

CoMP Aware Radio Resource Management in Integrated PON-OFDM Network

by

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

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Abstract

Radio resource management (RRM) is an important component of a mobile wireless network that efficiently utilizes the limited radio resources such as spectrum, transmission power, and network infrastructure. Unfortunately, current RRM schemes do not support cooperative multiple point (CoMP), a promising technology that extends coverage, increases capacity, and improves the spectral efficiency of the next generation broadband network, i.e., 4G network. Specifically, to coordinate with CoMP, a RRM scheme should be aware of three main properties of CoMP - cooperative transmitting information, coordinated scheduling transmission, and single interference noise ratio (SINR) improvement. However, few of the existing RRM schemes consider these properties, since they were designed based on the conventional mobile data networks without CoMP technology.

In this dissertation, I present a series of new CoMP aware RRM schemes for ensuring users' throughput and maximizing network capacity in an integrated PON-OFDM network, which is a norm of the 4G network and can best implement the CoMP technology. I call the PON-OFDM network with CoMP a CoMP Network (CoMPNet). I provide two classes of RRM schemes for two practical CoMP technologies, cooperative transmission (CT) and coordinated scheduling (CoS), respectively.

In the first class, I propose two groups of RRM schemes using the CT technology. In the first group, three OFDM-TDMA based RRM schemes are designed for three different users' moving speeds. The objective of these schemes is to minimize time slot consumption. The RRM schemes in the third group are contrived for an OFDM-FDMA based CoMPNet. I provide four linear programming (LP) based optimal schemes, one for minimizing bandwidth usage, one for minimizing transmission power consumption, and two for balancing resource costs. An optimized resource allocation solution can be obtained by flexibly choosing one of the schemes according to network load.

In the second class, I present a sub-optimal RRM scheme for an OFDM-FDMA based CoMP-

Net. The CoS technology is applied for ICI mitigation. I formulate the system optimal task into constrained optimization problems for maximizing network capacity. To improve the computation efficiency, fast yet effective heuristic schemes are introduced for divide-and-conquer. The proposed heuristic schemes are featured by CoS based timeslots/subcarriers assignment mechanisms, which are further incorporated with intelligent power control schemes.

Through simulations, I study the proposed RRM schemes performances and discuss the effect of the CoMP technology. The performance benefits of CoMP on bandwidth saving and capacity increasing are shown by comparing the new schemes with the conventional schemes without CoMP.

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Dedication

This is dedicated to the one I love.

Contents

List of Tables	xi
List of Figures	xiv
List of Schemes	xv
List of Abbreviations	xviii
1 Introduction	1
1.1 CoMP Aware RRM Schemes	1
1.2 CoMP Technology	3
1.3 CoMP PON-OFDM Network (CoMPNet)	5
1.4 My New CoMP Aware RRM Schemes	6
1.5 Outline	7
2 Related Research	9
2.1 Optical and Wireless Broadband Access Network	9
2.2 OFDM Systems RRM Schemes	10

2.3	Cooperative Communication	12
2.4	Frequency Reuse Schemes and ICI Management	13
3	CT Aware RRM Schemes	17
3.1	Introduction	17
3.2	System Model	18
3.2.1	Structure and Propagation Model	18
3.2.2	User Mobility and User Classification	21
3.2.3	Efficiency Analysis	22
3.3	RRM Schemes	27
3.3.1	Multi-user LP Scheme (CT_LP)	29
3.3.2	Single-user LP Scheme (H_CT_LP)	33
3.3.3	Heuristic Scheme (H_CT)	34
3.4	Simulation Results	36
3.4.1	Simulation Environment	36
3.4.2	LP Failure Ratio	38
3.4.3	Total Time Slot Usage	45
3.4.4	Percentage of Unassociated Users	51
3.4.5	Computation Time	56
3.5	Chapter Conclusion	57
4	Optimized CT Aware RRM Schemes for SSs	58
4.1	Introduction	58

4.2	System Model	59
4.3	RRM Approaches	62
4.3.1	RRM Procedure	62
4.3.2	Three Approaches	63
4.4	RRM LP Models	65
4.4.1	Four LP Models	65
4.4.2	SOS1 Linearization	69
4.4.3	Problem Formulation for Non-CT (NCT)	71
4.5	Simulation Results	72
4.5.1	Scenario 1: 7 Cells Network	72
4.5.2	Scenario 2: 9 Cells Network	85
4.6	Chapter Conclusion	89
5	CoS Aware RRM Scheme	90
5.1	Introduction	90
5.2	System Model	92
5.3	RRM Problem Formulation	94
5.4	The New RRM Scheme	98
5.5	Simulation Results	104
5.5.1	Simulation Environment	104
5.5.2	Capacity Performance	108
5.5.3	Power Usage Performance	111

5.5.4	Computation Time	113
5.6	Chapter Conclusion	115
6	Conclusion and Future Work	116
6.1	Conclusion	116
6.2	Future Work	117
	APPENDICES	119
A	Non-CT RA Schemes	120
A.1	Multi-user Optimization Model for Non-CT (NCT_LP)	120
A.2	Single User Optimal Model for Non-CT (H_NCT_LP)	123
A.3	Single User Heuristic Model for Non-CT (H_NCT))	124
B	Frequency Reuse Subcarriers Allocation Schemes	125
B.1	Traditional Frequency Reuse (FR=X)	125
B.2	Fractional Frequency Reuse	127
B.2.1	Partial Frequency Reuse (PFR)	129
B.2.2	Soft Frequency Reuse	130
	Bibliography	141

List of Tables

3.1	Notations of Chapter 3	19
3.2	Parameters of the 2-D Scenario	24
3.3	Bit (b_{jm}) Map of Association Mode	30
3.4	Simulation Parameters Setting	38
3.5	Simulation Scenario Setting	39
3.6	Computation Time (s) (100 Users)	56
3.7	Computation Time (s) (160 Mbps)	56
4.1	Chapter 4 Notations	60
4.2	Simulation parameters setting	73
4.3	Simulation Scenario Setting	74
4.4	Simulation parameters setting	85
5.1	Chapter 5 Notations	93
5.2	Simulation Parameters Setting	105
5.3	MCS Levels and Related SINR	108

List of Figures

1.1	Cooperative Transmission (CT)	4
1.2	Coordinated Scheduling (CoS)	4
1.3	A Typical CoMPNet	5
3.1	2-D Scenario	23
3.2	Relationship between $\Delta SINR$ and Δt (Walking Speed)	25
3.3	Relationship between $\Delta SINR$ and Δt (Driving Speed)	26
3.4	Flowchart of RRM	28
3.5	Users with Two or More Associating BSs	35
3.6	Snapshot on the Mobile User Distribution in the AOI; the 7 BSs are Fixed.	38
3.7	LP Failure Ratio (1)	40
3.7	LP Failure Ratio (1) cont.	41
3.8	LP Failure Ratio (2)	43
3.8	LP Failure Ratio (2) cont.	44
3.9	Total Time Slot Usage (1)	46
3.10	Total Time Slot Usage (2)	47

3.10	Total Time Slot Usage (2) cont.	48
3.11	Total Time Slot Usage (3)	49
3.11	Total Time Slot Usage (3) cont.	50
3.12	Percentage of Unassociated Users (1)	52
3.13	Percentage of Unassociated Users (2)	54
3.13	Percentage of Unassociated Users (2) cont.	55
4.1	Frequency Reuse	61
4.2	RRM Procedure	64
4.3	A Snapshot on the SSs Distribution in the AOI. The 7 BSs are Fixed.	73
4.4	Total bandwidth consumption gap between CT and NCT models	74
4.5	Geographical distribution of the CT users	75
4.6	Total Bandwidth Allocation by the Four LP Models	76
4.7	Total Bandwidth Allocation for Different Number of SSs	78
4.8	Total Power Allocation by the Four LP Models	79
4.9	Total Power Allocation for Different Number of SSs	80
4.10	Computation Time for the Four LP Models	82
4.11	Computation Time for Different Number of SSs	84
4.12	A Snapshot on the SSs Distribution in the 9 BSs Network	86
4.13	Bandwidth Cost	87
4.14	Power Cost	87
4.15	Computation Time	88

5.1	A snapshot on the mobile user distribution in the two test networks	106
5.2	Assignments of Frequency Sub-bands	107
5.3	Percentage of Rejected Demands	110
5.4	Percentage of Subcarriers Usage	111
5.5	Percentage of Power Usage	112
5.6	Computation Time	114
B.1	Traditional Frequency Reuse Schemes	128
B.2	Partition Frequency Reuse (PFR)	131
B.3	Soft Frequency Reuse (SFR)	133

List of Schemes

1	CT aware RRM: Multi-user LP Scheme (CT_LP)	31
2	CT aware RRM: Sub-Optimal Scheme (H_CT_LP)	33
3	CT aware RRM: Heuristic Scheme (H_CT)	34
4	LP Model to Min B/W (MB_LP)	66
5	LP Model to Min Power (MP_LP)	67
6	LP Model to Balance B/W and Power for (LBPG_LP)	68
7	LP Model to Min Resources (MR_LP)	68
8	Sub-Optimal CoS Aware Scheme: Stage I	100
9	Sub-Optimal CoS Aware Scheme: Stage II	103

List of Abbreviations

AMC	Adaptive Modulation Coding
BS	Base Station
BUA	BS-User Association
CDMA	Code Division Multiple Access
CO	Central Office
CoMP	Coordinated Multiple Point
CoMPNet	CoMP PON-OFDM Network
CoS	Coordinated Scheduling
CSI	Channel Status Index
CT	Cooperative Transmission
FDMA	Frequency Division Multiple Access
FFR	Fractional Frequency Reuse
FMC	Fixed Mobile Convergence
FR	Frequency Reuse

FRF	Frequency Reuse Factor
ICI	Inter-Cell Interference
LP	Linear Programming
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MS	Moving Station
NCT	Non-Cooperative Transmission
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLT	Optical Line Terminator
ONU	Optical Network Unit
PFR	Partial Frequency Reuse
PON	Passive Optical Network
PS	Portable Station
QoS	Quality of Service
RA	Resource Allocation
RRM	Radio Resource Management
SDH	Synchronous Digital Hierarchy
SFR	Soft Frequency Reuse

SINR	Signal Interference Noise Ratio
SS	Static Station
TDMA	Time Division Multiple Access
VIP	Very Important Point
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

1.1 CoMP Aware RRM Schemes

Radio resource management (RRM), which is an important control component of a mobile broadband network, is designed to effectively allocate limited radio resources. Interference management is one of the most challenging issues in the modern mobile broadband network design. It becomes more critical when each base station (BS) is getting closer (or, the cells become more overlapped) which yields increased inter-cell interference (ICI). So, an effective RRM scheme of the next generation mobile broadband network should carefully consider ICI management. Unfortunately, current RRM schemes do not support cooperative multiple point (CoMP), which has been well recognized as an effective strategy for ICI management by performing a tight coordination among the distributed BSs [1]. To coordinate with CoMP, a RRM scheme should be aware of the three main properties of CoMP:

1. one or more BSs can transmit the signal to one user. When two or more BSs cooperatively transmit the same signal to one user, they need to use the radio channels at the same positions.

2. when multiple BSs do coordinated radio resource allocation to mitigate ICI, the radio channels at the same positions can only be used by one of these BSs.
3. user's signal interference noise ratio (SINR) can be improved to save radio resources; however, the CoMP itself costs radio resources on multiple BSs at the same time.

Few of the existing RRM schemes consider above properties, since they are designed based on conventional mobile data networks without the CoMP technology. Besides ignoring these properties, the existing RRM schemes are normally distributed schemes based on the distributed network structure of traditional mobile network. However, a centralized RRM scheme is better than the distributed scheme to take advantage of the CoMP technology by supervising the whole network status.

In this dissertation, I will focus on the research of centralized CoMP aware RRM schemes, including the BS user association, radio channel allocation, and power allocation schemes. I will provide two series of RRM schemes for two practical CoMP technologies, e.g., cooperative transmission (CT) and coordinated scheduling (CoS), respectively. My new CoMP aware centralized RRM schemes are designed to achieve the following two QoS targets of the next generation mobile broadband network:

1. at application level: to guarantee the end users data rate requirement, i.e., promise user's throughput;
2. at connection level: to increase network capacity, i.e., accept a maximum number of connections by creasing wireless spectrum utilization and extending mobile, especially for the users at the edge of a cell.

The remainder of this chapter is organized as follows. In Section 1.2, the details of the CoMP technology will be introduced. Section 1.3 describes an integrated passive optical network and orthogonal frequency division multiplexing system (PON-OFDM) network structure for 4G

networks to which the new CoMP aware RRM schemes are applied. The outline of this thesis is listed in Section 1.5.

1.2 CoMP Technology

CoMP technology can substantially mitigate ICI for extending coverage, increasing capacity, and improving spectral efficiency. So, it is proposed and included as a key technology in 4G network standards, such as IMT-Advance [2], 3GPP LTE-Advance [3], and IEEE WiMAX2 [4]. Although CoMP naturally increases system complexity, it has potentially significant capacity and coverage benefits, making it worth a more detailed development in both reception and transmission [5].

In the CoMP reception technology for uplink, the data transmitted by the user is received at multiple cells, which can improve especially cell-edge user upload throughput [6] [7]. CoMP reception is out of the scope of this thesis, which mainly studies the RRM schemes with considering the CoMP transmission technology for downlink. To be specific, CoMP transmission is mainly characterized into two classes: cooperative transmission (CT) and coordinated scheduling (CoS).

In the class of cooperative transmission (CT), shown in Figure 1.1, the data segments are coded with different space-time codes in multiple associated BSs. These orthogonal space-time codes are then transmitted to the receiver where the same copy or a portion of the data can be aggregated and jointly decoded. In this way, the ICI signal from the neighbor BSs can be replaced by the useful signal, and then the SINR can be significantly improved for end users.

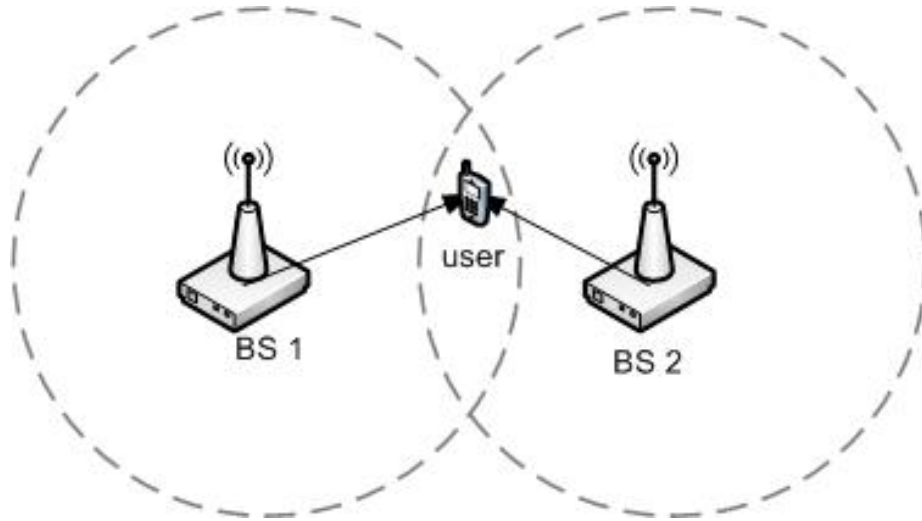


Figure 1.1: Cooperative Transmission (CT)

In the class of coordinated scheduling (CoS), shown in Figure 1.2, data to single user is transmitted from one BS; and multiple BSs are controlled by a coordinated radio resource allocation scheme to transmit data to multiple users. ICI can be mitigated via allocating different wireless channels to the users at the cell edge of adjoint cells, then the SINR of the user can be improved.

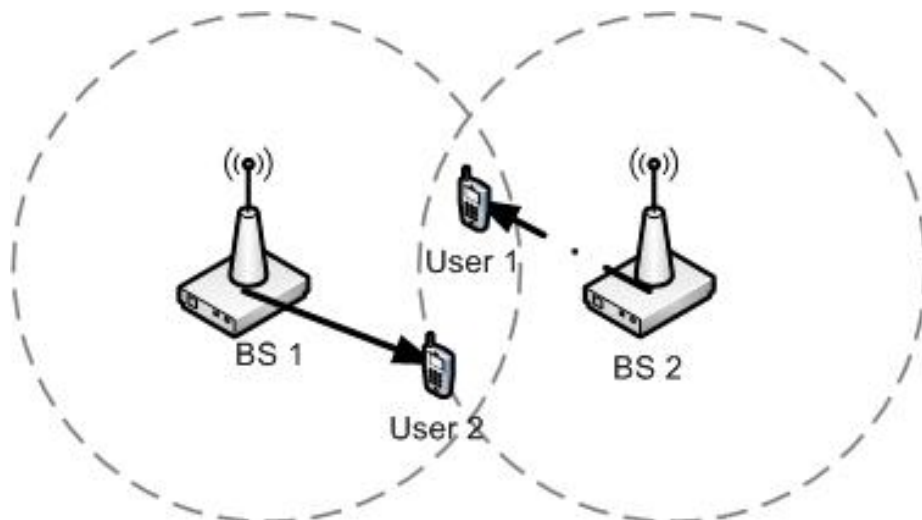


Figure 1.2: Coordinated Scheduling (CoS)

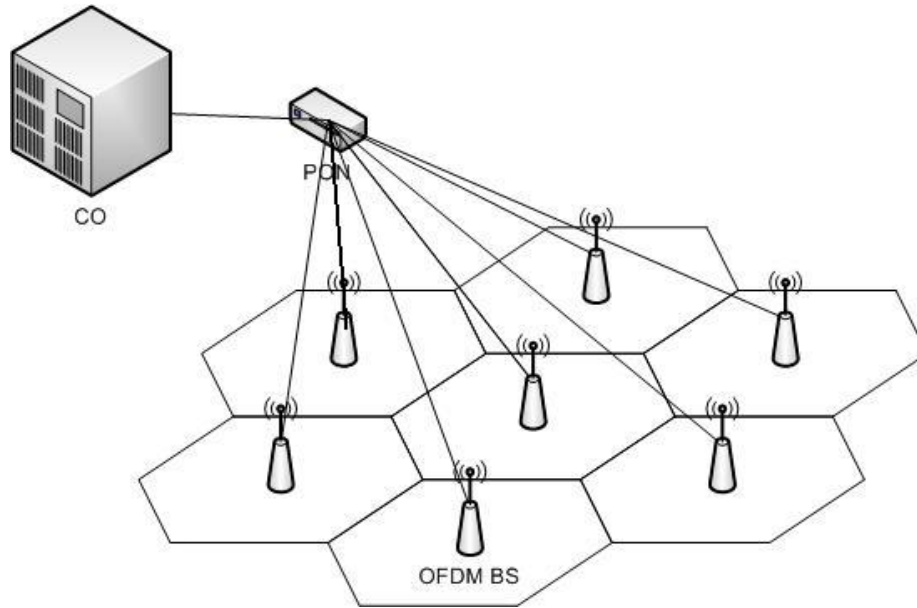


Figure 1.3: A Typical CoMPNet

1.3 CoMP PON-OFDM Network (CoMPNet)

Integrating state-of-the-art wireless and optical broadband access technologies has become a norm to satisfy the increasing demands for the mobile broadband multimedia services in metropolitan areas [8]. In this dissertation, I employ such a network as integrating an OFDM wireless system and PON access network, called a PON-OFDM network. In a PON-OFDM network, the OFDM wireless system is concatenated with the PON by integrating a base station (BS) with an optical network unit (ONU), denoted as ONU-BS, so that service coverage extension and superb support of user mobility can be achieved with fast, easy and cost-effective deployment [9]. By the PON architecture, the messages from the optical line terminal (OLT) are broadcasted to all ONU-BS, OLT can centrally control one or more ONU-BS(s) to send it out to achieve CT technology. CoS technology among distributed cells can be supported by the centralized coordination at the OLT. I define such a PON-OFDM network with CoMP technology as a CoMP PON-OFDM network (CoMPNet), shown in Figure 1.3.

A typical CoMPNet consists of a number of ONU-BSs connected to an OLT, which is a central office (CO) with the capability of implementing centralized network control and management functions. By taking the best advantage of coordination among the BSs, my new intelligent RRM mechanism that initiates multi-cell collaboration should be in place to achieve quality of service (QoS) provisioning and efficient ICI management for better system capacity.

1.4 My New CoMP Aware RRM Schemes

The two practical CoMP technologies, CT and CoS, can be individually employed in a CoMPNet. So, I provide two classes of CoMP aware RRM schemes with CT technology and CoS technology respectively in this thesis.

OFDM combined with time division multiple access (OFDM-TDMA) or frequency division multiple access (OFDM-FDMA) are two basic multiple access techniques of the CoMPNet. Both OFDM-TDMA and OFDM-FDMA are adopted by the next generation mobile broadband network as two options. These two division multiple access types are separately considered in each class of my new CoMP aware RRM schemes.

In the first class of schemes, three groups of RRM schemes are proposed for the CoMPNet with CT technology. The first group is developed for OFDM-TDMA based CoMPNet. This group includes three schemes for three different users' moving speeds, namely fixed, slow moving, and fast moving, aiming at improving network capacity, i.e. reducing the number of rejected users' demands. The three new RRM schemes with different computation complications which are an optimal scheme, a sub-optimal scheme, and a heuristic scheme. The objective of these schemes is to minimize time slot usage. The second group of RRM schemes is contrived for OFDM-FDMA based CoMPNet. I provide four linear programming (LP) based optimal schemes, one for minimizing bandwidth usage, one for minimizing transmission power consumption, and two for balancing resource cost. An optimized resource allocation solution can be

obtained by flexibly choosing one of the schemes according to network load. My new CT aware RRM schemes can assign one or more BSs to serve one user according to its data rate requirement, interference, noise level, and network resource utilization. Radio resources are allocated to satisfy user's requirement based on the SINR improved by CT technology. The performance benefits of CT technology on the bandwidth saving and capacity increasing are shown by comparing the new schemes with conventional schemes without CT technology.

In the second class of schemes, I present a RRM scheme for OFDM-FMDA based CoMP-Nets. The CoS technology is applied for ICI mitigation. I formulate the system optimal task into constrained optimization problems for maximizing network capacity. To improve the computation efficiency, a fast yet effective heuristic schemes are introduced for divide-and-conquer. The proposed heuristic scheme is featured by CoS based subcarriers assignment mechanisms, which are further incorporated with intelligent power control schemes that take advantage of adaptive modulation and coding (AMC) technology for interference reduction and energy conservation. Since the SINR can be improved, my new CoS aware RRM schemes can utilize less radio resources to satisfy users' requirements than the CoS unaware RRM schemes. Simulation results demonstrate that the proposed CoS based RRM schemes can significantly improve the network capacity compared with common frequency reuse approaches without CoS.

1.5 Outline

The remaining part of the thesis is organized as follows. Chapter 2 gives an overview of the related work about fiber-wireless access networks, OFDM radio resource management, CoMP transmission technology, and ICI management.

