results, the SR performance with MMSE receiver is significantly different from that with MF receiver. Last, in terms of performance metric, ergodic OFDM throughput was adopted in [77] and [81], while instantaneous OFDMA throughput is adopted in our work. In a nutshell, the thesis adopts the system model, implementation scenario, mathematical method, study emphasize and contribution that are all different from [77] and [81].

2.3.2 SR with Passive Infrastructure Sharing

With passive infrastructure sharing, the OFDMA system shares the legacy spectrum and legacy cell site, but adopts its own BS antenna that is separate from the legacy BS antenna. This sharing requires less stringent negotiation between the OFDMA and legacy systems and thus can be easily adopted within or among different operators. By assuming the C-CSI is known, various resource allocation problems with different emphasizes have been formulated and solved [30, 33, 31, 77]. Considering the imperfectness of C-CSI, the C-CSI is modeled as an estimated C-CSI plus a random but bounded error. Then, robust optimization is employed to sufficiently protect the primary system [82, 47, 83, 84]. However, a critical and realistic problem in such non-sharing of BS antenna is that the channel power gains from OFDMA users to legacy receiver are unavailable. This problem is inevitable, as cellular operators are unwilling to upgrade their legacy networks as this will involve extra investment. Let the fading from OFDMA user to CDMA receiver to as cross channel state information (C-CSI), and the fading from OFDMA user to OFDMA receiver to as self channel state information (S-CSI). To address the problem of C-CSI unavailability, effort has been paid in the emerging literatures to release the assumption of the explicit C-CSI information. In [43] and [85], the STx sent a probing signal to trigger the primary power adaptation. By observing the adapted transmission power of PTx, the secondary system can determine the C-CSI. Such a probe-and-react method requires the secondary system to redesign the protocol where a jamming slot should be added, and is especially suitable for the single-band spectrum sharing system, where the exact C-CSI can be obtained. Instead of listening to the PTx transmission power, in [86, 81, 44], the secondary system listened to the control feedback, such as automatic repeat requests (ARQ), sent by the PRx. If an ARQ is heard, the STx decreases its transmission power, and vice versa. These schemes need stringent convergence performance of secondary power control.

In our work, the sharing of cell site offers a fantastic advantage that the distance-based path loss from a mobile user to each of the receivers are identical, which inspires us in two aspects described as follows. Take the uplink OFDMA/CDMA SR system as an example. From the OFDMA system perspective, the channel power gains from OFDMA users to CDMA receiver are prerequisite to predict the interference power to the CDMA users. In most existing literatures on spectrum sharing, this channel power gains has been assumed to be known either perfectly or erroneously [30, 31, 33, 87], which relies on the communication between the primary and secondary system. Notably, this assumption is rather ambitious for their practical implementation. In practice, due to the lack of communication between the primary and secondary systems, the channel power gains across systems are rarely available. Thus, a more pragmatic assumption should be the channel power gains from OFDMA users to CDMA receiver are unavailable. As channel power gain is comprised by the distance-based path loss and small-scale fading, due to the collocation of the receivers, the path loss is naturally known from the channel power gain from the OFDMA user to its own receiver. Thus, only the fading is remained to be determined. Suppose the C-CSI and S-CSI follow the same distribution. If the OFDMA system uses S-CSI in stead of C-CSI to predict the interference power to CDMA users, somewhat surprisingly, the CDMA users can still be protected. This interesting observation indicates that the spectrum can be safely shared, despite the C-CSI is unavailable.

In addition, we notice that CDMA system employs inner power control that adapts the user transmission power to interference so that the receive signal-to-interference-plus-noise ratio (SINR) is equal to the target value. Due to the collocation of OFDMA and CDMA receivers, the OFDMA system can derive the target CDMA receive power easily from the interference power. Based on the CDMA power control law, the actual interference power suffered by the CDMA system can be derived, with which the OFDMA system can quantify the exploitable sharing opportunity. This means that if the CDMA system adapts the user transmission power, the OFDMA receiver can simultaneously detects it.

2.3.3 SR without Infrastructure Sharing

Generally, the SR technique can be implemented without infrastructure sharing. A typical application scenario is heterogeneous networks where multiple small cells refarm the spectrum of macrocell networks. Such system is especially attractive if the legacy spectrum owned by the cellular operator is underutilized. In this case, the small cells only need to control the interference to the legacy network users in order to protect their normal service. Among the rare related literatures, [75] was the recent one that investigates the OFDMA small cells coexisting with the GSM macrocell, where they share the GSM frequency band in an opportunistic manner. However, the OFDMA small cell refarming the spectrum of CDMA macrocell has not been investigated. Moreover, since the small cell and macrocell use individual BSs, the unavailability of interference channel power gains is needed to be taken into consideration.

In this thesis, we focus on the multiple OFDMA small cells share the spectrum of macrocell. The SR system is designed so that the inter-macro-small-cell interference is controllable. Moreover, rather than using the traditional centralized resource allocation, we design the decentralized resource allocation algorithm for the small cells. This will be useful to investigate the SR system with mutliple macrocells and multiple user-centric dynamic deployed small cells.

Chapter 3

Spectrum Refarming (SR) with Active Infrastructure Sharing

This chapter focuses on the SR techniques applied to the OFDMA/CDMA coexistent system with active infrastructure sharing. We first establish the signal model of the OFDMA/CDMA SR system, in which the OFDMA uplink transmission is synchronized with the uplink transmission with the legacy CDMA system. Both OFDMA and CDMA systems share the same cell site and same BS antenna which belongs to the active infrastructure sharing. This is an interesting and fundamental model for the SR system, from which various studies could be made. With the proposed model, we quantify the asymptotic SINR performance of the CDMA users in the proposed SR system using random matrix theory and large number law, from which the interference margin tolerable by CDMA system is derived. By using the interference margin together with the transmit power constraints, the resource allocation problem of the OFDMA system is formulated and solved through dual decomposition method. We highlight that the interference from CDMA users to OFDMA receiver is taken into consideration in this study, which was ignored by most existing works [30, 31, 33, 60]. This consideration also inspires the interesting idea of joint resource allocation of the two systems which exploit the tradeoff the OFDMA throughput over the receive power of CDMA system. The joint OFDMA/CDMA resource allocation scheme is proposed which is conducted by OFDMA system only. Due to the power control of CDMA system, it will force the CDMA to adjust the transmission power to its optimal value.

The rest of the chapter is organized as follows. In Section 3.1, the system model and signal transmission model are presented. In Section 3.2, the signal detection for CDMA and OFDMA users is investigated, based on which the asymptotic SINR of CDMA users with different CDMA receive filters are analyzed, and the interference margin that can be exploited by OFDMA system is determined. The optimal OFDMA resource allocation and joint OFDMA/CDMA resource allocation problems are formulated and solved in Section 3.3 and section 3.4, respectively. Simulation results are presented in Section 3.5 and finally, the paper is concluded in Section 3.6.

The content of this chapter is based on our works [88], [89] and [90].

3.1 System Model

3.1.1 SR System Description

In this chapter, the uplink of OFDMA/CDMA SR system is considered. The signal transmission model from user terminals to the BS is illustrated in Fig. 3.1. Here, we assume that single antenna is deployed at the BS and all user terminals. Furthermore, both systems share the same cell site and same BS antenna. This sharing is reasonable, because the operator can adopt SR technique by adding OFDMA transceiver to the CDMA cell site. The signal received by the common antenna can be passed to the CDMA module and the OFDMA module for their respective signal detection. It is pointed out that the results obtained in this paper can also be extended to the case that different antennas are used at the BS of the two systems that will be presented in Chapter 4.

Denote W as the effective bandwidth licensed to the CDMA system operation, U the total number of CDMA users. Each CDMA user is assigned with a random spreading code with spreading gain N. Thus the chip duration and symbol duration for the CDMA system can be denoted as $T_c = \frac{1}{W}$, and $T_s = \frac{N}{W}$, respectively. The OFDMA system

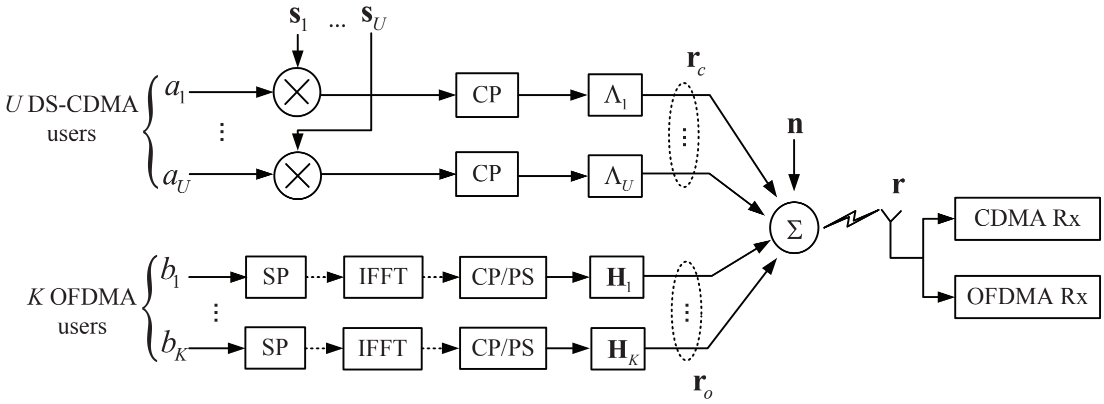


Figure 3.1: The signal transmission model of uplink OFDMA/CDMA SR with active infrastructure sharing.

operates in the same spectrum as the CDMA system. Let K be the total number of OFDMA users. Suppose the FFT size is N, and the OFDMA symbol duration is chosen to be equal to the CDMA symbol duration T_s. The cyclic-prefix (CP) is used to take care of the multipath effect of the wireless channel. The overall bandwidth W is thus split into N equally-spaced orthogonal subcarriers.

Take the wideband CDMA (WCDMA) uplink as an example. In practice, it operates at a 5MHz bandwidth with the chip rate of 3.84Mcps. The spreading gain can vary from 2 to 256 [91]. The LTE can adopt 256 subcarriers when working at 5MHz mode with subcarrier spacing of 15kHz. The sampling rate is thus 15KHz × 256 = 3.84MHz that equals the WCDMA chip rate. Thus, the two systems can easily get synchronized with the same clock reference.

All the wireless links are quantified by distance-dependent path loss, large-scale shadowing, and small-scale fading. For simplicity, the distance-dependent path loss and large-scale shadowing are treated to be 1, and the average power of small-scale fading is also normalized to be 1. With this normalization, the transmission power in fact defines the average receive power at the BS. Furthermore, the small-scale fading is modeled with L equally-spaced multipaths, and the time delay between two consecutive paths is T_c.

Moreover, the channels are assumed to be invariant within each symbol duration. Next, we will look into the details of signal transmissions in the SR system.

3.1.2 CDMA Signal

As shown in Fig. 3.1, let a_u be the data symbol to be transmitted by CDMA user u. The symbol a_u is spread by spreading code $\boldsymbol{s}_u$, where $\boldsymbol{s}_u = [s_{u,1}, s_{u,2}, \ldots, s_{u,N}]^T$ with unit power, i.e., $\mathbb{E}[\|\boldsymbol{s}_u\|^2] = 1$, and covariance of $\mathbb{E}\left[\boldsymbol{s}_u\boldsymbol{s}_u^H\right] = \frac{1}{N}\boldsymbol{I}$. The spreading codes $\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_U$ for different users are chosen to be independent with each other. With perfect power control, we assume that all users have equal average receive power q, i.e., $\mathbb{E}[|a_1|^2] = \mathbb{E}[|a_2|^2] = \cdots = \mathbb{E}[|a_U|^2] = q$.

For ease of presentation, we assume the CDMA system also has CP, similar to the OFDMA system, though the results derived in the paper can be readily extended to normal CDMA systems[1]. For every N chips coming from the same symbol, a CP containing G ($G \geq L-1$) chips are inserted before the chip signals are transmitted over the wireless channel. The insertion of CP at transmitter and removal of CP at receiver avoid the inter-symbol-interference (ISI) between successive symbols caused by multipath effect.

The time-domain CDMA received signal at the BS after CP removing is given by

$$\boldsymbol{r}_c = \sum_{u=1}^{U} \boldsymbol{C}_u \boldsymbol{s}_u a_u, \tag{3.1}$$

where $\boldsymbol{r}_c$ is $N \times 1$ vector, $\boldsymbol{C}_u$ is $N \times N$ matrix

$$\boldsymbol{C}_u = \begin{pmatrix} h_{u,L} & h_{u,L-1} & \cdots & h_{u,1} & \cdots & 0 \\ 0 & h_{u,L} & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{u,L} & \cdots & h_{u,1} \end{pmatrix}, \tag{3.2}$$

---

[1] The effect of ISI in normal CDMA systems without CP insertion can be negligible, when the number of the interfered chips is small compared to the spreading gain. This is true especially when $N \to \infty$. In the normal CDMA system with limited spreading gain, the ISI can be largely mitigated by post-processing, such as the overlap-save scheme [92].

whose entry $h_{u,l}$ is the impulse response of the lth path of user u. Because $\boldsymbol{C}_u$ is circulant, it can be factorized as

$$\boldsymbol{C}_u = \boldsymbol{W}^H \boldsymbol{\Lambda}_u \boldsymbol{W}, \tag{3.3}$$

where $\boldsymbol{W}$ is the N-point Fourier transform matrix whose entries are $\frac{1}{\sqrt{N}}(e^{-\frac{2\pi i}{N}ab})_{a,b=0,1,\ldots,N-1}$, and $\boldsymbol{\Lambda}_u = \mathrm{diag}(\lambda_{u,1}, \lambda_{u,2}, \ldots, \lambda_{u,N})$ contains the frequency-domain channel response of user u. Substituting (3.3) in (3.1) yields

$$\boldsymbol{r}_c = \sum_{u=1}^{U} \boldsymbol{W}^H \boldsymbol{\Lambda}_u \boldsymbol{W} \boldsymbol{s}_u a_u. \tag{3.4}$$

3.1.3 OFDMA Signal

According to Fig. 3.1, the N-dimensional OFDMA received signal can be written as [93]

$$\boldsymbol{r}_o = \sum_{k=1}^{K} \boldsymbol{W}^H \boldsymbol{H}_k \boldsymbol{b}_k = \boldsymbol{W}^H \boldsymbol{H} \boldsymbol{b}. \tag{3.5}$$

Here, $\boldsymbol{b}_k = [b_{k,1}, b_{k,2}, \ldots, b_{k,N}]^T$ is the transmission data vector for each user $k = 1, \ldots, K$, and $\mathbb{E}[|b_{k,n}|^2] = p_{k,n}$ is the transmission power of user k on subcarrier n. $\boldsymbol{H}_k = \mathrm{diag}\,(H_{k,1}, H_{k,2}, \ldots, H_{k,N})$ is frequency-domain channel response matrix for user k. Moreover, $\boldsymbol{b} = \sum_{k=1}^{K} \boldsymbol{b}_k$ and $\boldsymbol{H} = \mathrm{diag}\left(H_{k[1],1}, H_{k[2],2}, \ldots, H_{k[N],N}\right)$, where $\{k[n]\}_{n=1,\ldots,N}$ are the user index, indicating the user that is transmitting over subcarrier n.

3.1.4 Compound Received Signal at BS

Assume that both systems share the same receive antenna at the BS, and the OFDMA symbols are synchronously received at the BS with the CDMA symbols[2]. The receive

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[2] The OFDMA system can adopt a timing advance mechanism that is widely used in 2G/3G cellular networks [94]. As OFDMA transmits, it first synchronizes the frame with CDMA system. Then they will keep synchronous as they have the same symbol duration, and the use of CP can tolerate certain amount timing mismatch.

signal $\boldsymbol{r}$ is thus composed by $\boldsymbol{r}_c$, $\boldsymbol{r}_o$ and the additive white Gaussian noise $\boldsymbol{n}$, where $\boldsymbol{n} \sim \mathcal{CN}\left(0, \sigma^2 \boldsymbol{I}\right)$, which is represented as

$$\boldsymbol{r} = \sum_{u=1}^{U} \boldsymbol{W}^H \boldsymbol{\Lambda}_u \boldsymbol{W} \boldsymbol{s}_u a_u + \boldsymbol{W}^H \boldsymbol{H} \boldsymbol{b} + \boldsymbol{n}. \tag{3.6}$$

The corresponding frequency-domain compound signal is

$$\tilde{\boldsymbol{r}} = \sum_{u=1}^{U} \boldsymbol{\Lambda}_u \tilde{\boldsymbol{s}}_u a_u + \boldsymbol{H} \boldsymbol{b} + \tilde{\boldsymbol{n}}, \tag{3.7}$$

where $\tilde{\boldsymbol{r}} = \boldsymbol{W}\boldsymbol{r}$, $\tilde{\boldsymbol{s}}_u = \boldsymbol{W}\boldsymbol{s}_u$, and $\tilde{\boldsymbol{n}} = \boldsymbol{W}\boldsymbol{n}$.

It can be seen from (3.7) that when the OFDMA and CDMA uplink transmissions co-occur in the system, they will interfere with each other at the BS. In the following sections, we will describe the respective signal detections for the two systems, and quantify their mutual interference, which will then be used to design the resource allocation scheme for the OFDMA system.

3.2 Disjoint Signal Detection in SR System

Without cooperation between the two systems, disjoint detection is applied to CDMA receiver and OFDMA receiver which abstract their desired data by treating the remained part as interference plus noise. Although it can be expected a better performance when joint detection is enabled, by interference cancelation for instance, when CDMA and OFDMA cooperate, this work will focus on the disjoint detection in order to provide fundamental insight for further extension. In practice, linear receivers are adopted by CDMA system due to their complexity advantage. Denoting $\boldsymbol{e}_u$ as the MF receiver and $\boldsymbol{d}_u$ as the MMSE receiver of CDMA user $u, \forall u = 1, \ldots, U$, in the following subsections, we will derive the SINR expressions for the CDMA and OFDMA users when disjoint detection is applied.

3.2.1 CDMA SINR with MF Receiver

Taking the CDMA user u as an example, the MF is designed as $\boldsymbol{e}_u = \boldsymbol{\Lambda}_u \tilde{\boldsymbol{s}}_u$, and the MF output, $\hat{a}_{u,\mathrm{MF}} = \boldsymbol{e}_u^H \tilde{\boldsymbol{r}}$, can be expressed as

$$\hat{a}_{u,\mathrm{MF}} = \boldsymbol{e}_u^H \boldsymbol{e}_u a_u + \boldsymbol{e}_u^H \left(\sum_{i=1, i \neq u}^{U} \boldsymbol{\Lambda}_i \tilde{\boldsymbol{s}}_i a_i + \boldsymbol{H}\boldsymbol{b} + \tilde{\boldsymbol{n}} \right). \tag{3.8}$$

The first term in (3.8) is the desired signal, and the remainder is interference plus noise. The SINR can be calculated as

$$\gamma_{u,\mathrm{MF}}^{a} = \frac{q \left| \boldsymbol{e}_u^H \boldsymbol{e}_u \right|^2}{\boldsymbol{e}_u^H \left(\sum_{i=1, i \neq u}^{U} q \boldsymbol{e}_i \boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2 \boldsymbol{I} \right) \boldsymbol{e}_u}. \tag{3.9}$$

The matrix $\boldsymbol{\Sigma}$ is the $N \times N$ covariance matrix of $\boldsymbol{H}\boldsymbol{b}$ with nth diagonal entry being σ_n^2. By denoting $g_{k,n} = |H_{k,n}|^2$ as the channel gain of OFDMA user k on subcarrier n, σ_n^2 can be expressed as $\sigma_n^2 = \sum_{k=1}^{K} p_{k,n} g_{k,n}$, which represents the interference power seen by CDMA on subcarrier n.

Eq. (3.9) shows that the SINR of a CDMA user depends on the specific spreading codes as well as the CSI of all CDMA users in the system. With the spectrum sharing between the CDMA and OFDMA system, the SINR of CDMA user is further affected by the transmission power and CSI of OFDMA system. Without knowing these information, it is difficult to exactly calculate the SINR of the CDMA users. Fortunately, it has been proven that when $\boldsymbol{\Sigma} = \boldsymbol{0}$, (3.9) converges in probability to a deterministic value when the dimensions, (N, U), of the CDMA system become large, which means the asymptotic SINR of pure CDMA system is independent of the specific spreading codes. This inspires us to investigate the asymptotic SINR of CDMA users when OFDMA system co-exists.

AS1: We consider a large CDMA system, in which $N \to \infty, U \to \infty$, but $\frac{U}{N}$ converges to a constant parameter α, which represents the CDMA system load.

Corollary 3.1 *With* **AS1***, the SINR of CDMA user u, $\gamma^a_{u,\mathrm{MF}}$, in the SR system converges in probability to*

$$\tilde{\gamma}^a_{u,\mathrm{MF}} = \frac{q\left(\frac{1}{N}\sum_{n=1}^{N}|\lambda_{u,n}|^2\right)^2}{\frac{1}{N^2}\sum_{n=1}^{N}\left(|\lambda_{u,n}|^2\sum_{i=1,i\neq u}^{U} q\,|\lambda_{i,n}|^2\right)+\frac{1}{N}\sum_{n=1}^{N}(|\lambda_{u,n}|^2\sigma_n^2)+\frac{1}{N}\sum_{n=1}^{N}|\lambda_{u,n}|^2\sigma^2}, \tag{3.10}$$

where $\sigma_n^2 = \sum_{k=1}^{K} p_{k,n} g_{k,n}, \forall n = 1, \ldots, N.$

Proof: To derive the asymptotic value of $\gamma^a_{u,\mathrm{MF}}$, we can derive asymptotic values of the nominator and denominator in (3.9) separately. First, the nominator in (3.9) is given by

$$q\left|\boldsymbol{e}_u^H\boldsymbol{e}_u\right|^2 = q\left|\tilde{\boldsymbol{s}}_u^H\boldsymbol{\Lambda}_u^H\boldsymbol{\Lambda}_u\tilde{\boldsymbol{s}}_u\right|^2 = q\left|\mathrm{Tr}\left\{\tilde{\boldsymbol{s}}_u^H\boldsymbol{\Lambda}_u^H\boldsymbol{\Lambda}_u\tilde{\boldsymbol{s}}_u\right\}\right|^2. \tag{3.11}$$

As $N \rightarrow \infty$, according to [76], $\mathrm{Tr}\left\{\tilde{\boldsymbol{s}}_u^H\boldsymbol{\Lambda}_u^H\boldsymbol{\Lambda}_u\tilde{\boldsymbol{s}}_u\right\} \overset{a.s.}{\rightarrow} \frac{1}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u^H\boldsymbol{\Lambda}_u\right\} = \frac{1}{N}\sum_{n=1}^{N}|\lambda_{u,n}|^2$, (3.11) is thus given by

$$q\left|\boldsymbol{e}_u^H\boldsymbol{e}_u\right|^2 \overset{a.s.}{\rightarrow} q\left(\frac{1}{N}\sum_{n=1}^{N}|\lambda_{u,n}|^2\right)^2. \tag{3.12}$$

Similarly, the asymptotic value of the denominator in (3.9) can be derived as

$$\begin{aligned}&\boldsymbol{e}_u^H\left(\sum_{i=1,i\neq u}^{U} q\boldsymbol{e}_i\boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2\boldsymbol{I}\right)\boldsymbol{e}_u\\ &\overset{a.s.}{\rightarrow} \frac{1}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H\left(\sum_{i=1,i\neq u}^{U} q\boldsymbol{e}_i\boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2\boldsymbol{I}\right)\right\},\end{aligned} \tag{3.13}$$

which can be further derived to the denominator of (3.11). Then the corollary is proven.

Corollary 3.1 offers us the following insights. Besides the inter-user-interference due to the independence and randomness of the spreading codes used by CDMA users, the OFDMA introduces interference on each subcarrier, acting as colored noise across the overall spectrum due to the non-uniform power allocation among subcarriers and channel fading selectivity, which is whitened at the output of the MF.

Corollary 1 describes the asymptotic SINR for CDMA users with frequency selective fading channels. If the CDMA users are with flat fading channels, i.e., $\boldsymbol{\Lambda}_u = \lambda_u \boldsymbol{I}$, (3.11) can be simplified as

$$\tilde{\gamma}^a_{u,\mathrm{MF}} = \frac{q\left|\lambda_u\right|^2}{\frac{1}{N}\sum_{i=1,i\neq u}^{U} q\left|\lambda_i\right|^2 + \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} + \sigma^2}. \tag{3.14}$$

If the CDMA users are with AWGN channels, i.e., $\lambda_u = 1$, (3.14) can be further simplified to

$$\tilde{\gamma}^a_{u,\mathrm{MF}} = \frac{q}{\alpha q + \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} + \sigma^2}. \tag{3.15}$$

Eq. (3.11) still cannot be used by OFDMA system to predict the interference margin, since the SINR in (3.11) depends on the CSI of CDMA users, which is not available to OFDMA system in practice. Next, we will solve this problem by looking at the case when the CDMA users are with rich multipath components. We make the following additional assumption:

AS2: The number of multipaths L for CDMA users is large, and the wireless channel follows uniform power delay profile [93]. That is, each channel tap follows complex Gaussian distribution, $h_{u,l} \sim \mathcal{CN}(0, \frac{1}{L})$.