Chapter 3 addresses the issues of RRM in OFDM-TDMA based CoMPNet with CT technology. In order to maximize the network capacity with limited wireless spectrum resource, I provide three new RRM schemes which employ the cooperative transmission. The three schemes

are designed as optimal, sub-optimal, and heuristic schemes with three different computation complexities respectively. By considering the user's mobility, the three new RRM schemes can be suitable for fixed users, slow moving users and fast moving users, respectively. Simulations are conducted to verify the proposed RRM schemes by comparing with those without cooperative transmission technology. The results demonstrate the efficiency of the proposed schemes, which are based on mathematical formulations and linearization.

Chapter 4 proposes a novel framework of optimal RRM schemes of the OFDM-FDMA based CoMPNet with CT technology. I provide three optimized resource allocation approaches for minimizing bandwidth usage, minimizing transmission power consumption, and balancing resource cost respectively. The optimized resource allocation scheme is implemented by adaptively choosing one of the approaches according to network load. The simulation results show the efficiency of the proposed mathematical formulations and linearization approach of my scheme. The performance benefit of CT technology on the bandwidth saving is shown by comparing the new LP RRM scheme with the conventional non-cooperative transmission (NCT).

Chapter 5 investigates RRM via power control for ICI mitigation in an OFDM-FDMA based CoMPNet with CoS technology. The proposed scheme is featured by a novel subcarrier assignment mechanism at a central controller for ICI, which is further incorporated with an intelligent power control scheme. I formulate the problem into a constrained optimization problem for maximizing accepted users' requirements. To improve the computation efficiency, a fast yet effective heuristic approach is introduced for divide-and-conquer. Simulation results demonstrate that the proposed resource allocation schemes can significantly improve the network capacity compared with a common approach by frequency reuse.

Chapter 6 provides conclusions and future work.

Chapter 2

Related Research

2.1 Optical and Wireless Broadband Access Network

Passive optical network (PON), such as ethernet passive optical network (EPON) [10] and gigabit capable passive optical network (GPON) [11], is established on point-to-multipoint (P2MP) optical access technology without employing any active equipment in the data pathway from the source to destination. Thanks to the tree topology and P2MP architecture of PONs, the establishment and maintenance expenditure of fibers could be reduced significantly compared with that of traditional point-to-point networks. The finance and performance advantages of PON make it desirable to serve as a backhaul network for connecting multiple optical network units (ONUs).

Orthogonal frequency division multiplexing (OFDM) [12] [13] is used as the multiple access technology, which is a frequency division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation technique. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data signal is split into several small sub-signals, which are transmitted simultaneously by different sub-carriers to the receiver. With the advantages of efficient wireless frequency usage, scalable transmission data rate, inter symbol interference (ISI) cancellation, low complexity of implementation and multiple-input and multiple-output (MIMO)-applicableness,

the OFDM wireless system is widely adopted in both 3.9G (LTE [14] and WiMAX [15]) and 4G (LTE-A [3] and WiMAX2 [4]) mobile broadband networks.

Researches on either optical or broadband wireless access networks has been extensively reported in the past, yet few research presents the integration of the two networks [8]. In [8], the wireless-optical broadband-access network (WOBAN) was described as a promising architecture for next-generation mobile access networks, meanwhile, the authors reviewed some popular optical and wireless access technologies, such as EPON, GPON, WiFi, and WiMAX. Novel hybrid WOBAN architecture has also be proposed in the article, further, some BS placement and routing algorithms have been compared based on the architecture. In [16], a framework on the integration of EPON and WiMAX for broadband fixed/mobile convergence (FMC) access was proposed, added to the research issues on the MAC layer and integrated control plane were elaborated. Despite the fact that NEC is extending the product scope of PON-WiMAX for broadband access network applications not only at academic level but also in industry field [17], little research of integrated PON-OFDM networks have focused on the issue of CoMP aware RRM scheme.

2.2 OFDM Systems RRM Schemes

In the past ten years, plenty of RRM schemes have been proposed for various OFDM systems. In this section, I will review some of them, including the BS selection schemes, the single cell RRM schemes, and the multi-cell RRM schemes.

In [18], two BS association schemes were put forward in two cases: 1) BS allocates the same amount of time to its users and 2) BS allocates the same network throughput to its users. In the end, it has been found that the first case was better than the second in terms of fairness and efficiency. In [19], two BS selection algorithms were presented in a cooperative cellular network, which turned out to be a genetic-based approach and a sphere decoder inspired approach.

Nevertheless, few research of BS association schemes have jointly taken resource allocation into account.

In [20], an adaptive subcarrier-bit-and-power allocation algorithm was proposed to achieve a dramatic increase in power efficiency. A Lagrangian method of optimization was adopted to minimize the total transmit power under the constraints of users' QoS requirements. However, the prohibitively high computational complexity renders it impractical. After that, many other adaptive allocation algorithms with various objectives have been proposed to reduce the complexity of the resource allocation algorithm [21], [22], and [23].

Added to the above single cell resource allocation schemes, some researchers focused on the multi-user and multi-cells resource allocation scheme. Paper [24] has given an overview of adaptive multi-user resource allocation methodologies, among which, adaptive modulation, adaptive multiple-access control and adaptive cell selection for SISO-OFDM as well as MIMO-OFDM have been introduced. Compared with multi-user algorithms, multi-cell algorithms achieve resource allocation for multi-user in the multi-cell network environment, where frequency reuse and ICI must be fully considered. Paper [25] presents two multi-cell resource management strategies for OFDMA-based cellular systems. In the article, an inter-cell interference model has been developed, as well as spectral efficiency and the service outage probability models have been established in the research. Research in [26] illustrates a distributed game theory approach, which is to adaptively allocate the sub-channels, rates, and power for multi-cell OFDMA networks. To regulate the competition for the resource usage, they employed a virtual referee scheme which made their algorithm outperform the iterative water-filling method in terms of both transmission power consumption and throughput.

2.3 Cooperative Communication

An LP formulation for optimal BS placement in integrated EPON-WiMAX networks was proposed in article [9], where the cooperative communication, bandwidth and power breakdown assignment are jointly considered in the initial long-term network planning and dimensioning phase. It provides the basics for future QoS provisioning with adaptive control and flexible network resource management.

In [27], the authors described various cooperative diversity algorithms which can increase the data rate in relay networks. CT technology has been elaborated in the article, which is used to improve the SNR by combining the signals received from the base station with that received from the relay stations.

However, for the best consideration of my survey, few studies have jointly considered the RRM model in the multi-user & multi-cell network scenarios with CT technology. Because of the lack of a central controller structure, the research of cooperative resource allocation schemes adopt relay nodes or occupy other wireless users resources to achieve cooperative communication [28] [29].

Generally, CoMP and resource allocation schemes are associated together to achieve high data rates [30] [31] [32]. In [30], the authors proposed a joint linear precoding and power allocation for CoMP with multi-user MIMO under the single antenna power constraint to the total increase rate. They assumed that only one user could be assigned to each sub-band to simplify the performance analysis.

Research [31] introduces a joint nonlinear precoding and power allocation for CoMP with multi-user MIMO under both total BS and per-BS power constraints, according to the core theory, the SINR for each user could be improved through this process, and the rate could thereby be increased. In [32], the author developed a method to increase the sum rate by applying convex optimization techniques to optimize the joint linear precoding and power allocation for CoMP,

with multiuser MIMO under the per-BS power constraint. [33] presents new resource allocation schemes with (or without) adaptive modulation for CoMP with multi-user multiple input multiple output orthogonal frequency division multiple access (MIMO-OFDMA). In the proposed schemes, a practical linear pre- and post-processing technique is used to cancel inter-user interference and decompose a single user's MIMO channel into parallel non-interfering spatial layers. The transmit power is allocated to spatial layers with (or without) adaptive modulation under the total BS power and per-BS power constraint. The user group for each subcarrier is determined by the exhaustive search user allocation, sum rate-based user allocation, and random user allocation. Simulation results show that the proposed schemes increase the sum rate.

2.4 Frequency Reuse Schemes and ICI Management

A mobile user device in a cellular network can be generally affected by intra-cell interferences and inter-cell interferences (ICI). Intra-cell interference mainly results from the frequency-selective multi-path propagation that distorts the signal orthogonality in each OFDM pulse, while the ICI occurs among the transmissions on common frequency bands within two geographically adjacent cells. To achieve interference mitigation, research has been carried out at the device level via interference cancellation [34] [35]. Meanwhile at the system level, methods of interference avoidance for single-cell interference scenarios have been extensively studied and further formulated as problems of resource allocation and scheduling.

Different from single cell schemes such as the one be presented in [21], the design of a multi-cell resource allocation algorithm must fully consider the interference as a key issue [24], and in many cases, a centralized scheme can significantly outperform a distributed version at the expense of computation complexity and reliability [36].

Frequency reuse [37] via space division multiplexing (SDM) is a widely employed design principle to improve the spectrum utilization and avoid possible ICI by assigning different fre-

quency bands to different cells. In a frequency reuse scheme, the full bandwidth (B) is divided into X sub-bands ($B_X = B/X$), and the parameter X is also known as the frequency reuse factor (FRF). Each BS is assigned with one sub-band. The BSs using the same sub-band are defined in a common frequency reuse group (frg_x). Therefore, there are X frequency reuse groups in a FR= X frequency reuse scheme, and interference only exists among the BSs in the same frg_x . In general, BSs that are geographically close to each other should belong to different $frgs$ to promote interference free transmission.

Obviously, FR1 leads to a universal reuse of frequency spectrum where each cell accesses common set of frequency bands, in which serious ICI could be induced specifically for edge users. FR- M (with M as the number of BSs in the CO-domain) is the other extreme of the design spectrum where every BS uses a different frequency sub-band, thereby yielding a frequency reuse factor of M . This deployment leads to the lowest interference within a CO-domain at the expense of possibly minimal frequency resource utilization volume. A classical interference avoidance scheme that has been widely employed in state-of-the-art cellular systems is a switching status of above two, called reuse 3 (FR3), which divides the frequency into 3 equal sub-bands. FR3 promises that all adjacent cells could always use different frequencies to avoid any interference between two adjacent cells.

FR3 achieves better frequency spectrum utilization than FR1 and FR M , however there are only 1/3 total spectrum resources available in each cell. Thus, a fractional frequency reuse (FFR) design principle was employed to improve FR x , which involves partitioning the network spectrum into a number of sub-bands and assigning sub-bands to each cell based on accurate designed frequency planning as well as transmission power allocations that minimize ICI. In [38], partial frequency reuse is employed as the means for ICI mitigation and load balancing in order to improve cell edge performance and sustain a healthier data flow rate among all users.

It is known that users could be subject to serious ICI or low spectrum utilization by adopting the traditional FR x schemes; meanwhile, fractional frequency reuse (FFR) schemes were estab-

lished as a remedy, which includes partial frequency reuse (PFR) [39] and soft frequency reuse (SFR) [40].

In [38], partial frequency reuse is employed as the means of ICI mitigation and load balancing in order to improve cell edge performance and enable balanced data rates among all users. PFR employs a zone-based reuse factor in central and edge areas of a cell, respectively. The full system bandwidth is divided into a general sub-band and a special sub-band, where the former can only be used by central users and the reuse factor is 1; while the reuse factor of the special sub-band is $X(X > 1)$, normally $X = 3$. Thus, each cell can only use no more than $1/X$ of the special sub-band, and the edge users can only use the special sub-band. A fixed power control scheme can be employed under PFR, by allocating lower transmission power to the general sub-band and a higher power to the special sub-band users.

Compared with PFR, the idea of soft frequency reuse (SFR) is to optimize the use of the resources so that the entire spectrum could be employed by all cells. To regulate the spectrum usage, and to reduce interferences, zone-based reuse factors are activated in the cell-centre and the cell-edge areas. Initially, FR3 functions in the cell-centre area while the rest of the frequency is applied in the cell-edge area. Secondly, lower power has been used as they are affected by lower ICI, and the effect of ICI to other cells could be minimized at the same time.

I assume that dynamic frequency reuse is a key to broaden the cell bandwidth and increase spectrum utilization. In [41] and [42], soft frequency reuse schemes were developed for maximizing overall data rate, which aims to dynamically identify edge users with different transmission power according to specific users' distribution. The study in [43] reveals that a network based on the same design premises is allowed to reuse factors. The study in [44] presented a dynamic interference avoidance scheme that adopts inter-cell coordination for interference mitigation without carrying out any frequency planning measures. Overall, the scheme described in the study outperforms PFR in terms of cell throughput. In [26], a distributed game theory based approach was developed to adaptively allocate the sub-channels and transmission power for in-

dividual user in multi-cell OFDMA networks. To manage the competition for resource usage, the scheme proposed in [26] employs a virtual referee scheme which outperforms of an iterative water-filling method in terms of both transmission power consumption and overall throughput.

Chapter 3

CT Aware RRM Schemes

3.1 Introduction

Quality of service (QoS) in mobile broadband networks can be divided into the two following levels [45]: application and connection. QoS at the Application level is about perceiving quality at the user end, mainly in aspects like delay/delay jitter, error/loss and data rate, etc. Connection-level QoS is focused on connection establishment and management, for example, the new-call-blocking and handoff-dropping probability. Efficient RRM schemes play critical roles in solving some QoS problems. In this chapter, I focus on the RRM to accomplish the following two QoS targets: 1) satisfy the end user's data rate requirement at the application level; 2) at the connection level try to achieve a maximum new calls number by increasing wireless spectrum utilization and extending mobile transmission, especially for users at the edge of a cell.

Mobility supporting is also a major issue of the RRM scheme. In this chapter, I will define the moving user type according to the moving speed of users, and there are three moving types: fixed, slow-moving, and fast-moving.

For all of the above purposes, three new RRM schemes are developed to minimize the re-

source usage, each designed for a specific group of users with a different moving type, which is known as Static Station (SS) with fixed moving type, Portable Station (PS) with slow-moving (normally walking speed), and Mobile Station (MS) with fast-moving type (normally driving speed), respectively. I first provide an optimal RRM scheme (CT_LP) with cooperative transmission. In this scheme, a multi-user nonlinear optimal model is provided with the objective of minimizing time slot usage, and then it is linearized to a linear programming (LP) model. This optimal scheme is designed for SSs which is fixed and can tolerate relative long computing time period. On the other hand, I use the optimal results to evaluate two other efficient RRM schemes, i.e. H_CT_LP and H_CT, which are introduced for mobile users (PSs and MSs). An analysis of RRM efficiency for moving users is provided in Section 3.2.3. By adaptively choosing one of the three novel RRM schemes based on different moving types of users and network loads, a near-optimal RRM solution can be achieved.

The remainder of the chapter is organized as follows. Section 3.2 describes the system model of an OFDM-TDMA based CoMPNet. The RRM mentioned previously is proposed in Section 3.3. Section 3.4 gives the simulation results and analyses of the RRM schemes, conclusions are provided in Section 3.5.

3.2 System Model

3.2.1 Structure and Propagation Model

By using OFDM-TDMA to fulfill the multi-access technology of the CoMPNet, I define the percentage of time slot according to the amount of network resources to be allocated to each user. I assume that all network states, such as time slot usage of each BS, status of wireless channel, data rate requirement of each user, and user's moving speed are stored and dynamically updated at the CO. Based on the given data, the CO can compute the resources and associated BS(s) for the user upon arriving to satisfy its data rate requirement by the RRM schemes.

In the system model, the data rate of a user is estimated by Shannon's channel capacity function, which is based on information theory and the wireless resource allocation research that are widely employed [46]. In Equation (3.1), $B \times \log(1 + SINR_n)$ is the Shannon's channel capacity of user n , which also represents the maximum data rate that the system can allocate to a user n ; $T p_n$ is the percentage of time slot allocated to the user to satisfy its data rate requirement. All notions of this chapter are listed and explained in Table 3.1.

Table 3.1: Notations of Chapter 3

Symbol	Notation
R_n	The data rate of user n
α	The path-loss exponent
d_0	The reference distance to BS antenna
N_0	The thermal noise power
d_{mn}	The distance between user n and BS m
N	The number of total users
M	The number of total BSs
B	The total wireless bandwidth
R_n^{Req}	The data rate required by user n
A_{mn}	The associating indicator of user n and BS m
$T p_{mn}$	The normalized time slot allocated to user n from BS m
x_{jn}	The associating indicator of user n and *AM _j
$T p_{jn}$	The normalized time slot allocated to user n by *AM _j
$T p_n$	The normalized time slot allocated to user n
P_n^R	The data signal power received by user n
P_n^I	The interference power received by user n
P_{mn}^r	The transmission power received by user n from BS m
P_m^t	The transmission power of BS m

*AM: associating mode

$$R_n = B \times T p_n \times \log(1 + SINR_n) \quad (3.1)$$

$$SINR_n = \frac{P_n^R}{N_0 + P_n^I} \quad (3.2)$$

In the case of the conventional wireless communications without CT technology, i.e., Non

Cooperative Transmission (NCT), one user is associated with only one BS; I assume BS m is associating user n . Then the received signal power (P_n^R) of user n can be estimated by the radio wave propagation function $f(\cdot)$ of the transmission power from BS m .

$$P_n^R = P_{mn}^r = f(P_m^t) \quad (3.3)$$

Interference power (P_n^I) is the summation of the transmission power from the BSs other than the associated one, which is formulated as follows.

$$P_n^I = \sum_{k=1, k \neq m}^M P_{kn}^r \quad (3.4)$$

In the CoMPNet with CT, one or more BSs can cooperatively transmit the same packets to one user. Therefore, in Equation (3.5), P_n^R is the summation of the transmission power of all associated BS(s) [47], and P_n^I can be calculated by Equation (3.6).

$$P_n^R = \sum_{m=1}^M A_{mn} P_{mn}^r \quad (3.5)$$

$$P_n^I = \sum_{m=1}^M (1 - A_{mn}) P_{mn}^r \quad (3.6)$$

where

$$A_{mn} = \begin{cases} 1 & \text{BS } m \text{ is associated with user } n \\ 0 & \text{otherwise} \end{cases} \quad (3.7)$$

For the sake of simplicity, I use the path loss model [48] to estimate the received power of user n from BS m in my simulation.

$$P_{mn}^r = P_m^t \times \left(\frac{d_0}{d_{mn}} \right)^\alpha \quad (3.8)$$

The propagation model can be improved by combining the shadowing fading model [49] or small-scale fading model [50]. However, the improvement does not affect the simulation results as the receive power and SINR of each user are parameters applied by my RRM schemes. In practical applications, these parameters are measured by the users and fed back to the CO [51].

The percentage of time slot (Tp_n) in Equation (3.1) assigned to the user n is the resource allocated by the RRM schemes. The BS user association is determined by the variable (A_{mn}), if $A_{nm} = 1$, the BS m is associating with user n , otherwise $A_{nm} = 0$.

3.2.2 User Mobility and User Classification

User's mobility in the network impacts the variance ratio of its channel status information (CSI) and efficiency requirement of the RRM scheme, So I classify the users into the following three categories according to their moving type: 1) static station (SS), 2) portable station (PS), and 3) mobile station (MS).

1) Static Station (SS) is a static mode which is fixed in the network. It normally produces a stable traffic load and requires high QoS guarantee. Wireless service providers consider this kind of user as VIPs, such as schools, big companies, and business buildings. Since the CSI of SS is a relatively stable, capacity-efficient and optimized resource allocation scheme which can bring significant improvement in network operations. Therefore, the optimization process for resources is longer and the capacity allocation is relatively tolerable in this case. In this chapter, the RRM scheme proposed for this class of users is based on a LP model (also called multi-user LP scheme, denoted as CT_LP) which aims to minimize the resource usage (in terms of time slot) for all SSs. Such design premises are important and necessary so that the system can have more available resources to be offered to other mobile users.

For mobile subscribers, i.e. PS and MS, the corresponding RRM scheme should be more computationally efficient than that for the SS due to the mobility difference that causes frequent changes of CSI of the users, in which circumstances the resource allocation should be updated from time to time.

2) A Portable Station (PS) is a movable subscriber with a slow mobility (such as walking speed), in which the CSI changes relatively slowly. In this case, a dynamic resource allocation process should take place to cope with the change of network states, where users are sequentially allocated with the required resources in terms of time slot by solving a simple LP model (also called single-user LP scheme, H_CT_LP).

3) A Mobile Station (MS) is a fast-moving subscriber with a continually changing CSI. In this case, resource allocation for each MS is refreshed quickly via a heuristic resource allocation scheme (also called a single-user heuristic scheme, H_CT) as its moving type is fast-moving and comprises a high moving speed.

It can be concluded from the above that different kinds of users who with different moving types can tolerate different RRM calculation efficiencies, which is elaborated upon the following sub-section.

3.2.3 Efficiency Analysis

The RRM scheme frequently allocates the resources to moving users based on the users' data rate requirements and their current SINR. The SINR changes with the mobility of user, therefore the RRM scheme should be efficient enough to satisfy the user's requirement. In other words, the RRM scheme should function faster than the rate of the SINR variation. In addition, I only need to worry about the moving type and real-time position of the user in the RRM scheme, but no moving direction issues need to be taken into account.

I use a two-dimensional space scenario to investigate the SINR variance ratio and the resource

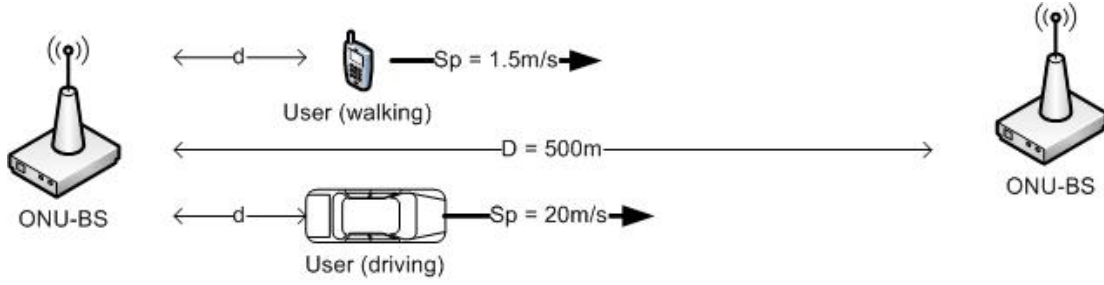


Figure 3.1: 2-D Scenario

allocation efficiency for mobile users, as explained in Figure 3.1. In the scenario, two users move from left BS to right BS with walking speed and driving speed, respectively.

I consider the worst case that a user moves from its associated BS to another one. The user begins to move at t_0 on time axis t , and SINR is $SINR_{t_0}$ at the time, therefore it can be estimated by Equation (3.9) from Equation (3.2) and Equation (3.8).

$$SINR_{t_0} = \frac{P_{t_0}^R}{N_0 + P_{t_0}^I} = \frac{P_1^t \times \left(\frac{d_0}{d_{t_0}}\right)^\alpha}{N_0 + P_2^t \times \left(\frac{D-d_0}{D-d_{t_0}}\right)^\alpha} \quad (3.9)$$

The system begins to calculate the resource allocation for the user at time point t_0 . t_1 represents the time when resource allocation is achieved, therefore, the duration for resource allocation is $\Delta t = t_1 - t_0$. When the user is moving, the SINR at t_1 ($SINR_{t_1}$) is no longer the same as t_0 ($SINR_{t_1} \neq SINR_{t_0}$). The gap between $SINR_{t_0}$ and $SINR_{t_1}$ is denoted as $\Delta SINR$. In order to guarantee the user's QoS, the $\Delta SINR$ should be less than a small value which is defined by the system QoS policy. Later I can obtain the maximum resource allocation duration Δt from the given $\Delta SINR$ for computing the resource allocation as follows:

$$\begin{aligned}
\Delta SINR &= SINR_{t_0} - SINR_{t_1} \\
&= \frac{P_1^t \times \left(\frac{d_0}{d_{t_0}}\right)^\alpha}{N_0 + P_2^t \times \left(\frac{d_0}{D-d_{t_0}}\right)^\alpha} - \frac{P_1^t \times \left(\frac{d_0}{d_{t_1}}\right)^\alpha}{N_0 + P_2^t \times \left(\frac{d_0}{D-d_{t_1}}\right)^\alpha} \\
&= \frac{P_1^t \times \left(\frac{d_0}{d_{t_0}}\right)^\alpha}{N_0 + P_2^t \times \left(\frac{d_0}{D-d_{t_0}}\right)^\alpha} - \frac{P_1^t \times \left(\frac{d_0}{d_{t_0} + Sp \times \Delta t}\right)^\alpha}{N_0 + P_2^t \times \left(\frac{d_0}{D + Sp \times \Delta t}\right)^\alpha}
\end{aligned} \tag{3.10}$$

- D is the distance between the two BSs
- d_{t_0} and d_{t_1} are the distances between the user and its associated BS at time t_0 and t_1
- Sp is the user's moving speed

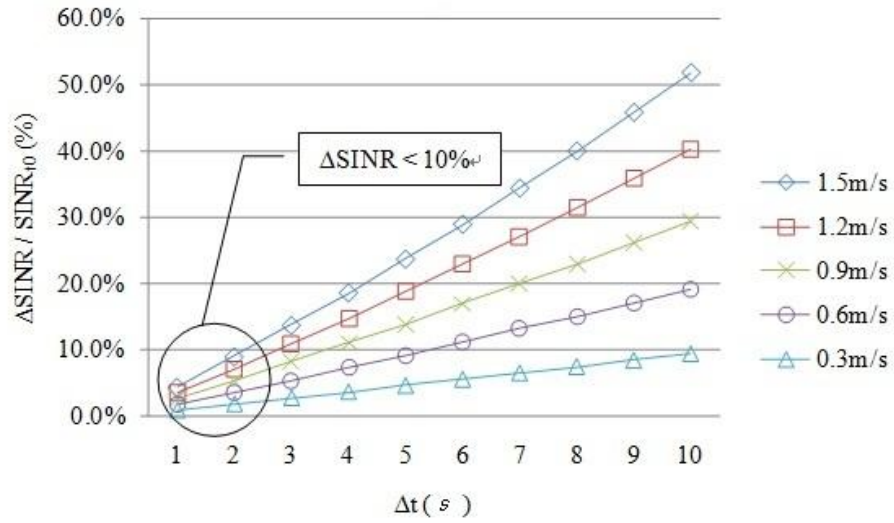
Other notations are same as those provided in Table 3.1.

The numerical results of the relationship between $\Delta SINR$ (percentage of $SINR_{t_0}$) and Δt are shown in Figure 3.2 and Figure 3.3. The parameters are set as Table 3.2. The walking speed is set from 0.3 m/s to 1.5 m/s and the driving speed is from 8 m/s to 20 m/s [52].

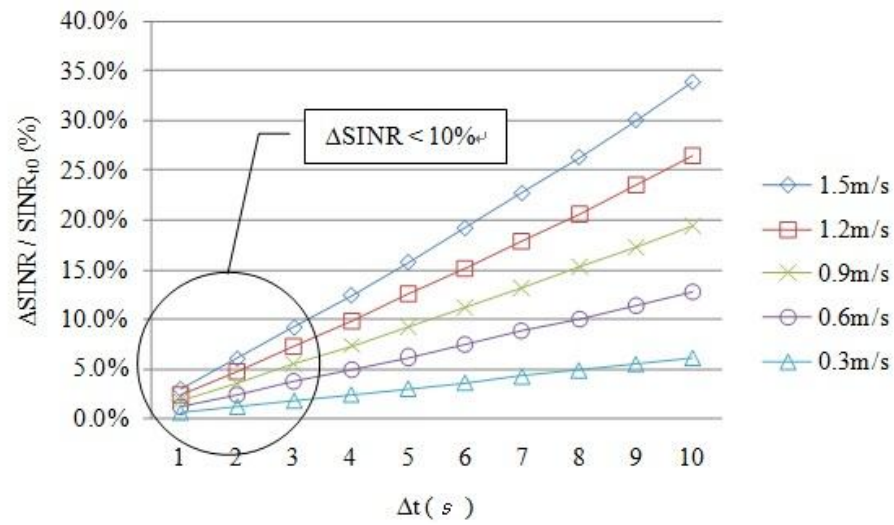
Table 3.2: Parameters of the 2-D Scenario

Parameters	D (m)	P_m^t (w)	N_0 (w)	d_0 (m)	α	Sp (m/s)
Value	500	20	1×10^{-6}	1	2.5	1.5(walking), 20(driving)

I assume that the acceptable $\Delta SINR$ is not larger than 10% of the $SINR_{t_0}$; and the resource allocation duration Δt for walking speed users is no longer than 2 s (by observe Figure 3.2). In Figure 3.3, the duration Δt for the driving speed users is not longer than 0.15 s to insure a value of $\Delta SINR$ no more than 10%. The frame length is defined as 2.5 ms to 20 ms in the WiMAX [15]. Therefore a PS shall renew its resource allocation every 75 frames to 600 frames, and a MS shall be renewed its resource allocation by every 5 frames to 40 frames. In a wireless system,

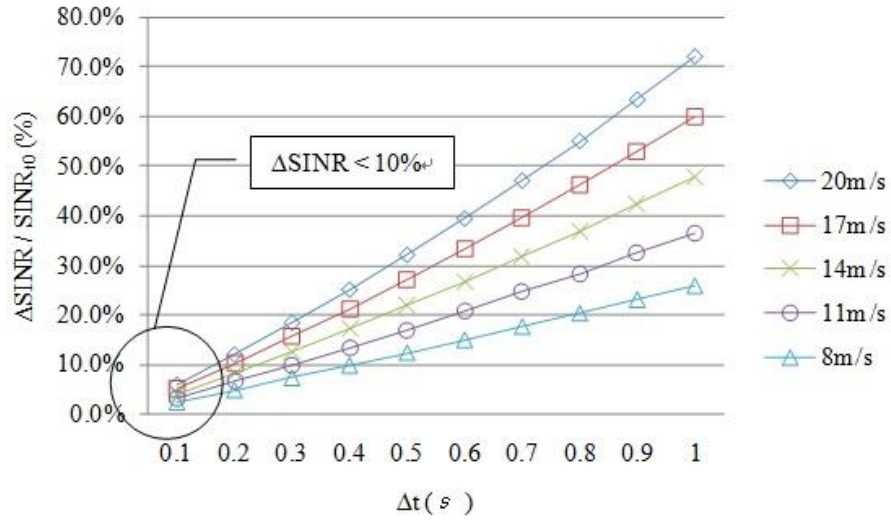


(a) $d_{t_0} = 100\text{m}$

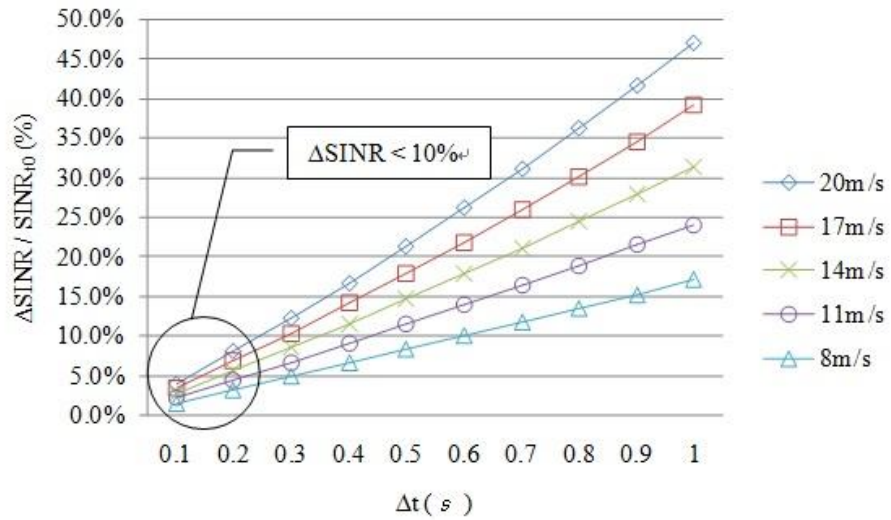


(b) $d_{t_0} = 200\text{m}$

Figure 3.2: Relationship between ΔSINR and Δt (Walking Speed)



(a) $d_{t_0} = 100$ m



(b) $d_{t_0} = 200$ m

Figure 3.3: Relationship between $\Delta SINR$ and Δt (Driving Speed)

the propagation delay and transmission delay are normally less than 1 ms [53], so I ignore these delays.

3.3 RRM Schemes

In this section, I introduce the three CT aware RRM schemes for the OFDM-TDMA based CoMPNet. The RRM schemes define that BS(s) should be associated with a specific user; and they determine the percentages of system resources (e.g., time slot in this case) that should be allocated to a specific user from the associated BS(s) within a CoMPNet.

The RRM procedure in the CoMPNet is shown in Figure 3.4. Once initiated, the CT_LP scheme would be adopted and solved by a LP solver, in which the time slot of the BSs are allocated to the SSs, so that the remainder of the time slot are available for moving users (PSs and MSs). If there are any changes in SSs, such as installation of a new subscriber, leaving of an existing subscriber or changing of a user's data rate, the optimal scheme will re-assign BSs and resources to all fixed stations, followed by updating the remainder of the resources. I assume that all real-time network states, such as time slot usage of each BS, wireless channel status information, data rate requirements of each user, moving types of users, user position are stored and dynamically updated at the CO. Firstly, the CO obtains the receive signal power of each user from each BS based on specific position. Subsequently, the resources and associated BS(s) for moving users are processed by the second RRM scheme or the third one according to their moving types, although the user's requirements will be rejected due to insufficient resources. If the user moves out of the CoMPNet zone, the originally allocated resources will be released and re-allocated.

My schemes are based on the following assumptions. First of all, I assume that all the users' positions, moving speeds, and moving types in the network are acquired and live updated at the CO. Secondly, I assume that all the user connection requirements have the same priority. Thirdly,

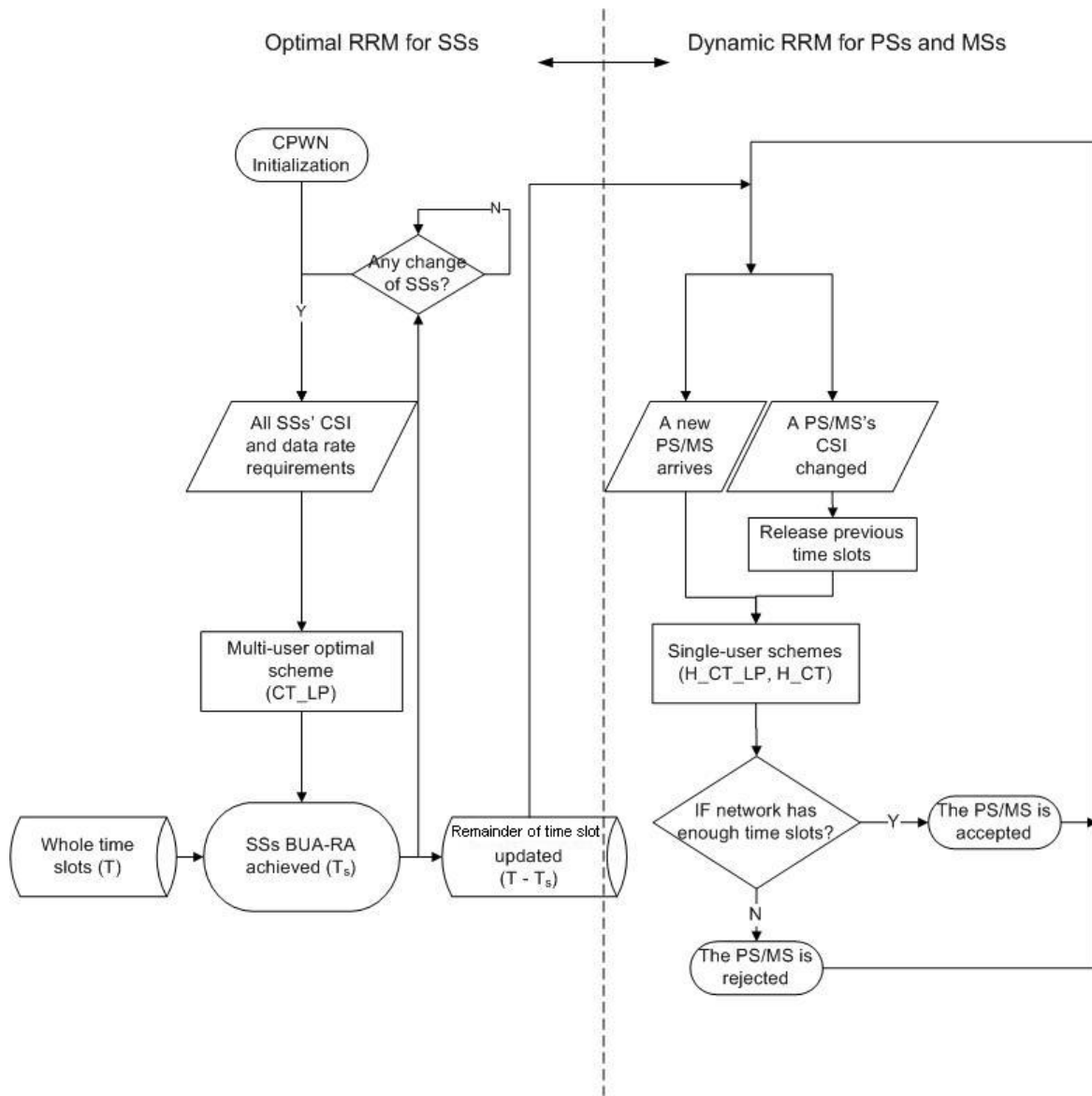


Figure 3.4: Flowchart of RRM

the system renews the connection and considers it as new connection try if the user moves.

Based on the assumptions of RRM schemes and the system model described in Section 3.2, I present my CT aware RRM schemes in the following sub-sections. Meanwhile, notations are adopted in the problem formulations which are introduced as follows. The decision variable Tp_{mn} denotes the time slot allocated to user n from BS m , and Tp_{mn} is normalized to the percentage of total time slot of a BS, therefore if Tp_{mn} is larger than 0, it means that BS m is associated with user n ; otherwise it does not associate with the user. Please see Table 3.1 for all notations.

3.3.1 Multi-user LP Scheme (CT LP)

In the optimal scheme, the RRM problem is formulated as a multi-user optimization model to minimize the total time slot consumption of the BSs in a CoMPNet, where the CT technology is employed. Figuratively, the objective can be presented by the following formulation:

$$\text{minimize } \sum_{m=1}^M \sum_{n=1}^N Tp_{mn}A_{mn} \quad (3.11)$$

which is subject to the following constraints:

1) Total time slot constraint

$$\sum_{n=1}^N Tp_{mn}A_{mn} \leq 1, \forall m = 1 \dots M \quad (3.12)$$

2) Data rate requirement of each user

$$R_n = B \times T p_{mn} \times \log \left(1 + \frac{\sum_{m=1}^M A_{mn} P_{mn}^r}{N_0 + \sum_{m=1}^M (1 - A_{mn}) P_{mn}^r} \right) \geq R_n^{\text{Req}} \quad (3.13)$$

$$\forall n = 1 \dots N$$

Since constraints (3.12) and (3.13) are non-linear, I adopt the following approach for linearization. As a user can be associated with one or more BSs because of CT technology, the number of associated BS(s) of a user, varies from 1 to M . Here I define $J(= 2^M - 1)$ as the first *associating mode* which indicates the number of BSs to be potentially chosen to associate a user in the CoMPNet. Please refer to the following table for j th association mode with binary number.

Table 3.3: Bit (b_{jm}) Map of Association Mode

j	b_{jM}	\dots	b_{jm}	\dots	b_{j2}	b_{j1}
1	0	\dots	0	\dots	0	1
2	0	\dots	0	\dots	1	0
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
J	1	\dots	1	1	1	1

The m th bit (b_{jm}) of the integer number j indicates whether BS m is associated with a user or not, in the j th association mode.

$$b_{jm} = \begin{cases} 1 & m\text{th BS associates a user in } j\text{th association mode} \\ 0 & \text{otherwise} \end{cases} \quad (3.14)$$

Then, I conclude:

$$LOG_SINR_{jn} = \log \left(1 + \frac{\sum_{m=1}^M b_{jm} P_{mn}^r}{N_0 + \sum_{m=1}^M (1 - b_{jm}) P_{mn}^r} \right) \quad (3.15)$$

The LP model of this RRM scheme (CT_LP) can be expressed as follows:

Scheme 1 CT aware RRM: Multi-user LP Scheme (CT_LP)

Objective:

$$\text{minimize } \sum_{m=1}^M \sum_{n=1}^N \sum_{j=1}^J (b_{jm} \times T p_{jn}) \quad (3.16)$$

Constraints:

1) Total time slot constraint of each BS

$$\sum_{n=1}^N \sum_{j=0}^J (b_{jn} \times T p_{jn}) \leq 1, \forall m = 1 \dots M \quad (3.17)$$

2) Data rate requirement of each user

$$R_n = \sum_{j=0}^J (T p_{jn} \times (B \times \text{LOG_SINR}_{jn})) \geq R_n^{\text{Req}} \quad (3.18)$$

$$\forall n = 1 \dots N$$

3) A user can only use one associating mode

$$\sum_{j=0}^J x_{jn} = 1 \quad (3.19)$$

$$x_{jn} - T p_{jn} \geq 0, \forall j = 0 \dots J, \forall n = 1 \dots N \quad (3.20)$$

4) Variables

$$T p_{jn} \in [0, 1] \quad (3.21)$$

$$x_{jn} \in \{0, 1\} \quad (3.22)$$

$$x_{jn} = \begin{cases} 1 & \text{jth association mode is used for user } n \\ 0 & \text{otherwise} \end{cases} \quad (3.23)$$

Constraint (3.17) ensures that the total allocated time slot to each user are no more than the total time slot of one BS. Constraint (3.18) makes sure that the data rate requirement of each user shall be satisfied. Constraints (3.19) and (3.20) stipulate that one user can only access one

associating mode. Equations (3.21) and (3.22) state the boundaries of the decision variables.

Practically, the SSs mainly refer to the residential and business user groups which have certain rate requirements when subscribed. The optimal RRM for each SS can be acquired offline by solving the above LP model. However, the acquisition of RRM for mobile users are required to operate online, therefore a quick response to the instantaneous connection requests of mobile users require fast RRM schemes.

In the following two sub-sections, I present two schemes for PS and MS respectively. These two schemes assign BSs and resources to individual new users based on specific requirements and current network status. I set $TS_m (= 1)$ to be the normalized total time slot of BS m , and F_m to be the free time slot of BS m . W_m is the total reserved working time slot of BS m ($TS_m = W_m + F_m$).

3.3.2 Single-user LP Scheme (H_CT_LP)

In the second RRM scheme, I use a similar LP model and the same notations as the above optimal scheme to minimize the time slot usage to satisfy the data rate requirement of a new user. The single user LP model can be expressed as follows:

Scheme 2 CT aware RRM: Sub-Optimal Scheme (H_CT_LP)

Objective:

$$\text{minimize } \sum_{m=1}^M \sum_{j=1}^J (b_{jm} \times T p_{jn}) \quad (3.24)$$

Constraints:

1) All the associating BS(s) should have enough free time slot

$$\sum_{j=1}^J (b_{jm} \times T p_{jn}) \leq F_m \quad (3.25)$$

2) Data rate requirement of the new user

$$R_n = \sum_{j=0}^J (T p_{jn} \times (B \times \text{LOG_SINR}_{jn})) \geq R_n^{\text{Req}} \quad (3.26)$$

3) The new user can only use one association mode

$$\sum_{j=1}^J x_{jn} = 1 \quad (3.27)$$

$$x_{jn} - T p_{jn} \geq 0 \quad (3.28)$$

4) Variables

$$T p_{jn} \in [0, 1] \quad (3.29)$$

$$x_{jn} \in \{0, 1\} \quad (3.30)$$

If the LP has no solution, the user's requirement will be rejected.

3.3.3 Heuristic Scheme (H_CT)

Heuristic scheme (H_CT) is designed for MS; the effect of the scheme is to associate a new user via the following five steps:

Scheme 3 CT aware RRM: Heuristic Scheme (H_CT)

Step 1: Find the closest BS m to user n , denote the minimum distance as $d_{min} = d_m$; initialize the associated BS group of user n , $\mathbb{G} = \{m\}$.

Step 2: Find the next closest BS l whose distance to user n is d_l .

Step 3: Update \mathbb{G}

- 1: **if** $d_l - d_{min} < \Delta d_{ct}$ **then**
- 2: $\mathbb{G} = \mathbb{G} \cup l$;
- 3: GOTO *Step 2*;
- 4: **else**
- 5: GOTO *Step 4*;
- 6: **end if**

Step 4: Calculate the amount of time slot (Tp_n) to be allocated to user n by following formulas.

$$Tp_n = \frac{R_n}{B \times SINR_{CT_n}} \quad (3.31)$$

$$SINR_{CT_n} = \log \left(1 + \frac{\sum_{m=1}^M A_{mn} P_{mn}^r}{N_0 + \sum_{m=1}^M (1 - A_{mn}) P_{mn}^r} \right) \quad (3.32)$$

Step 5: Check if user n can be accepted or not.

- 1: **if** all the BS(s) in \mathbb{G} have enough time slot **then**
- 2: user n is associated with the BS(s) in \mathbb{G} ;
- 3: update time slot usage info of all associated BS(s) at CO by Equation (3.33) and Equation (3.34)
- 4:

$$TS_m = W_m + Tp_n \quad (3.33)$$

$$F_m = F_m - Tp_n \quad (3.34)$$

- 5: **else**
 - 6: user n will be rejected
 - 7: **end if**
-

d_m is the distance from the BS m to the new user n . Δd_{ct} is the maximum acceptable difference between the distance of the cooperative BSs to the user and the d_{min} , if the distance difference is greater than Δd_{ct} , the BS will not be selected for cooperative association. Figure 3.5 labels the users (geographical distribution marked with small points) who have two or more associating BSs (marked with big points). This figure is acquired by simulation of the CT_LP scheme. It can be found from the figure that the users with CT are always distributed in the middle area of two or three BSs, so I can conclude that a user may use CT when it locates at the edge area of the cells. Meanwhile, I use Δd_{ct} to control the scope of this area. By observing the FU-1 scheme simulation results such as Figure 3.5, I can estimate the suitable value of the Δd_{ct} .