Corollary 3.2 *With* **AS1** *and* **AS2**, *the asymptotic SINR of all the CDMA users in* (3.11) *converges to*

$$\gamma^a_{\mathrm{MF}} = \frac{q}{\alpha q + \overline{\sigma^2_n} + \sigma^2}, \tag{3.16}$$

where $\overline{\sigma^2_n} = \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n}$.

Proof: The proof is given in Appendix A.

The limiting SINR for CDMA users shown in (3.16) manifests the essence of the underlay SR system. For pure CDMA system ($K = 0$), we can quantify the supportable CDMA load as follows. Let $\frac{q}{\sigma^2}$ and β^* be the receive SNR and target SINR for CDMA users, both are the parameters related to system design and target Quality-of-Services (QoS). From the equation, $\frac{q}{\alpha_{\mathrm{MF}}^* q+\sigma^2} = \beta^*$, we can obtain the supportable CDMA load as

$$\alpha_{\mathrm{MF}}^* = \frac{1}{\beta^*} - \frac{1}{q/\sigma^2}. \tag{3.17}$$

When the CDMA load decreases from α_{MF}^* to α, to maintain the same target SINR β^*, there is interference margin tolerable by CDMA system, which we denote as T_{MF}. Based on the equation $\frac{q}{\alpha q+T_{\mathrm{MF}}+\sigma^2} = \beta^*$, T_{MF} can be derived as

$$T_{\mathrm{MF}} = (\alpha_{\mathrm{MF}}^* - \alpha)q, \tag{3.18}$$

which is the maximal interference level that can be introduced by OFDMA system.

3.2.2 CDMA SINR with MMSE Receiver

When the CDMA system adopts MMSE receiver, the receiver for user u, $\boldsymbol{d}_u$, can be denoted as [93]

$$\boldsymbol{d}_u = \left(\sum_{u=1}^{U} q \boldsymbol{e}_i \boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2 \boldsymbol{I} \right)^{-1} \boldsymbol{e}_u q, \tag{3.19}$$

where $\boldsymbol{e}_i = \boldsymbol{\Lambda}_i \tilde{\boldsymbol{s}}_i$. Then, the output of the receiver is $\hat{a}_{u,\mathrm{MMSE}} = \boldsymbol{d}_u^H \tilde{\boldsymbol{r}}$, whose SINR can be evaluated as

$$\gamma_{u,\mathrm{MMSE}}^a = q \boldsymbol{e}_u^H \left(\sum_{i=1}^{U} q \boldsymbol{e}_i \boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2 \boldsymbol{I} \right)^{-1} \boldsymbol{e}_u. \tag{3.20}$$

Similar to MF, the SINR of MMSE receiver cannot be evaluated without knowing the specific spreading codes and CSI of all users. It has been proven that the asymptotic CDMA SINR with MMSE receiver without OFDMA users converges to a deterministic value, under the help of random matrix theory. To derive the asymptotic CDMA SINR in the OFDMA/CDMA SR system, we first recall the following theorem, whose derivation considers the interference among CDMA users only.

Theorem 3.1 (Theorem 6.10 of [95]) *With* **AS1***, the SINR of user u without OFDMA users converges to* $x_u(-\sigma^2)$ *in probability, where* $x_u(z)$*,* $z \in \mathbb{C}\backslash\mathbb{R}^+$ *is the unique Stieltjes transform that satisfies*[3]

$$x_u(z) = \frac{1}{N}\sum_{n=1}^{N} \frac{q\left|\lambda_{u,n}\right|^2}{\frac{1}{N}\sum_{i=1}^{U}\frac{q}{1+x_i(z)}\left|\lambda_{i,n}\right|^2 - z}. \tag{3.21}$$

Considering the interference introduced by OFDMA transmission, the asymptotic SINR of CDMA users is given in the following corollary.

Corollary 3.3 *With* **AS1***, the SINR of user u,* $\gamma^a_{u,\mathrm{MMSE}}$*, in the SR system converges in probability to* $x_u(-\sigma^2)$*, where* $x_u(z)$*,* $z \in \mathbb{C}\backslash\mathbb{R}^+$ *is the unique Stieltjes transform that satisfies*

$$x_u(z) = \frac{1}{N}\sum_{n=1}^{N} \frac{q\left|\lambda_{u,n}\right|^2}{\frac{1}{N}\sum_{i=1}^{U}\frac{q}{1+x_i(z)}\left|\lambda_{i,n}\right|^2 + \sigma_n^2 - z}. \tag{3.22}$$

Proof: As $N, U \to \infty$,

$$\gamma^a_{u,\mathrm{MMSE}} \overset{a.s.}{\to} \frac{q}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H\left(\sum_{i=1}^{U} q\boldsymbol{e}_i\boldsymbol{e}_i^H + \boldsymbol{\Sigma} + \sigma^2\boldsymbol{I}\right)^{-1}\right\}. \tag{3.23}$$

As $\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H$ is Hermitian matrix with uniformly bounded spectrum norm, and $\boldsymbol{\Sigma} = \mathrm{diag}(\sigma_1^2, \ldots, \sigma_N^2)$, the trace in (3.23) can be further derived as

$$\begin{aligned} &\frac{q}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H\left(\sum_{i=1}^{U} q\boldsymbol{e}_i\boldsymbol{e}_i^H + \boldsymbol{\Sigma} - z\boldsymbol{I}\right)^{-1}\right\} \\ &\overset{a.s.}{\to} \frac{q}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H\left(\sum_{i=1}^{U} \frac{q}{1+x_i(z)}\boldsymbol{\Lambda}_i\boldsymbol{\Lambda}_i^H + \boldsymbol{\Sigma} - z\boldsymbol{I}\right)^{-1}\right\}, \end{aligned} \tag{3.24}$$

where $x_i(z)$ is the unique functional solution of

$$x_i(z) = \frac{q}{N}\mathrm{Tr}\left\{\boldsymbol{\Lambda}_u\boldsymbol{\Lambda}_u^H\left(\sum_{j=1}^{U} \frac{q}{1+x_j(z)}\boldsymbol{\Lambda}_i\boldsymbol{\Lambda}_i^H + \boldsymbol{\Sigma} - z\boldsymbol{I}\right)^{-1}\right\}, \tag{3.25}$$

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[3] The proof is provided as a special case in [96].

such that all $\{x_i(z)\}_{i=1,\ldots,U}$ are Stieltjes transforms of non-negative finite measure on $\mathbb{R}^+$. Since $\mathbf{\Lambda}\mathbf{\Lambda}^H$ and $\mathbf{\Sigma}$ are diagonal matrices, the trace in (3.24) can be readily derived as

$$\sum_{n=1}^{N} \frac{|\lambda_{u,n}|^2}{\frac{1}{N}\sum_{i=1}^{U} \frac{q}{1+x_i(z)} |\lambda_{i,n}|^2 + \sigma_n^2 - z}. \tag{3.26}$$

Thus we can conclude that $\gamma^a_{u,\text{MMSE}}$ converges to $x_u(-\sigma^2)$ in probability, where $x_u(z)$ is the unique Stieltjes transform that satisfies (3.26). Then, the corollary is proven.

The asymptotic SINR of CDMA users with MMSE receiver under colored noise was also investigated in [79], where the asymptotic SINR of CDMA users depends on the distribution of the covariance of noise on each dimension. The distribution is pre-assumed in the context of that work, since the colored noise modeled the interference from neighboring cells with CDMA transmission, which can be estimated but cannot be controlled. In this study, however, the colored noise reflects the interference introduced by the OFDMA transmission, whose transmission strategy, i.e. resource allocation, will be controlled by the OFDMA system.

Similar to the MF scenario, the result obtained under selective-fading channel shown in (3.22) can be extended to flat-fading and AWGN channel, respectively. Under the flat-fading channel condition, (3.22) can be simplified as

$$x_u(z) = \frac{1}{N}\sum_{n=1}^{N} \frac{q\,|\lambda_u|^2}{\frac{1}{N}\sum_{i=1}^{U} \frac{q}{1+x_i(z)} |\lambda_i|^2 + \sum_{k=1}^{K} p_{k,n} g_{k,n} + \sigma^2}, \tag{3.27}$$

while under the AWGN channel condition, (3.27) can be further simplified as

$$x_u(z) = \frac{1}{N}\sum_{n=1}^{N} \frac{q}{\frac{1}{N}\sum_{i=1}^{U} \frac{q}{1+x_i(z)} + \sum_{k=1}^{K} p_{k,n} g_{k,n} + \sigma^2}. \tag{3.28}$$

Solving (3.22) to find the SINR for each user involves solving U coupled non-linear equations. Moreover, it also needs to know the explicit CSI of all the CDMA users. To overcome these difficulties, we provide the following corollary.

Corollary 3.4 *With* **AS1** *and* **AS2**, *the SINR of all the CDMA users with MMSE receivers converges to* γ^a_{MMSE}, *which is the unique solution of*

$$x = \mathbb{E}_n \left[\frac{q}{\frac{\alpha q}{1+x} + \sigma_n^2 + \sigma^2} \right], \tag{3.29}$$

where $\mathbb{E}_n[\cdot]$ *denotes taking the arithmetic mean on* $\{\sigma_n^2\}_{n=1,\ldots,N}$.

Proof: The proof is given in Appendix B.

Similar to the MF case, without the OFDMA sharing ($K = 0$), the supportable CDMA load when MMSE is adopted can be derived as

$$\alpha^*_{\text{MMSE}} = \left(\frac{1}{\beta^*} - \frac{1}{q/\sigma^2} \right) (1 + \beta^*) \,. \tag{3.30}$$

Similar to the MF scenario, when α^*_{MMSE} decreases to α, there is interference margin provided by the CDMA system. Let $t_{n,\text{MMSE}}$ denote the interference margin on subcarrier n, based on equation $\beta^* = \mathbb{E}_n[\frac{q}{\frac{\alpha q}{1+\beta^*} + t_{n,\text{MMSE}} + \sigma^2}]$, we can see that $\{t_{n,\text{MMSE}}\}$ can be different across subcarriers.Therefore, it is difficult to derive the specific interference margin for all subcarriers. In the following section, we will solve this problem by reinforcing the protection to the CDMA users, by which the average interference margin, T_{MMSE}, is needed to be derived only.

3.2.3 OFDMA SINR

At the OFDMA receiver, the output of the FFT processor can be shown in (3.7). The second component is the desired signal, while the first and last components are interference plus noise. Then, the SINR of OFDMA user $k, \forall k = 1, \ldots, K$, on subcarrier $n, \forall n = 1, \ldots, N$, becomes

$$\gamma^b_{k,n} = \frac{p_{k,n} g_{k,n}}{\frac{1}{N} \sum_{u=1}^{U} q \left| \lambda_{u,n} \right|^2 + \sigma^2}. \tag{3.31}$$

Under **AS1** and **AS2**, the SINR in (3.31) converges to

$$\gamma^b_{k,n} = \frac{p_{k,n} g_{k,n}}{\alpha q + \sigma^2}. \tag{3.32}$$

Based on OFDMA definition, we make

$$p_{k,n} \begin{cases} > 0, & \text{if subcarrier } n \text{ is allocated to user } k \\ = 0, & \text{otherwise} \end{cases} \tag{3.33}$$

to guarantee the subcarriers being exclusively assigned among users. With (3.32), the overall uplink throughput achieved by OFDMA system can be written as

$$C = \sum_{k=1}^{K} \sum_{n=1}^{N} \log_2 \left(1 + \gamma_{k,n}^{b}\right). \tag{3.34}$$

In next section, we will formulate and solve the OFDMA resource allocation problem with the protection to the CDMA users.

3.3 Optimal OFDMA Resource Allocation in SR System

3.3.1 CDMA Protection

To protect the CDMA services, we have to guarantee its SINR no less than the target SINR, β^*, i.e.,

$$\gamma_{\mathrm{MF}}^{a} \geq \beta^* \text{ or } \gamma_{\mathrm{MMSE}}^{a} \geq \beta^*. \tag{3.35}$$

Since the interference margin when CDMA adopts MF receiver has been given by (3.16), to meet $\gamma_{\mathrm{MF}}^{a} \geq \beta^*$, we can restrict the total interference introduced by OFDMA system according to

$$\overline{\sigma_n^2} \leq T_{\mathrm{MF}}. \tag{3.36}$$

To meet the requirement for the CDMA system with MMSE receiver is not straightforward, since $\gamma_{\mathrm{MMSE}}^{a}$ is self-contained and dependent on the value of $\{\sigma_n^2\}_{n=1,\ldots,N}$ that is to be determined by the OFDMA resource allocation. To avoid solving (3.29) directly, the following proposition is provided.

Proposition 3.1 *Suppose* (3.29) *has the unique solution* γ. *For any given* β^*, $\gamma \geq \beta^*$ *if and only if*

$$\mathbb{E}_n \left[\frac{q}{\frac{\alpha q}{1+\beta^*} + \sigma_n^2 + \sigma^2} \right] \geq \beta^*. \tag{3.37}$$

Proof: Letting $f(x) = \mathbb{E}_n \left[\frac{q/x}{\frac{\alpha q}{1+x} + \sigma_n^2 + \sigma^2} \right]$, which is a continuous and strictly decreasing function. Since γ is the unique solution of (3.29), $f(\gamma) = 1$, we have $\gamma \geq \beta^*$ is equivalent to $f(\beta^*) \geq 1$ according to the monotonicity of $f(x)$.

3.3.2 Problem Formulation

Based on above analysis, the OFDMA resource allocation problem in the SR system can be formulated as

Problem 3.1:

$$\max_{\boldsymbol{P}} \sum_{k=1}^{K} \sum_{n=1}^{N} \log_2 \left(1 + \frac{p_{k,n} g_{k,n}}{\alpha q + \sigma^2} \right) \tag{3.38}$$

$$s.t. \ (3.36) \text{ or } (3.37) \tag{3.39}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, k = 1, \ldots, K \tag{3.40}$$

with $p_{k,n}$ being defined as in (3.33), and $\boldsymbol{P}$ is the $K \times N$ power allocation matrix with entries of $\{p_{k,n}\}_{k=1,\ldots,K,n=1,\ldots,N}$. $\bar{P}_k$ is the maximum transmission power for each user k.

3.3.3 OFDMA Resource Allocation with CDMA MF Receiver

When CDMA adopts MF receiver, **Problem 3.1** should be solved with first constraint being (3.36). Apparently, **Problem 3.1** is not a convex problem on $\boldsymbol{P}$, which makes the problem difficult to solve; and the exhaustive search becomes prohibitively complex as the numbers of subcarriers and users getting large. It has been shown that the duality gap vanishes, as the number of subcarriers becomes large, by using dual decomposition method [52], which is also adopt in the uplink resource allocation [97]. Therefore, as a benchmark performance, we also adopt this method in solving **Problem 3.1**. The details of dual decomposition optimization for solving **Problem 3.1** is provided in Appendix C. In solving the problem, $K+1$ dual variables are involved, where δ is the one associated with the interference constraint and $\lambda_k, k=1,...,K$, associated with power constraints for each OFDMA user. Subgradient method is adopted to update the dual variables.

3.3.4 OFDMA Resource Allocation with CDMA MMSE Receiver

When CDMA adopts MMSE receiver, we should solve **Problem 3.1** with the first constraint being (3.37). However, the problem cannot be decoupled completely w.r.t. OFDMA users and subcarriers; thus the dual decomposition method cannot be applied. To make the problem tractable, we will reinforce this constraint.

Since the interior function of the expectation in (3.37) is concave, we have

$$\mathbb{E}_n\left[\frac{q}{\frac{\alpha q}{1+\beta}+\sigma_n^2+\sigma^2}\right] \geq \frac{q}{\frac{\alpha q}{1+\beta}+\overline{\sigma_n^2}+\sigma^2}. \tag{3.41}$$

If we make that

$$\frac{q}{\frac{\alpha q}{1+\beta}+\overline{\sigma_n^2}+\sigma^2} \geq \beta^*, \tag{3.42}$$

the constraint (3.37) can be guaranteed. By solving the equation $\frac{q}{\frac{\alpha q}{1+\beta}+T_{\text{MMSE}}+\sigma^2}=\beta^*$, we can get the interference margin provided by the CDMA system with MMSE receiver as

$$T_{\text{MMSE}} = \frac{(\alpha^*_{\text{MMSE}}-\alpha)\,q}{1+\beta^*}, \tag{3.43}$$

where α^*_{MMSE} is given by (3.31). Thus, to guarantee (3.37), we can restrict the interference power introduced by OFDMA system according to

$$\overline{\sigma_n^2} \leq T_{\text{MMSE}}. \tag{3.44}$$

Now, the problem can be solved by the same algorithm as that of MF case, by updating the interference margin to T_{MMSE}.

3.3.5 Remarks

Besides solving the problem by typical numerical method, we would like to investigate some interesting structures of the solution for **Problem 3.1**. First, we consider a situation that the power limitation is dominant for this problem, for either fairly small $\bar{P}_k$ or large interference margin due to light CDMA load. The interference constraint can be ignored.

Problem 3.2:

$$\max_{\boldsymbol{P}} \sum_{k=1}^{K}\sum_{n=1}^{N} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right) \tag{3.45}$$

$$s.t. \sum_{n=1}^{N} p_{k,n} \le \bar{P}_k, k=1,\ldots,K \tag{3.46}$$

The optimal power allocation is

$$p_{k,n} = \left[\frac{1}{\lambda_k \ln 2} - \frac{\alpha q+\sigma^2}{g_{k,n}}\right]^+, \tag{3.47}$$

which is a typical water-filling solution.

As a counterpart, when the interference constraint is stringent, due to a heavy CDMA load or high power supply of the OFDMA user, the problem becomes

Problem 3.3:

$$\max_{\boldsymbol{P}} \sum_{k=1}^{K}\sum_{n=1}^{N} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right) \tag{3.48}$$

$$s.t. \sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,g} \le T \tag{3.49}$$

where T represents either T_{MF} or T_{MMSE}. Associating dual variable δ with the constraint, the optimal $p_{k,n}$ is

$$p_{k,n} = \frac{1}{g_{k,n}}\left[\frac{1}{\delta \ln 2} - \left(\alpha q+\sigma^2\right)\right]^+. \tag{3.50}$$

The above equation shows that OFDMA allocates power in a channel-inverse manner. In this case, the OFDMA achievable throughput has the closed form expressed as

$$C' = N\log_2\left(1+\frac{T}{\alpha q+\sigma^2}\right). \tag{3.51}$$

3.4 Optimal Joint OFDMA/CDMA Resource Allocation in SR System

In the above, the SINR performance of the uplink OFDMA/CDMA SR system has been addressed, where the CDMA target receive power at BS is treated to be fixed, based on which the OFDMA system predicts the exploitable interference margin and conducts resource allocation to maximize its throughput. The fixed receive power of CDMA users at BS results in a fixed and predictable interference to the OFDMA system. Note in conventional spectrum sharing studies, the interference power from PTx to SRx was either ignored [31] or assumed to be a pre-determined value [41].

For spectrum sharing systems, the PTx transmission power has two contradictory effects towards the secondary system. First, the high PTx transmission power results in a high SINR of primary user. To maintain the target SINR, the primary system can provide high interference margin, which allows the secondary user to transmit with high power. This thus contributes to the secondary throughput. However, high PTx transmission power increases the interference to the SRx, which degrades the SRx SINR. Therefore, a tradeoff of secondary throughput over the PTx transmission power (equivalently, the PTx receive power in this context) exists. It is worth noting that the existing uplink CDMA system adopts the power control mechanism, which adapts the transmission power to make the receive SINR equal to the target value [98]. This means when the OFDMA system transmits with higher power, the CDMA transmitter will increase its transmission power to accommodate such increment of interference. Such power control provides the OFDMA/CDMA SR system an opportunity to exploit the aforementioned tradeoff to improve the OFDMA system throughput.

In this section, we will exploit this tradeoff by jointly optimizing the OFDMA resource allocation and CDMA receive power, which is named as joint resource allocation. By proving that the OFDMA throughput is quasiconcave over CDMA receive power, the joint resource allocation algorithm is proposed. It is shown that the scheme can effectively optimize the OFDMA throughput by fully exploiting the interference margin provided by the CDMA system.

The difficulty in evaluating the user SINR in SR system comes from three aspects: different access schemes adopted by the two systems, the randomness of CDMA spreading codes, and the unavailability of CDMA specific spreading codes and channel state information to the OFDMA system. By considering a large CDMA system (i.e., $U \to \infty$, $N \to \infty$, and $\frac{U}{N} \to \alpha$, where α is a constant, representing the CDMA traffic load.) with rich multipath and uniform power delay profile [93], the asymptotic SINR of CDMA user when adopting MF or MMSE receiver is given by

$$\text{MF} : \gamma^a = \frac{q}{\alpha q + \bar{I}_n + \sigma^2} \tag{3.52}$$

$$\text{MMSE} : \gamma^a = \mathbb{E}_n \left[\frac{q}{\frac{\alpha q}{1+\gamma^a} + I_n + \sigma^2} \right], \tag{3.53}$$

where I_n denotes the interference from OFDMA system on subcarrier n, and $I_n = \sum_{k=1}^{K} p_{k,n} g_{k,n}$, $g_{k,n} = |H_{k,n}|^2$. Moreover, $\bar{I}_n = \frac{1}{N} \sum_{n=1}^{N} I_n$.

On the other hand, the SINR of OFDMA user k on subcarrier n is give by

$$\gamma_{k,n}^b = \frac{p_{k,n} g_{k,n}}{\alpha q + \sigma^2}. \tag{3.54}$$

3.4.1 Interference Margin as Function of q

To deal with the near-far effect in the uplink transmission, CDMA system adopts the power control that adjusts the user transmit power to keep the receive SINR at the target value β^*, i.e., $\gamma^a = \beta^*$. From (3.52) and (3.53) we can see that, for a given q, there is corresponding interference margin, denoted by $m(q)$ and $m_n(q)$ for MF and MMSE receiver respectively, allowing $\bar{I}_n \leq m(q)$ and $I_n \leq m_n(q), \forall n$. This indicates the CDMA tolerable interference from the OFDMA spectrum sharing. For MF case, $m(q)$ can be directly derived from $\frac{q}{\alpha q + m(q) + \sigma^2} = \beta^*$. For MMSE case, however, it is extremely difficult to find $m_n(q), \forall n$, directly from $\beta^* = \mathbb{E}_n[\frac{q}{\frac{\alpha q}{1+\beta^*} + m_n(q) + \sigma^2}]$. To deal with this problem, we solve $m(q)$ from $\beta^* = \frac{q}{\frac{\alpha q}{1+\beta^*}+m(q)+\sigma^2}$. As $m(q) \leq \frac{1}{N}\sum_{n=1}^{N} m_n(q)$, such an approximation will provide an over-protection towards the CDMA system, which will be illustrated in the simulation. Thus, the interference margin can be generally written as

$$m(q) = m_\alpha q - \sigma^2, \tag{3.55}$$

where

$$m_\alpha = \begin{cases} \frac{1}{\beta^*} - \alpha, & \text{for MF receiver} \\ \frac{1}{\beta^*} - \frac{\alpha}{1+\beta^*}, & \text{for MMSE receiver} \end{cases}. \tag{3.56}$$

Here, $q \in [q_0, Q]$, where $q_0 = \frac{\sigma^2}{m_\alpha}$ is the minimum receive power leading to zero interferon margin, and Q is the maximal receive power considering the transmission power limit of CDMA user terminal.

3.4.2 Problem Formulation

As $m(q)$ increases with q, OFDMA can increase the transmission power to exploit the interference margin. This however decreases the SINR in (3.54). To exploit such tradeoff of the OFDMA throughput over q, we formulate the combined resource allocation problem as

Problem 3.4:

$$\max_{q,\boldsymbol{P}} \; C(q,\boldsymbol{P}) \triangleq \sum_{k=1}^{K}\sum_{n=1}^{N} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right) \tag{3.57}$$

$$s.t. \; \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} \leq m(q) \tag{3.58}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, k = 1,\ldots,K \tag{3.59}$$

Similarly, $p_{k,n}$ is defined as in (3.33) to guarantee the subcarriers being exclusively assigned among users. Again, $\bar{P}_k$ is the maximum transmission power for user k.

3.4.3 Optimal Joint Resource Allocation

As variables q and $p_{k,n}$ are coupled in **Problem 3.4**, prime decomposition can be employed to decouple them in a two-level optimization [99]. In the low-level, $p_{k,n}$ is optimized for a given q, while q is optimized in the high-level optimization. The low-level optimization problem can be readily solved by dual decomposition method as indicated in Appendix C. To find the optimal q, however, the complexity will be very high if exhaustive search is adopted. To provide an efficient algorithm, we investigate the convexity of the problem in the following theorem.

Theorem 3.2 *The OFDMA throughput is continuously differentiable and quasiconcave over the CDMA receive power q, $q \in [q_0, \infty)$.*

Proof: Firstly, we can observe that $m(q)$ is strictly increasing over q. Then, we divide $\mathcal{S} = [q_0, \infty)$ into three sections: $\mathcal{S} = \mathcal{S}_1 \cup \mathcal{S}_2 \cup \mathcal{S}_3$, where $\mathcal{S}_1 = [q_0, q_1)$, $\mathcal{S}_2 = [q_1, q_2]$ and $\mathcal{S}_3 = (q_2, \infty)$.

When $q \in \mathcal{S}_1$, $m(q)$ is so small that the interference constraint is dominant, while the individual power limit does not affect the searching of optimal $p_{k,n}$. By ignoring the second constraint, **Problem 3.4** becomes

<u>Problem 3.5:</u>

$$\max_{q,\boldsymbol{P}} \sum_{k=1}^{K}\sum_{n=1}^{N} \log_2\left(1 + \frac{p_{k,n} g_{k,n}}{\alpha q + \sigma^2}\right) \tag{3.60}$$

$$s.t.\ \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n} g_{k,n} \le m(q) \tag{3.61}$$

The objective function is maximized when the equality in the constraint holds. Associating dual variable δ with the constraint, the optimal power can be derived as $p^*_{k,n} = \frac{1}{g_{k,n}}[\frac{1}{\delta} - (\alpha q + \sigma^2)]^+$. Substituting it into the constraint shows the interference on each subcarrier is uniform that equals to $m(q)$; thus, the OFDMA throughput becomes

$$C(q) = \sum_{n=1}^{N} \log_2\left(1 + \frac{M(q)}{\alpha q + \sigma^2}\right). \tag{3.62}$$

Obviously, $C(q)$ is continuously increasing and concave over $q \in \mathcal{S}_1$.

When $q \in \mathcal{S}_3$, $m(q)$ is large enough to invalidate the interference constraint, while all the power constraints affect the optimal $p_{k,n}$. Since q does not affect the optimal $p_{k,n}$, but only decreases the objective function when it increases, the OFDMA throughput $C(q)$ is continuously decreasing and convex over $q \in \mathcal{S}_3$.

When $q \in \mathcal{S}_2$, the moderate $m(q)$ makes the interference constraint and partial (or all) power constraints affect the optimization. For any subcarrier allocation, denote $\mathcal{K}_1$ as the users that have not reach their power limit, while $\mathcal{K}_2$ as the users have reached their power limit. Accordingly, $\mathcal{N}_1$ denotes the subcarriers allocated to $\mathcal{K}_1$, while $\mathcal{N}_2$ denotes the subcarriers are allocated to $\mathcal{K}_2$. Then, $\sum_{n\in\mathcal{N}_1} p_{k,n} < \bar{P}_k, \forall k \in \mathcal{K}_1$ and $\sum_{n\in\mathcal{N}_2} p_{k,n} = \bar{P}_k, \forall k \in \mathcal{K}_2$. Denoting $A = \frac{1}{N}\sum_{n\in\mathcal{N}_2}\sum_{k\in\mathcal{K}_2} p_{k,n}g_{k,n}$, **Problem 3.4** can be written as

Problem 3.5:

$$\max_{q,\boldsymbol{P}} \sum_{n\in\mathcal{N}_1}\sum_{k\in\mathcal{K}_1} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right) + \sum_{n\in\mathcal{N}_2}\sum_{k\in\mathcal{K}_2} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right) \tag{3.63}$$

$$s.t.\ \frac{1}{N}\sum_{n\in\mathcal{N}_1}\sum_{k\in\mathcal{K}_1} p_{k,n}g_{k,n} \le m(q) - A \tag{3.64}$$

Similar to the situation when $q \in \mathcal{S}_1$, the optimal throughput can be achieved when the equality of the constraint holds, i.e.,

$$C(q) = \sum_{n\in\mathcal{N}_1} \log_2\left(1+\frac{m(q)-A}{\alpha q+\sigma^2}\right) + \sum_{n\in\mathcal{N}_2}\sum_{k\in\mathcal{K}_2} \log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right). \tag{3.65}$$

Thus, we have

$$\lim_{\Delta q\to 0}\frac{C(q+\Delta q)-C(q)}{\Delta q} = \sum_{n\in\mathcal{N}_1}\frac{m_\alpha\sigma^2+\alpha\sigma^2+\alpha A}{(\alpha q+\sigma^2)(\alpha q+m_\alpha q-A)} \tag{3.66}$$

$$-\sum_{n\in\mathcal{N}_2}\sum_{k\in\mathcal{K}_2}\frac{\alpha p_{k,n}g_{k,n}}{(\alpha q+\sigma^2)(\alpha q+\sigma^2+p_{k,n}g_{k,n})} \tag{3.67}$$

The existence of the derivative means the OFDMA throughput is continuously differentiable over $q \in \mathcal{S}_2$. When $\mathcal{K}_2 = \varnothing$, (3.66) becomes $\sum_{n=1}^{N}\frac{\sigma^2}{(\alpha q+\sigma^2)q}$, which equals to the derivative of (3.62). When $\mathcal{K}_1 = \varnothing$, (3.66) becomes $-\sum_{n=1}^{N}\sum_{k=1}^{K}\frac{\alpha p_{k,n}g_{k,n}}{(\alpha q+\sigma^2)\left(\alpha q+\sigma^2+p_{k,n}g_{k,n}\right)}$, which equals to the derivative of OFDMA throughput when $q \in \mathcal{S}_3$. Thus, $C(q)$ is continuously differentiable over $q \in \mathcal{S}$.

Denote $\mathcal{S}_\eta, \eta \in \mathbb{R}$, as the superlevel set of $C(q)$, i.e.,

$$\mathcal{S}_\eta = \left\{ M(q) \geq \frac{1}{N}\sum_{n\in\mathcal{N}_1}\sum_{k\in\mathcal{K}_1} p_{k,n}g_{k,n} + A \middle| C(q) \geq \eta \right\}. \tag{3.68}$$

$C(q) \geq \eta$ is equivalent to

$$\sum_{n\in\mathcal{N}_1}\log_2\left(1+\frac{M(q)-A}{\alpha q+\sigma^2}\right) \geq \eta - \sum_{n\in\mathcal{N}_2}\sum_{k\in\mathcal{K}_2}\log_2\left(1+\frac{p_{k,n}g_{k,n}}{\alpha q+\sigma^2}\right). \tag{3.69}$$

Because $\sum_{n\in\mathcal{N}_1}\log_2(1+\frac{M(q)-A}{\alpha q+\sigma^2})$ is strictly concave, $\mathcal{S}_\eta$ is strictly convex. Thus, $C(q)$ is quasiconcave over $q \in \mathcal{S}_2$. Considering the continuity and convexity over $\mathcal{S}_1$ and $\mathcal{S}_3$, the theorem is proved.

Theorem 3.2 provides us two observations. First, the quasiconcave property of the OFDMA throughput guarantees the existence of global optimum over q. Second, the derivative bisection search can be used because of the continuous differentiability of the OFDMA throughput. Therefore, we propose Algorithm 1 to solve **Problem 3.4**, where the steps for finding $\{p^*_{k,n}\}$ for a given q is the same as in the previous section, and thus omitted here for brevity.

Algorithm 1 Bisection Search for Solving Problem 3.4

```
Let $q = Q$, find $\{p^*_{k,n}\}$ and derive (3.66)
if (3.66) $\geq 0$, then $q^* = Q$
else, let $q_{\min} = q_0$, $q_{\max} = Q$, given a small tolerance $\epsilon$
while $q_{\max} - q_{\min} > \epsilon$ do
    $q_{\text{mid}} \leftarrow \frac{q_{\min}+q_{\max}}{2}$, find $\{p^*_{k,n}\}$ and derive (3.66)
    if (3.66) $> 0$, then $q_{\min} \leftarrow q_{\text{mid}}$
    else, $q_{\max} \leftarrow q_{\text{mid}}$
end while
```

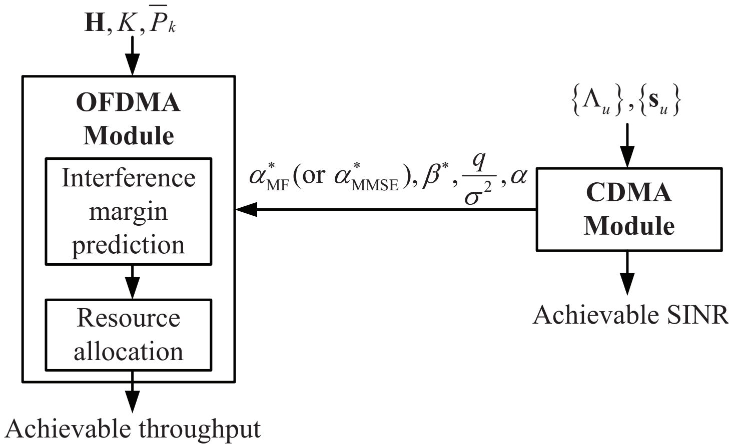

Figure 3.2: Block diagram of the simulation and information flows.

3.5 Performance Evaluation

3.5.1 SR Performance with Optimal OFDMA Resource Allocation

In this subsection, simulation results are provided to evaluate the performance of the proposed OFDMA/CDMA SR system with OFDMA resource allocation where CDMA target receive power q is assumed to be fixed. The spreading gain of CDMA system and the FFT size of the OFDMA system are set to be $N = 256$, which is large enough to verify the asymptotic results obtained in this paper. The power of white Gaussian noises is normalized to $\sigma^2 = 1$. The number of multipaths L is set as $N/8$, and each of the time-domain delay taps follows the distribution of $\mathcal{CN}(0, 1/L)$. The target SINR threshold β^* for CDMA system is set to be 2dB. The designed receive SNR q/σ^2 and CDMA load α will be varied in the simulations. There are two users in the OFDMA system, and the maximal transmission SNR for each OFDMA user $\bar{P}_k/\sigma^2$ is assumed to be 30dB.

The block diagram of the simulation and information flows is illustrated in Fig. 3.2. The CDMA system passes its system parameters, (α^*_{MF} or α^*_{MMSE}, $\beta^*, q/\sigma^2, \alpha$), to the OFDMA system for predicting the interference margin. This is the only inter-system information flow needed in the SR system. In order to get the simulated SINRs for CDMA users, the spreading codes for each user are independently and randomly generated, and the interference power introduced by OFDMA system is passed back to the CDMA system. In practice, however, this information flow is not necessary since the interference power can be estimated by the CDMA receiver directly [100], [101].

Firstly, we adopt MF as the CDMA receiver to study the OFDMA resource allocation results. For one particular channel realization shown in Fig.3.3 (a) , Fig. 3.3 (b) and (c) illustrate the OFDMA power allocation at each subcarrier for light CDMA load scenario and heavy CDMA load scenario, respectively. It can be observed that for both scenarios, each subcarrier is allocated to the user with the better channel gain. Moreover, in the light CDMA load scenario, the OFDMA power is allocated in a water-filling way as shown in Fig. 3.3 (b), while in the heavy CDMA load scenario, the OFDMA power is allocated in channel-inverse manner as shown in Fig. 3.3 (c). These observations are consistent with the discussions in Part E of Section IV.

Fig. 3.4 and Fig. 3.5 further validate the convergence of the proposed OFDMA resource allocation algorithm. Fig. 3.4 (a)-(c) represent light CDMA load case, while Fig. 3.4 (d)-(f) represent heavy CDMA load case. The duality gap for both scenarios converges to zero as shown in Fig. 3.4 (a) and (d). In Fig. 3.4 (b) and (c), the converged dual variables $\{\lambda_k\}_{k=1,2}$ are around 0.08, and δ is close to zero. This means that the user transmits at its maximum allowable power, and interference to CDMA is less than the interference margin, which are demonstrated in Fig. 3.5 (b) and (c). In the heavy load counterpart, the converged $\{\lambda_k\}_{k=1,2}$ approch zeros, while the converged δ is around 0.02. This demonstrates that the total interference introduced by the OFDMA system to the CDMA system reaches the interference margin, while the transmission power is less the the maximal value, which can be seen in Fig. 3.5 (e) and (f). All these validate the effectiveness of the proposed OFDMA resource allocation algorithm.

Next, we evaluate the OFDMA achievable throughput by varying the CDMA load, when CDMA adopts different receivers, i.e., MF and MMSE receiver. From Fig. 3.6, we

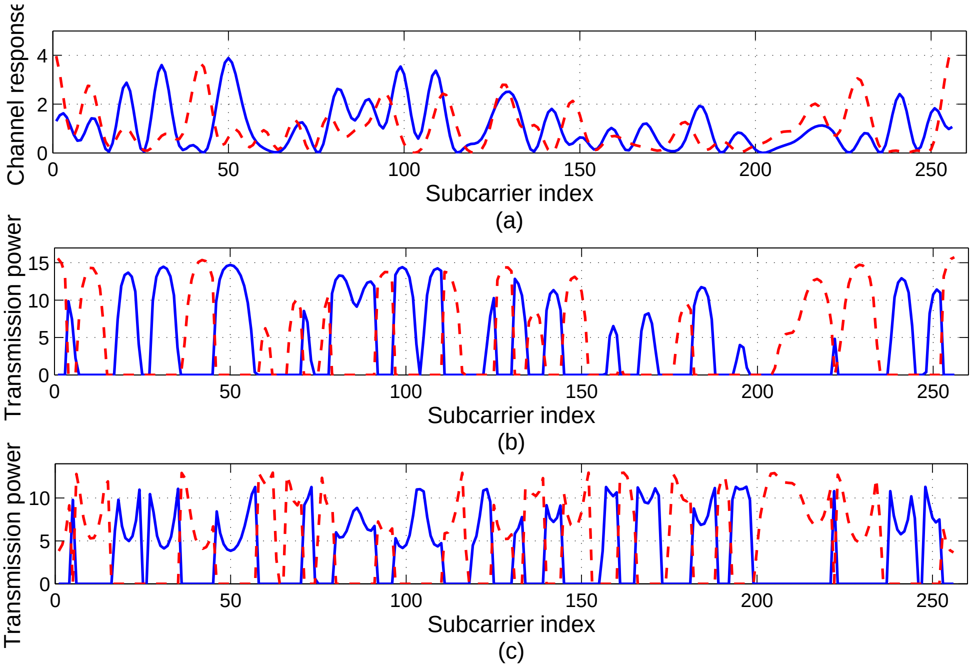

Figure 3.3: OFDMA resource allocation results: (a) Channel responses of OFDMA users; (b) Subcarrier and power allocation with light CDMA load; (c) Subcarrier and power allocation with heavy CDMA load. The solid line and dashed line represent OFDMA user 1 and OFDMA user 2, respectively.

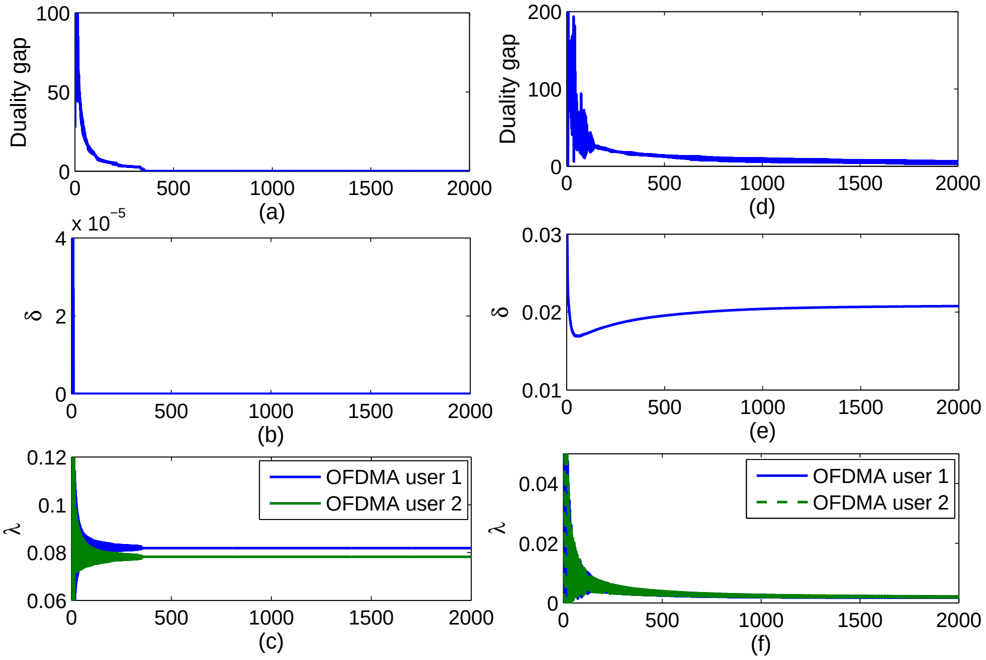

Figure 3.4: Evolution of duality gap and dual variables. δ is associated with interference constraint, while λ is associated with maximal transmission power constraint. (a)-(c) for light CDMA load; (d)-(f) for heavy CDMA load.

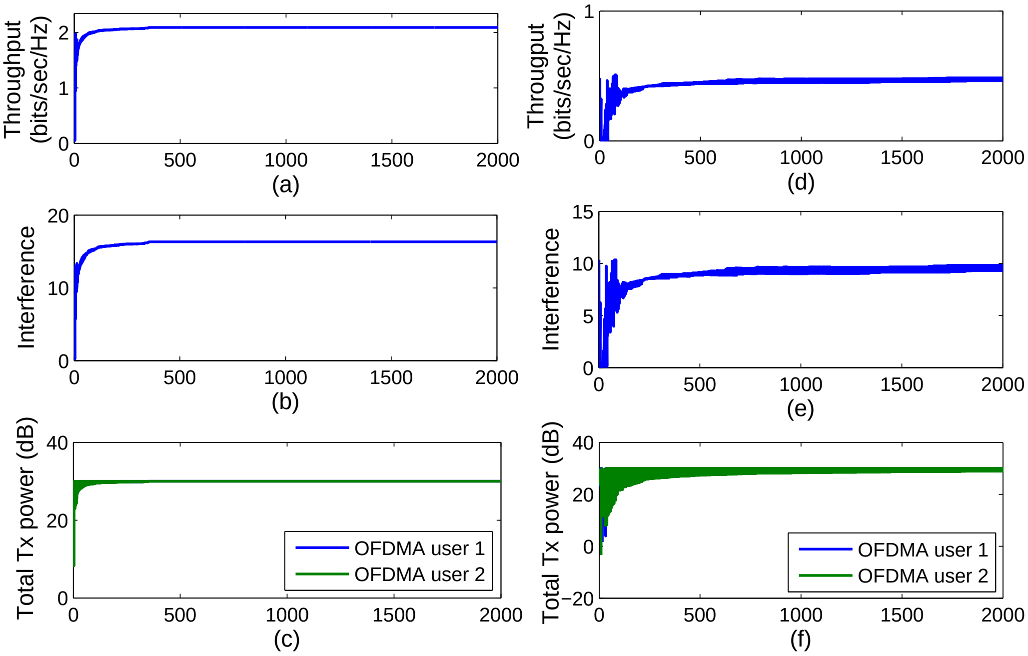

Figure 3.5: Evolution of OFDMA throughput, interference power to CDMA, and total OFDMA transmission power by each user: (a)-(c) for light CDMA load; (d)-(f) for heavy CDMA load.

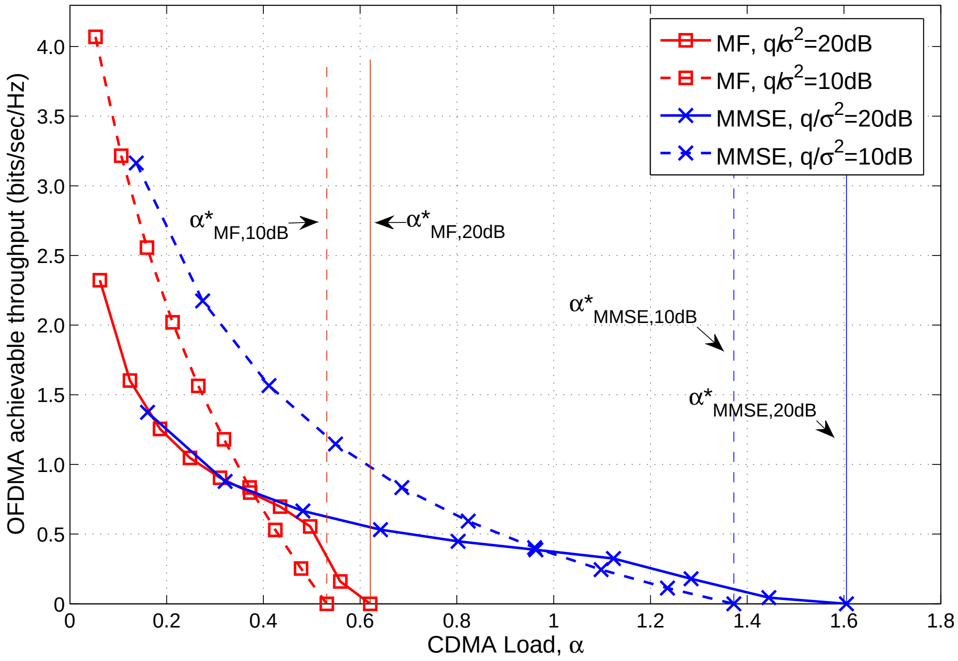

Figure 3.6: OFDMA achievable throughput vs CDMA load.

find that OFDMA can achieve much higher throughput when the CDMA system adopts MMSE receiver, as compared with that of MF receiver. This is because the CDMA system with MMSE receiver can provide higher interference margin than that with MF receiver, which can be seen from (3.18) and (3.43). Moreover, the feasible range of CDMA load with MMSE receiver is much larger than that with MF receiver. We also consider two levels of CDMA receive SNR, $q/\sigma^2 = 20$dB and $q/\sigma^2 = 10$dB to represent high and low CDMA receive power. When the CDMA load is light, the OFDMA system can achieve high throughput. But when the CDMA load is relative high for both receivers, the 10dB-curve outperforms the 20dB-curve. This is because the high receive SNR of the CDMA system provides higher interference margin, but also imposes higher interference to OFDMA users.

Only looking into the OFDMA throughput is not enough, since the scheme should protect the CDMA services well. In Fig. 3.7, we compare the theoretical and simulated average SINR of the CDMA users by varying the CDMA load, and applying different

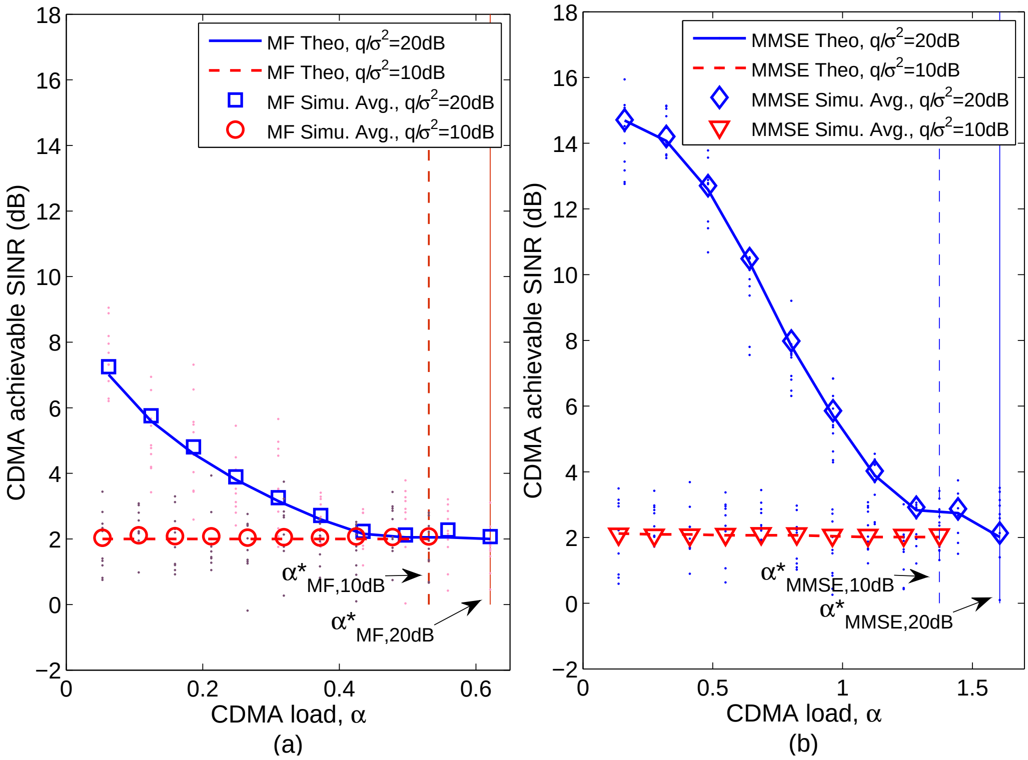

Figure 3.7: CDMA achievable SINR vs CDMA load: (a) MF receiver; (b) MMSE receiver

types of CDMA receivers. It can be seen that these two values match very well for all the cases. Furthermore, for both types of CDMA receivers, when the CDMA receive power is high and the CDMA load is light, the achieved CDMA SINR is higher than the target SINR. The reason is, although small α provides high interference margin, it cannot be exploited by the OFDMA system due to the transmit power limit. As α increases, the interference margin becomes less, and eventually can be fully exploited by the OFDMA system. Thus, the achieved SINR for the CDMA system converges to the target value, when the CDMA load becomes heavy.