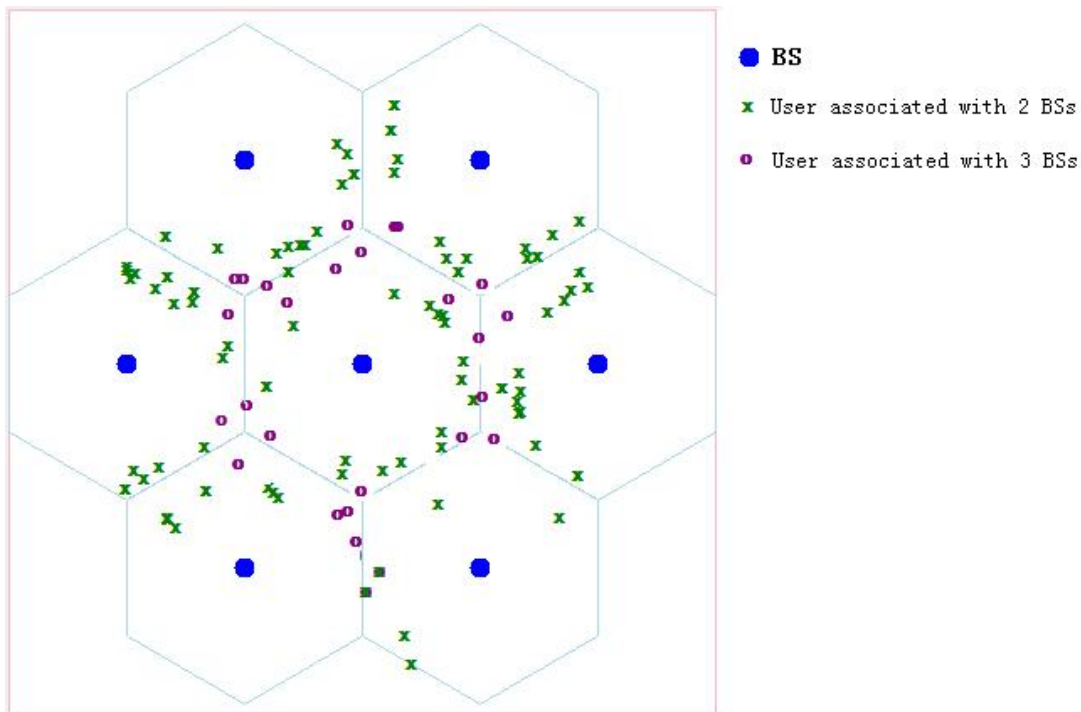


Figure 3.5: Users with Two or More Associating BSs

3.4 Simulation Results

3.4.1 Simulation Environment

In this section, the proposed RRM schemes are evaluated by comparing with conventional resource allocation schemes without adopting CT technology. Specifically, three non-CT RRM schemes (NCT_LP, H_NCT_LP, and H_NCT) correspond to the proposed schemes used as the benchmarks. The simulation program is coded in C# based on the principles stated in [54], and the LP models are solved by the CPLEX version 11.0 [55]. All the simulations were conducted on a computer with Intel Pentium D-805 CPU and 1 GB memory.

The program simulates a CoMPNet network, which includes a number of BSs and users, each BS has the following characteristics: positions, time slot (continually), and transmission power. The parameters of each user are positions (randomly assigned) and data rate requirements. The simulation process is described as follows:

- 1) The program generates a CoMPNet with M BSs. Figure 3.6 illustrates the simulated CoMPNet which is similar to conventional cellular networks [48]. In the network, seven BSs ($M = 7$), represented as the big points in Figure 3.6, are located in a 1500×1500 m² area. The setting of network parameters is shown in Table 3.4.

- 2) In the above CoMPNet, I examined 63 scenarios, where different numbers of mobile users are randomly placed in the area of interest (AOI) in each scenario, and all users have the same data rate requirements and same moving types. Three moving types are tested individually under the same users' topology. Table 3.5 shows the data rates of a user for all 63 scenarios, in which the minimum data rate is about 50 kbps which matches the modem speed, and the maximum rate is 20 Mbps which is more than 2 times of the rate of ADSL.

- 3) Apart from evaluating the data rates of all users, the program calculates the received signal and SINR of each user by the Equations (3.8) and (3.2).

4) The program employs one of the RRM schemes to assign BSs and allocate the time slot to all users according to their moving types.

After running a RRM scheme in each scenario, the expected outputs are the total time slot usage (in percentage), total unassociated users (in percentage), and the computation time for each user. Based on these outputs and the assumption that all users have same moving type in one simulation scenario, I will be able to compare the simulation results about time slot usage performance, resulting network capacity (the total data rate of associated users in the network), and the computation complexity of these schemes among all the RRM schemes.

To generalize the randomness result from the user mobility, each data in the simulation is the average result of values obtained from operating the RRM scheme on 50 different user distributions in each scenario. I present the criteria in two dimensions, 1) the results are shown as a function of the total data rate requirements under the premise of same number users; 2) the results are shown as a function of the number of users under the same total data rate requirement. A criterion for the multi-user LP scheme is also introduced in the following sub-section before the three performance results.

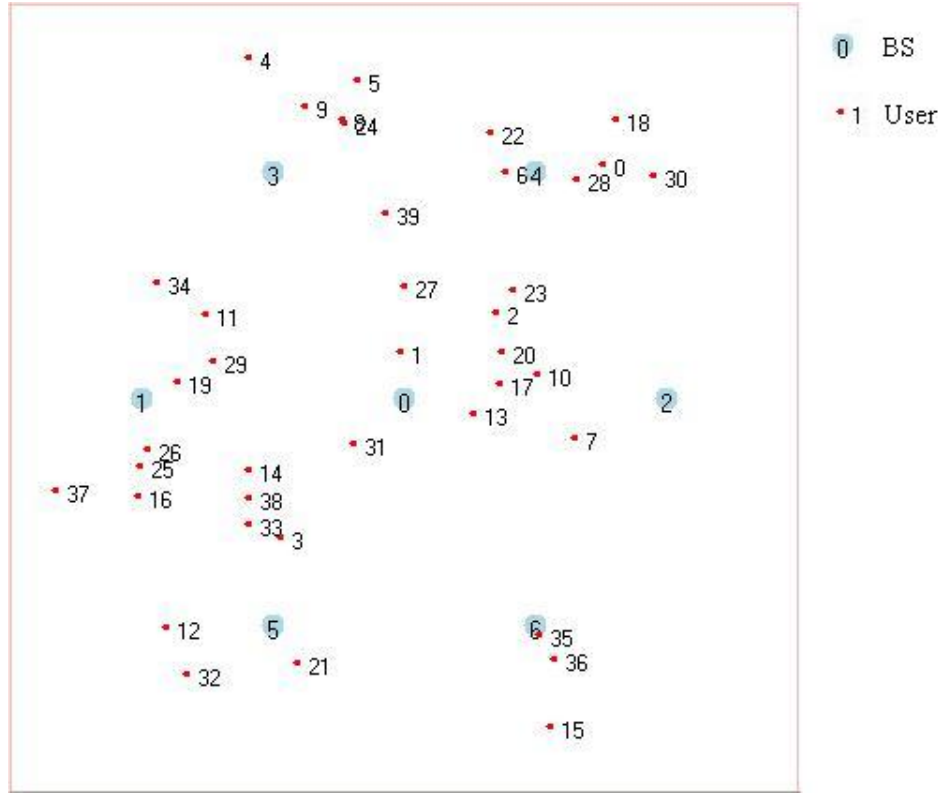


Figure 3.6: Snapshot on the Mobile User Distribution in the AOI; the 7 BSs are Fixed.

Table 3.4: Simulation Parameters Setting

Parameters	B	P_m (W)	N_0 (W)	d_0 (m)	α	Δd_{ct} (m)
Value	20	20	1×10^{-6}	1	2.5	100

The thermal noise power (N_0) is assumed equivalent at any point in the network.

3.4.2 LP Failure Ratio

The multi-user LP schemes are aimed at accepting all SSs in the network and satisfying their data rate requirements. However, the schemes can fail to operate if the LP model cannot be solved, which means that the users' requirements cannot be fully satisfied and thereby cannot be accepted in the network. Obviously, if the total data rate requirement is higher than the network

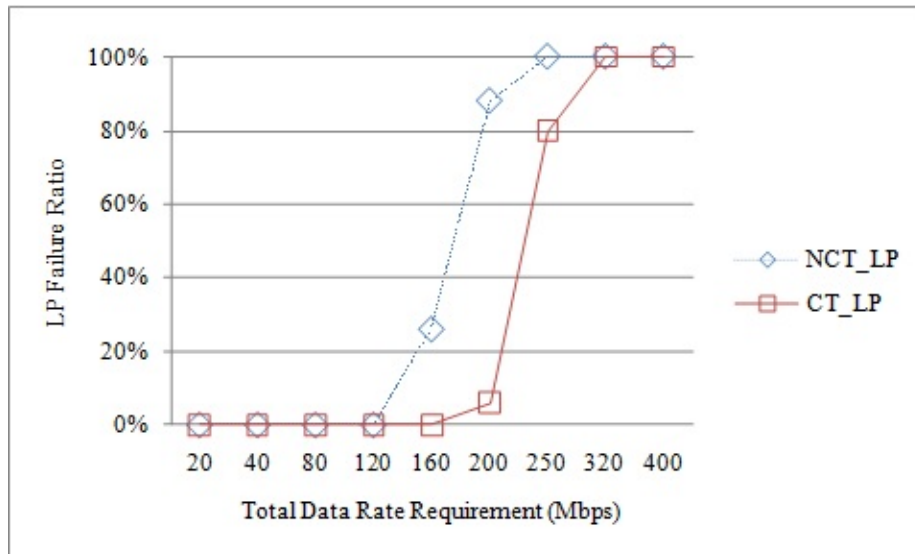
Table 3.5: Simulation Scenario Setting

<i>Number of users</i>	<i>Total Data Rate Requirement (Mbps)</i>								
	20	40	80	120	160	200	250	320	400
20	1	2	4	6	8	10	12.5	16	20
40	0.5	1	2	3	4	5	6.25	8	10
80	0.25	0.5	1	1.5	2	2.5	3.125	4	5
100	0.2	0.4	0.8	1.2	1.6	2	2.5	3.2	4
160	0.125	0.25	0.5	0.75	1	1.25	1.5625	2	2.5
250	0.08	0.16	0.32	0.48	0.64	0.8	1	1.28	1.6
400	0.05	0.1	0.2	0.3	0.4	0.5	0.625	0.8	1

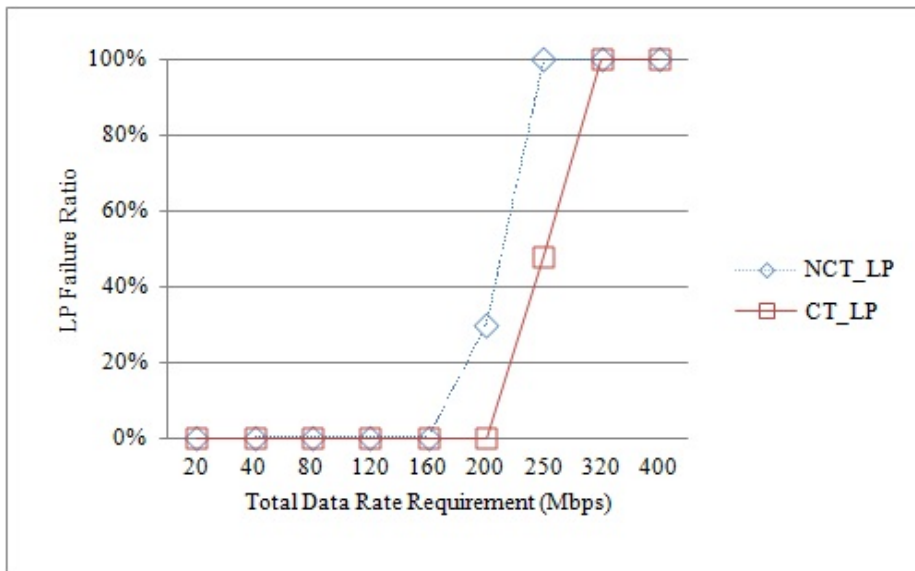
capacity, the LP model will fail to find a solution. In the following, I provide the simulation results by comparing the multi-user LP scheme (CT_LP) with the NCT scheme (NCT_LP).

1) Under same number of users and different total data rates

Figure 3.7 shows that the LP failure ratio of the NCT_LP scheme is higher than the CT_LP scheme, when the total data rate requirement reaches 80 Mbps or higher. Since CT_LP uses cooperative transmission technology, the network capacity is increased by the volume of using cooperative transmission. All of my results describe the same situation, and here I will illustrate the issue with some of the figures, which are shown in Figure 3.7

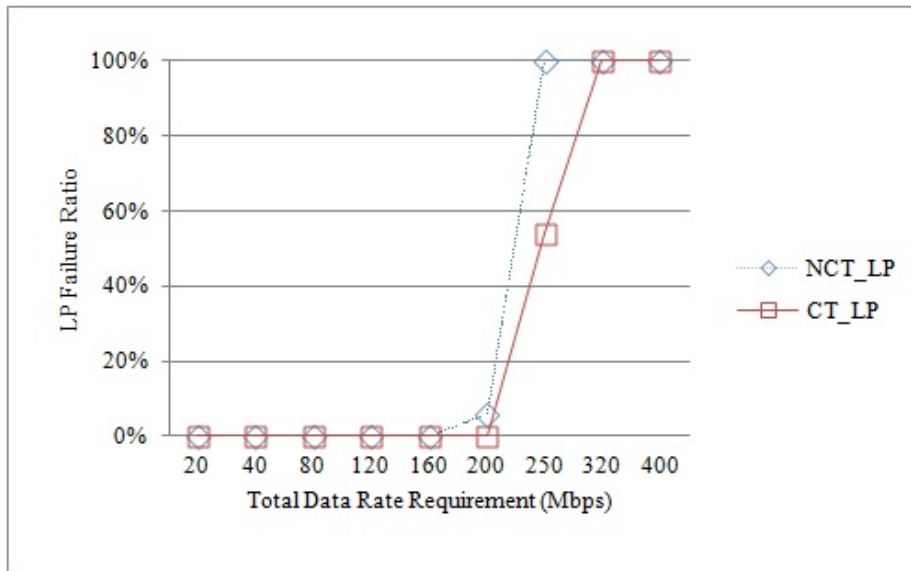


(a) 40 Users

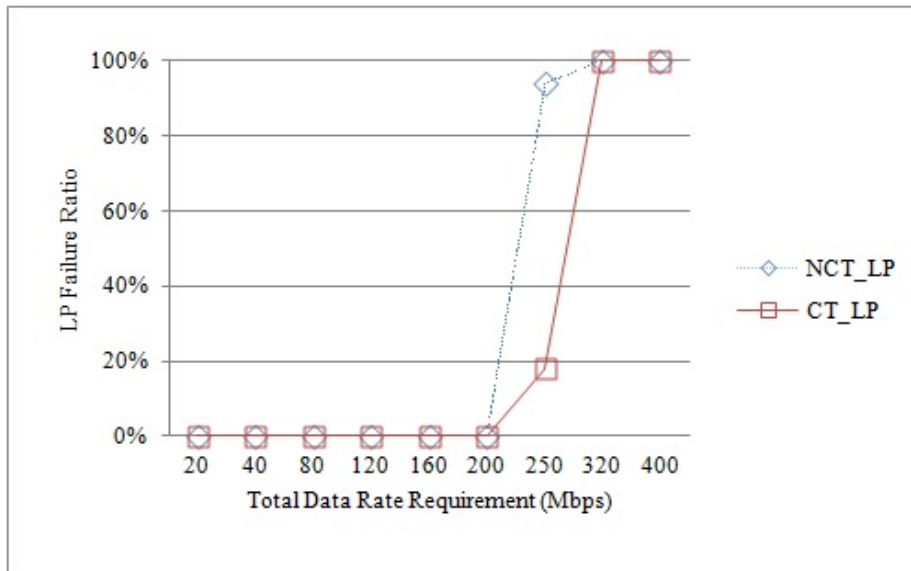


(b) 80 Users

Figure 3.7: LP Failure Ratio (1)



(c) 160 Users

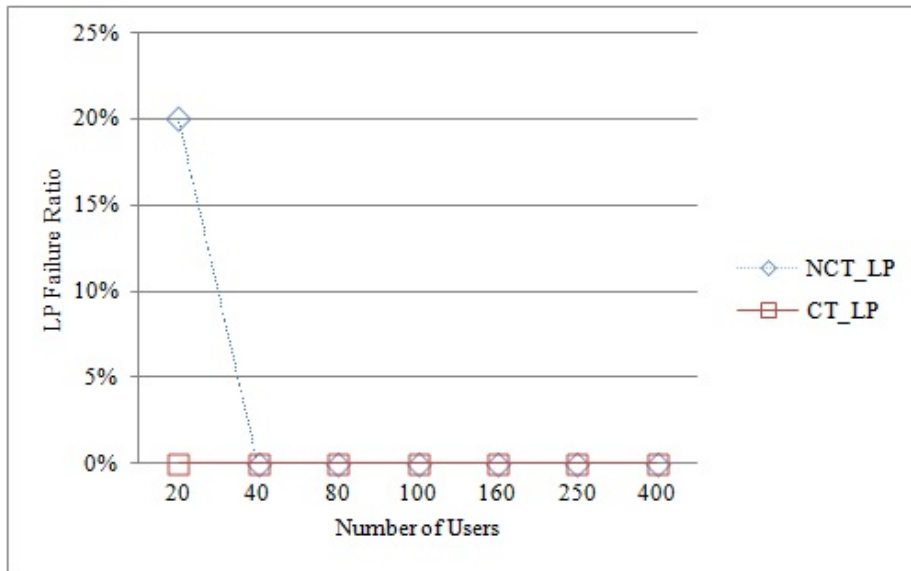


(d) 400 Users

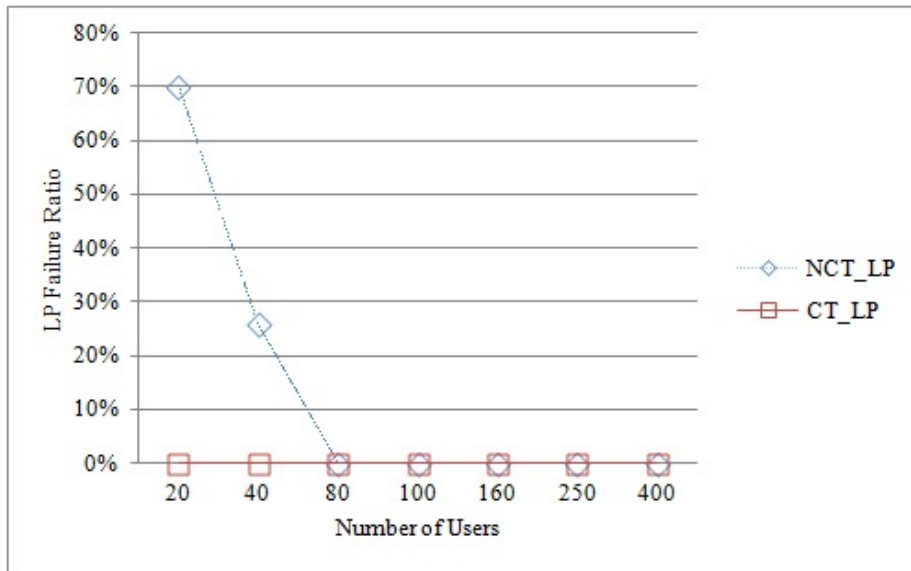
Figure 3.7: LP Failure Ratio (1) cont.

2) Under same total data rates and different number of users

From the simulation results, it can be concluded that both CT and NCT LP models can be solved when the total data rate requirement is less than 120 Mbps, and when the total data rate requirement reaches higher than 250 Mbps, neither CT nor NCT LP model can be solved. From Figure 3.8, I can see that when there are more users in the network when the total data rate requirements are the same, and there is a lower LP failure ratio. Overall, I can summarize that when the number of users in the network increases, the resources of the network can be more efficiently used and the network capacity increases. Further, it is observed that the CT_LP scheme outperforms NCT_LP in terms of network capacity.

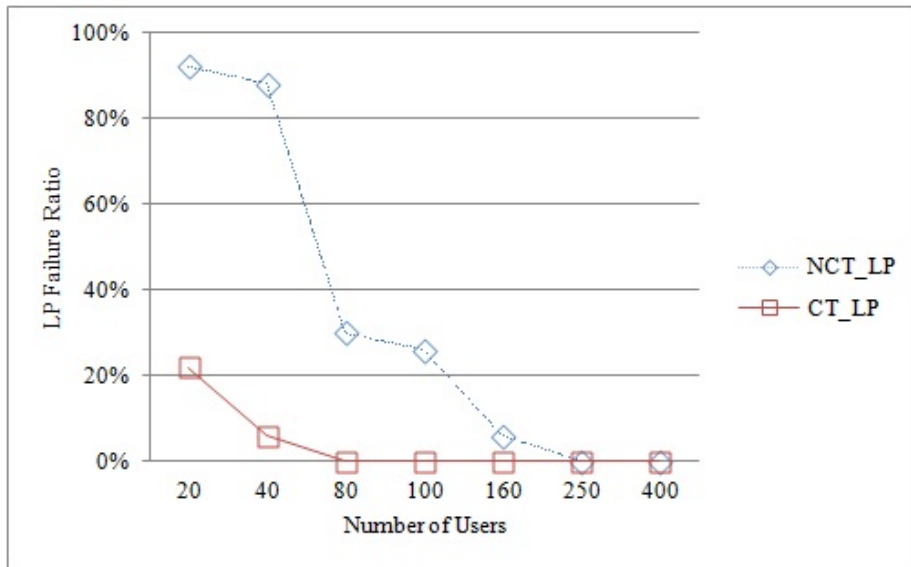


(a) 120 Mbps

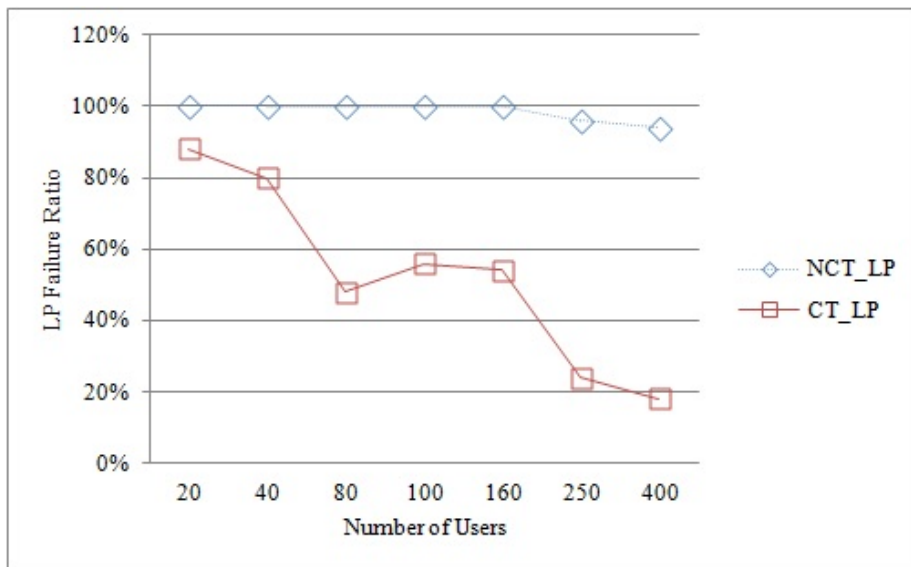


(b) 160 Mbps

Figure 3.8: LP Failure Ratio (2)



(c) 200 Mbps



(d) 250 Mbps

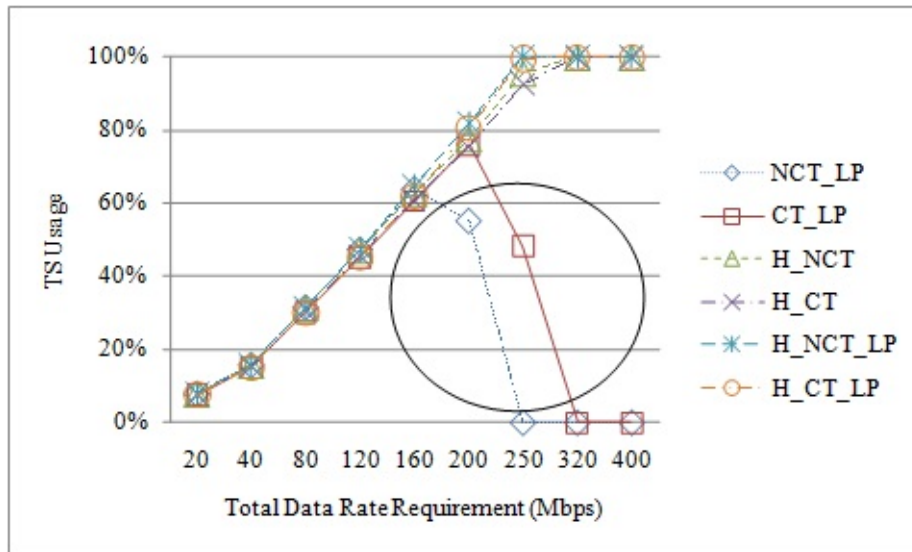
Figure 3.8: LP Failure Ratio (2) cont.

3.4.3 Total Time Slot Usage

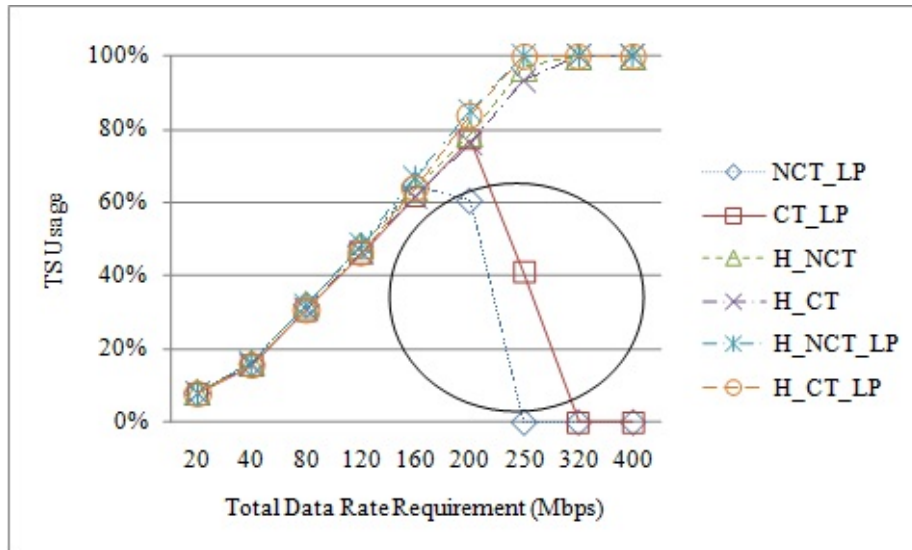
I take the summation of time slot (normalized to percentage) allocated to each user as the parameter for estimating the required amount of system resources to satisfy the given traffic load demand. Generally, a specific RRM scheme achieves better performance if less total time slot is consumed in a wireless network to satisfy a given pattern of traffic load demand.

1) Under same number of users and different total data rates

From Figure 3.9, I can merely conclude that time slot usage increases directly proportional with total data rate requirement, however, it is difficult to determine which of the six methods has the best time slot usage performance (which is elaborated in the next sub-section). It can be observed from the figure that the graphs of CT_LP and NCT_LP (in circles) are going down to zero, which means these two LP schemes cannot determine a solution when the total data rate requirement is higher than network capacity.



(a) 80 Users

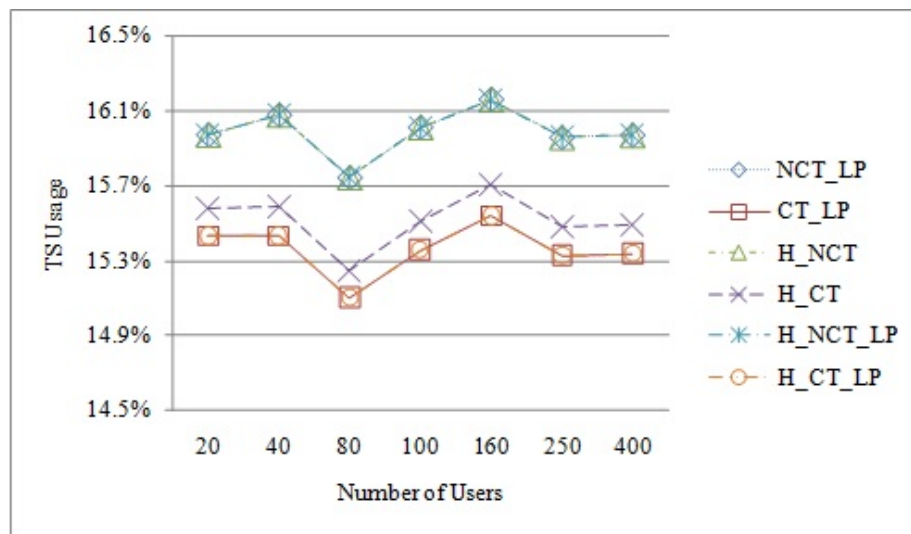


(b) 160 Users

Figure 3.9: Total Time Slot Usage (1)

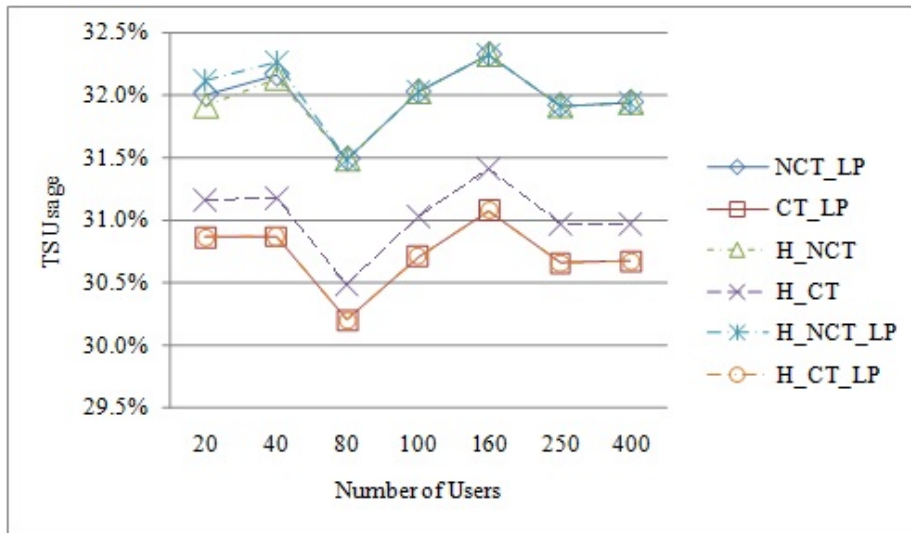
2) Under same total data rates and different number of users

Figure 3.10 shows that the CT_LP and H_CT LP schemes outperform H_CT in terms of time slot usage performance under the premise of low and mid network load (total data rate requirement < 160 Mbps). Although H_CT costs a slight larger amount of time slot (about 1%) than these two schemes; more resources (about 8%) can be saved than the other three NCT schemes. In Figure 3.10, the results difference between different numbers of users results from the stochastic situation where different scenarios were tested. The difference is not larger/less than $\pm 1\%$.

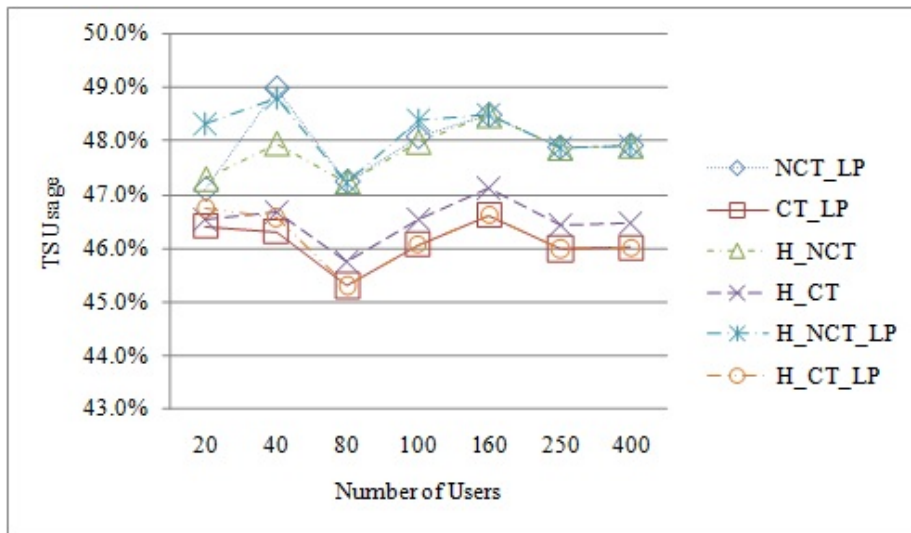


(a) 40 Mbps

Figure 3.10: Total Time Slot Usage (2)



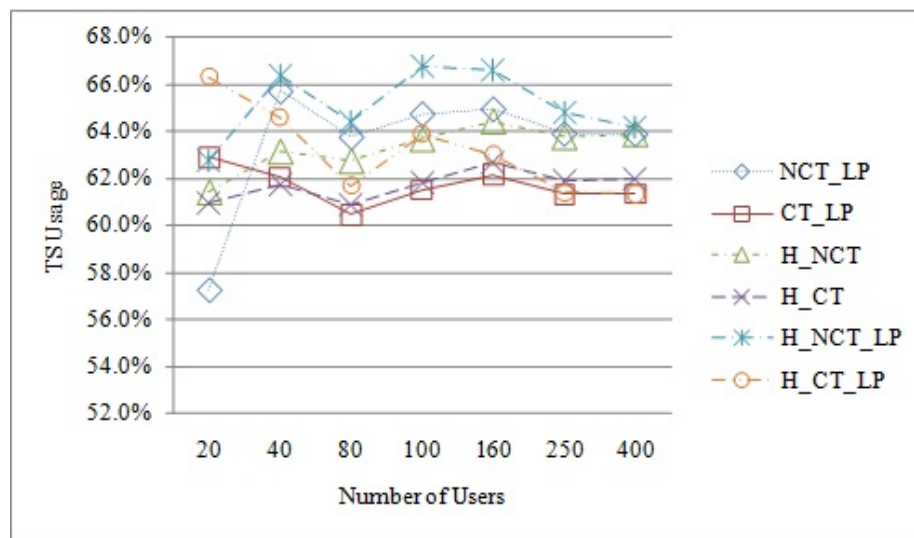
(b) 80 Mbps



(c) 120 Mbps

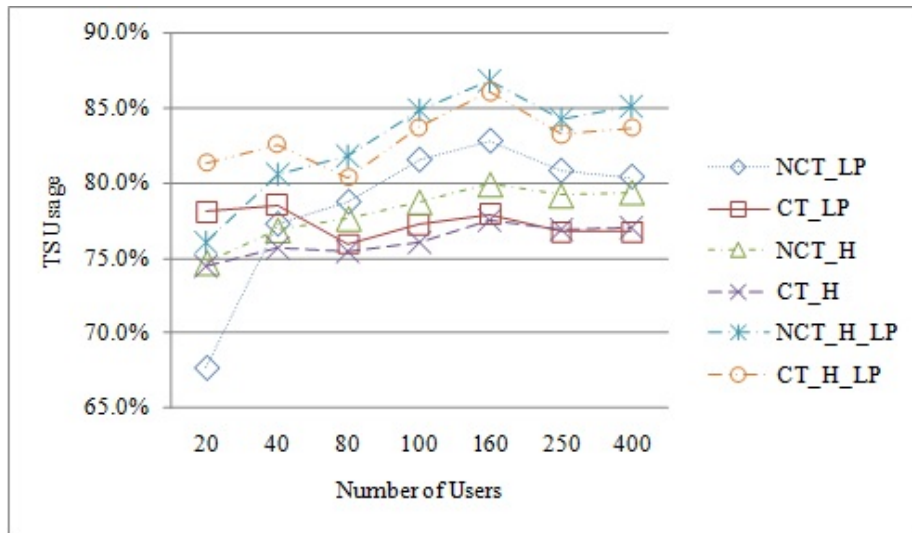
Figure 3.10: Total Time Slot Usage (2) cont.

Figure 3.11 shows that the performance of H_CT_LP becomes worse when network load becomes high (total data rate requirement 160 Mbps), which is owing to the large amount of resources (time slot) losing from the persistent requirement of attempting to satisfy the user's data rate of the H_CT_LP scheme, despite the poor channel status of a new user occasionally. However, the H_CT scheme performs more flexibly under this circumstance; it can reject any new user whose channel status is not good since it costs a large amount of resources to accept such a user. Therefore resources can be saved to accept future users with good channel condition. Generally, in a high network load, the H_CT scheme can save 5% to 10% of the time slot than other schemes. In Figure 3.11 (c), the curves of NCT_LP and CT_LP have been omitted, because the LP cannot be solved, therefore no result for these two schemes can be presented.

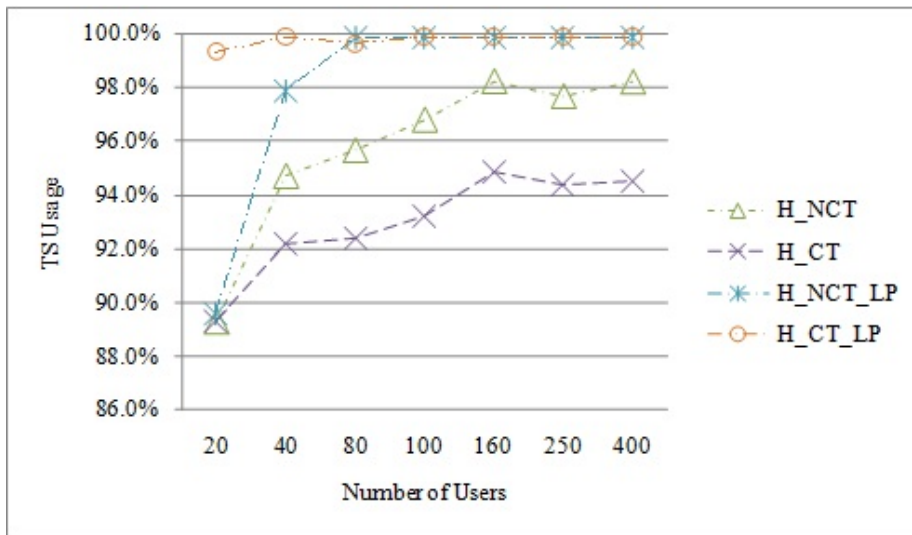


(a) 160 Mbps

Figure 3.11: Total Time Slot Usage (3)



(b) 200 Mbps



(c) 250 Mbps

Figure 3.11: Total Time Slot Usage (3) cont.

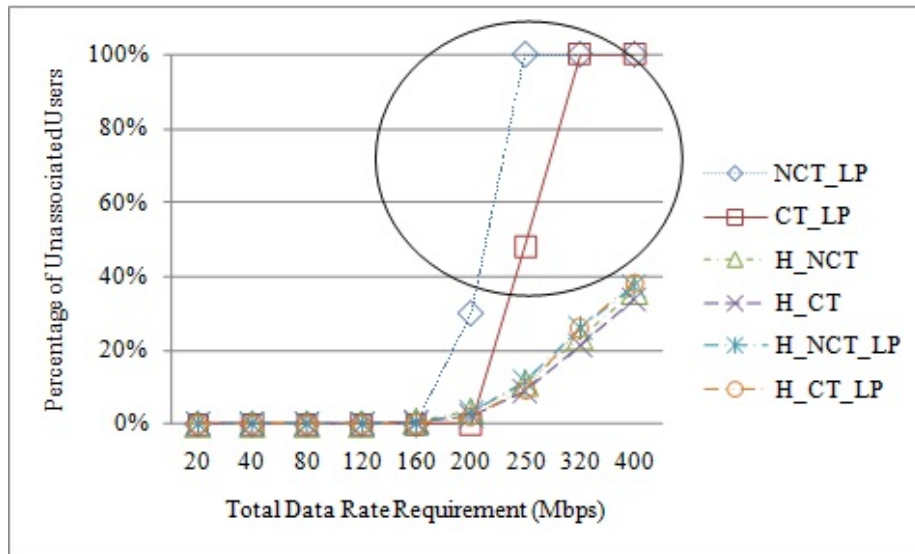
When the total data requirement reaches higher than 300 Mbps, the network is overloaded and the time slot usage reaches 100%.

3.4.4 Percentage of Unassociated Users

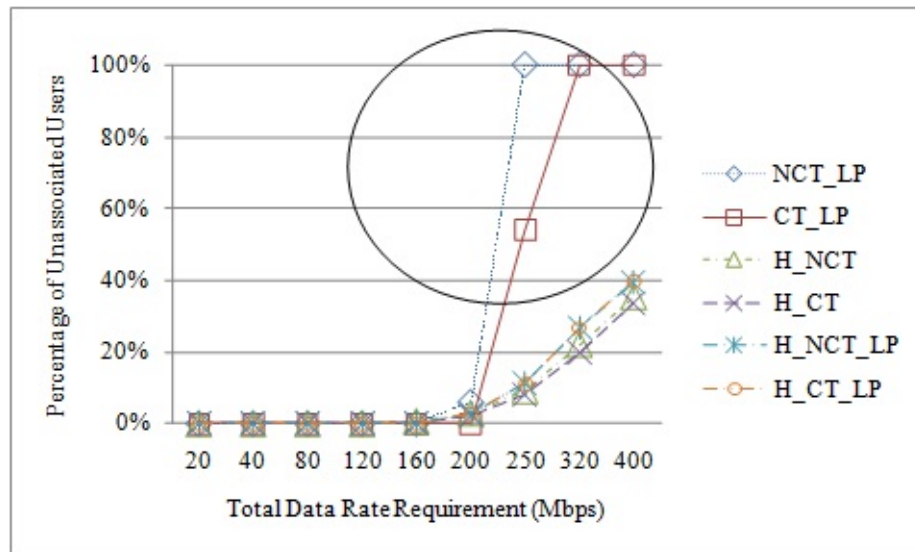
Network capacity of an efficient RRM scheme should be able to accept as many users as possible; in other words, the network capacity (i.e., total accepted data rate) is higher. In this study, I use the total number of unassociated users (normalized to percentage) as the criteria to measure network capacity efficiency.

1) Under same number of users and different total data rates

In multi-user LP scheme, the LP problem will not be solved as long as the users are not accepted by the network, the issue is presented in the first sub-section (Section 3.4.2), and from Figure 3.12 I can see that the graphs of CT_LP and NCT_LP in the circles are going up to 100%. On the other hand, under the circumstances of the heuristic scheme, the user will be rejected by the network when the requirement cannot be satisfied, then the user will be recorded as unassociated by my simulation program. Figure 3.12 shows that the percentages of unassociated user grow directly proportional with the total data rate requirement. By comparing the performances of the six schemes, I can conclude that no unassociated user existed with any scheme at low network load (total data requirement 80Mbps), however, at mid load (120 Mbps to 160 Mbps), CT_LP is accessible to all users, while other schemes continuing reject some users; in the circumstance of high load (total data rate requirement of 200 Mbps to 250 Mbps), the CT_LP scheme is dysfunctional while H_CT_LP is the best, specifically, the H_CT scheme operates not as good as LP yet better than the NCT schemes; finally, when the network is overload (total data rate requirement > 250 Mbps), H_CT outperforms all other schemes in terms of unassociated users performance, and H_CT_LP is worse. Overall, the result matches what has been observed in the previous sub-section (Section 3.4.2), and it can be concluded that the CT schemes perform better than the NCT ones.



(a) 80 Users

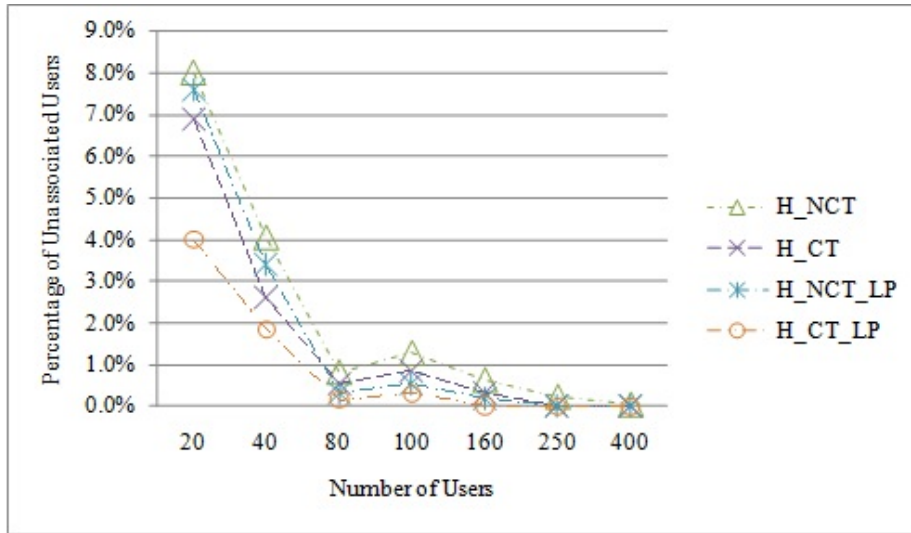


(b) 160 Users

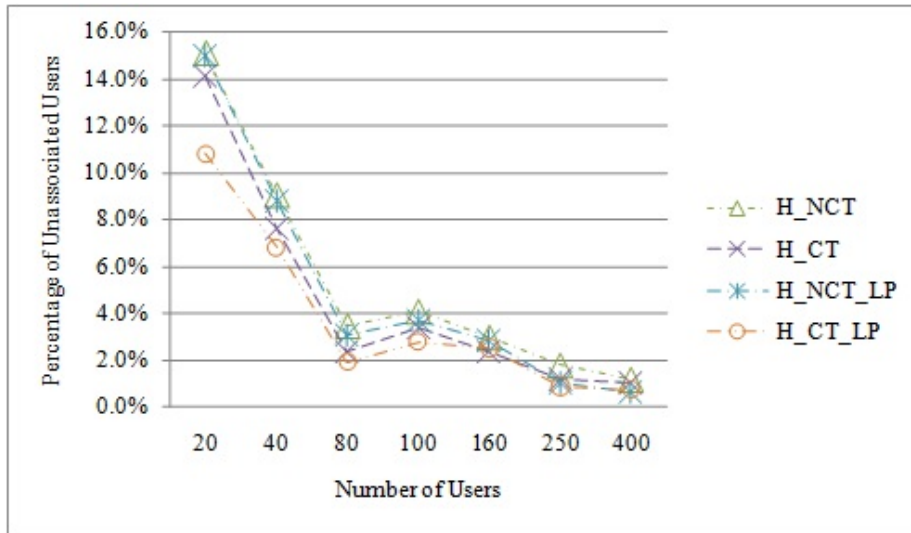
Figure 3.12: Percentage of Unassociated Users (1)

2) Under same total data rates and different number of users

The number of unassociated users is zero under the circumstance of a low network load (total data rate requirement ≤ 80 Mbps), therefore no figures on this issue can be presented here. By observing Figure 3.13 (a) and (b), I obtain the same conclusions as it has been described in the previous sub-section (Section 3.4.4-2)). On the other hand, characteristics that have been described in sub-section (Section 3.4.3-2)) can also be found in Figure 3.13 (c) and (d); that is, the percentage of unassociated users decreases when the number of users increases. In Figure 3.13 (c) and (d), I have omitted the curves of NCT_LP and CT_LP because the LP is unable to be solved.