Furthermore, we verify the OFDMA achievable throughput by varying the CDMA receive SNR q/σ^2. Two levels of CDMA load, i.e., $\alpha = 0.05$ and $\alpha = 0.2$ are considered. Fig. 3.8 shows that for a given CDMA load, the OFDMA system achieves higher throughput when the CDMA system adopts the MMSE receiver. For the same type of CDMA receiver, the OFDMA system achieves higher throughput when the CDMA load

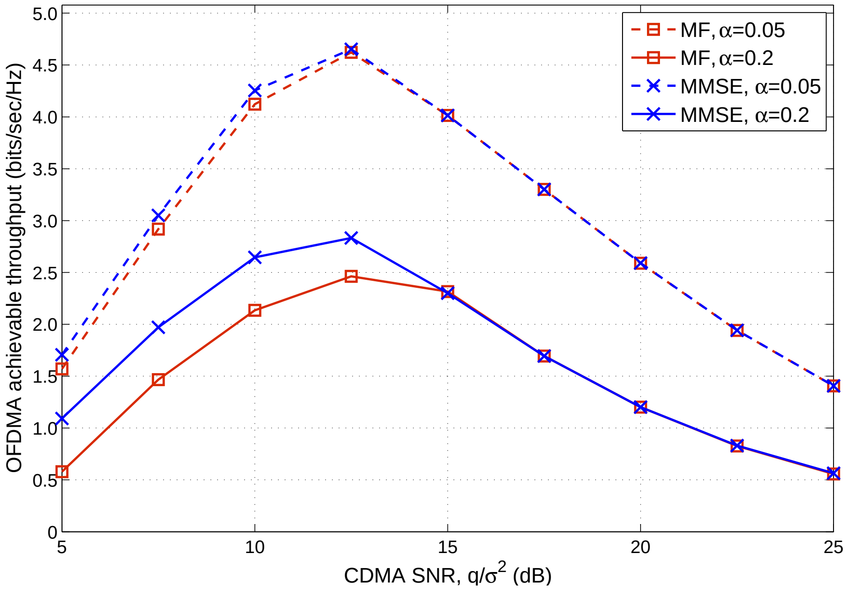

Figure 3.8: OFDMA achievable throughput vs CDMA receive SNR.

is light. In addition, there is an optimal CDMA receive SNR value that maximizes the OFDMA achievable throughput. The reason can be stated as follows. When the CDMA receive SNR is small, the interference margin that can be exploited by OFDMA is small; thus, the OFDMA can only achieve low throughput even though it has extra transmission power. As the CDMA receive SNR increases, the interference margin increases, thus OFDMA can achieve higher throughput through transmitting at higher power. When the CDMA receive SNR further increases, although higher interference margin is provided by the CDMA system, this margin cannot be fully exploited by OFDMA system due to the transmission power limit of the OFDMA users. On the other hand, the interference from the CDMA system to the OFDMA users increases, making the OFDMA achieved throughput deteriorate.

In the CDMA counterpart shown in Fig. 3.9, we can see that the CDMA achieved SINR increases with the receive SNR, and the theoretical and simulated average SINR match very well. The increment of CDMA receive SNR provides higher interference margin to the OFDMA system, but the OFDMA system will not be able to exploit it due

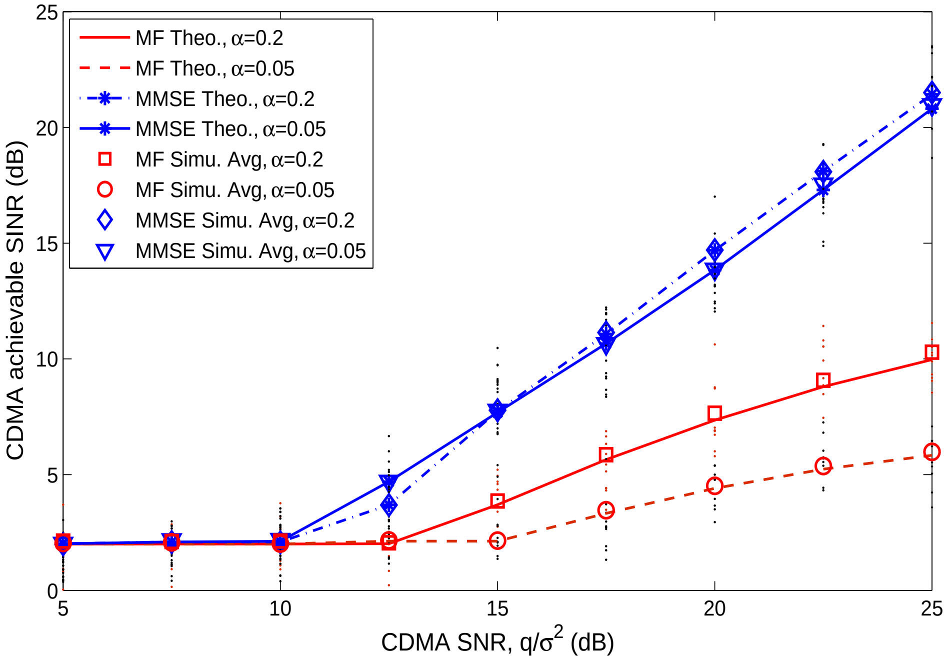

Figure 3.9: CDMA achievable SINR vs CDMA receive SNR.

to its power limit. Eventually, the interference from OFDMA to CDMA will converge to a limit. Thus, the CDMA achieved SINR will keep increasing as the receive SNR increases. We also obverse that although the reinforcement of the constraint should have brought along an over-protection to CDMA user, the effect is negligible as the number of subcarriers N is large.

3.5.2 SR Performance with Optimal Joint OFDMA/CDMA Resource Allocation

In this subsection, the simulation results are provided to evaluate the performance of the joint OFDMA/CDMA resource allocation scheme for the SR system. Similar to the previous subsection, the spreading gain and the number of subcarriers are set to be N=256. The number of multipath is set as $\frac{N}{8}$. The power of Gaussian noise is normalized to be σ^2=1. We set the maximum CDMA receive SNR $\frac{Q}{\sigma^2}$ as 30dB, and the target CDMA SINR β^* as 2dB.

Firstly, the OFDMA achieved throughput w.r.t. the CDMA SNR $\frac{q}{\sigma^2}$ is shown in Fig. 3.10, which illustrates the OFDMA achieved throughput is quasiconcave over the CDMA receive power. For each value of $P_k=\frac{\bar{P}_k}{\sigma^2}$, the MMSE receiver outperforms the MF receiver when the OFDMA power limits are not achieved, and all the interference margin can be exploited by the OFDMA system. This is because the MMSE receiver can provide higher interference margin than MF receiver. When all the OFDMA power limits are achieved, the MF and MMSE curves are coincident, because the extra interference margin cannot be exploited by OFDMA system due to the OFDMA power limit.

Next, we vary the CDMA load α to observe the optimal OFDMA achieved throughput and the corresponding q^*. Fig. 3.11 shows two observations. First, for any α, MMSE outperforms the MF receiver for each level of P_k; for each kind of receiver, the higher P_k can help the OFDMA exploit more interference margin, resulting in a higher throughput. Second, as α increases, the OFDMA throughput decreases, because the available interference margin decreases. In Fig. 3.12 we can observe that, for any α, the q^* with MF receiver is higher than that with MMSE receiver for each P_k. Furthermore, for each kind of receiver, higher P_k requires higher q^* to maximize the OFDMA throughput. This phenomenon is consist with the information shown in Fig. 3.10.

Last, we illustrate in Table 1 the CDMA achieved SINR when OFDMA throughout is optimized. The interference $\bar{I}_n$ and I_n in (3.52) and (3.53) are derived based on the OFDMA resource allocation. Each CDMA user in the simulation is assigned with random spreading code, based on which the simulated SINR are calculated. In each data entry in Table 1, the first data is the average simulated SINR, while the second one is the theoretical SINR derived from (3.52) and (3.53) for MF and MMSE receiver, respectively. It is shown that, under MF scenario, when the optimal OFDMA throughput is achieved, the interference margin provided by CDMA is fully exploited by the OFDMA system; so its achieved SINR is almost equal to β^*. Moreover, the MMSE receiver provides overprotection to the CDMA system, because of the approximation adopted when deriving

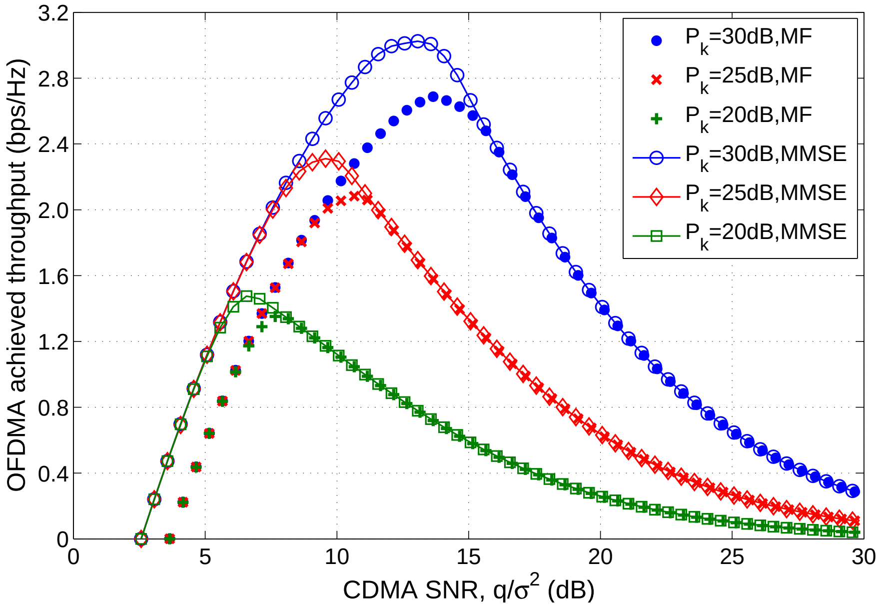

Figure 3.10: OFDMA achieved throughput vs. CDMA SNR. $\alpha = 0.2$.

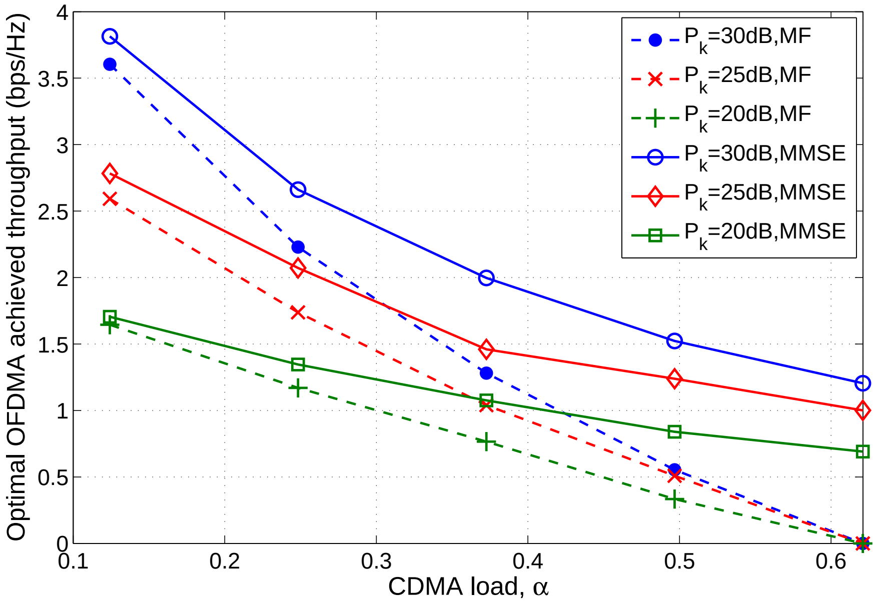

Figure 3.11: Optimal OFDMA achieved throughput vs. CDMA load.

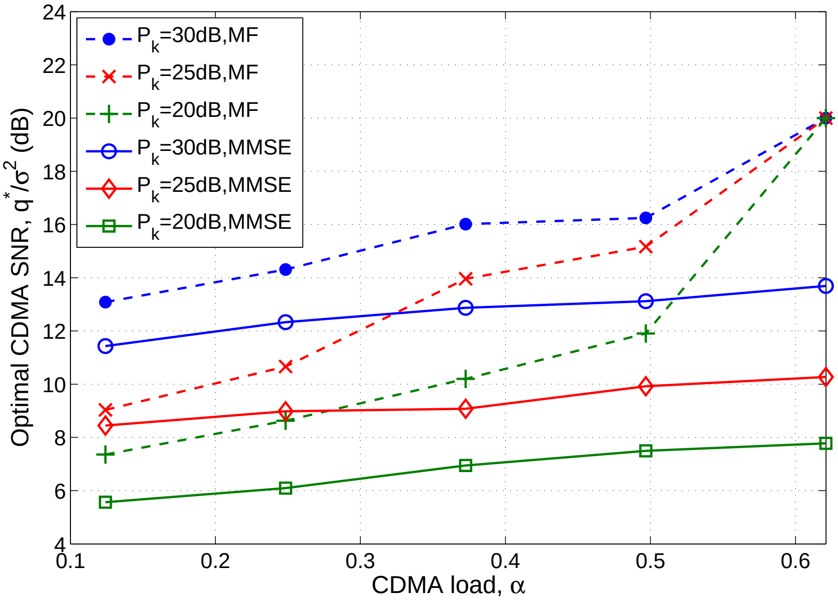

Figure 3.12: Optimal CDMA SNR vs. CDMA load.

the interference margin for the MMSE scenario. However, the gap is small since N is large.

Table 3.1: CDMA Achieved SINR (in dB)

MF	α=0.124	α=0.248	α=0.372	α=0.496	α=0.62
P_k=30	2.05|2.00	2.06|2.00	2.06|2.00	2.06|2.00	2.09|2.00
P_k=25	2.06|2.00	2.08|2.00	2.07|2.00	2.06|2.00	2.09|2.00
P_k=20	2.07|2.00	2.08|2.00	2.07|2.00	2.07|2.00	2.09|2.00
MMSE	α=0.124	α=0.248	α=0.372	α=0.496	α=0.62
P_k=30	2.35|2.43	2.32|2.30	2.24|2.20	2.23|2.22	2.28|2.20
P_k=25	2.38|2.43	2.33|2.36	2.26|2.30	2.30|2.33	2.41|2.43
P_k=20	2.49|2.46	2.36|2.25	2.29|2.23	2.31|2.25	2.45|2.41

3.6 Conclusions

In this chapter, we have proposed an underlaid OFDMA/CDMA SR system which allows OFDMA network to operate in the spectrum allocated to the CDMA network. We have quantified the mutual interference between uplink transmissions of the two systems, and derive the asymptotic SINR of the CDMA users. The interference margin that can be tolerated by the CDMA system is derived by the random matrix theory and the large number law. With the interference margin together with the transmit power constraints, we have formulated the OFDMA resource allocation problem by regarding the CDMA target receive power is fixed. The problem has been solved through dual decomposition method. Next, we formulated the joint OFDMA/CDMA resource allocation problem, by exploiting the tradeoff of the OFDMA throughput over the receive power of CDMA system. By proving that the OFDMA throughput is quasiconcave over CDMA receive power, the efficient joint resource allocation algorithm is proposed. The proposed algorithm is applied by the OFDMA system only, but due to the power control of CDMA system, it will force the CDMA to adjust the transmission power to its optimal value. Our simulation results have verified our theoretical analysis, and validated the effectiveness of the proposed resource allocation algorithms and their capability to protect the legacy CDMA users. The proposed SR system requires the least information flow from the CDMA system to the OFDMA system, and no upgrading of the legacy CDMA system is needed, thus it can be deployed by telecom operators to improve the spectral efficiency of their cellular networks.

The SR model that has been studied in this chapter adopts the active infrastructure sharing, i.e., the cell site and BS antenna of the legacy CDMA system are both shared by the OFDMA system. By investigating the SINR performance of CDMA system and the resource allocation problem of OFDMA system, this study provides fundamental insights in the SR technique applied in the wireless cellular networks. It is worth noting that, in a generic case of the mobile infrastructure sharing, only the cell site of legacy system is permitted to be shared while the active elements, such as antenna, cannot be accessed by the unlicensed system. Generally speaking, without antenna sharing, the SR model is less restricted by the negotiation between the licensed and unlicensed systems and thus could be easy to be deployed either by the same or different operators who take charge of the two systems. Moreover, due to the additional antenna installed on the cell site, additional diversity is introduced that can be exploited to improve the refarming performance. In next chapter, the SR with passive infrastructure sharing will be thoroughly investigated.

Chapter 4

Spectrum Refarming (SR) with Passive Infrastructure Sharing

Passive infrastructure sharing refers to the sharing of passive elements in their radio access networks, such as cell sites. When the SR technique is applied with passive infrastructure sharing, the licensed legacy and unlicensed systems are equipped with separate BS antennas. At first glance, this additional BS antenna should bring along more diversity, such as multi-channel diversity, that can be exploited by the secondary system to improve the refarming performance. However, without active participation of legacy system, it is extremely difficult to obtain the channel power gain from STx to PRx, which is the necessary information for the secondary system to predict the interference it imposes to primary system. This problem is more unavoidable for the OFDMA/CDMA coexistent system, where the legacy CDMA system is reluctant to be upgraded. This realistic but crucial problem was widely relaxed by assuming these interference channel power gains are available perfectly or imperfectly in the existing literatures [30, 31, 87].

In this chapter, we investigate the SR technique to the OFDMA/CDMA coexistent system where the OFDMA system shares the radio band licensed to the CDMA system and the cell site of the CDMA system. Faced with the problem of unavailability of interference channel power gain, a novel OFDMA resource allocation scheme is designed which can achieve moderate throughput with sufficient protection to the CDMA normal services. Moreover, the CDMA system inner power control is exploited to propose two resource allocation schemes for the OFDMA system to farthest utilize the sharing opportunity provided by the CDMA system.

The remainder of this chapter is organized as follows. In Section 4.1, the uplink OFDMA/CDMA SR system with passive infrastructure sharing is presented, based on which the OFDMA resource allocation problem is formulated. In Section 4.2, to deal with the C-CSI unavailability problem, we propose a resource allocation scheme for OFDMA system which is proven to be able to sufficiently protect the CDMA users. Since the actual interference suffered by CDMA users is always no larger than the predicted value, we propose in Section 4.3 and Section 4.4 two novel iterative-based resource allocation schemes to increase the actual interference towards the tolerable level. In Section 4.5, we consider the scenarios when the OFDMA system adopts typical suboptimal resource allocation schemes. Simulation results are presented in Section 4.6, and the conclusion is drawn in Section 4.7.

The content of this chapter is based on our works [102] and [103].

4.1 System Model and Problem Formulation

4.1.1 System Model Description

Throughout this chapter, we consider the uplink OFDMA/CDMA SR system with passive infrastructure sharing, which is shown in Fig. 4.1. The two systems share a common cell site, while being equipped with separate receive antennas at the BS. The two antennas are far apart with each other (i.e., the inter-antenna distance is larger than half wavelength), so that the CSI from a mobile user to them can be treated as independent. There are U CDMA users and K OFDMA users simultaneously access to the BS. Each of the user terminals is equipped with single antenna.

The CDMA and OFDMA transmission symbols are assumed to be aligned, which can be achieved by two conditions. First, the OFDMA shares the whole CDMA spectrum with the Fast Fourier Transform (FFT) size equal the CDMA spreading gain, both of

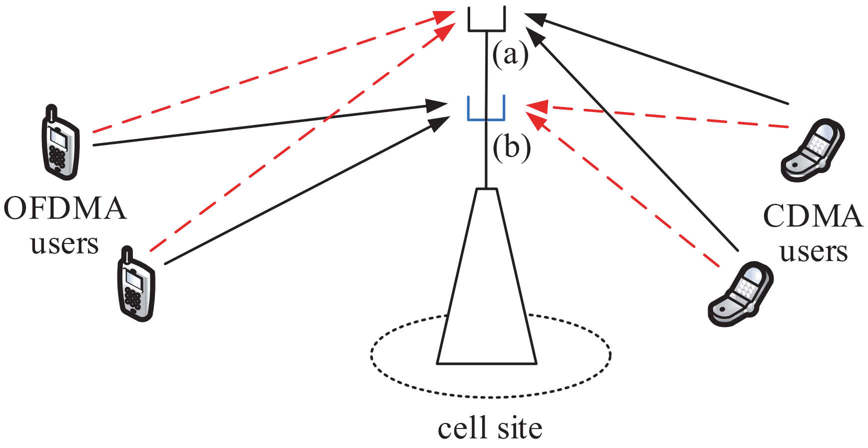

Figure 4.1: Uplink OFDMA/CDMA SR system with passive infrastructure sharing. (a) is CDMA antenna and (b) is OFDMA antenna.

which are denoted by N. Thus, the symbol durations of both systems are the same. Second, the OFDMA uplink transmission is synchronized with the CDMA system [94]. Thus, the CDMA and OFDMA symbols are synchronously received by the two receive antennas. Channels are assumed to be invariant within each transmission frame, which includes a sequential symbols. Thus, we can focus on the analysis within a specific symbol duration. It is noted that the study with aligned transmission symbols can be extended for the non-aligned scenario in which one OFDMA symbol duration contains multiple CDMA symbols. This reflects a practical system where the OFDMA adopts much larger FFT size than the CDMA spreading gain.

Regarding the CDMA system as primary and the OFDMA system as secondary, the presented system indicates a collocation of the primary and secondary receivers. A fantastic advantage of the receiver collocation lies in that the distance-based path loss from a mobile user to each of the receivers are identical. Look into the details of the channel power gain from OFDMA users to CDMA receiver that accounts for the distance-based path loss and small-scale fading. Due to the collocation of receivers, the path loss is naturally known from the channel power gain from OFDMA users to its own receiver. Thus, only the fading is remained to be determined. We refer the fading from OFDMA user to CDMA receiver to as cross channel state information (C-CSI), and the fading from OFDMA user to OFDMA receiver to as signal channel state information (S-CSI). Both of them follow the independent identical distribution. For simplicity, the path loss and shadowing of OFDMA users are treated to be 1. This represents a homogeneous distribution of OFDMA users, with which we target on maximizing the OFDMA sum rate in this study. By doing this, the resource allocation bias due to the uplink near-far effect is excluded. It is noted that our study can be extended to the system with heterogeneous distributions of user terminals, where fairness schemes, such as weighted sum rate or proportional fairness can be considered. Furthermore, the average power of small-scale fading is normalized to be 1. Thus, the transmission power defines the average received power at the BS.

Consistently, we consider a large CDMA system where U and N are both large, and $\frac{U}{N} \to \alpha$ where α is defined as CDMA system load [76]. Considering the CDMA system may adopt match filter (MF) or minimum mean square error (MMSE) receivers, the interference margin provided by the CDMA system that is derived in (3.55) and (3.56) is recalled as

$$m(q) = \begin{cases} (\frac{1}{\beta^*} - \alpha)q - \sigma^2, \text{ for MF} \\ (\frac{1}{\beta^*} - \frac{\alpha}{1+\beta^*})q - \sigma^2, \text{ for MMSE} \end{cases} \tag{4.1}$$

where q is the CDMA target receive power, β^* is the CDMA target SINR, and σ^2 is power of white Gaussian noise. Eq. (4.1) indicates that the interference margin provided by CDMA system is a monotonically increasing function over q, meaning that the higher CDMA receive power allows higher transmission power from OFDMA users. By letting $m(q) = 0$, the designed maximum system load supportable by CDMA system is calculated as

$$\begin{cases} \alpha^*_{\text{MF}} = \frac{1}{\beta^*} - \frac{\sigma^2}{q} \\ \alpha^*_{\text{MMSE}} = \left(\frac{1}{\beta^*} - \frac{\sigma^2}{q}\right)(1+\beta^*) \end{cases} \tag{4.2}$$

Taking into consideration the interference power introduced by CDMA users which equals αq, the SINR of OFDMA user k on subcarrier n is given by [88]

$$\gamma_{k,n}^{b} = \frac{p_{k,n} g_{k,n}}{\alpha q + \sigma^2}, \tag{4.3}$$

where $g_{k,n}$ is the S-CSI from OFDMA user k to OFDMA receiver on subcarrier n, and $p_{k,n}$ is the transmission power of OFDMA user k on subcarrier n. To guarantee the subcarriers being exclusively allocated among OFDMA users, we define $p_{k,n} > 0$ if subcarrier n is allocated to user k; otherwise, $p_{k,n} = 0$. Denoting the $K \times N$ matrix $\boldsymbol{P} = \{p_{k,n}\}$, the throughput achieved by OFDMA system is the function of q and $\boldsymbol{P}$ which can be expressed as

$$C(q, \boldsymbol{P}) = \sum_{k=1}^{K} \sum_{n=1}^{N} \log_2 \left(1 + \gamma_{k,n}^{b}\right). \tag{4.4}$$

4.1.2 OFDMA Resource Allocation Problem

As α and β^* are the CDMA system parameters that can be easily known, when the CDMA target receive power q is given, the OFDMA system can predict the interference margin according to (4.1), and maximize its throughput by efficiently allocating the subcarrier and power resource to exploit the interference margin. Denoting the C-CSI from OFDMA user k to CDMA receiver on subcarrier n as $h_{k,n}$, the interference suffered by each CDMA user is $\frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n} h_{k,n}$ [88]. Then, the resource allocation problem can be formulated as

Problem 4.1:

$$\max_{\boldsymbol{P}} \; C(\boldsymbol{P}) \tag{4.5}$$

$$s.t. \; \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n} h_{k,n} \leq m(q) \tag{4.6}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, \; k = 1, \ldots, K \tag{4.7}$$

where $\bar{P}_k$ is the maximum transmission power of user k.