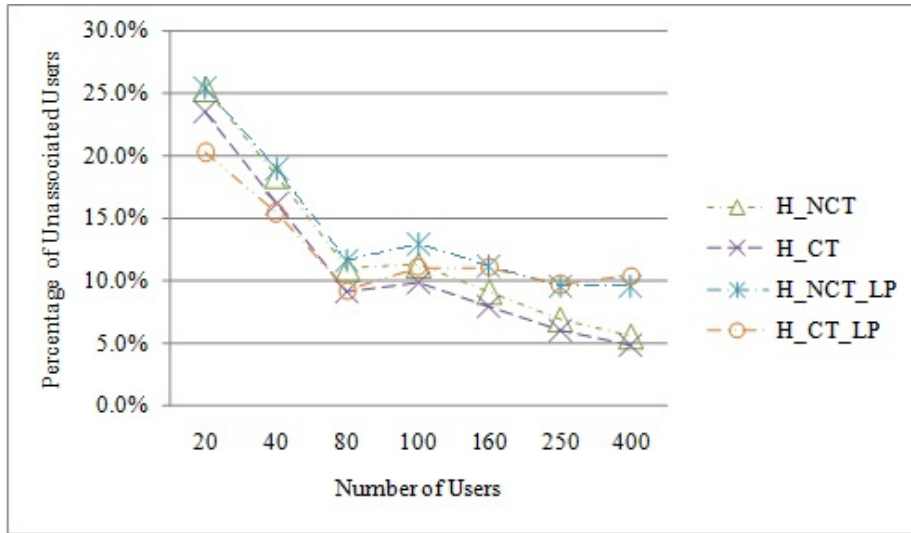


(a) 160 Mbps

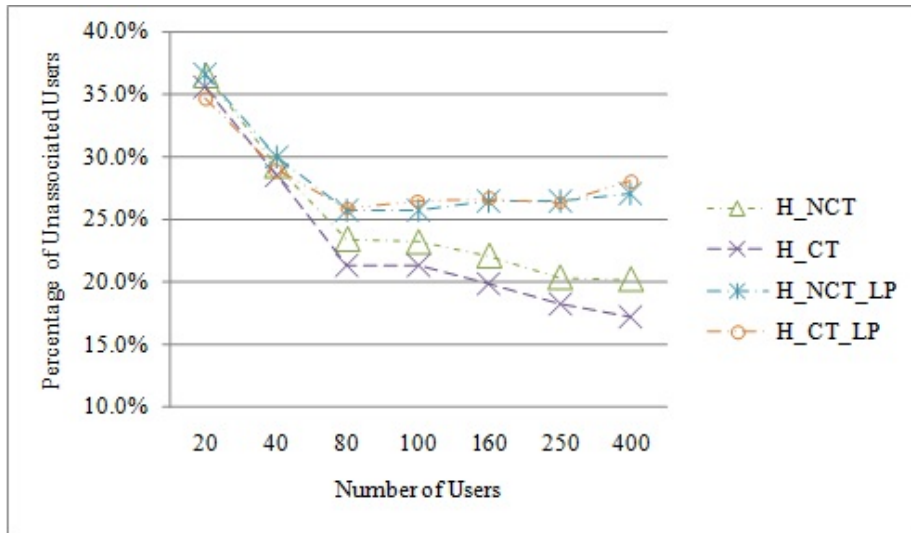


(b) 200 Mbps

Figure 3.13: Percentage of Unassociated Users (2)



(c) 250 Mbps



(d) 320 Mbps

Figure 3.13: Percentage of Unassociated Users (2) cont.

3.4.5 Computation Time

Since all results of computation time under a different number of users and total data rate requirements presented are similar, here I only provide the result of 100 users and 160 Mbps results as it has been shown in Table 3.6 and 3.7.

From the following tables I can see that the CT LP scheme takes the longest time to obtain a solution, especially when the network is close to a full load, however the single-user LP scheme (H_CT_LP) costs much less time than the optimal one, and the 1.33 s computation time is good enough for the H_CT_LP scheme for slow-moving users. And it is noted that H_CT scheme works so efficiently that it only costs around 10 ms to calculate the associated BS and time slot for a fast-moving user.

Table 3.6: Computation Time (s) (100 Users)

<i>RRM schemes</i>	<i>Total Data Rate Requirement (Mbps)</i>					
	20	80	160	200	250	320
CT_LP	9.90	10.10	49.18	120.53	1595.78	10.051
H_CT_LP	1.33	1.33	1.33	1.34	1.35	1.31
H_CT	0.0090	0.0089	0.0092	0.0091	0.0090	0.0090

Table 3.7: Computation Time (s) (160 Mbps)

<i>RRM schemes</i>	<i>Total Data Rate Requirement (Mbps)</i>					
	20	40	80	100	160	250
CT_LP	23.54	25.23	60.63	49.18	30.55	61.84
H_CT_LP	1.31	1.33	1.34	1.33	1.33	1.33
H_CT	0.0091	0.0089	0.0095	0.0092	0.0102	0.0118

3.5 Chapter Conclusion

This chapter introduced three RRM schemes for the CoMPNet with supporting techniques such as OFDM-TDMA and inter-cell CT. I have carried out a number of case studies to demonstrate the advantages in using the proposed schemes and also compared them with the conventional non-CT based RRM schemes. The simulation results show that the network capacity and resource usage efficiency can be significantly increased, which particularly benefits to the users at the edge of cells. Based on the study, I can conclude that the multi-user LP scheme (CT_LP) can obtain the optimal resource allocation for the SSs. The H_CT_LP scheme is suitable for the SSs when the network load is not high, as it is able to obtain a better solution than the H_CT scheme in a relative short time period (less than 1.5 second), however, the H_CT scheme functions better in a high network load environment. For the MSs whose wireless channel statuses are changing frequently, the H_CT scheme is a good choice since the RRM result can be obtained within 10 ms. By comparing the results of H_CT_LP and H_CT with the optimal results of CT_LP, these two heuristic schemes are more acceptable as they work more efficiently, despite a little flaw. The effect of using the proposed schemes upon a specific application, such as file transfer, VoIP, and IPTV, is certainly better than the effect of a more dynamic and short-term scheduling schemes, which will be focused in my future research.

Chapter 4

Optimized CT Aware RRM Schemes for SSs

4.1 Introduction

In this Chapter, I propose a novel optimization framework to investigate the RRM scheme for static stations (SSs) in OFDM-FMDA mode based CoMPNet with CT technology. Wireless service providers generally consider the SSs as very important points (VIPs) which require a static data rate under normal circumstances [9]. I provide three resource allocation approaches for minimizing bandwidth usage as well as transmission power consumption, and balancing resources cost respectively, meanwhile, four linear programming (LP) models are established to achieve these approaches. I suggest that an adaptive RRM should pick one of the four LP models according to corresponding network load, so that the limited network resources can be utilized efficiently and effectively. The simulation results show the efficiency of the proposed mathematical formulas and linearization approach of my scheme. The performance advantage of CT technology on bandwidth saving is shown in the result by comparing the new RRM scheme with the conventional NCT scheme.

The remainder of this chapter is organized as follows. Section 4.2 describes the system used in the chapter. In Section 4.3, the BS assignment and resource allocation procedures are presented, as well as the three approaches for the SSs in the CO-domain. The four LP models are provided in Section 4.4, and the simulation results are presented in Section 4.5. Later, I suggest an optimized adaptive BS assignment and resource allocation scheme based on the results. Section 4.6 is the conclusion of the chapter.

4.2 System Model

Orthogonal frequency-division multiple access (OFDM-FMDA) is considered as the multiple access method in this chapter. With OFDM-FMDA, the wireless spectrum is divided into a number of closely-spaced orthogonal subcarriers. In an OFDM-FMDA based CoMPNet, the network resources including OFDM sub-carriers and the transmission power of BS(s) can be assigned simultaneously to different users, to support differentiated Quality of Service (QoS), i.e., to control the data rate and error probability for each user individually. In my system model, Shannon's channel capacity function is used to estimate the data rate of a user. The notations are listed in Table 4.1.

$$R_n = w_n \log(1 + SNR_n) \quad (4.1)$$

$$R_n \geq R_n^{req} \quad (4.2)$$

Based on the idea of code division multiple access (CDMA), all the cells are grouped into clusters; and each neighbor cluster has its own CDMA orthogonal code, and with a common code, the cells share wireless bandwidth within one cluster. An example is shown in Figure 4.1, three clusters with orthogonal CDMA code 1, 2 and 3 is presented, and each cluster is enclosed with black broad lines. I assume there is no interference between two cells in different clusters

Table 4.1: Chapter 4 Notations

Symbol	Notation
R_n	The data rate of user n
α	The path-loss exponent
d_0	The reference distance to BS antenna
N_0	The thermal noise power
d_{mn}	The distance between user n and BS m
P_r	The received power of a user
P_{nm}^r	The received power of user n from BS m
p_{nm}	The transmission power allocated to user n from BS m
N	The number of total users
M	The number of total BSs
w_n	The bandwidth allocated to user n
B	The total wireless bandwidth
B'	The predefined maximum bandwidth for SSs
P_m	The total power of BS m
P_m'	The predefined maximum power of BS m for SSs
R_n^{req}	The data rate required by user n
G	The acceptable gap between bandwidth utilization ratio and power consumption ratio
R_B	The bandwidth utilization ratio
R_P	The power utilization ratio
A_{mn}	The associating indicator of user n and BS m
Δw	The bandwidth of a subcarriers
S	The number of subcarriers

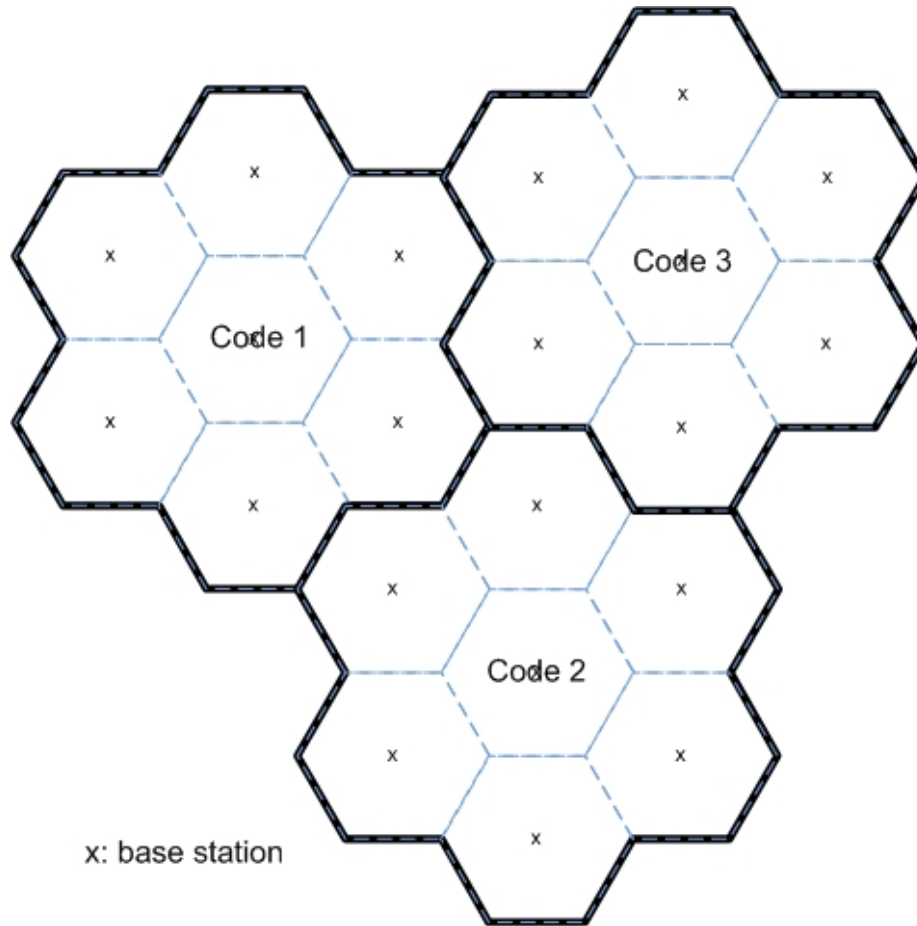


Figure 4.1: Frequency Reuse

because of the usage of different orthogonal codes despite the same frequency they are used. In this chapter, I only focus on one cellular cluster, which can be easily extended to multiple cluster scenarios.

SNR_n is the signal to noise ratio of the user n , which can be improved by CT technology. With CT, one or more BSs can be provisioning service to a user simultaneously, and the received signal power of the user is the summation of the received signal power from its associated BS(s). Therefore the SNR_n is calculated as follows.

$$SNR_n = \frac{P_r}{N_0} \quad (4.3)$$

$$P_r = \sum_{m=1}^M P_{nm}^r = \sum_{m=1}^M \left[p_{nm} \cdot \left(\frac{d_0}{d_{nm}} \right)^\alpha \right] \quad (4.4)$$

In Equations (4.3) and (4.4), P_r is the received signal power of user n , which is the summation of the signal power from all associated BS(s). P_{nm}^r is the received power of user n from BS m , which can be obtained by the path loss model as $P_{nm}^r = p_{nm} \cdot \left(\frac{d_0}{d_{nm}} \right)^\alpha$. p_{nm} is the transmission power allocated to user n from BS m . If $p_{nm} > 0$, the BS m is associated with user n ; otherwise $p_{nm} = 0$.

4.3 RRM Approaches

4.3.1 RRM Procedure

In this section, I will review the concept of user classification and the RRM procedure. Generally, I classify users into two categories: fixed user (i.e., SS) and mobile user (PS and MS). Fixed users are static nodes that normally generate stable traffic load and require a high QoS guarantee, the classic example of fixed users include schools, big companies, and business buildings, which are generally considered as VIPs by the wireless service providers. I assume that the number of SSs is rarely changed, the data rate requirements of fixed users are invariable, and the CSI of an SS is relatively stable, then I can conclude that the corresponding RRM scheme can employ an optimized method requiring a longer computation period. Mobile users are movable nodes in the network, typically represented by personal subscribers with notebook PCs, netbooks, or smart-phones. Mobile users may locate uncertainly and comprise various mobility forms. Since their CSI changes frequently, the RRM schemes should function more efficiently than the heuristic schemes. In this chapter, I will focus on the available schemes for SSs.

The RRM procedure is shown in Figure 4.2. As known from the results of the optimized RRM scheme, BSs and resources have been distributed to all SSs after the network is initiated, and the rest of the resources are assigned to mobile users through a dynamic scheme. If any changes occur to the status of SSs, such as a new subscriber installation, an active subscriber leaving, or changing a user's data rate, the optimized scheme will be operated again for reassigning BSs and resources. As a result, the remaining amount of the resources will be updated.

4.3.2 Three Approaches

In the Figure 4.2, total bandwidth is B and total transmission power of a BS is P in a CoMP-Net, and the SSs are allocated with certain amount of bandwidth (B^{SS}) and transmission power (P_m^{SS}) from BS m , then the remaining bandwidth ($B^{remaining} = B - B^{SS}$) and transmission power ($P_m^{remaining} = P - P_f, \forall m = 1 \dots M$) can be allocated to mobile users. Generally, the more resources left in the network, the more mobile users can be accepted. During the network planning stage, the bandwidth and transmission power are divided into two parts respectively, one for mobile users and another for SSs [9]. The allocated resources amount for SSs includes the predefined maximum bandwidth (B') and the predefined common transmission power (P') limit per BS. Therefore, I adopt B' and P' as the baseline to design resource allocation approaches for SSs. Overall, I provide three resource allocation approaches to save the largest amount of bandwidth and transmission power, and propose four LP models with four different objectives to fulfill the approaches.

The aim of the first resource allocation approach is to minimize the total bandwidth usage of all SSs, and it guarantees the allocated transmission power just satisfies (but does not exceed) the predefined maximum transmission power (P') for SSs. Through this method, the network is able to spare maximum bandwidth for mobile users. To achieve this goal, the LP model (MB_LP) is designed with the objective of minimizing bandwidth usage.

The second approach is to minimize the total transmission power consumption of all SSs, and

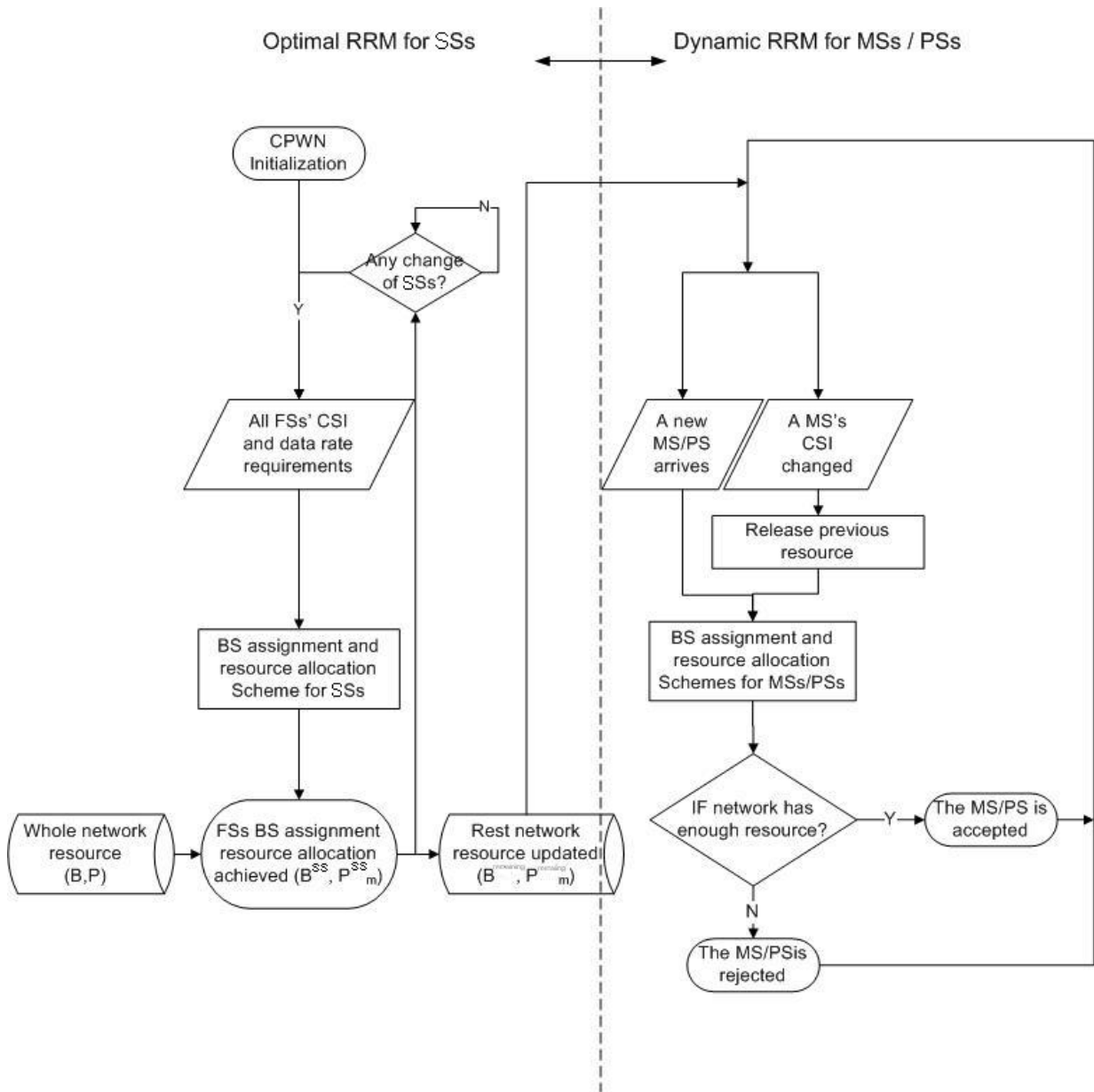


Figure 4.2: RRM Procedure

the allocated bandwidth satisfies (but does not to exceed) the predefined maximum bandwidth (B') for SSs, whereby the network can maintain maximum transmission power for mobile users. The corresponding LP model (MP_LP) for this approach minimizes power consumption as its objective.

The third approach is to balance both two resources costs and to minimize both costs at the same time, in order to maintain the amount of both two resources for mobile users. The two LP models (LBPG_LP and MR_LP) are specifically designed. The objective of LBPG_LP is limiting bandwidth usage and minimizing the power consumption ratios' gap, while the objective of MR_LP is minimizing total resource costs.

None of the above approaches can be used alone for a perfect RRM scheme. Therefore I integrate them to one scheme by adopting one of the four LP models according to network load, which is the summation of all users' data rate. The scheme will be elaborated at the end of Section 4.5 with according simulation results.

4.4 RRM LP Models

The four linear programming (LP) models for RRM are formulated in this section. The notations adopted in the formulations are introduced as follows. The decision variable w_n denotes the wireless bandwidth allocated to user n , and p_{nm} denotes the transmission power allocated to user n from BS m . When p_{nm} is larger than 0 w, BS m is associated with user n ; otherwise, the user has not been connected.

4.4.1 Four LP Models

The four LP models introduced in the study are designed based on different premises, and each premise corresponds with one of the three resource allocation approaches.

1) The first model, denoted as MB_LP, which is designed for the first resource allocation approach, is aimed to minimize the total bandwidth consumption of all SSs in each cluster.

Scheme 4 LP Model to Min B/W (MB_LP)

Objective:

$$\text{(MB_LP) minimize } \sum_{n=1}^N w_n \quad (4.5)$$

Constraints:

1) Total bandwidth for SSs constraint

$$\sum_{n=1}^N w_n \leq B' \quad (4.6)$$

2) Transmission power limit of each BS for SSs

$$\sum_{n=1}^N p_{nm} \leq P'_m, \forall m = 1 \dots M \quad (4.7)$$

3) Data rate requirement of each SS

$$R_n \geq R_n^{\text{req}}, \forall n = 1 \dots N \quad (4.8)$$

$$R_n = w_n \log \left(1 + \sum_{m=1}^M \left[\frac{p_{nm}}{N_0} \left(\frac{d_0}{d_{nm}} \right)^\alpha \right] \right) \quad (4.9)$$

4) Variable boundaries

$$w_n \in [0, B'], \forall n = 1 \dots N \quad (4.10)$$

$$p_{nm} \in [0, P'_m], \forall n = 1 \dots N, \forall m = 1 \dots M \quad (4.11)$$

The constraint in Equation (4.6) ensures that the summation of the bandwidth allocated to each SS is not larger than the predefined maximum wireless bandwidth within one cellular cluster. The constraint in Equation (4.7) is the upper limit of the maximum transmission power of a BS which is predefined for SSs. The constraints (4.8) and (4.9) make sure that the data rate

requirement of each user is satisfied. Equations (4.10) and (4.11) illustrate the boundaries of the decision variables.

2) The second model, denoted as MP_LP for the second approach, aims to minimize the total power consumption of all SSs in each cluster.

Scheme 5 LP Model to Min Power (MP_LP)

Objective:

$$\text{(MP_LP) minimize } \sum_{m=1}^M \sum_{n=1}^N p_{nm} \quad (4.12)$$

Constraints:

Equations from (4.6) to (4.11);

3) In addition to minimizing the total bandwidth usage or power consumption, the third approach considers the trade-off between the consumption of network resources of the two types. Thus, the third model is denoted as LBPG_LP, in which the gap of the ratio between total bandwidth and power consumption is limited by the acceptable gap (G), which weights them evenly. For this purpose, the constraint (4.13) is added to the first model with all the other formulations unchanged. In Equation (4.13), R_B is the bandwidth utilization ratio expressed as

$$R_B = \frac{\sum_{n=1}^N w_n}{B'} \times 100\%, \text{ and } R_P \text{ is the power usage ratio expressed as } R_P = \frac{\sum_{m=1}^M \sum_{n=1}^N p_{nm}}{\sum_{m=1}^M P'_m} \times 100\%.$$

4) The fourth model is another achievement of the third resource allocation approach. It is denoted as MR_LP and aims to minimize the total resource cost ratios. The goal is defined as shown in Equation (4.14). It can be concluded from the figure that the bandwidth and power consumption ratios which are obtained by resource possessing, dividing by the predefined total bandwidth and power for SSs (i.e., B' and the summation of P'_m).

Scheme 6 LP Model to Balance B/W and Power for (LBPG_LP)

Objective:

$$\text{(LBPG_LP) minimize } \sum_{n=1}^N w_n$$

Constraints:

$$|R_B - R_P| < G, G > 0 \quad (4.13)$$

AND

Equations (4.6) to (4.11);

Scheme 7 LP Model to Min Resources (MR_LP)

Objective:

$$\text{(MR_LP) minimize } \left[\frac{\sum_{n=1}^N w_n}{B'} + \frac{\sum_{m=1}^M \sum_{n=1}^N p_{nm}}{\sum_{m=1}^M P'_m} \right] \quad (4.14)$$

Constraints:Equations (4.6) to (4.11);

4.4.2 SOS1 Linearization

Due to the intractability of nonlinearity in Equation (4.9), I applied a linear approximation approach which based on the Special Ordered Set of Type 1 (SOS1) [9] to reformulate the problem as a linear one so that the LP problem can be solved by CPLEX [55]. In an OFDM-FMDA system, each subcarrier is a small segment of frequency within the entire bandwidth. By using SOS1, I divide the total bandwidth (B') into a number (S) of Δw , which can be considered as the bandwidth of each subcarrier, and S represents the number of subcarriers of the OFDM-FMDA system. The total transmission power (P'_m) for all Ss has also been divided to S small segments (Δp) of a BS. As a result, (4.9) can be reformulated to a set of piece-wise linear functions, each can be obtained by taking advantage of logarithms that transforms multiplication operations to addition by the formula $\log(x \cdot y) = \log x + \log y$.

SOS1 are sets of non-negative variables, generally, at most one of the variables can be non-zero in the final solution for each set. I hereby define two SOS1 variables as following:

$$\lambda_{ns} \in \{0, 1\}, \forall n = 1 \dots N, \forall s = 1 \dots S \quad (4.15)$$

$$\beta_{ns} \in \{0, 1\}, \forall n = 1 \dots N, \forall s = 1 \dots S \quad (4.16)$$

since S is the column number of SOS1 variables, thereby

$$\sum_{s=1}^S \lambda_{ns} = 1, \forall n = 1 \dots N \quad (4.17)$$

$$\sum_{s=1}^S \beta_{ns} = 1, \forall n = 1 \dots N \quad (4.18)$$

Four parameter vectors (or matrices) are further defined in piecewise linear approximations

as elaborated from Equations (4.19) to (4.22):

$$(W_s)_{1 \times S} = \left(0 \quad \Delta w \quad \cdots \quad k\Delta w \quad \cdots \quad B' \right) \quad (4.19)$$

$$\Delta w = \frac{B'}{S}, k = 0, 1, \dots, S$$

$$(P_{ns})_{N \times S} = \left(\begin{array}{cccccc} 0 & \Delta p(1) & \cdots & k\Delta p(1) & \cdots & pp^{UB}(1) \\ 0 & \Delta p(2) & \cdots & k\Delta p(2) & \cdots & pp^{UB}(2) \\ \cdots & & & & & \\ 0 & \Delta p(N) & \cdots & k\Delta p(N) & \cdots & pp^{UB}(N) \end{array} \right) \quad (4.20)$$

where

$$pp^{UB}(n) = 1 + \sum_{m=1}^M \left[\frac{P'_m}{N_0} \left(\frac{d_0}{d_{nm}} \right)^\alpha \right]$$

$$\Delta p(n) = \frac{pp^{UB}(n)}{S}$$

$$(LOGW_s)_{1 \times S} = (\log(W_s))_{1 \times S} \quad (4.21)$$

$$(LOGP_{ns})_{N \times S} = (\log[\log(P_{ns})])_{N \times S} \quad (4.22)$$

With approximate piecewise linearization, w_n can be represented as the following function

$$w_n = \sum_{s=1}^S W_s \lambda_{ns} \quad (4.23)$$

Provided that only one of the SOS1 variable $\lambda_{ns}(s)$ in a row is allowed to be 1. Accordingly,

this part of the log of Equation (4.9) can be presented as following:

$$1 + \sum_{m=1}^M \left[\frac{p_{nm}}{N_0} \left(\frac{d_0}{d_{nm}} \right)^{\alpha} \right] = \sum_{s=1}^S P_{ns} \beta_{ns} \quad (4.24)$$

Provided that only one of $\beta_{ns}(s)$ in a row is allowed to be 1. After taking the logarithm of Equations (4.8) and (4.9), I get

$$\log(w_n) + \log \left[\log \left(1 + \sum_{m=1}^M \left[\frac{p_{nm}}{N_0} \left(\frac{d_0}{d_{nm}} \right)^{\alpha} \right] \right) \right] \geq \log(R_n^{\text{req}}) \quad (4.25)$$

With Equations (4.23) and (4.24), Equation (4.25) can be represented as

$$\log \left(\sum_{s=1}^S W_s \lambda_{ns} \right) + \log \left[\log \left(\sum_{s=1}^S P_{ns} \beta_{ns} \right) \right] \geq \log(R_n^{\text{req}}) \quad (4.26)$$

As a result, the following linear constraint can be concluded from Equations (4.21), (4.22), and (4.26).

$$\sum_{s=1}^S \text{LOG} W_s \lambda_{ns} + \sum_{s=1}^S \text{LOG} P_{ns} \beta_{ns} \geq \log(R_n^{\text{req}}) \quad \forall n = 1 \dots N \quad (4.27)$$

4.4.3 Problem Formulation for Non-CT (NCT)

Two mathematical optimization models, MB_LP_NCT and MBPG_LP_NCT, are used as benchmarks for the conventional wireless network. Three NCT constraints as shown in Equations (4.28), (4.29) and (4.30), have been added into MB_LP and LBPG_LP respectively.

$$\sum_{m=1}^M A_{mn} = 1 \quad (4.28)$$

$$A_{mn} - \frac{p_{nm}}{P'_m} \geq 0 \quad (4.29)$$

$$A_{mn} \in \{0, 1\} \quad (4.30)$$

The constraints in Equations (4.28) and (4.29) ensure one user can only be associated with one BS. Equation (4.30) states the integrity of the associating indicator of user n and BS m (A_{mn}). When A_{mn} equals one, BS m associating user n ; otherwise, user n has not been connected.

4.5 Simulation Results

Simulation results are presented in this section. Particularly, I am interested in the performance metrics with respect to the total allocated bandwidth (in MHz) and the total consumed transmission power (in W), in order to satisfy the given traffic load demand of the SSs in one cluster. The simulation program is coded in C#, and the Linear Programs are solved by CPLEX 11 [55] on a computer with Intel Pentium D-805 CPU and 1 GB memory. In the end, a specific resource allocation scheme achieves better performance if less total bandwidth and transmission power consumption is used at the BSs to satisfy a given pattern of traffic load demand. Meanwhile, I define the summation of data rate requirements as the network load (in Mbps), and the LP models can fit into any BSs distribution. In the simulation, I study them in two popular wireless network scenarios with 7 BSs and 9 BSs respectively.

4.5.1 Scenario 1: 7 Cells Network

The 7 cells network topology is similar to a conventional cellular cluster illustrated in Figure 4.3. There are seven BSs in a $4200 \times 4200(\text{m}^2)$ area in the network, as represented by big points in Figure 4.3, which is a snapshot for the area of interest (AOI). The setting of simulation parameters is shown in Table 4.2. Table 4.3 shows the condition of 20 simulation scenarios with 5 different network loads; i.e. 20 Mbps, 40 Mbps, 60 Mbps, 80 Mbps and 100 Mbps; and 4

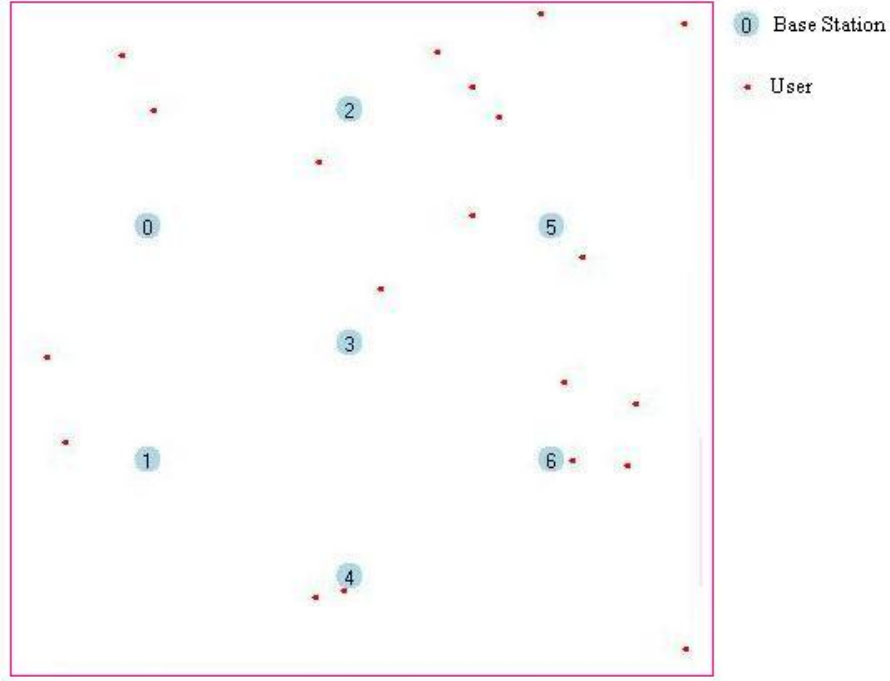


Figure 4.3: A Snapshot on the SSs Distribution in the AOI. The 7 BSs are Fixed.

different numbers of SSs; 20, 30, 40, and 50; under a given distribution of 7 BSs network. The SSs are randomly placed in the AOI as represented by the small points in Fig. 4.3. To normalize the randomness of the SSs placement, each data in the simulation is the average result by solving an LP on 50 different random user distributions in each scenario.

Table 4.2: Simulation parameters setting

Parameters	B' (MHz)	P'_m (w)	N_0 (w)	d_0 (m)	α	S	Δw (kHz)	G
Value	20	20	1×10^{-6}	1	2.5	400	50	0.01

The thermal noise power (N_0) is assumed equivalent at any point in the network.

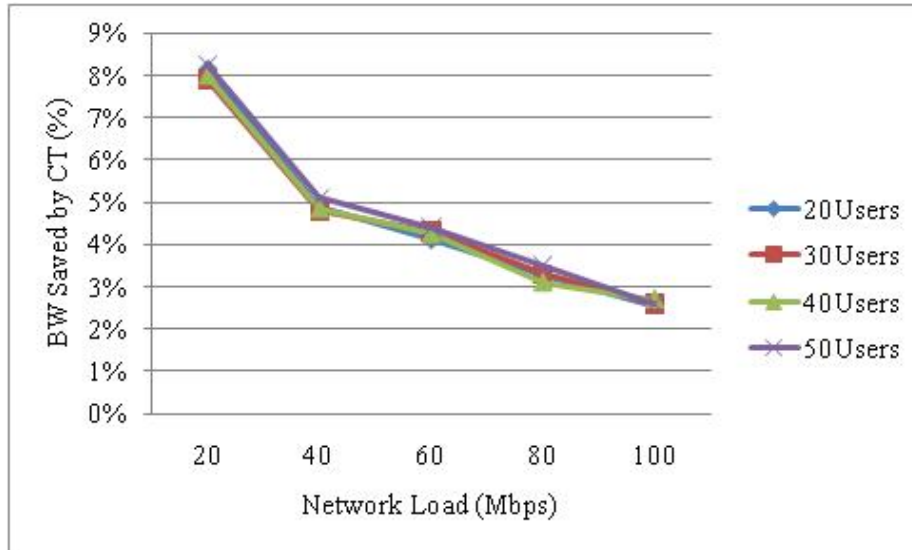


Figure 4.4: Total bandwidth consumption gap between CT and NCT models

Table 4.3: Simulation Scenario Setting

Scenario	I	II	III	IV	V
20 Users Date Rate (Mbps)	1	2	3	4	5
30 Users Date Rate (Mbps)	0.67	1.33	2	2.67	3.33
40 Users Date Rate (Mbps)	0.5	1	1.5	2	2.5
50 Users Date Rate (Mbps)	0.4	0.8	1.2	1.6	2
Network Load(Mbps)	20	40	60	80	100

Bandwidth Allocation Performance

The bandwidth amount (percentage) saved by CT technology is shown in Figure 4.4. In Figure 4.4, I found that if some users are associated by two or more BSs with CT technology, less bandwidth is required than that for users only associated with one BS (NCT). It has also been found that number of users in the network doesn't affect the results of bandwidth saving with CT technology.

In Figure 4.5, the small points represent the users who are using CT from two or more BSs.

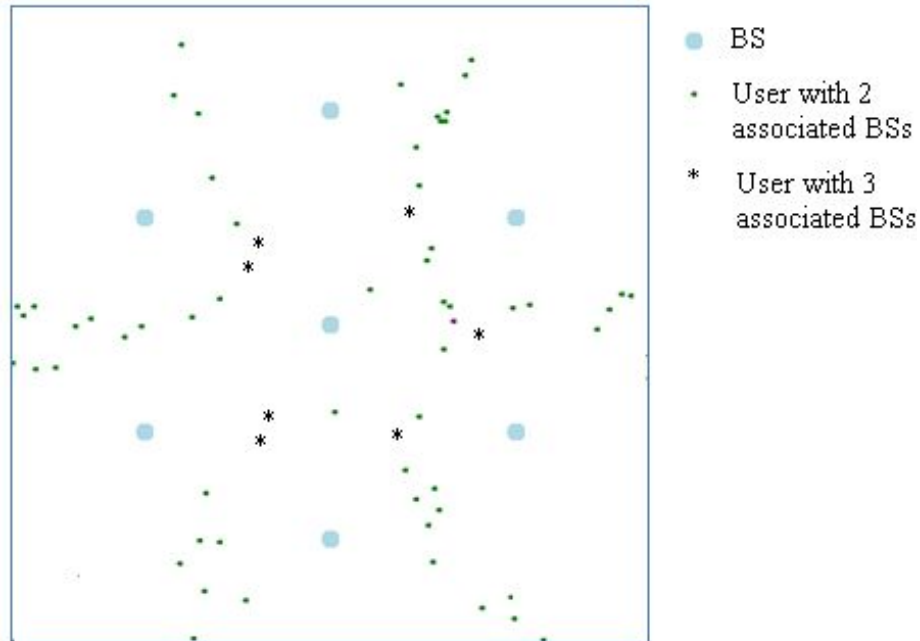
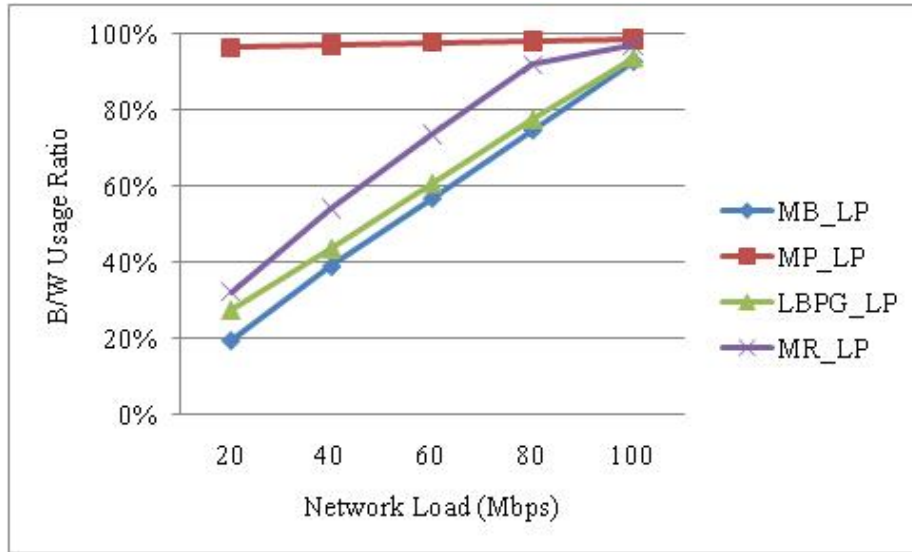


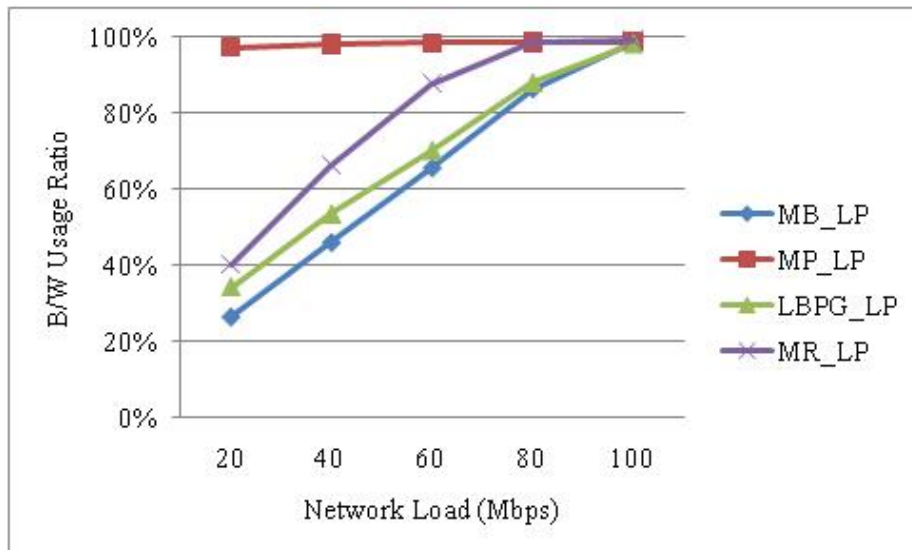
Figure 4.5: Geographical distribution of the CT users

Obviously, most of these users are located at the middle area of two or three BSs, or areas far from the BSs, therefore CT technology is able to help to provide effective services to the users whose positions are at the middle area of two or three BSs or far away from the BSs.

Figure 4.6 shows the total bandwidth allocation which is able to satisfy the data rate requirement of each user in the five scenarios. The results are similar despite different numbers of users in the network; therefore, I merely show the results of 20 users (a) and 50 users (b) in Figure 4.6. And I conclude that the MB_LP model uses the least amount of bandwidth as expected since its target is to minimize bandwidth consumption at the BSs; on the other hand, MP_LP consumes the largest amount of bandwidth among the four models, since its objective is to attain the minimum power consumption. LBPG_LP performs worse (about 10%) than MB_LP in low network load, and almost the same at high network load. MR_LP functions worse (about 25%) than MB_LP in both low network load and high network load. Furthermore, when network load reached as high as 100 Mbps, the bandwidth for the SSs is almost exhausted, thereby, the network capacity for



(a) 20Users



(b) 50Users

Figure 4.6: Total Bandwidth Allocation by the Four LP Models

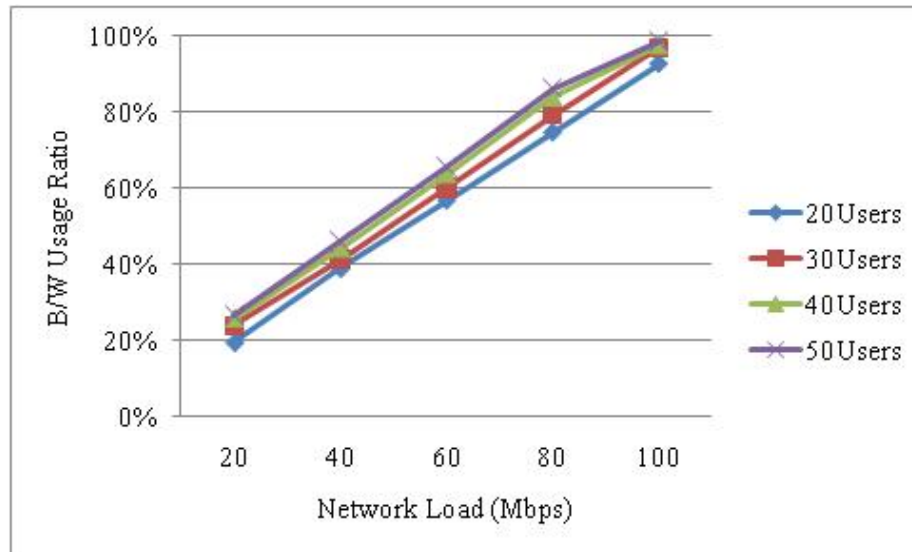
the SSs is nearly fully loaded.