Obviously, **Problem 4.1** can be solved by dual decomposition method when $h_{k,n}$ is known [52]. However, the assumption of available C-CSI is idealistic for most practical cases. In the remainder of this chapter, we will advocate the resource allocation schemes for the OFDMA system when C-CSI is unavailable.

4.2 OFDMA Resource Allocation with Unavailable C-CSI

4.2.1 Using S-CSI as C-CSI

Without the knowledge of C-CSI, the OFDMA system only has its S-CSI, i.e., $g_{k,n}$, at hand. If $h_{k,n}$ is replaced with $g_{k,n}$, **Problem 4.1** can be recast as

Problem 4.2:

$$\max_{\boldsymbol{P}} \; C(\boldsymbol{P}) \tag{4.8}$$

$$s.t. \; \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n} g_{k,n} \leq m(q) \tag{4.9}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, \; k = 1, \dots, K \tag{4.10}$$

Comparing **Problem 4.1** and **Problem 4.2**, the feasibility of using S-CSI as C-CSI can be intuitively observed. In solving **Problem 4.1**, a subcarrier n is allocated to the user with large $p_{k,n}$ but small $h_{k,n}$, which efficiently utilizes the OFDMA power while minimizing the interference to the CDMA system. This can be seen as the exploitation of the multiuser diversity brought along by the additional BS antenna of OFDMA system. In solving **Problem 4.2**, on the other hand, the subcarrier is allocated to the user with the largest $g_{k,n}$ only. Observing the interference constraint function (4.9), choosing the largest $g_{k,n}$ also induces highest interference to CDMA system. In another word, the OFDMA system predicts interference to CDMA system by regarding the interference channel being in the worst case. This intuitively shows that by using S-CSI as C-CSI, the CDMA can be still protected. The rigorous proof is provided in the following theorem.

4.2.2 Protecting the CDMA System

Theorem 4.3 *During the resource allocation, when the OFDMA system predicts the interference imposed to CDMA users based on S-CSI rather than C-CSI, the CDMA users can be sufficiently protected.*

Proof: We begin the proof with solving **Problem 4.2**. By associating the non-negative dual variables δ and $\boldsymbol{\lambda}_{K\times 1}$ to the interference constraint and K individual power constraints, respectively, solving the KKT conditions yields the power and subcarrier allocation that follows

$$p_{k,n} = \left(\frac{1}{\lambda_k + \delta g_{k,n}} - \frac{\alpha q + \sigma^2}{g_{k,n}}\right)^+, \tag{4.11}$$

$$k_n = \arg\max_k \left\{\frac{g_{k,n}}{\lambda_k + \delta g_{k,n}}\right\}. \tag{4.12}$$

Based on (4.11) and (4.12), the OFDMA predicted interference imposed to CDMA users can be calculated as

$$\begin{aligned} I(\boldsymbol{P}) &= \frac{1}{N}\sum_{n=1}^{N} p_{k_n,n} g_{k_n,n} \\ &= \frac{1}{N}\sum_{n=1}^{N}\left(\frac{1}{\min\limits_k\{\frac{\lambda_k}{g_{k,n}}\} + \delta} - (\alpha q + \sigma^2)\right). \end{aligned} \tag{4.13}$$

Since N is large, (4.13) becomes

$$I(\boldsymbol{P}) = \mathbb{E}\left[\left(\frac{1}{\lambda_k + \delta g_{k_n,n}} - \frac{\alpha q + \sigma^2}{g_{k_n,n}}\right) g_{k_n,n}\right] \tag{4.14}$$

$$\geq \mathbb{E}\left[\left(\frac{1}{\lambda_k + \delta g_{k_n,n}} - \frac{\alpha q + \sigma^2}{g_{k_n,n}}\right)\right]\mathbb{E}\left[g_{k_n,n}\right]. \tag{4.15}$$

On the other hand, the actual interference suffered by CDMA users can be evaluated as

$$\begin{aligned}\tilde{I}(\boldsymbol{P}) &= \frac{1}{N}\sum_{n=1}^{N} p_{k_n,n}h_{k_n,n} \\ &= \frac{1}{N}\sum_{n=1}^{N}\left[\left(\frac{1}{\lambda_k+\delta g_{k_n,n}} - \frac{\alpha q+\sigma^2}{g_{k_n,n}}\right)h_{k_n,n}\right]. \qquad (4.16)\end{aligned}$$

Similarly, since N is large and $h_{k_n,n}$ is independent from the other parameters, (4.16) can be derived as

$$\tilde{I}(\boldsymbol{P}) = \mathbb{E}\left[\left(\frac{1}{\lambda_k+\delta g_{k_n,n}} - \frac{\alpha q+\sigma^2}{g_{k_n,n}}\right)\right]\mathbb{E}\left[h_{k_n,n}\right]. \qquad (4.17)$$

To compare $I(\boldsymbol{P})$ and $I(\tilde{\boldsymbol{P}})$, we notice that

$$\begin{aligned}\frac{\mathbb{E}\left[g_{k_n,n}\right]}{\mathbb{E}\left[h_{k_n,n}\right]} &= \frac{\mathbb{E}\left[\max\limits_k\left\{\frac{g_{k,n}}{\lambda_k}\right\}\lambda_{k_n}\right]}{\mathbb{E}\left[h_{k_n,n}\right]} \qquad (4.18)\\ &\geq \frac{\mathbb{E}\left[\max\limits_k\left\{\frac{g_{k,n}}{\lambda_k}\right\}\right]\mathbb{E}\left[\lambda_{k_n}\right]}{\mathbb{E}\left[h_{k_n,n}\right]} = \frac{\mathbb{E}\left[\max\limits_k\left\{\frac{g_{k,n}}{\lambda_k}\right\}\right]}{\frac{\mathbb{E}\left[h_{k_n,n}\right]}{\mathbb{E}\left[\lambda_{k_n}\right]}} \qquad (4.19)\\ &\geq \frac{\mathbb{E}\left[\max\limits_k\left\{\frac{g_{k,n}}{\lambda_k}\right\}\right]}{\mathbb{E}\left[\frac{h_{k_n,n}}{\lambda_{k_n}}\right]} \geq \frac{\mathbb{E}\left[\frac{g_{k,n}}{\lambda_{k_n}}\right]}{\mathbb{E}\left[\frac{h_{k_n,n}}{\lambda_{k_n}}\right]} = 1 \qquad (4.20)\end{aligned}$$

Thus, we have $\mathbb{E}[g_{k_n,n}] \geq \mathbb{E}[h_{k_n,n}]$, and the relationship between $I(\boldsymbol{P})$ and $\tilde{I}(\boldsymbol{P})$ becomes

$$\tilde{I}(\boldsymbol{P}) \leq I(\boldsymbol{P}). \qquad (4.21)$$

This shows that the actual interference suffered by CDMA users is no larger than the predicted value, which completes the proof.

Remark 1: The above theorem provides us an interesting observation. In the conventional CR system, whether the C-CSI is available by the secondary system determines whether the spectrum of primary system can be shared. In the proposed SR system, however, although the C-CSI is unavailable, the secondary system can still share the spectrum with sufficient protection to the primary system. One reason is the interference power received by the CDMA users is the average of the interference power of all subcarriers. The other reason is, the user selection inherent in the OFDMA resource allocation makes the S-CSI statistically better than the C-CSI. Using S-CSI to predict the interference to CDMA users is equivalent to enlarge the C-CSI.

Remark 2: In fact, the proposed SR model is comparable to the SR model with BS antenna being shared which has been studied in Chapter III. The OFDMA system in the two model can achieve the same throughput, but the CDMA users in the passive sharing model suffer less interference. From the proof of Theorem 4.3, we notice a gap between the actual and predicted interference powers, which we define as $\psi(\boldsymbol{P}) = I(\boldsymbol{P}) - \tilde{I}(\boldsymbol{P})$. If the OFDMA system can properly increase its transmission power which makes the actual interference suffered by CDMA users approach the tolerable interference level, the OFDMA throughput can be improved. In the next section, we will propose resource allocation schemes for the OFDMA system to fully utilize the sharing opportunity provided by the CDMA system by exploiting the interference gap.

4.3 Iterative-Based OFDMA Resource Allocation

4.3.1 CDMA Power Control Law

In order to exploit the interference gap $\psi(\boldsymbol{P})$, the OFDMA system has to known the actual interference power $\tilde{I}(\boldsymbol{P}) = \frac{1}{N}\sum_{n=1}^{N} \tilde{i}_n(\boldsymbol{P})$, where $\tilde{i}_n(\boldsymbol{P})$ denotes actual interference on subcarrier n. Here, the inner power control of CDMA system becomes the key point. The CDMA system inner power control is designed for keeping the receive SINR equal the target value β^* by adapting the CDMA user transmission power with the suffered interference. Based on the CDMA SINR expression in the OFDMA/CDMA SR system given in Chapter III, the CDMA power control law can be written as

$$\frac{q}{\alpha q + \tilde{I}(\boldsymbol{P}) + \sigma^2} = \beta^*, \text{ for MF} \tag{4.22}$$

$$\mathbb{E}_n\left[\frac{q}{\frac{\alpha q}{1+\beta^*} + \tilde{i}_n(\boldsymbol{P}) + \sigma^2}\right] = \beta^*, \text{ for MMSE} \tag{4.23}$$

Eq. (4.22) and (4.23) indicate that q should be increased when $\tilde{I}(\boldsymbol{P})$ (or $\tilde{i}_n(\boldsymbol{P})$ for MMSE case) increases, and vice versa. Due to the collocation of receive antennas of the two systems, when CDMA users transmit with target receive power q, the OFDMA system can detect it from its suffered interference αq. In another word, when q is adjusted, it can be received and detected by the OFDMA receiver timely. With the detected q, the OFDMA system can derive $\tilde{I}(\boldsymbol{P})$ from the power control law of CDMA system. Consequently, the OFDMA system can calculate $\psi(\boldsymbol{P})$ by differentiating $I(\boldsymbol{P})$ and $\tilde{I}(\boldsymbol{P})$. In the following part, an iterative resource allocation scheme is proposed for OFDMA system to exploit $\psi(\boldsymbol{P})$.

4.3.2 Iterative OFDMA Resource Allocation

Given the fixed q which is detected by OFDMA receiver, the OFDMA resource allocation problem is exactly **Problem 4.2**. Suppose the solution derived from **Problem 4.2** is $\boldsymbol{P}^*$. When the OFDMA users transmit with $\boldsymbol{P}^*$, the actual interference suffered by CDMA system is $\tilde{I}(\boldsymbol{P}^*)$ that is smaller than $I(\boldsymbol{P}^*)$, as shown in Theorem 4.3. To maintain the target receive SINR, the CDMA system adjusts its target receive power to q' according to its power control law. Because $\tilde{I}(\boldsymbol{P}^*) \leq I(\boldsymbol{P}^*)$, $q' \leq q$. When the CDMA users adjust their transmission power so that the receive power is q', it can be detected by OFDMA receiver, with which the actual interference $\tilde{I}(\boldsymbol{P}^*)$ can be derived. Then, the OFDMA system increases the interference margin by $\psi(\boldsymbol{P}^*) = I(\boldsymbol{P}^*) - \tilde{I}(\boldsymbol{P}^*)$, which allows higher transmission power from OFDMA users. However, one shot of interference margin increment cannot fully exploit the sharing opportunity as the actual interference power imposed by the OFDMA system is still smaller than the predicted level. *To this end, we propose an iterative-based resource allocation for the OFDMA system,which can fully exploit the sharing opportunity by iteratively pushing the actual interference power to approach the tolerable interference offered by the CDMA system.*

It should be noted that when the CDMA system employs MMSE receiver, it adjusts q according to (4.23). With the detected q, however, it is difficult for the OFDMA system to derive the actual interference on each subcarrier, i.e., $\tilde{i}_n(\boldsymbol{P}^*)$, from (4.23). To make it tractable, we allow the OFDMA system to derive the actual interference $\tilde{I}(\boldsymbol{P}^*)$ according to

$$\frac{q}{\frac{\alpha q}{1+\beta^*} + \tilde{I}(\boldsymbol{P}) + \sigma^2} = \beta^*. \tag{4.24}$$

In this case, $\tilde{I}(\boldsymbol{P}^*) \leq \frac{1}{N}\sum_{n=1}^{N} \tilde{i}_n(\boldsymbol{P}^*)$, leading to a conservative evaluation of $\psi(\boldsymbol{P}^*)$.

The OFDMA resource allocation problem for exploiting the interference gap be recast as

Problem 4.3:

$$\max_{\boldsymbol{P}} \; C(\boldsymbol{P}) \tag{4.25}$$

$$s.t. \; \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} \leq m(q) + \psi(\boldsymbol{P}) \tag{4.26}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, \; k = 1, \ldots, K \tag{4.27}$$

which can be solved by an iterative resource allocation scheme implemented by the OFDMA solely. The procedure of the scheme is shown in Fig. 4.2 where we can see the resource allocation scheme is iteratively conducted by the OFDMA system, while the CDMA passively adjusts its target receive power to accommodate the interference from OFDMA system. The corresponding algorithm is shown in Algorithm 2.

4.3.3 Convergence

The convergence of Algorithm 2 is guaranteed by the convergence of interference margin. Given q, $m(q)$ is fixed. For each iteration, the $\psi(\boldsymbol{P}^*)$ increases and converges to a constant. Thus, $m(q)+\psi(\boldsymbol{P}^*)$ converges, which guarantees the convergence of Algorithm 2. When the algorithm converges, the CDMA system operates with the given receive power q and the actual interference suffered by CDMA system equals its tolerable level; otherwise, the transmission power constraints of (4.27) are all tight, meaning that the OFDMA system can fully utilize the sharing opportunity provided by the CDMA system.

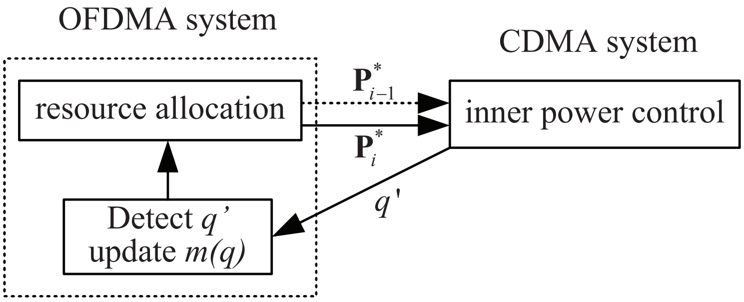

Figure 4.2: The procedure of the iterative resource allocation implemented by OFDMA system.

Algorithm 2 Iterative-based OFDMA Resource Allocation

```
Given $q$, initialize interference margin with $m(q)$ according to (4.1)
Find $\boldsymbol{P}_0^*$ by solving Problem 4.2, calculate interference $I(\boldsymbol{P}_0^*)$ and $\tilde{I}(\boldsymbol{P}_0^*)$ according
    to (4.13) and (4.14), and the interference gap $\psi(\boldsymbol{P}_0^*) = I(\boldsymbol{P}_0^*) - \tilde{I}(\boldsymbol{P}_0^*)$.
Given a small tolerance $\tau$,
while $|\psi(\boldsymbol{P}_i^*) - \psi(\boldsymbol{P}_{i-1}^*)| \geq \tau$ do
    $i = i + 1$;
    update interference margin with $m(q) + \psi(\boldsymbol{P}_{i-1}^*)$.
    find $\boldsymbol{P}_i^*$ by solving Problem 4.2 and derive $I(\boldsymbol{P}^*)$.
    detect the updated CDMA receive power $q$
    derive the actual interference $\tilde{I}(\boldsymbol{P}_i^*)$ from CDMA power control law
    calculate interference gap $\psi(\boldsymbol{P}_i^*) = I(\boldsymbol{P}_i^*) - \tilde{I}(\boldsymbol{P}_i^*)$
end while
```

4.4 Iterative OFDMA/CDMA Resource Allocation

Consider that the CDMA target receive power can vary within a range in practice, i.e., $q \in [q_0, Q]$ where q_0 is the minimum CDMA target receive power to achieve the target CDMA SINR and Q is maximum receive power limited by mobile terminal power supply. It can be seen a pair of contrary effects of q on OFDMA throughput, i.e., a higher q provides higher interference margin that allows higher transmission power from OFDMA system, but also introduces higher interference that is harmful to OFDMA throughput. Thus, there expects an optimal q that maximizes the OFDMA throughput. The optimization of OFDMA resource allocation considering the adaptive q is thus formulated as

Problem 4.4:

$$\max_{q,\boldsymbol{P}} \ C(q,\boldsymbol{P}) \tag{4.28}$$

$$s.t. \ \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} \leq m(q) \tag{4.29}$$

$$\sum\nolimits_{n=1}^{N} p_{k,n} \leq \bar{P}_k, \ k = 1,\ldots,K \tag{4.30}$$

In the OFDMA/CDMA SR system with shared receive antenna, an OFDMA resource allocation that jointly optimizes q and $\boldsymbol{P}$ was proposed in Chapter 3, which is only implemented by the OFDMA system. When the OFDMA system transmits with the optimal $\boldsymbol{P}$, the CDMA system can adaptively adjust user transmission power to the optimal q, which is realized by its inner power control.

Nevertheless, if the same scheme is adopted to solve **Problem 4.4**, the solution will be no longer optimal. Suppose the solution of **Problem 4.4** is $(\hat{q},\hat{\boldsymbol{P}})$. When the OFDMA system operates with $\hat{\boldsymbol{P}}$, $\tilde{I}(\hat{\boldsymbol{P}})$ will be less than $I(\hat{\boldsymbol{P}})$. The actual receive power of CDMA system will be smaller than $\hat{q}$.

It shows in the Section 4.3, the proposed resource allocation scheme makes the OFDMA system fully exploit the interference gap and push the CDMA system to operate under the given target receive power q. In fact, the given q can be any value in its feasible region. This motivate us to propose the resource allocation that optimizes q and $\boldsymbol{P}$ simultaneously to further maximize the OFDMA throughput. The problem can be formulated as

Problem 4.5:

$$\max_{q,\boldsymbol{P}} \ C(q,\boldsymbol{P}) \tag{4.31}$$

$$s.t. \ \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} \leq m(q) + \psi(\boldsymbol{P}) \tag{4.32}$$

$$\sum_{n=1}^{N} p_{k,n} \leq \bar{P}_k, \ k = 1,\ldots,K \tag{4.33}$$

First, we can see that for each target CDMA receive power $q \in [q_0, Q]$, the optimal OFDMA resource allocation can be solved by Algorithm 2. Then, we provide the following proposition based on which the optimal q can be searched efficiently.

Proposition 4.2 *The OFDMA throughput* $C(q, \boldsymbol{P})$ *in Problem 4.5 is quasiconcave over* q, $q \in [q_0, Q]$.

Proof: Algorithm 2 indicates that given q, as the resource allocation scheme converges, $\psi(\boldsymbol{P})$ converges to a constant value which is denoted as Ψ. It is increasing over q. Thus, the converged interference margin can be written as $M(q) = m(q) + \Psi$. Theorem 3.2 shows that the OFDMA throughput function in **Problem 3.4** is quasiconcave over q and its proof tells that the convexity has nothing to do with the interference margin which is the function of q but does not relate to the OFDMA transmission power $\boldsymbol{P}$. Since **Problem 4.5** has the same structure with **Problem 3.4** and the converged interference margin $M(q)$ only depends on q, we can claim that $C(q, \boldsymbol{P})$ in **Problem 4.5** is also quasiconcave over q.

Based on above proposition, **Problem 4.5** can be solved by bisection search which is summarized in Algorithm 3.

Algorithm 3 Bisection Search for Iterative OFDMA/CDMA Resource Allocation

```
Initial $q_{\min} = q_0, q_{\max} = Q$. Given a small tolerance $\epsilon$
while $q_{\max} - q_{\min} > \epsilon$ do
    Let $q = \frac{q_{\min}+q_{\max}}{2}$. Find $\boldsymbol{P}^*$ by using Algorithm 2
    Calculate the derivative according to (3.66)
    if (3.66)$\geq 0$, $q_{\min} \leftarrow q$
    else $q_{\max} \leftarrow q$
end while
```

In the proposed iterative schemes, the BS computes the resource allocation strategy in each iteration, sends the control command to the mobiles, and the mobiles should change their transmission power and subcarriers accordingly. Thus, the scheme requires more frequent control command transmission from the BS to the mobile terminals.

4.5 Suboptimal OFDMA Resource Allocation Schemes

4.5.1 OFDMA Equal Power Allocation

Equal power allocation (EPA) is usually regarded as a suboptimal but low-complex power allocation scheme [104, 53, 97]. In the EPA scheme, the power of user k is uniformly allocated across its occupied subcarriers, i.e.,

$$p_{k,n} = p_k \leq \frac{\bar{P}_k}{N_k}, \tag{4.34}$$

where N_k is the number of subcarriers allocated to user k. For tractability, we assume that $\bar{P}_k = \bar{P}$ for all users, and each user is allocated with the same amount of subcarriers in each band, i.e., $N_k = \frac{N}{K}$. Then, we have

$$p_{k,n} = p \leq \frac{\bar{P}}{N/K}. \tag{4.35}$$

Considering that the subcarrier is allocated according to $k_n = \arg\max_k \{g_{k,n}\}$, the predicted interference can be derived as

$$I_{\text{EPA}} = \frac{p}{N}\left(\sum_{n\in\mathcal{F}_1} \max_{k=1,\dots,K}\{g_{k,n}\} + \right.$$
$$\left. \sum_{n\in\mathcal{F}_2} \max_{k=1,\dots,K-1}\{g_{k,n}\} + \dots + \sum_{n\in\mathcal{F}_K} \max_{k=1}\{g_{k,n}\}\right), \tag{4.36}$$

where $\mathcal{F}_k$ denotes the set of subcarriers occupied by user k. Represent the random variable $\max_k\{g_{k,n}\}$ by $G_{(K)}$. As $N \to \infty$, it is upper-bounded by

$$\overline{I_{\text{EPA}}} = \frac{p}{N}\sum_{n=1}^{N} \max_k\{g_{k,n}\} = p\mu_{G_{(K)}}, \tag{4.37}$$

and lower-bounded by

$$\underline{I_{\text{EPA}}} = \frac{p}{K}(\mu_{G_{(K)}} + \mu_{G_{(K-1)}}, \dots, \mu_{G_{(1)}}). \tag{4.38}$$

It is noted that the upper-bound and lower-bound are coincident as $K \to \infty$. To derive $\mu_{G_{(K)}} \triangleq \mathbb{E}[G_{(K)}]$, we denote $F(x)$ and $F_{G_{(K)}}(x)$ as the cumulative density function of $g_{k,n}$ and $G_{(K)}$. Then according to order statistics [105], $F_{G_{(K)}}(x) = F(x)^K$. Thus, we have

$$\mu_{G_{(K)}} = \int_0^\infty KF(x)^{K-1} f(x) x dx, \tag{4.39}$$

where $f(x) = dF(x)/dx$.

On the other hand, as $N \to \infty$, the actual interference can be derived as

$$\tilde{I}_{\text{EPA}} = p \sum_{n=1}^{N} \sum_{k=1}^{K} h_{k,n} = p\mu. \tag{4.40}$$

Then, the gap between I_{EPA} and $\tilde{I}_{\text{EPA}}$ can be derived as

$$\Psi_{\text{EPA}} = I_{\text{EPA}} - \tilde{I}_{\text{EPA}} = p(\mu_{G_{(K)}} - \mu), \tag{4.41}$$

which can be shown as increasing function over K. Since the transmission power is $p = \min\{\frac{m(q)}{\mu}, \frac{\bar{P}}{N/K}\}$, when the interference constraint is valid, (4.41) can be further derived as $\Psi_{\text{EPA}} = m(q)(\frac{\mu_{G(K)}}{\mu} - 1)$. Noted that $\mu_{G(K)}$ can be derived according to (4.39). By updating $m(q)$ with $m(q) + \Psi_{\text{EPA}}$, **Problem 4.2** can be cast as

$$\max_{\boldsymbol{P}} \sum_{n=1}^{N} \log_2 \left(1 + \frac{p g_{k_n,n}}{\alpha q + \sigma^2}\right) \tag{4.42}$$

$$s.t. \ \frac{1}{N} \sum\nolimits_{n=1}^{N} p g_{k_n,n} \leq m(q) + \Psi_{\text{EPA}} \tag{4.43}$$

$$p \frac{N}{K} \leq \bar{P} \tag{4.44}$$

where $k_n = \arg\max_k \{g_{k,n}\}$.

4.5.2 OFDMA Channel Inverse Power Allocation

Besides EPA, the channel-inverse power allocation (CIPA) is another power control scheme that makes each user on each subcarrier achieve the same SINR performance. Moreover, when the the interference constraint is dominant making the individual power constraints invalid, the CIPA is optimal for maximizing the OFDMA throughput. In this part, we will evaluate the interference gap when CIPA is adopted.

First, subcarriers are allocated according to $k_n = \arg\max_k \{g_{k,n}\}$. Second, power allocated on subcarrier n is

$$p_{k_n,n} = \frac{\delta(\alpha q + \sigma^2)}{g_{k_n,n}}, \tag{4.45}$$

where δ is the coefficient that makes $\boldsymbol{P}$ meet the interference and power constraints. When the interference constraint is invalid, it is no need to update the interference margin. Otherwise, the equality in the interference constraint holds. Substituting (4.45) into the interference constraint, we have

$$p_{k_n,n} g_{k_n,n} = m(q), \tag{4.46}$$

which is also equal the predicted interference I_{CIPA}. As $N \to \infty$, the actual interference suffered by CDMA users can be calculated as

$$\tilde{I}_{\text{CIPA}} = \mathbb{E}[p_{k_n,n} h_{k_n,n}] = m(q)\mathbb{E}\left[\frac{h_{k_n,n}}{G_{(K)}}\right] = m(q)\mu\mathbb{E}\left[\frac{1}{G_{(K)}}\right]. \tag{4.47}$$

Thus, the interference gap becomes

$$\Psi_{\text{CIPA}} = I_{\text{CIPA}} - \tilde{I}_{\text{CIPA}} = m(q)\left(1 - \mu\mathbb{E}\left[\frac{1}{G_{(K)}}\right]\right), \tag{4.48}$$

where $\mathbb{E}[\frac{1}{G_{(K)}}] = \int_0^\infty f_{G_{(K)}}(x)\frac{1}{x}dx$.

4.6 Simulation Results

In this section, the performance of the proposed SR system is evaluated by simulations. The CDMA spreading gain is chosen to be $N = 256$, which equals the FFT size of OFDMA system. The number of multipath is set as $N/8$. The power of white Gaussian noise is normalized to be $\sigma^2 = 1$. The small-scale fading for both OFDMA and CDMA channels follows Rayleigh distribution with mean of 1. The maximal transmission SNR, i.e., $P = \bar{P}_k/\sigma^2$, for each OFDMA user is set as 30dB. Each of the C-CSI and S-CSI of OFDMA and CDMA systems are generated as exponential distributed random variables. For simulating CDMA SINR, Monte Carlo method is adopted where the N-length spreading code is generated randomly for each CDMA user. Noted that the CDMA SINR presented in the following is the average of the simulated values in each realization of spreading code. The target CDMA SINR is set to be $\beta^* = 2$dB. For the resource allocation scheme with fixed q, the CDMA receive SNR q/σ^2 is set as 10dB, while for the resource allocation scheme with adaptive q, the feasible range of q is $[q_0, Q]$ where $Q = 20$dB.

Above all, we solve **Problem 4.2** by using the dual decomposition to validate Theorem 4.3. The subgradient-based algorithm is adopted as in Appendix C. Let $\frac{q}{\sigma^2} = 10$dB. By varying the CDMA system load and the number of OFDMA users in Fig. 4.3and Fig. 4.4, respectively, the SINR which is actually achieved by the CDMA users and the SINR which is predicted by the OFDMA system are compared. α^*_{MF} and α^*_{MMSE} are calculated as in (4.2). It has been shown in both figures, the actual CDMA SINR is no worse than the predicted value which equals the target CDMA SINR, i.e., 2dB, in both MF and MMSE scenarios. This validates that the actual interference suffered by the CDMA users is no more than the predicted interference power by using S-CSI as C-CSI to solve the OFDMA resource allocation problem, thus validates Theorem 4.3. Moreover, Fig. 4.3 shows that the gap between the actual and predicted SINR decreases as CDMA system load increases, meaning that there is less sharing opportunity that can be exploited by the OFDMA system when the CDMA system carries heavy system load. In Fig. 4.4, on the other hand, the gap increases as number of OFDMA users K increases, because large number of OFDMA users can provide high multiuser diversity. Finally, the CDMA SINR performance with MMSE receiver always outperforms that with MF receiver, as the CDMA system with MMSE receiver can provide larger interference margin under the same system setting as shown in (4.1).

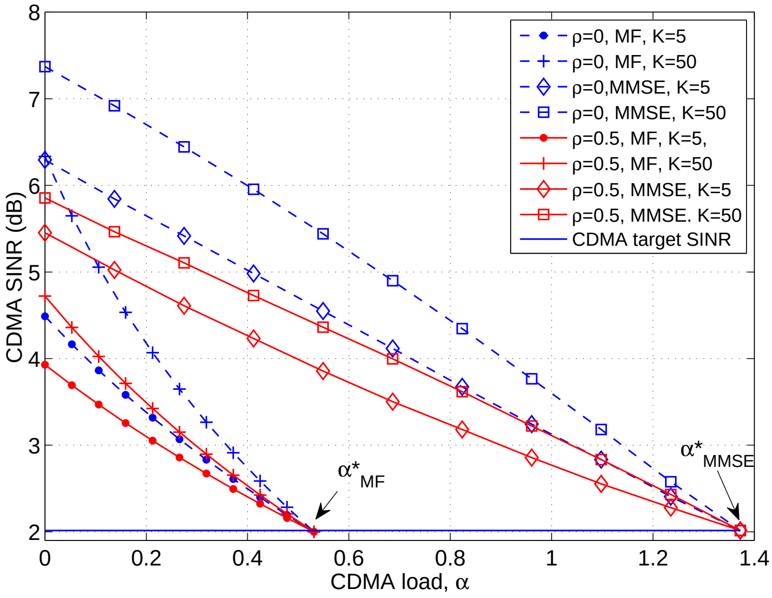

Figure 4.3: The CDMA SINR actually achieved by CDMA users and predicted by OFDMA system vs. α. ρ is the correlation coefficient between C-CSI and S-CSI.

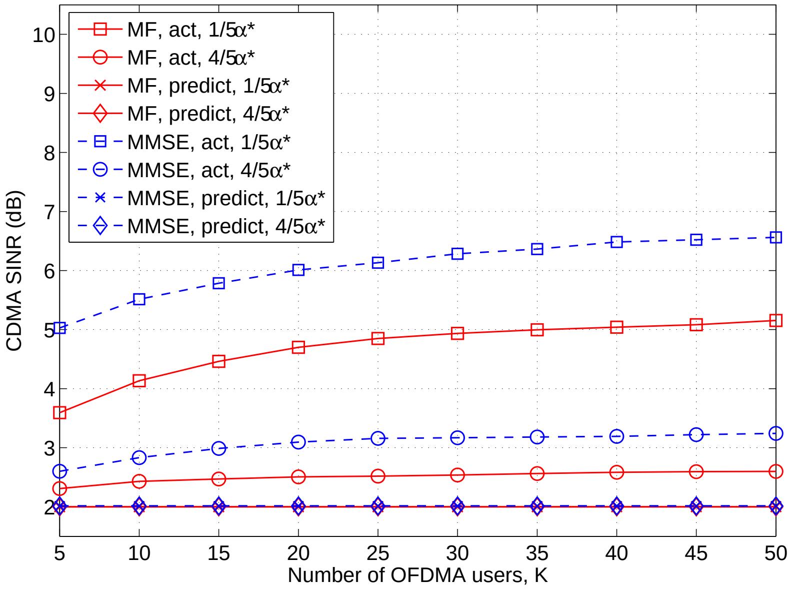

Figure 4.4: The CDMA SINR actually achieved by CDMA users and predicted by OFDMA system vs. K ($\alpha^* = \alpha^*_{\mathrm{MF}}$).

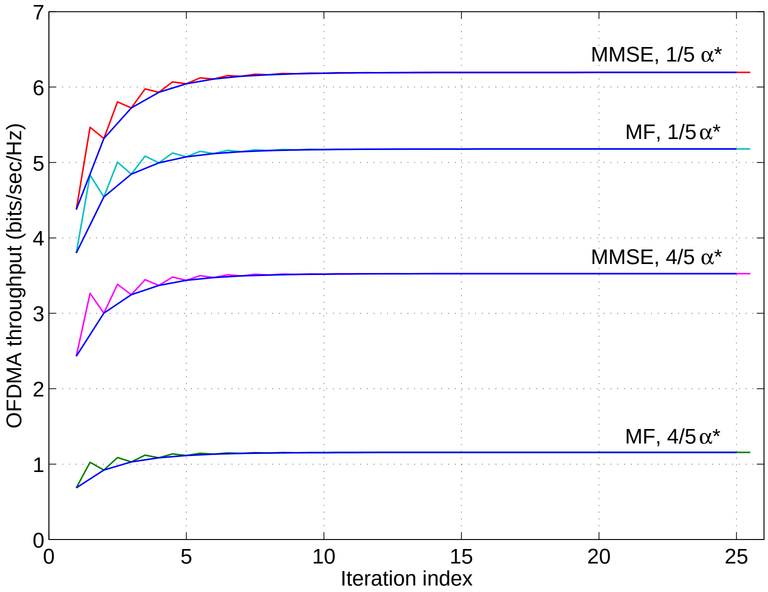

Figure 4.5: Convergence of OFDMA throughput ($\alpha^* = \alpha^*_{\mathrm{MF}}$, $K = 5$).

Next, the performance of the proposed resource allocation schemes that exploits interference gap is evaluated.

First, we validate the convergence of Algorithm 1. Without loss of generality, we choose $K = 5$. Two levels of CDMA system load, i.e., $\alpha = \frac{1}{5}\alpha^*_{\mathrm{MF}}$ and $\alpha = \frac{4}{5}\alpha^*_{\mathrm{MF}}$, are considered. Fig. 4.5 illustrates that the OFDMA throughput gets converged within 10 iteration for each kind of receiver and CDMA system load under consideration. When the algorithm converges, the OFDMA throughput with MMSE receiver outperforms that with MF receiver. Correspondingly, the SINR of CDMA users also gets converged to the target value within 10 iterations, which is illustrated in Fig. 4.6. The curves except the blue ones in both figures show the performance changes due to the interaction between the OFDMA and CDMA systems in each iteration.

Second, we compare the system performance with three different resource allocation schemes: 1) the OFDMA resource allocation with one iteration that involves one-shot interaction between OFDMA and CDMA systems, 2) the OFDMA resource allocation with 10 iterations that represents the converged optimal performance given the fixed

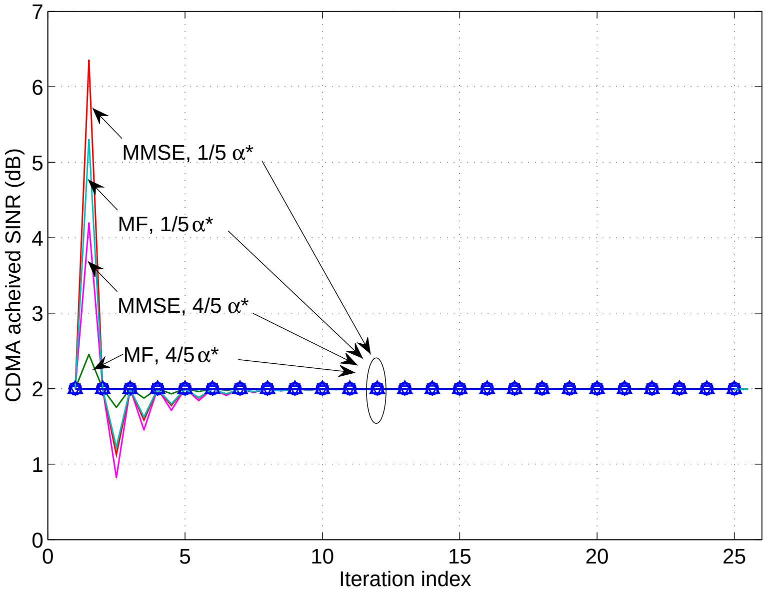

Figure 4.6: Convergence of CDMA SINR ($\alpha^* = \alpha^*_{\text{MF}}$, $K = 5$).

$\frac{q}{\sigma^2} = 10$dB, and 3) the OFDMA resource allocation with both optimal $\frac{q^*}{\sigma^2}$ and optimal power allocation $\boldsymbol{P}^*$. The last two schemes are realized by Algorithm 2 and Algorithm 3, respectively. We consider different number of OFDMA users, i.e., $K = 5, K = 20$ and $K = 50$, to shows the OFDMA throughput gain brought by multiuser diversity. For each level of K, MF and MMSE scenarios are both considered. From Fig. 4.7 to Fig. 4.9 we can observe that, OFDMA throughput with MMSE receiver is better than that with MF receiver. As α increases, the OFDMA throughput decreases due to more stringent interference margin provided by the CDMA system. The OFDMA throughput achieved with 10 iterations is much better than that achieved with only 1 iteration. This is consistent with the OFDMA throughput evolution shown in Fig. 4.5, where for each curve the converged value is much larger than the beginning point. Furthermore, considering the feasible range $[q_0, Q]$ within which the q can vary, by implementing Algorithm 2, the OFDMA throughput can be further improved by finding the optimal q^* and $\boldsymbol{P}^*$.

Correspondingly, the CDMA SINR performance with the three resource allocation schemes is shown in Table 4.1, where we can observe that all the CDMA SINR equal the

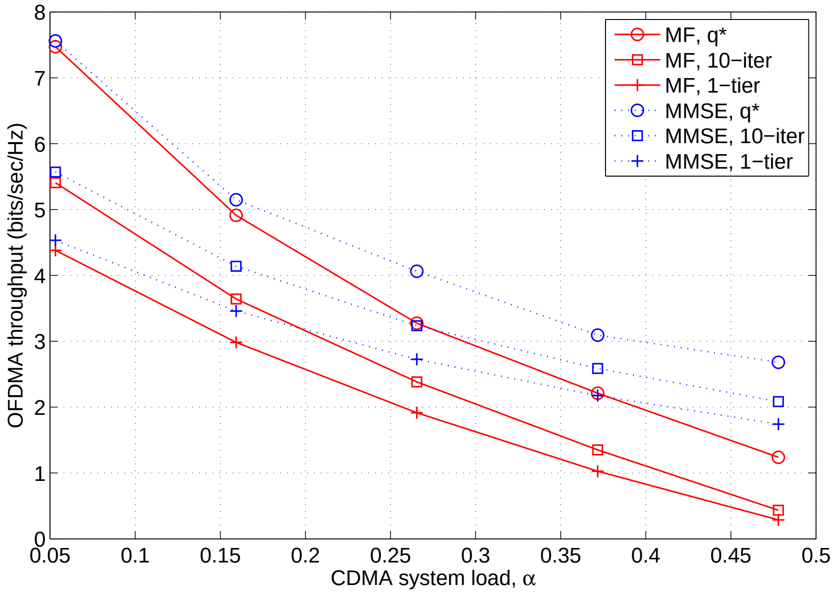

Figure 4.7: OFDMA throughput vs. α ($K = 5$).

Table 4.1: CDMA SINR (in dB)

K=5,20,50	α=0.053	α=0.159	α=0.266	α=0.372	α=0.478
q^*	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0
10-iter	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0
1-iter	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0	2.0|2.0

target value because of the CDMA inner power control. Moreover, the optimal CDMA receive power q^* is shown in Table 4.2. It tells that to maximize the OFDMA throughput, the CDMA system needs a higher q when the CDMA system load α is large or the number of OFDMA users K is large. It also shows that the maximum q is not always good to the OFDMA throughput although it can provide higher interference margin, because it also introduces higher interference to OFDMA users. This is more obvious in Table 4.2 when the CDMA system takes light system load or there are less OFDMA users in the system.

Finally, we provide the system performance when the OFDMA adopts the typical suboptimal resource allocation schemes, by varying the number of OFDMA users. In

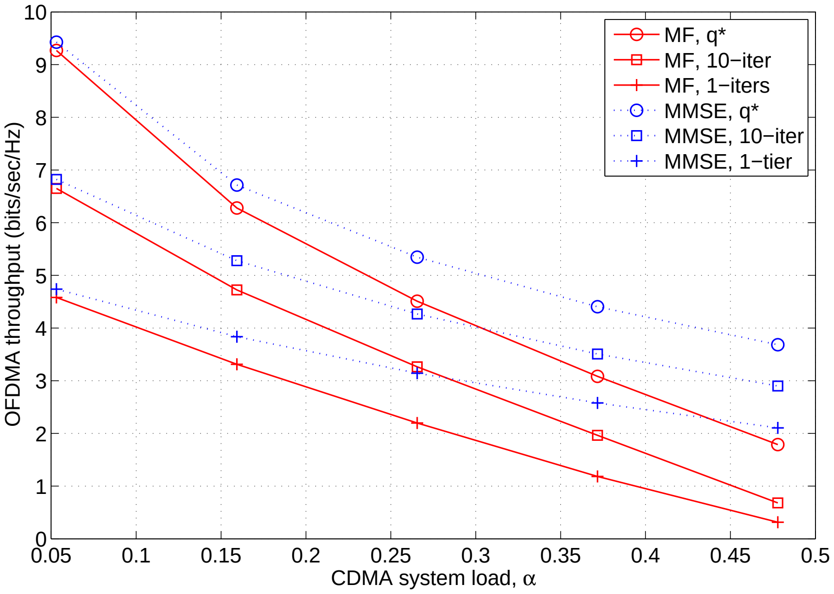

Figure 4.8: OFDMA throughput vs. α ($K = 20$).

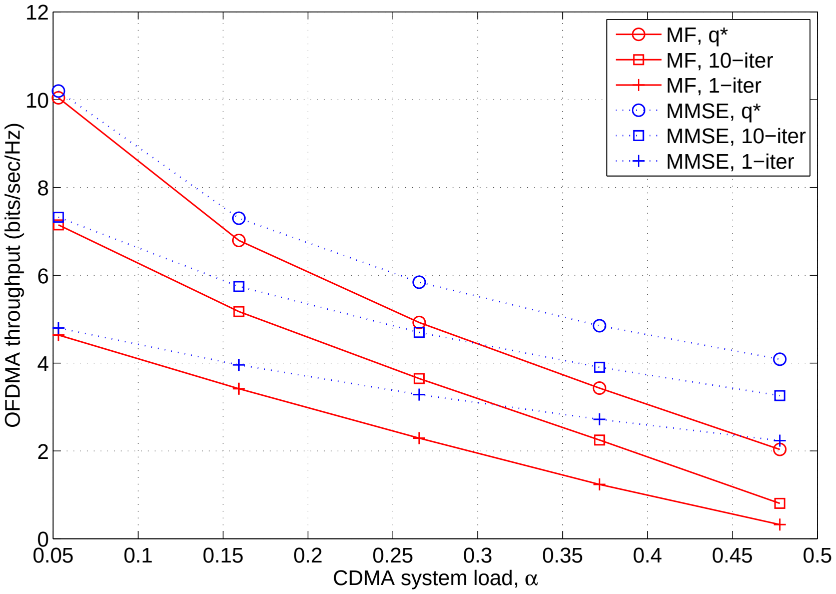

Figure 4.9: OFDMA throughput vs. α ($K = 50$).

Table 4.2: Optimal CDMA Receive Power, q^* (in dB)

MF	α=0.053	α=0.159	α=0.266	α=0.372	α=0.478
K=5	16.20	16.82	17.90	19.46	20.00
K=20	18.78	19.48	20.00	20.00	20.00
K=50	20.00	20.00	20.00	20.00	20.00

MMSE	α=0.053	α=0.159	α=0.266	α=0.372	α=0.478
K=5	15.60	16.05	16.48	16.82	17.30
K=20	18.45	18.82	19.00	19.32	19.80
K=50	20.00	20.00	20.00	20.00	20.00

Fig. 4.10 and Fig. 4.11, the OFDMA throughput with EPA and CIPA are illustrated, respectively. Both MF and MMSE scenarios are considered, for each of whom $\alpha = \frac{1}{5}\alpha^*_{\text{MF}}$ and $\alpha = \frac{4}{5}\alpha^*_{\text{MF}}$ are simulated. In each system setting, we compare the throughput performance without increasing interference margin (I-IM) by directly solving **Problem 4.2** with the throughput performance with 1-iteration I-IM. It can be observed that the OFDMA throughput without I-IM quickly converges as K increases; while that with I-IM keeps increasing with K. The reason can be stated as follows. The resource allocation in **Problem 4.2** can protect the CDMA users by choosing the user with better S-CSI which also introduces higher interference to the CDMA users. Thus, the multiuser diversity cannot be exploited. As shown in (4.41) and (4.48), the interference gaps, i.e., Ψ_{EPA} and Ψ_{CIPA} are increasing functions over K. Increasing the interference margin can help to exploit the multiuser diversity. This is why the achieved OFDMA throughout with I-IM is continuously increasing as K increases.

4.7 Conclusions

In this chapter, we have investigated an uplink OFDMA/CDMA SR system with passive infrastructure sharing. With the pragmatic assumption that the C-CSI is unavailable,

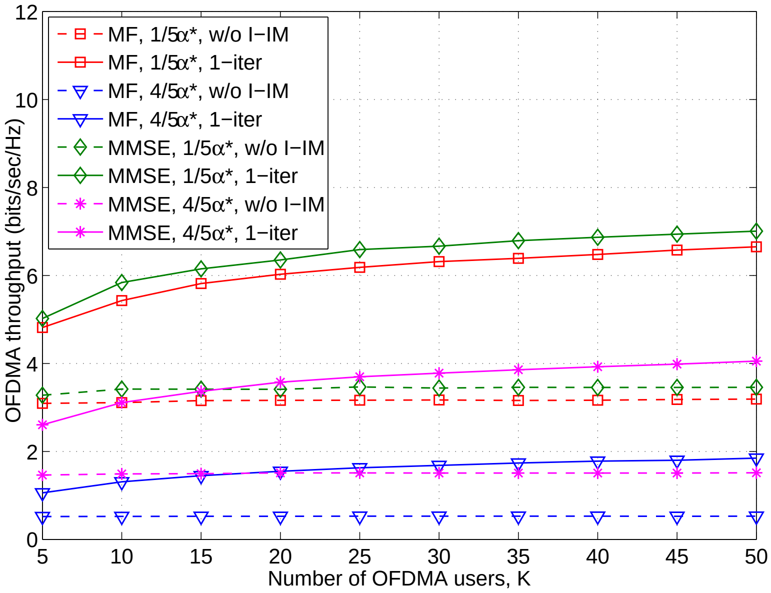

Figure 4.10: OFDMA throughput with EPA vs. K.

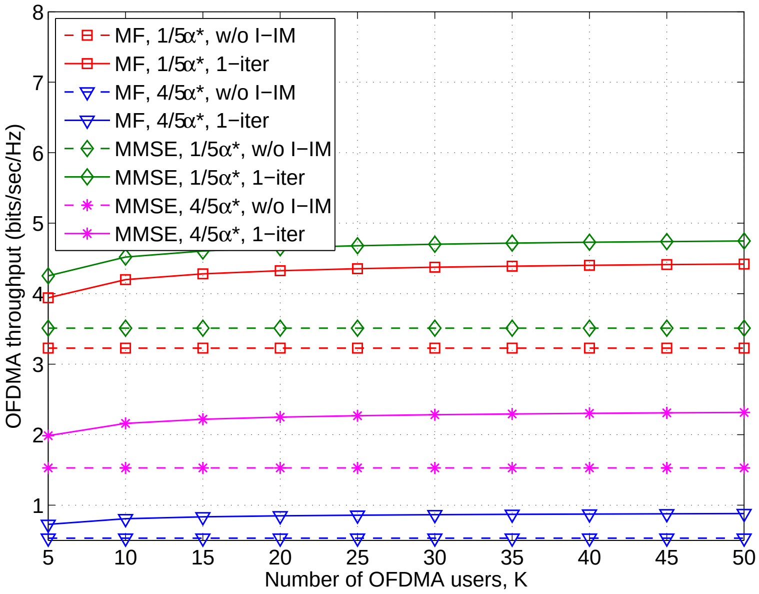

Figure 4.11: OFDMA throughput with CIPA vs. K.

we have found, somewhat surprisingly that, if the OFDMA system uses S-CSI instead of C-CSI to predict the interference power it imposes to CDMA users, the transmission strategy derived from the OFDMA resource allocation problem can protect the CDMA system sufficiently. By observing the sharing opportunity to be exploited, we have proposed two innovative resource allocation schemes that are solely conducted by the OFDMA system in an iterative manner. Due to the CDMA system inner power control, the CDMA system can adjust itself to operate under the desired optimal target received power level. It has been proved that they can not only provide sufficient protection to the CDMA system, but also fully exploit the sharing opportunity provided by CDMA system. Simulation results have been provided to validate the proposed resource allocation schemes.

It is worth noting that the proposed resource allocation schemes without C-CSI in this chapter is also applicable to the SR system without mobile infrastructure sharing, where the distance-based path loss between the secondary transmitter and the primary receiver is available. In particular, the location of secondary transmitter and primary receiver is fixed (such as installed access point) or with slow mobility where the distance between them can be notified via geographic information. In next chapter, we will study the SR without mobile infrastructure sharing, i.e., in the heterogeneous networks, where the OFDMA-based small cells shares the spectrum of legacy CDMA macrocell networks.

Chapter 5

Spectrum Refarming (SR) in Heterogeneous Networks

In this chapter, the SR technique applied for the OFDMA/CDMA coexistent system is relaxed with the mobile infrastructure sharing. In particular, we consider the application of SR technique in a heterogenous networks.

To provide high throughput and seamless coverage for future wireless communications, small cells have been proposed to overlay the conventional cellular networks [66]. According to [68], 11 million small cells have been deployed by 47 operators around the world in residential, enterprise and public area by 2013. Conventionally, small cells are deployed to share the same radio spectrum and the same multiple-access scheme with the macrocell. For example, in [69] and [70], CDMA small cells coexisting with CDMA macrocell was investigated; while in [71] and [72] the OFDMA small cells overlaying OFDMA macrocell was considered. By doing so, the small cells can offload the macrocell traffic directly, however, they will introduce interference to the users in the macrocell and thus degrade their performance.

This chapter considers an SR heterogenous networks where a number of OFDMA-based small cells share the spectrum licensed to the CDMA-based macrocell. Due to the wideband nature of the OFDMA and CDMA systems, it is highlighted that the interference analysis in this paper is fundamentally different from that in [75]. In order to control the interference from the OFDMA small cells to the CDMA macrocell and to predict the interference margin tolerable by the CDMA network, the downlink transmissions of OFDMA small cells are synchronized with the uplink transmission of the CDMA macrocell. We first analyze the interferences between the OFDMA small cells and CDMA macrocell, then formulate the OFDMA resource allocation problem for this proposed SR system. Through assigning the interference margins to each OFDMA small cell, a new resource allocation algorithm is proposed to solve the formulated problem efficiently. Finally, the unavailability of the C-CSI from each small cell base station (SBS) to the macrocell base station (MBS) is considered for the resource allocation of OFDMA small cells.

The remainder of the chapter is organized as follows. In Section 5.1, the proposed SR system is presented, based on which the interferences between the small cells and macrocell system are analyzed in Section 5.2. In Section 5.3, we formulate the resource allocation problem for OFDMA small cells and propose the highly efficient algorithm to solve it. In Section 5.4, the unavailability of interference CSI is considered, based on which the OFDMA small cell resource allocation is developed. The simulation results are presented in Section 5.5, and the conclusion is drawn in Section 5.6.

The content of this chapter is based on our works [106].

5.1 System Model

As shown in Fig. 5.1, throughout this chapter we consider an SR system where a legacy CDMA macrocell is overlaid with M OFDMA small cells, each with K small cell user equipments (SUEs). In order to control the interference from the OFDMA small cells to the CDMA macrocell and to predict the interference margin tolerable by the CDMA network, the downlink transmissions of OFDMA small cells are synchronized with the uplink transmission of the CDMA macrocell. It is easy to be implemented when the CDMA system adopts frequency-division duplexing (FDD). When the CDMA system

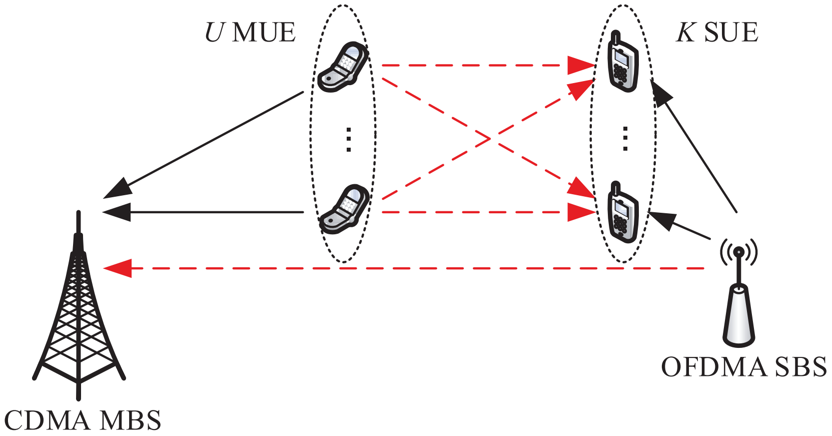

Figure 5.1: System model of OFDMA small cells overlaying CDMA macrocell.

adopts time-division duplexing (TDD), the synchronization will be realized with the help of the inter-macro-and-small-cell signalling. The U macrocell user equipments (MUEs) are randomly distributed within the macrocell coverage, and the K SUEs in each small cell are randomly located within the coverage of its own SBS. The distance between SBS m and the MBS is denoted by D_m. The base stations and user equipments are all equipped with signal antenna.

For CDMA macrocell, each of the MUEs is assigned with a random spreading code with spreading gain N. To achieve the target SINR which is denoted as β^*, the CDMA system adopts power control so that the receive power at the MBS is identical for each of the MUEs, and this received power is represented by q. The legacy CDMA spectrum is shared by all the OFDMA small cells, each with FFT size N. We assume that the OFDMA symbol duration is the same with that of CDMA system, and the MBS and SBS can receive synchronous OFDMA and CDMA symbols. We also assume that the channels are invariant within each symbol duration; thus, we can focus on a specific symbol duration for the following derivations. We consider a large CDMA system where both U and N are large, but $\frac{U}{N} \rightarrow \alpha$, where α is defined as the CDMA system load [76]. We consider that the CDMA MBS may adopt either MF receiver or MMSE receiver.

Let $g_{k,n,m}$ be the channel power gain from SBS m to SUE k on subcarrier n, which accounts for the path loss, small-scale fading and the shadowing ψ which follows log-normal distribution with mean μ_ψ and covariance σ_ψ^2. Similarly, we denote $h_{n,m}$ as the channel power gain from SBS m to MBS on subcarrier n, which also accounts for the path loss, fading and shadowing effect.

5.2 Interference between Macrocell and Small Cells

When the small cells are sparsely distributed, the inter-small-cell-interference can be safely ignored. However, when the small cells are densely distributed, the inter-small-cell-interference is bounded by a value because of the path loss and penetration loss if the SBS is deployed in indoor environment [107]. In this chapter, we ignore the inter-small-cell-interference and only focus on the interference between the macrocell and small cells, i.e., the interference from M SBSs to MBS and the interference from U MUEs to SUEs.

5.2.1 Interference from SBSs to MBS

Let $p_{k,n,m}$ denote the transmission power of SBS m to its kth user on subcarrier n. Based on the SINR analysis in Chapter 3, the interference power introduced by SBS m to the MBS can be calculated as

$$i_{\mathrm{S-M}}^{m} = \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} h_{n,m}. \tag{5.1}$$

Thus, the total interference power received by the MBS becomes

$$I_{\mathrm{S-M}} = \sum_{m=1}^{M} i_{\mathrm{S-M}}^{m}. \tag{5.2}$$

5.2.2 Interference from MUEs to SUE

First, we investigate the interference power from the MUE u to the SUE k in small cell m, which is denoted as $i_{\mathrm{M-S}}^{u,m}$. Notice that, due to the wideband nature and rich multipath in the wireless channel [93], the small-scale fading of the channel from MUE to MBS and that from the MUE to SUE are averaged to be 1. Thus, only distance-based path loss and shadowing are considered. We denote the distances from MUE u to MBS and SUE k in small cell m as $d_{u,\mathrm{M}}$ and $d_{u,m}$, respectively. Correspondingly, the shadowing coefficients are denoted as ϕ_u and φ_u that are i.i.d. random variables.

Since the CDMA target receive power at MBS is q, the transmission power of MUE u is $\frac{q}{N}\frac{1}{d_{u,\mathrm{M}}^{-\xi}\phi_u}$, where ξ is the path loss exponent. Thus, the interference power received by the SUE in small cell m becomes $\frac{q}{N}\frac{d_{u,m}^{-\xi}\varphi_u}{d_{u,\mathrm{M}}^{-\xi}\phi_u}$. Considering the total U MUEs, the overall interference power suffered by the SUE in small cell m is

$$I_{\mathrm{M-S}}^{m} = \alpha q \frac{1}{U}\sum_{u=1}^{U}\left(\frac{d_{u,\mathrm{M}}}{d_{u,m}}\right)^{\xi}\frac{\varphi_u}{\phi_u}. \tag{5.3}$$

As $U \to \infty$, the right hand side of (5.3) except αq becomes an expectation. Referring to Fig. 5.2, since the distance between an SBS to its SUE is much smaller than that between the SBS and MBS, we can approximately treat the distance between MBS and SUE to be equal to that between MBS and SBS, which equals D_m. Applying law of cosines to $\angle\theta$, we have

$$d_{u,\mathrm{M}}^2 = d_{u,m}^2 + D_m^2 - 2d_{u,m}D_m\cos\theta. \tag{5.4}$$

Thus we have

$$\left(\frac{d_{u,\mathrm{M}}}{d_{u,m}}\right)^{\xi} = \left(\frac{d_{u,m}^2 + D_m^2 - 2d_{u,m}D_m\cos\theta}{d_{u,m}^2}\right)^{\frac{\xi}{2}}. \tag{5.5}$$

Then, the expectation in (5.2) can be derived as

$$\int\left(\frac{x^2 + D_m^2 - 2xD_m\cos y}{x^2}\right)^{\frac{\xi}{2}} z f_{d_{u,m}}(x) f_{\theta}(y) f_{\frac{\varphi_u}{\phi_u}}(z)\mathrm{d}x\mathrm{d}y\mathrm{d}z \triangleq F(D_m). \tag{5.6}$$

Substituting (5.6) to (5.3) yields

$$I_{\mathrm{M-S}}^{m} = \alpha q F(D_m), \tag{5.7}$$

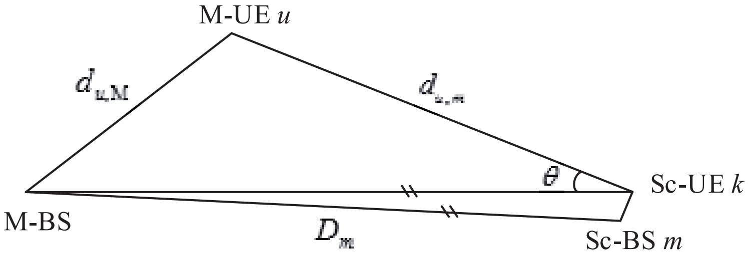

Figure 5.2: Geometry analysis for deriving $I^m_{\mathrm{M-Sc}}$.

which is monotonically increasing w.r.t. D_m which can be seen from (5.6).

We can conclude two observations from (5.7). First, as the number of CDMA users is very large, each SUE in the same small cell suffers identical interference from the MUEs, which only depends on the macrocell system parameters, i.e., α, q, and the distance between the SBS and MBS, i.e., D_m. Second, the interference level increases as the distance between its SBS and MBS gets large. This is because, to reach the same receive power level at the MBS, the MUE far from MBS will transmit with stronger signal that introduces higher interference to its nearby small cells, and vice versa. It is worth pointing out that in practice, $I_{\mathrm{M-S}}$ can be easily measured by the SBS.

5.3 Resource Allocation for OFDMA Small Cells

By considering the interference introduced by the MUEs, during downlink transmissions of OFDMA small cells, the SINR of SUE k on subcarrier n in small cell m is

$$\gamma_{k,n,m} = \frac{p_{k,n,m} g_{k,n,m}}{I^m_{\mathrm{M-S}} + \sigma^2}, \tag{5.8}$$

where σ^2 is the power of additive white Gaussian noise. To indicate the subcarriers being exclusively allocated among OFDMA users, we define that $p_{k,n,m} > 0$ if subcarrier n is allocated to user k; otherwise $p_{k,n,m} = 0$. Then, the achievable throughput of small cell m can be derived as

$$r_m = \sum_{k=1}^{K} \sum_{n=1}^{N} \log_2 \left(1 + \gamma_{k,n,m}\right). \tag{5.9}$$

Given CDMA system load α, target receive power q and target CDMA SINR β^*, according to the analysis in Chapter 3, the interference margin provided by the CDMA macrocell is given by

$$T = \begin{cases} (\frac{1}{\beta^*} - \alpha)q - \sigma^2, \text{ for MF} \\ (\frac{1}{\beta^*} - \frac{\alpha}{1+\beta^*})q - \sigma^2, \text{ for MMSE,} \end{cases} \tag{5.10}$$

which indicates the maximum total interference power, i.e., $I_{\text{S-M}}$, that can be introduced by the M small cells. Moreover, the designed maximum CDMA system load, i.e., α^*_{MF} and α^*_{MMSE}, can be derived from (5.10) by letting $T = 0$.

5.3.1 Problem Formulation

Based on the above analysis, the downlink resource allocation problem for OFDMA small cells can be formulated as

Problem 5.1:

$$\max_{\{p_{k,n,m}\}} \sum_{m=1}^{M} r_m \tag{5.11}$$

$$s.t. \ \frac{1}{N} \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{k=1}^{K} p^m_{k,n} h_{n,m} \leq T \tag{5.12}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} \leq \bar{P}_m, \tag{5.13}$$

where $\bar{P}_m$ is the maximum transmission power of SBS m. In this resource allocation problem, the objective is to maximize the total throughput of all small cells which is restricted by the total interference that can be introduced to the CDMA macrocell and the total transmission power for each SBS. As the locations of SBSs are fixed, given macrocell system parameters α and q, when there are a large number of CDMA users, the $I^m_{\text{M-S}}$ for each small cell m tends to be a fixed value. Thus, the problem can be solved by the standard dual decomposition method [108]. However, it can be observed from **Problem 5.1** that there is a hidden interference margin allocation, which optimally allocates the interference margin for each small cell. If the interference margin for each small cell has been allocated, the problem can be decoupled into M subproblems that can be solved within each small cell individually in parallel. Moreover, in each subproblem, the two constraints are all about the total power limit solving which needs only two dual variables. In the following subsection, we will transform **Problem 5.1** to a new form and exploit the hidden interference margin allocation, based on which the resource allocation problem can be solved more efficiently.

5.3.2 Transformed Resource Allocation Problem

We denote the interference margin allocated to the small cell m as t_m. Let $\boldsymbol{t} = \{t_m\}$ and $\boldsymbol{P}_m = \{p_{k,n,m}\}$, **Problem 5.1** can be transformed to

Problem 5.2:

$$R^* \triangleq \max_{\boldsymbol{t}, \{\boldsymbol{P}_m\}} \sum_{m=1}^{M} r_m \tag{5.14}$$

$$s.t. \ \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} h_{n,m} \le t_m \tag{5.15}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} \le \bar{P}_m \tag{5.16}$$

$$\sum_{m=1}^{M} t_m \le T. \tag{5.17}$$

Denoting relaxation variable as η, the constraint (5.17) can be combined with the objective function as

Problem 5.3:

$$R(\eta) \triangleq \max_{\boldsymbol{t}, \{\boldsymbol{P}_m\}} \sum_{m=1}^{M} r_m - \eta \left(\sum_{m=1}^{M} t_m - T \right) \tag{5.18}$$

$$s.t. \ \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} h_{n,m} \le t_m \tag{5.19}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} \le \bar{P}_m \tag{5.20}$$

Then the optimal total throughput can be achieved by

$$R^* = \min_{\eta \geq 0} R(\eta). \tag{5.21}$$

Thus, **Problem 5.3** can be readily decomposed into M parallel subproblems, with the mth subproblem being

$$\max_{t_m, \boldsymbol{P}_m} \; R_m - \eta t_m, \quad s.t. \; (5.15), (5.16). \tag{5.22}$$

Associating dual variable δ and λ with the two constraint functions (5.15) and (5.16), respective, the Lagrangian can be written as

$$\begin{aligned} &\mathcal{L}(\delta, \lambda, t_m, \boldsymbol{P}_m) = \\ &\sum_{n=1}^{N} \sum_{k=1}^{K} (\log_2(1 + \gamma_{k,n,m}) - \delta p_{k,n,m} h_{n,m} - \lambda p_{k,n,m}) + (\delta - \eta) t_m. \end{aligned} \tag{5.23}$$

Then, solving partial Karush-Kuhn-Tucker (KKT) conditions

$$\frac{\partial \mathcal{L}(\delta, \lambda, t_m, \boldsymbol{P}_m)}{\partial p_{k,n,m}} = 0 \quad \text{and} \quad \frac{\partial \mathcal{L}(\delta, \lambda, t_m, \boldsymbol{P}_m)}{\partial t_m} = 0 \tag{5.24}$$

yields

$$p_{k,n,m} = \left(\frac{1}{\lambda + \delta h_{n,m}} - \frac{I_{\text{M-S}}^m + \sigma^2}{g_{k,n,m}} \right)^+, \tag{5.25}$$

$$\delta = \eta. \tag{5.26}$$

As η is the same for all small cells, to find the optimal $\boldsymbol{P}_m$ in small cell m, we only need to find the optimal λ that makes $\boldsymbol{P}_m$ meet the power constraint indicated in (5.16). Note that the OFDMA downlink subcarrier allocation under interference and total power constraints follows

$$k_n = \arg\max_k \{g_{k,n,m}\}, \tag{5.27}$$

where k_n indicates the user who is allocated with subcarrier n. According to this, all the subcarriers can be allocated first, and then the total power is allocated in water-filling manner with water-level $\frac{1}{\lambda+\delta h_{n,m}}$ that meets

$$\lambda\left(\sum_{n=1}^{N}\left(\frac{1}{\lambda+\delta h_{n,m}}-\frac{I_{\mathrm{M-S}}^{m}+\sigma^2}{g_{k_n,n,m}}\right)^{+}-\bar{P}_m\right)=0 \tag{5.28}$$

$$s.t.\ \lambda\geq 0. \tag{5.29}$$

where λ can be solved efficiently by bisection search. With the optimal power allocation $\boldsymbol{P}_m^*$, the optimal interference margin t_m^* can be derived as

$$t_m^*=\frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K}p_{k,n,m}^*h_{n,m}. \tag{5.30}$$

Then, the remaining task is to find the optimal η in (5.21). Since **Problem 5.2** is a concave problem, the optimal η can be efficiently solved by subgradient method with the subgradient of $T-\sum_{m=1}^{M}t_m$ for instance.

The overall algorithm solving **Problem 5.2** is summarized in Algorithm 4.

Algorithm 4 Resource Allocation of OFDMA Small Cells

```
Initialize $\eta$.
while $\sum_{m=1}^{M} t_m \geq T$ do
    Update $\eta$ with subgradient $T-\sum_{m=1}^{M} t_m$.
    for each small cell $m$ do
        Let $\delta=\eta$. Solve $\lambda$ from (5.28) and (5.29) by bisection search. Solve $\boldsymbol{P}_m^*$ according to (5.25). Derive optimal $t_m^*$ according to (5.30)
    end for
end while
```

5.4 Resource Allocation for OFDMA Small Cells with Unavailable C-CSI

In practice, due to the limited signalling between the macrocell and small cells, the cooperation between the them are undesirable. Thus, the channel power gain between the SBS and MBS is usually absent. Since the channel power gain accounts for the distance-based path, small-scale fading and large-scale shadowing, only the latter two are to be determined as the distance between SBS and MBS is fixed and can be easily known from the global geographical information. In this section, we denote the path loss as $L(D_m)$ and detach it from the channel power gain from SBS m to MBS on subcarrier n, i.e., $h_{n,m}$. Let $\hat{h}_{n,m}$ be the remained unknown channel station information which is named as C-CSI; thus $h_{k,n} = L(D_m)\hat{h}_{n,m}$. In this section, we will investigate the resource allocation scheme for OFDMA small cells without the information of C-CSI.

Firstly, we can see in (5.12) that $\hat{h}_{n,m}$ affects the interference power evaluation. It shows in Eq. (5.27) that the subcarrier allocation in downlink scenario is determined only by the $g_{k,n,m}$ which is called as signal channel power gain. This results in the following proposition.

Proposition 5.3 *The optimal power allocation for Problem 5.3 is independent with C-CSI,* $\hat{h}_{n,m}, \forall n = 1, \ldots, N$.

Proof: Since the C-CSI $\hat{h}_{n,m}, \forall n = 1, \ldots, N$ is independent with SUEs within the small cell m, the subcarrier allocation only aims to maximize the small cell throughput. The corresponding power allocation is optimal in term of maximizing the small cell throughput only. Therefore, the optimal power $p_{k,n,m}$ is independent with C-CSI, which proves the proposition.

Based on the above proposition, **Problem 5.3** can be rewritten as

Problem 5.4:

$$R(\eta) \triangleq \max_{\boldsymbol{t}, \{\boldsymbol{P}_m\}} \sum_{m=1}^{M} r_m - \eta \left(\sum_{m=1}^{M} t_m - T \right) \tag{5.31}$$

$$s.t. \ \frac{\mu L(D_m)}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} \leq t_m \tag{5.32}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n,m} \leq \bar{P}_m \tag{5.33}$$

where μ is the statistic mean of $\hat{h}_{n,m}$. Similar to **Problem 5.3**, solving the Lagrangian of **Problem 5.4** yields the optimal power allocation

$$\begin{aligned} p_{k,n,m} &= \left(\frac{1}{\lambda + \delta \mu L(D_m)} - \frac{I^m_{\mathrm{M-S}} + \sigma^2}{g_{k,n,m}} \right)^+ && (5.34) \\ \delta &= \eta, && (5.35) \end{aligned}$$

and the optimal subcarrier allocation follows

$$k_n = \arg\max_k \left\{ g_{k,n,m} \right\}. \qquad (5.36)$$

Thus, the algorithm to solve **Problem 5.4** is the same with Algorithm 4 with the updated optimal power calculation with (5.34).

5.5 Simulation Results

In this section, the performance of the proposed SR heterogeneous networks is evaluated by simulations. The CDMA spreading gain is chosen to be $N = 128$, which equals the FFT size of OFDMA system. The number of multipath is set as $N/8$. The power of addictive white Gaussian noise is normalized to be $\sigma^2 = 1$. We set the MUE target receive SNR as $\frac{q}{\sigma^2} = 10$dB, and the MUE target SINR as $\beta^* = 2$dB. We consider $M = 2$ small cells in the macrocell coverage, in each small cell there are $K = 2$ SUEs. Two scenarios are considered. In the first scenario, the two small cells are located with equal distances from the MBS, and in the second one, one small cell is located near the MBS and the other one is located far from the MBS. The maximum transmission SNR of each SBS, $\frac{\bar{P}_m}{\sigma^2}$, is set as 25dB, 30dB or 40dB for comparison. We also consider the scenarios in which the MBS adopts MF receiver and MMSE receiver, respectively.

Firstly, we investigate the total throughput of small cells by varying the macrocell system load α from 0 to α^*_{MF}. By setting the distance-based path loss from each SBS to MBS as 0.5 which represents each SBS being located equally far from MBS, we observe the total throughput performance in Fig. 5.3. We can see that in both MF and MMSE

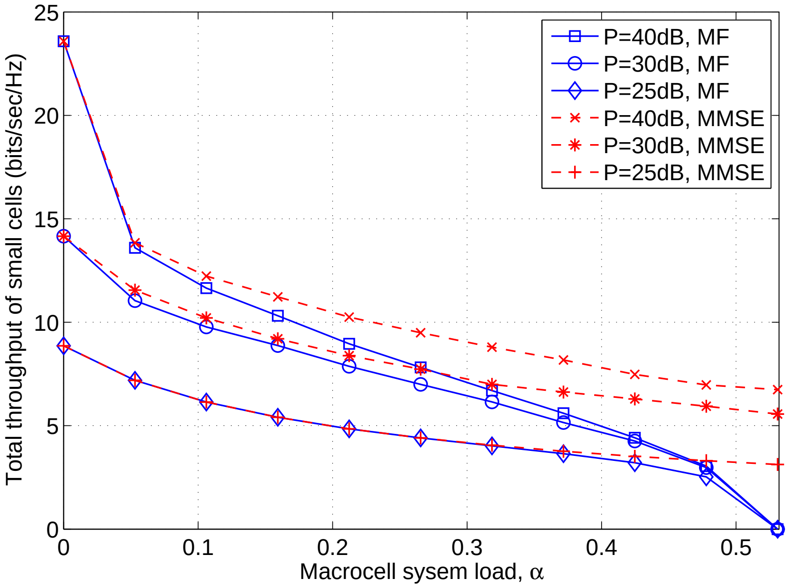

Figure 5.3: Total throughput of small cells vs. α: $G_1 = 0.5$, $G_2 = 0.5$.

scenarios, the total throughput decreases as α increases. This is because the higher macrocell system load provides less total interference margin that can be exploited by small cells, which has been shown in (5.10), and meanwhile, introduces higher interference to SUEs. For a given α, higher total transmission power of each SBS can achieve higher total small cell throughput. But the gain becomes marginal due to the constraint of interference margin. Fig. 5.4 illustrates the total throughput performance, when one SBS is located near to MBS ($G_1 = 0.9$) and the other far from MBS ($G_2 = 0.1$). It can be seen that the performance tendency is the same as that in Fig. 5.3, except that the performance with $\bar{P}_m/\sigma$=40dB outperforms that in Fig. 5.3. This is because in this scenario, the small cell with less interference to the macrocell can be allowed to transmit with higher power, thus utilizing more power resource.

Then, we look at the optimal interference margin allocated to each small cell, i.e., t_1 and t_2. Note that t_1 and t_2 indicate the actual interference margins that have been exploited by the small cells, the sum of which can be equal to or less than the total interference margin T.

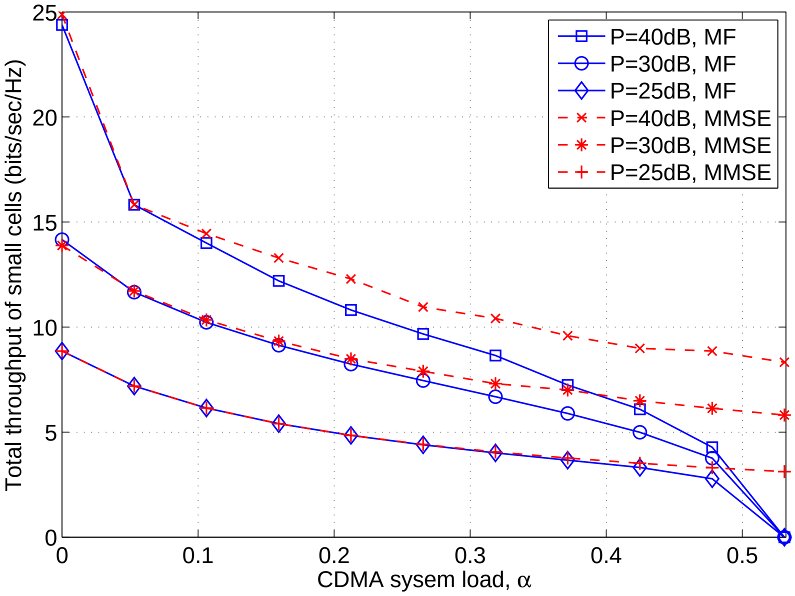

Figure 5.4: Total throughput of small cells vs. α: $G_1 = 0.9$, $G_2 = 0.1$.

In Table 5.1 and Table 5.2, the first data in each data entry is for MF scenario, and the second one is for MMSE scenario. Both tables show that as macrocell system load increases, the interference margins allocated to each small cell decrease. Small cells in MMSE scenario can exploit equal or higher interference margin than that in MF scenario. In the MF scenario, the total interference margins exploited by small cells, i.e., $t_1 + t_2$, under $\bar{P}_m/\sigma^2 = 25$dB and 30dB become the same as α increases. This indicates that the small cells are constrained by the total interference margin T. In the MMSE scenario, however, $t_1 + t_2$ for both $P_m/\sigma^2 = 25$dB and 30dB keeps increasing as the CDMA load α increases, indicating that the small cells are constrained by the maximum transmission power of each SBS, rather than by the total interference margin.

5.6 Conclusions

In this chapter, we have proposed an SR applied in the heterogeneous networks in which the CDMA cellular network is overlaid with multiple OFDMA small cells. In contrast from the previous two chapters, in this scenario, the SR technique is detached from the

Table 5.1: Interference Margin Allocated to Each Small Cell ($G_1 = 0.5, G_2 = 0.5$)

$\bar{P}_m/\sigma^2 = 25\text{dB}$

α	$0.1\alpha^*_{\text{MF}}$	$0.3\alpha^*_{\text{MF}}$	$0.5\alpha^*_{\text{MF}}$	$0.7\alpha^*_{\text{MF}}$	$0.9\alpha^*_{\text{MF}}$
t_1	1.76|1.76	1.75|1.75	1.58|1.73	0.79|1.73	0.28|1.73
t_2	1.13|1.13	1.11|1.11	1.06|1.10	0.80|1.08	0.26|1.07

$\bar{P}_m/\sigma^2 = 30\text{dB}$

α	$0.1\alpha^*_{\text{MF}}$	$0.3\alpha^*_{\text{MF}}$	$0.5\alpha^*_{\text{MF}}$	$0.7\alpha^*_{\text{MF}}$	$0.9\alpha^*_{\text{MF}}$
t_1	2.11|2.53	1.72|2.37	1.23|2.07	0.75|1.85	0.26|1.65
t_2	2.42|2.57	1.86|2.32	1.08|2.22	0.72|2.02	0.23|1.93

Table 5.2: Interference Margin Allocated to Each Small Cell ($G_1 = 0.9, G_2 = 0.1$)

$\bar{P}_m/\sigma^2 = 25\text{dB}$

α	$0.1\alpha^*_{\text{MF}}$	$0.3\alpha^*_{\text{MF}}$	$0.5\alpha^*_{\text{MF}}$	$0.7\alpha^*_{\text{MF}}$	$0.9\alpha^*_{\text{MF}}$
t_1	3.16|3.16	3.15|3.15	2.44|3.12	1.39|3.11	0.38|3.10
t_2	0.23|0.23	0.22|0.22	0.22|0.22	0.21|0.22	0.16|0.21

$\bar{P}_m/\sigma^2 = 30\text{dB}$

α	$0.1\alpha^*_{\text{MF}}$	$0.3\alpha^*_{\text{MF}}$	$0.5\alpha^*_{\text{MF}}$	$0.7\alpha^*_{\text{MF}}$	$0.9\alpha^*_{\text{MF}}$
t_1	4.05|4.38	3.02|4.00	2.03|3.22	1.09|3.01	0.26|2.80
t_2	0.73|0.73	0.68|0.70	0.63|0.68	0.51|0.68	0.26|0.65

mobile infrastructure sharing, which belongs to a generic case for wider application. We have analyzed the interferences between the small cells and macrocell and formulated the resource allocation problem for the OFDMA small cells. By transforming the original problem, we have proposed a new algorithm that can efficiently solve the resource allocation problem for the OFDMA small cells. The unavailability of interference channel power gains from the SBSs to MBS has been considered, due to which the resource allocation scheme of OFDMA small cells has to be updated. Due to the fixed geographical location of SBSs, the distance-based path loss is naturally known from the global geographic information of the cellular system, while only the fading and shadowing are remained to be known. Different from the resource allocation design for C-CSI unavailability in Chapter 3, we have found that the optimal power allocation is essentially independent from the C-CSI. Then, the corresponding resource allocation scheme has been proposed. Simulation results have been demonstrated the system performance and effectiveness of the proposed algorithm.

Chapter 6

Conclusions and Future Works

6.1 Conclusions

SR allows different generations of cellular networks to operate in the same frequency band, while infrastructure sharing, on the other hand, involves the sharing of passive or active elements of mobile infrastructure within or among operators. Both of them are important as multiple generations of cellular networks coexisting for their respective coverage of a common geographical area. Since the SR technique and infrastructure sharing can respectively improve the spectrum and infrastructure utilization, their joint implementation are drawing lots of attentions for efficiently designing the next generation of cellular networks.

Chapter 3 started by proposing a concurrent OFDMA/CDMA SR system with active infrastructure sharing which allows OFDMA network to operate in the spectrum allocated to the CDMA network and share the CDMA cell site as well as BS antenna. In this fundamental SR model, the interference powers between the two system have been quantified and the asymptotic SINR of the CDMA users has been derived based on which the interference margin that can be exploited by OFDMA system has been determined. The interference analysis and interference margin determination can be readily extended to other OFDMA/CDMA SR model which has been shown in the following chapters. With the interference margin together with the transmission power constraints, we have formulated and solved the OFDMA resource allocation problem by regarding the CDMA target receive power is fixed. After that, we have formulated the joint OFDMA/CDMA resource allocation problem, by exploiting the tradeoff of the OFDMA throughput over the receive power of CDMA system. Efficient resource allocation algorithm has been proposed which is conducted by the OFDMA system only, but due to the power control of CDMA system, it can force the CDMA to adjust the transmission power to its optimal value.

Note that in another generic case, where only the legacy cell site is permitted to share while the active elements (such as antenna) cannot be accessed by the unlicensed system, in Chapter 4, we have investigated an uplink OFDMA/CDMA SR system with passive infrastructure sharing where only legacy cell site is shared. With the pragmatic assumption that the C-CSI is unavailable, we have found, somewhat surprisingly, the legacy CDMA system can be sufficiently protected with aborative design of the OFDMA resource allocation scheme. Meanwhile, the spectrum sharing opportunity provided by CDMA system can be farthest exploited with the iterative-based resource allocation schemes that are conducted by OFDMA system only, where the CDMA system passively responses to the dynamic interference introduced by OFDMA systems which can be detected by OFDMA in turn. Without the requirement of the CSI between primary and secondary systems, the presented SR system can be easily deployed by the same or different operators who take charge of the two systems.

In Chapter 5, we have separated the SR technique from mobile infrastructure sharing. In particular, the SR in heterogeneous networks has been studied where the CDMA cellular network is overlaid with multiple OFDMA small cells. By analyzing the interferences between the small cells and macrocell, the resource allocation problem for the OFDMA small cells has been formulated and the efficient algorithm has been proposed by transforming the original problem. It has been shown that the overlaid OFDMA small cells can share the spectrum of CDMA legacy system efficiently with well protection to the CDMA users.

In each of the chapters, simulation results have been provided to verify our theoretical analysis, validate the effectiveness of the proposed resource allocation algorithms and illustrate their capability to protect the legacy CDMA users.

6.2 Future Works

This thesis includes several investigations on the SR technique applied to OFDMA/CDMA coexistent cellular networks, considering different types of mobile infrastructure sharing. The fundamental insights obtained from these investigations open the door to a new paradigm of spectrum sharing in cellular networks. Far from being exhaustively enumerated, future directions that is worth to be emphasized are listed as follows.

6.2.1 SR with Non-aligned OFDMA/CDMA Symbol Transmission

In all the SR systems that we have studied, the OFDMA and CDMA symbols are aligned by assuming the CDMA spreading gain equals the OFDMA FFT size. In some cases, the OFDMA system prefers to operate with much larger FFT size while the CDMA system would like use smaller spreading gain. In such scenarios, one OFDMA system will contain multiple CDMA symbols, which is of much interest for the SR technique being employed in wider range with higher flexibility in practice.

6.2.2 SR in Multi-cell Cellular Networks with Infrastructure Sharing

The SR technique for multi-cell cellular networks should be developed based on the single-cell SR technique, and new problems need to be addressed, such as network planning (infrastructure planning and frequency planning) and multi-cell resource allocation. On the network planning, as the 3G cellular network infrastructure has been deployed, when the OFDMA cellular network overlays the CDMA cellular coverage, the OFDMA should plans both of the infrastructure sharing and spectrum sharing methods, in order to maximize it throughput while provides sufficient protection to the CDMA cellular network. On the resource allocation, in single-cell SR system, the OFDMA users (in downlink) or BS (in uplink) are interfered only from the CDMA concurrent transmission, while the CDMA users (in downlink) or BS (in uplink) are interfered from OFDMA system and the intra-cell CDMA transmission. In the multi-cell scenario, however, the transmission in a cell will be additionally affected by the transmission strategy, i.e., the resource allocation, of the other cells. Thus, the resource allocation in multi-cell scenario will be different, and generally more complex, compared with that in the single-cell scenario. Distinct from the resource allocation in multi-cell OFDMA networks [57, 109, 110] or CDMA networks [111, 54, 79], the resource allocation of OFDMA system which concurrently transmit as a secondary system should also consider the interference constraint to protect CDMA system.

6.2.3 SR in Multi-cell Heterogeneous Networks

As the development of stochastic geometry theory in wireless communication, the performance analysis and system design of cellular networks can reflect the practical implementation more exactly [112]. It will be a powerful tool for deploying the secondary OFDMA cellular network on the top of legacy cellular networks by sharing the legacy spectrum. Considering a heterogeneous networks where a number of OFDMA small cells overlaying the CDMA legacy cellular networks, the planning of small cell networks, such as the BS density and the resource allocation, such as spectrum and power allocation can be designed by using stochastic geometry theory [113].

Appendix A

Proof of Corollary 2

Because the power of channel response in frequency domain is the same as that of impulse response in time domain, we have

$$\frac{1}{N}\sum_{n=1}^{N}\left|\lambda_{u,n}\right|^2=\sum_{l=1}^{L}\left|h_{u,l}\right|^2. \tag{A.1}$$

Considering **AS1** and **AS2**,

$$\lim_{N\to\infty}\frac{1}{N}\sum_{n=1}^{N}\left|\lambda_{u,n}\right|^2=\lim_{L\to\infty}\sum_{l=1}^{L}\left|h_{u,l}\right|^2. \tag{A.2}$$

Based on large number law, and considering that each path has the power of $\frac{1}{L}$ given in **AS 2**, the right hand side of (A.2) can be derived as

$$\lim_{L\to\infty}\sum\nolimits_{l=1}^{L}\left|h_{u,l}\right|^2=\lim_{L\to\infty}L\mathbb{E}[|h_{u,l}|^2]=1. \tag{A.3}$$

Thus, we have $\lim\limits_{L\to\infty}\frac{1}{N}\sum\limits_{n=1}^{N}\left|\lambda_{u,n}\right|^2=1$. Applying the large number law to the first term in the denominator of (3.11) yields

$$\begin{aligned}\lim_{N,U\to\infty}\frac{1}{N^2}\sum_{n=1}^{N}\left(\left|\lambda_{u,n}\right|^2\sum_{i=1,i\neq u}^{U}q\left|\lambda_{i,n}\right|^2\right)&=\lim_{N,U\to\infty}\frac{1}{N^2}\sum_{i=1,i\neq u}^{U}\left(q\sum_{n=1}^{N}\left|\lambda_{u,n}\right|^2\left|\lambda_{i,n}\right|^2\right)\\&=\lim_{N,U\to\infty}\frac{q}{N}\sum_{i=1,i\neq u}^{U}\left(\mathbb{E}\left[\left|\lambda_{u,n}\right|^2\left|\lambda_{i,n}\right|^2\right]\right)\\&=\alpha q.\end{aligned} \tag{A.4}$$

The last equation holds because of $\frac{U}{N} \to \alpha$. Note that the OFDMA resource allocation is NOT based on the channel condition of CDMA system, since the instantaneous CSI of CDMA is not available to OFDMA; thus it is reasonable to treat them as independent variables. Then, the second term in the denominator of (3.11) is

$$\begin{aligned}
\lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \left(\left|\lambda_{u,n}\right|^2 \sigma_n^2 \right) &= \mathbb{E}\left[\left|\lambda_{u,n}\right|^2 \sigma_n^2 \right] \\
&= \mathbb{E}\left[\left|\lambda_{u,n}\right|^2 \right] \mathbb{E}\left[\sigma_n^2 \right] \\
&= \mathbb{E}\left[\sigma_n^2 \right]. \qquad \text{(A.5)}
\end{aligned}$$

Substituting (A.3)-(A.5) into (3.11) yields (3.16). Thus, the corollary is proven.

Appendix B

Proof of Corollary 4

Substituting z with $-\sigma^2$ and applying large number law to (3.22), we have

$$\begin{aligned} x_u &= \lim_{U,N\to\infty,\frac{U}{N}\to\alpha} \frac{1}{N}\sum_{n=1}^{N} \frac{q\left|\lambda_{u,n}\right|^2}{\frac{1}{N}\sum_{i=1}^{U}\frac{q}{1+x_i}\left|\lambda_{i,n}\right|^2+\sigma_n^2+\sigma^2} \\ &= \lim_{U,N\to\infty} \frac{1}{N}\sum_{n=1}^{N} \frac{q\left|\lambda_{u,n}\right|^2}{\lim_{U\to\infty}\frac{1}{N}\sum_{i=1,i\neq u}^{U}\frac{q}{1+x_i}\left|\lambda_{i,n}\right|^2+\sigma_n^2+\sigma^2} \\ &= \lim_{U,N\to\infty,\frac{U}{N}\to\alpha} \frac{1}{N}\sum_{n=1}^{N} \frac{q\left|\lambda_{u,n}\right|^2}{\mathbb{E}\left[\frac{\alpha q}{1+x}\right]+\sigma_n^2+\sigma^2} \\ &= \mathbb{E}_n\left[\frac{q}{\mathbb{E}\left[\frac{\alpha q}{1+x}\right]+\sigma_n^2+\sigma^2}\right]. \end{aligned} \tag{B.6}$$

Here we can see the SINR among CDMA users is uniform. Thus, we can conclude the SINR of any user is the solutions of (B.6). Here, the corollary is proven.

Appendix C

Dual Decomposition in Solving Problem 1

By denoting $r_{k,n} = \log_2\left(1 + \frac{p_{k,n}g_{k,n}}{\alpha q + \sigma^2}\right)$, the Lagrangian of **Problem 1** becomes

$$\mathcal{L}(\boldsymbol{P}, \delta, \boldsymbol{\lambda}) = \sum_{k=1}^{K}\sum_{n=1}^{N} r_{k,n} - \delta\left(\frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} p_{k,n}g_{k,n} - T\right) - \sum_{k=1}^{K}\lambda_k\left(\sum_{n=1}^{N} p_{k,n} - \bar{P}_k\right), \tag{C.7}$$

where δ and $\{\lambda_k\}_{k=1,\ldots,K}$, are the Lagrangian dual variables for interference and power constraints, respectively. The Lagrangian dual function is thus

$$f(\delta, \boldsymbol{\lambda}) = \max_{\boldsymbol{P}} \mathcal{L}(\boldsymbol{P}, \delta, \boldsymbol{\lambda}), \tag{C.8}$$

and its Lagrangian dual problem is

$$\min_{\delta, \boldsymbol{\lambda}} f\left(\delta, \boldsymbol{\lambda}\right). \tag{C.9}$$

Decomposing (C.8) into N independent parallel maximization problems yields

$$f_n(\delta, \boldsymbol{\lambda}) = \max_{\boldsymbol{P}}\left\{\sum_{k=1}^{K}\left(r_{k,n} - \lambda_k p_{k,n} - \delta p_{k,n}g_{k,n}\right)\right\}. \tag{C.10}$$

Thus $f(\delta, \boldsymbol{\lambda})$ can be written as

$$f\left(\{\boldsymbol{\lambda}\}, \{\delta_u\}\right) = \sum_{n=1}^{N} f_n\left(\delta, \{\boldsymbol{\lambda}\}\right) + \sum_{k=1}^{K}\lambda_k\bar{P}_k + \delta T. \tag{C.11}$$

Letting the first-order derivative w.r.t. $p_{k,n}$ of the objective function in (C.10) equal to zero yields

$$p_{k,n} = \left(\frac{1}{(\lambda_k + \delta g_{k,n}) \ln 2} - \frac{\alpha q + \sigma^2}{g_{k,n}} \right)^+, \tag{C.12}$$

where $[x]^+ = \max(0, x)$. Substituting (C.12) into (C.10), the subcarrier can be allocated according to

$$f_n(\delta, \boldsymbol{\lambda}) = \max_k \left\{ r_{k,n} - \lambda_k p_{k,n} - \delta p_{k,n} g_{k,n} \right\}. \tag{C.13}$$

For each subcarrier n, traversing K OFDMA users and allocating it to the best OFDMA user. Then, δ and $\{\lambda_k\}$ will be searched by subgradient method [108]. And one of the subgradient is

$$\boldsymbol{d}_k = \begin{bmatrix} T - \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} p_{k,n} g_{k,n} \\ \bar{P}_1 - \sum_{n=1}^{N} p_{1,n} \\ \vdots \\ \bar{P}_K - \sum_{n=1}^{N} p_{K,n} \end{bmatrix}. \tag{C.14}$$

Appendix D

Background of Random Matrix Theory

The concept of random matrix is given as follows.

Definition D.1 (Random Matrix [95]) *An* $N \times M$ *matrix* $\boldsymbol{X}$ *is said to be a random matrix if it is a matrix-valued random variable on some probability space* $(\Omega, \mathcal{F}, P)$ *with entries in some measurable space* $(\mathcal{R}, \mathcal{G})$*, where* $\mathcal{F}$ *is the* σ*-field on* Ω *with probability measure* P *and* $\mathcal{G}$ *is a* σ*-field on* $\mathcal{R}$*.*

Considering the random Hermitian matrix $\boldsymbol{T}$ has K distinct eigenvalues, the $\boldsymbol{T}$ can be regarded to represent the channel covariance which has $\frac{N}{K}$ independent frequency bands. Suppose a random signal matrix $\boldsymbol{S}$ is transmitted throughout the channel, the received signal matrix is denoted as $\boldsymbol{Y} = \boldsymbol{T}^{\frac{1}{2}}\boldsymbol{S}$. Inferring the K eigenvalues from $\boldsymbol{Y}$ is extremely hard with finite size random matrix theory, as the maximum likelihood method becomes the a K-dimensional search. However, if we enlarge $\boldsymbol{T}$ and $\boldsymbol{S}$ by p-dimension using Kronecker product, the distribution function of the eigenvalue of $\boldsymbol{Y}\boldsymbol{Y}^H$ converges to a deterministic weak limit and thus efficient algorithm to find the K eigenvalues of the enlarged $\boldsymbol{T}$ can be adopted, which is a good approximation of the initial finite size $\boldsymbol{T}$.

The application of large dimension random matrix theory (RMT) to the finite size random matrix can be stated as follows. In adopting large dimension RMT, the dimensions of initial finite size random matrix (N, M) is artificially enlarged to infinity while their radio is kept constant. Then, the deterministic characteristics can be applied to the large random matrix. The results obtained can be adopted to predict the performance with the finite size random matrix.

List of Publications

Journal Articles

(i) * **S. Han**, B.-H. Soong, and Q. D. La, "Power control based on subcarrier exclusion to mitigate downlink cross-tier interference in OFDMA tiered networks," *IEEE Wireless Commun. Lett.*, vol. 2, no. 2, pp. 179-182, 2013.

(ii) **S. Han**, Y.-C. Liang, and B.-H. Soong, "Joint resource allocation in OFDMA/CDMA spectrum refarming system," *IEEE Wireless Commun. Lett.*, vol 3, no. 5, pp. 469-472, 2014.

(iii) **S. Han**, Y.-C. Liang, and B.-H. Soong, "Spectrum refarming: A new paradigm of spectrum sharing for cellular networks," *IEEE Trans. Commun.*, accepted for publication, 2015.

(iv) **S. Han**, Y.-C. Liang, and B.-H. Soong, "Spectrum Refarming for OFDMA/CDMA Coexistence with Passive Infrastructure Sharing," *IEEE Trans. Wireless Commun.*, under review, 2014.

Conference Proceedings

(i) * **S. Han**, B.-H. Soong, and Q. D. La, "Interference mitigation in resource allocation for OFDMA-based macro/femtocell two-tier wireless networks," in *Proc. IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, Seoul*, 2012.

(ii) [*] **S. Han**, B.-H. Soong, and Q. D. La, “Subcarrier allocation in multi-cell OFDMA wireless networks with non-coherent base station cooperation and controllable fairness,” in *Proc. IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications, Sydney*, 2012.

(iii) [*] **S. Han**, B.-H. Soong, and Y.-C. Liang, “JPAC: A long-term joint power and random access control in femtocell networks,” in *Proc. IEEE Vehicular Technology Society Asia Pacific Wireless Communications Symposium, Taiwan*, Aug. 2014.

(iv) **S. Han**, Y.-C. Liang, and B.-H. Soong, “Resource allocation for OFDMA/CDMA spectrum refarming with passive infrastructure sharing,” to appear in *Proc. IEEE Global Conference on Signal and Information Processing, Atlanta Georgia USA*, Nov. 2014.

(v) **S. Han**, Y.-C. Liang, and B.-H. Soong, “Spectrum refarming: A new paradigm of spectrum sharing for cellular networks,” to appear in *Proc. IEEE Global Commun. Conf., Austin, TX USA*, Dec. 2014.

(vi) **S. Han**, Y.-C. Liang, and B.-H. Soong, “Spectrum refarming for OFDMA small cells overlaying CDMA cellular networks,” to appear in *Proc. IEEE International Conference on Communication Systems, special session on Cognitive Cellular Networks, Macau*, Dec. 2014.

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[*] The content of these works are not presented in the thesis as they are different from the main thesis contents.

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