By observing Figure 4.7, I find that when network load is the constant, larger amount of bandwidth is possessed when there are higher numbers of SSs in the network. The situation is caused by the SOS1 linearizing technique. It has also been observed from the figure that when the network load is the constant, the data rate of each user (R_n) develops inversely proportional to the number of SSs, therefore the value of Δw in Equation (4.19) increases compared with R_n , and the linearized precision of SOS1 is decreased. As a result, the linearization process of SOS1 will cost more bandwidth with a higher number of SSs. Since all the four LP models show the same phenomenon, I only show the results of MB_LP (a) and MR_LP (b) as displayed in Figure 4.7.

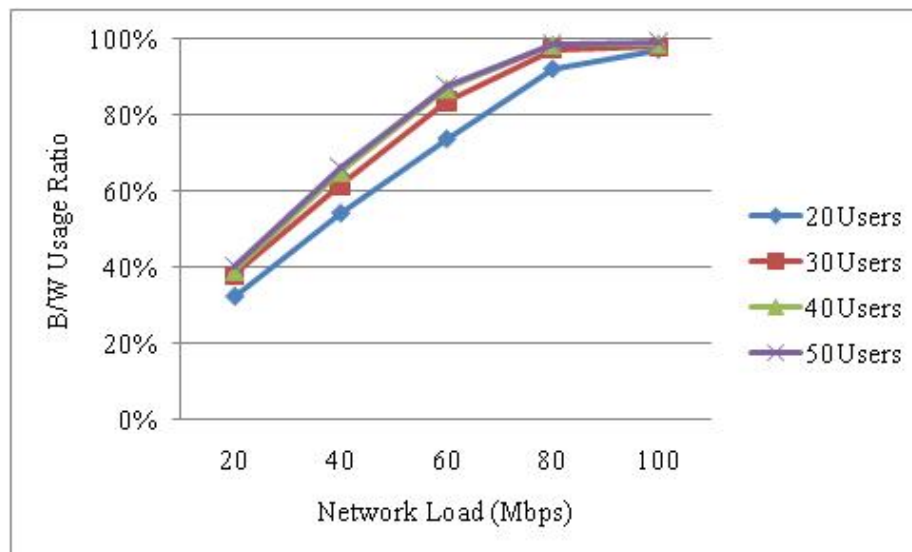
Power Allocation Performance

The performance of power transmission of the four models is shown in Fig. 4.8. The results of performances with different numbers of SSs in the network are similar; therefore, I only show the results of 20 users (a) and 50 users (b) respectively in Figure 4.8. In the end, the MP_LP model has required the least amount of transmission power as expected from the BSs, which has been defined in its target function. On the other hand, the MB_LP model has required the highest transmission power among the four to save bandwidth. In the meantime, MR_LP costs a bit more power than the MP_LP in the process. It is noted that LBPG_LP performs not as good as MP_LP yet better than MB_LP, furthermore, when the network load is high, MB_LP and LBPG_LP almost consumed all the transmission power for the SSs, In contrast, MP_LP and MR_LP consume power at the expense of costing almost all the bandwidth resources.

Figure 4.9 shows that the greater transmission power is required when there are higher numbers of users in the network. It is caused by the SOS1 technique and the effect is similar to what has been presented in the bandwidth performance results. When the network load is constant, the data rate of each user (R_n) decreases when the number of SSs increases. Therefore, the value of

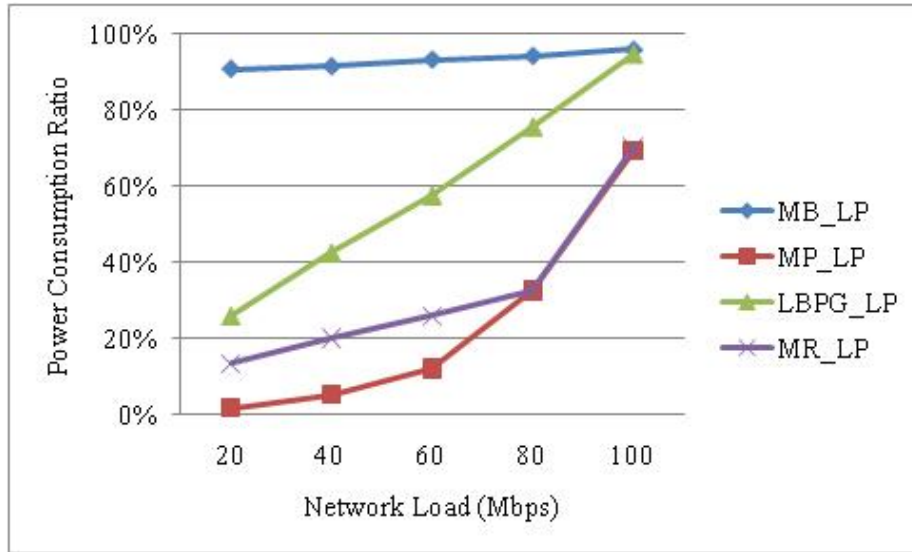


(a) MB.LP

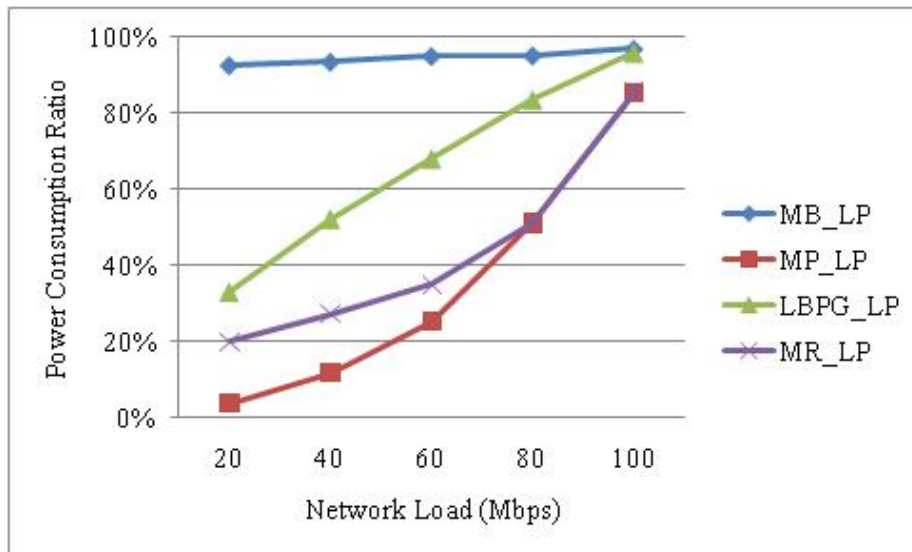


(b) MR.LP

Figure 4.7: Total Bandwidth Allocation for Different Number of SSs

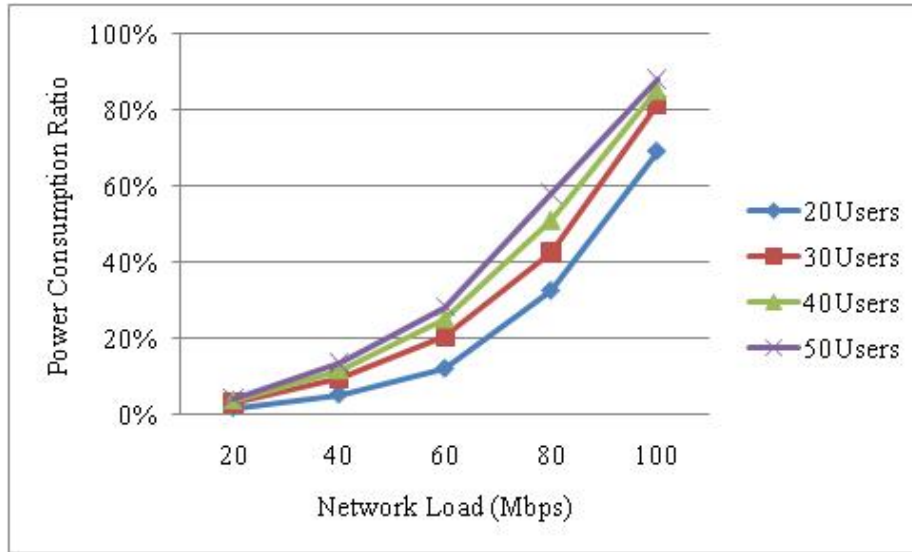


(a) 20 Users

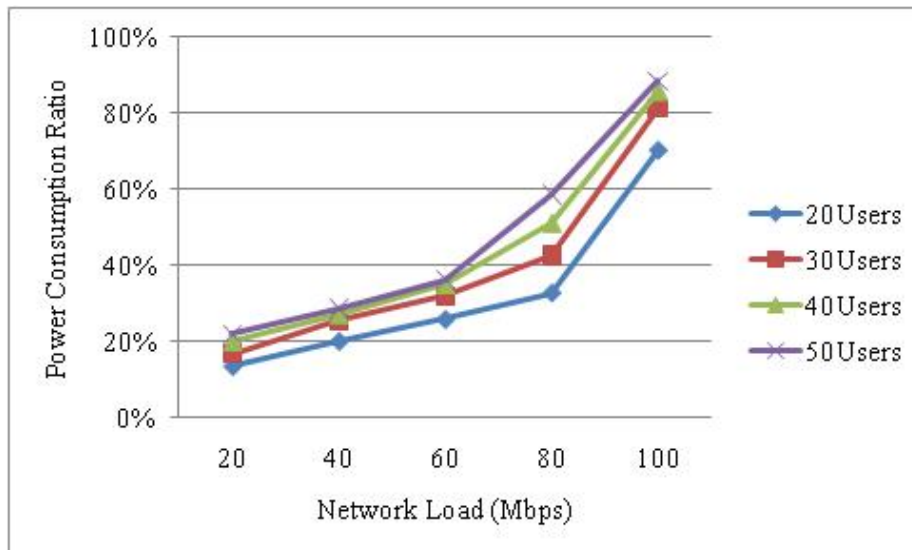


(b) 50 Users

Figure 4.8: Total Power Allocation by the Four LP Models



(a) MP.LP

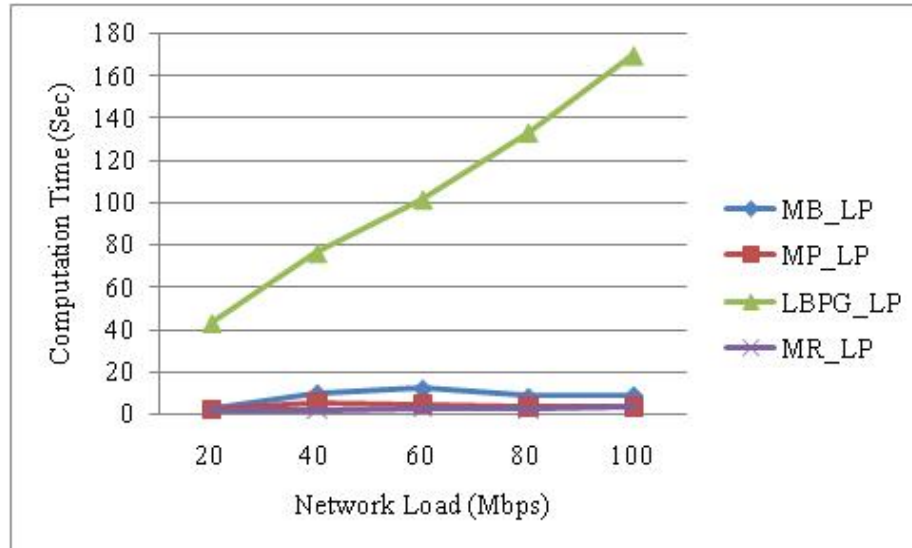


(b) MR.LP

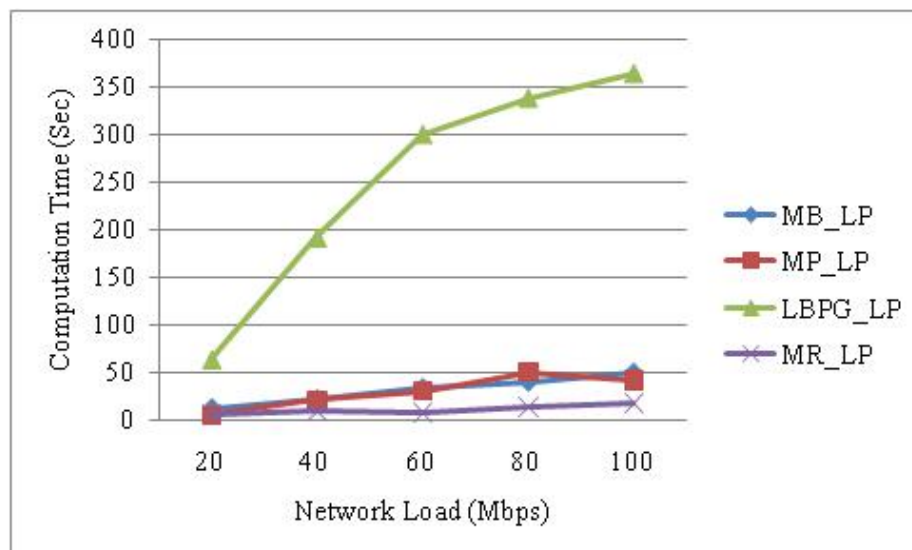
Figure 4.9: Total Power Allocation for Different Number of SSs

Δp in Equation (4.20) is bigger compared with the p_{nm} in Equation (4.9), thereby the linearizing precision of SOS1 is decreased. In conclusion, the linearizing process of the SOS1 will cost more power when there are a larger amount of SSs. Hereby I only show the results of MP_LP (a) and MR_LP (b) in Figure 4.9, since the results are similar for all the four LP models.

Computation Time



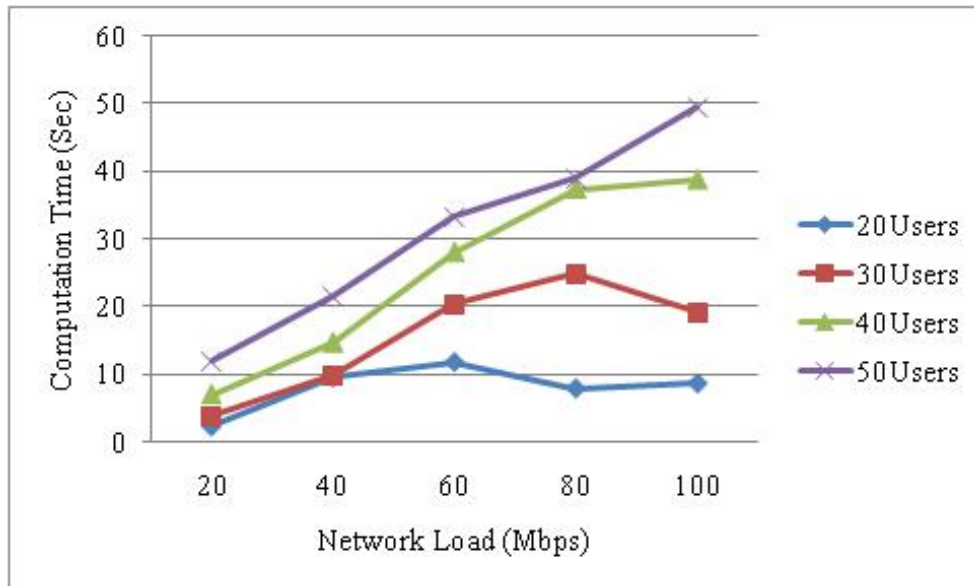
(a) 20 Users



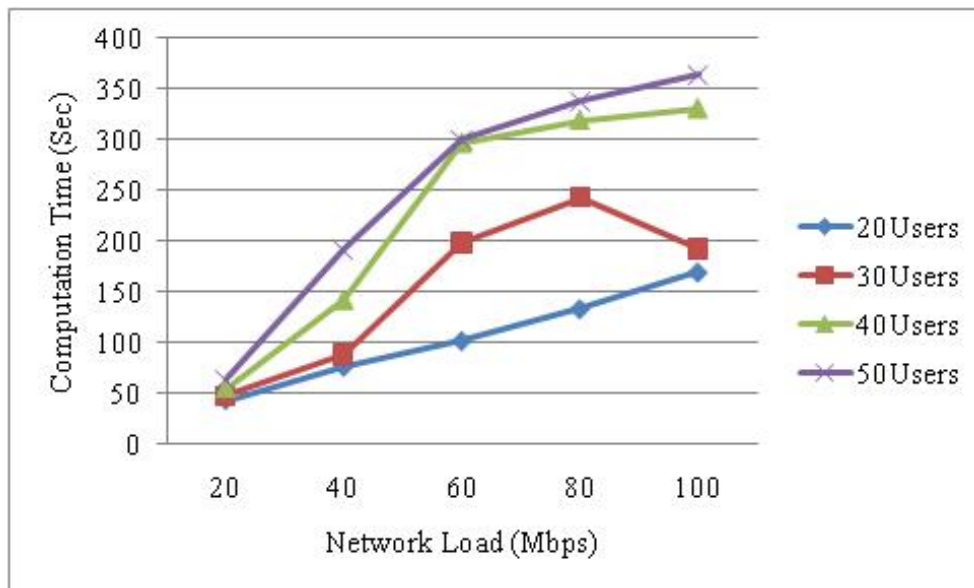
(b) 50 Users

Figure 4.10: Computation Time for the Four LP Models

The computation time results of the four LP models are shown in Figure 4.10. Since the results of different numbers of SSs in the network are similar, I just show the results of 20 users (a) and 50 users (b) respectively in Figure 4.10. By observing these results, I conclude that: 1) LBPG_LP costs more computation time than the other three models, because it has one more constraint as shown in Equation(4.13) than the others. 2) When network load increases, the computation time increases slightly. When the network load amounts 100%, the LP models cannot be solved because there is no solution for accepting all users' requirements.



(a) MB_LP



(b) LBPG_LP

Figure 4.11: Computation Time for Different Number of SSs

Figure 4.11 shows the computation time results for different number of SSs in a CoMPNet for all four LP models. As the results are similar, I only present the results of MB_LP (a) and

Table 4.4: Simulation parameters setting

Parameters	B' (MHz)	P'_m (W)	N_0 (W)	d_0 (m)	α	S	Δw (kHz)	G
Value	20	20	1×10^{-6}	1	2.5	400	50	0.01

The thermal noise power (N_0) is assumed equivalent at any point in the network.

LBPG-LP (b) as displayed in Figure 4.11. By observing these results, I can conclude that more time will be taken to solve the LP models if there are more users in the network

The computation complexity of the four LP models is related to the number of SSs N and BSs M in a CoMPNet. However, the number of SSs and BSs are limited, and computation time of the simulation is reasonable for a resource allocation scheme (which is offline and time-tolerant). Therefore the four LP models are suitable to be employed in the resource allocation scheme for SSs for CoMPNet.

4.5.2 Scenario 2: 9 Cells Network

The second test network topology is a square CO-domain with nine BSs in a $4200 \times 4200(\text{m}^2)$ area, shown in Figure 4.12. The setting of simulation parameters is shown in Table 4.4. In this test, I arrange 30 SSs with 5 different network loads; i.e. 40 Mbps, 60 Mbps, 80 Mbps, 100 Mbps, and 120 Mbps, and the SSs are randomly placed in the AOI as indicated by the small points in Figure 4.12. To normalize the randomness of the SSs placement, each data in the simulation is the average result of values after LP solving 50 different random user distributions. As a result, I have obtained the similar test results as Scenario 1. The performance of bandwidth cost, power cost, and computation time are shown in Figure 4.13, Figure 4.14, and Figure 4.15, respectively.

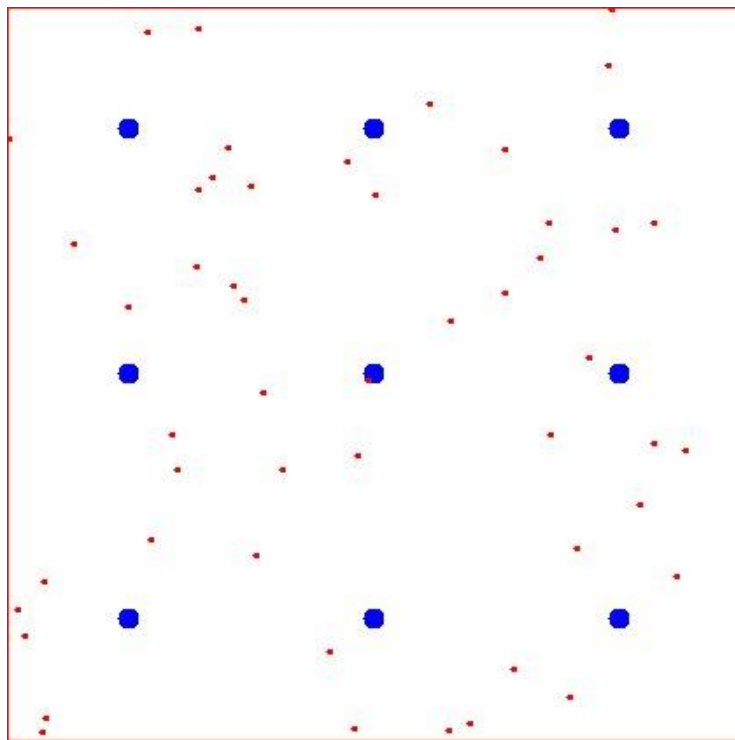


Figure 4.12: A Snapshot on the SSs Distribution in the 9 BSs Network

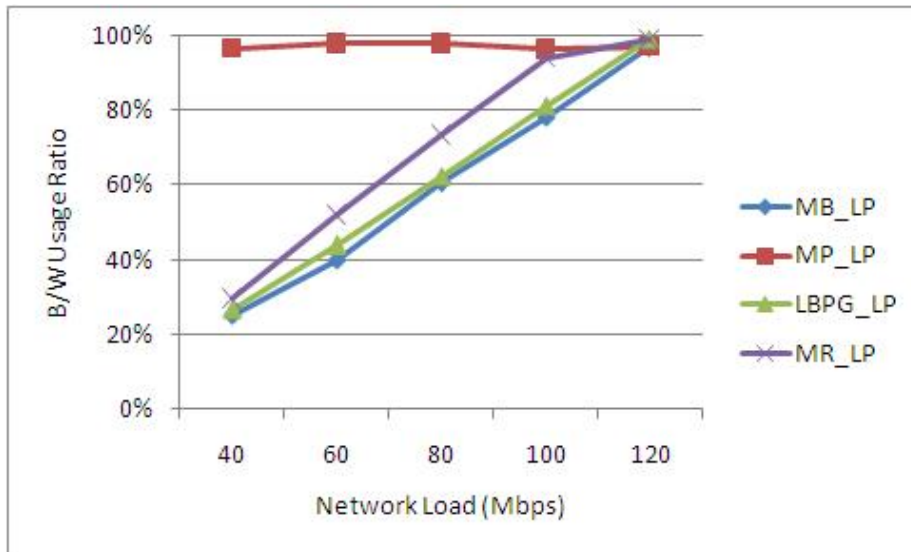


Figure 4.13: Bandwidth Cost

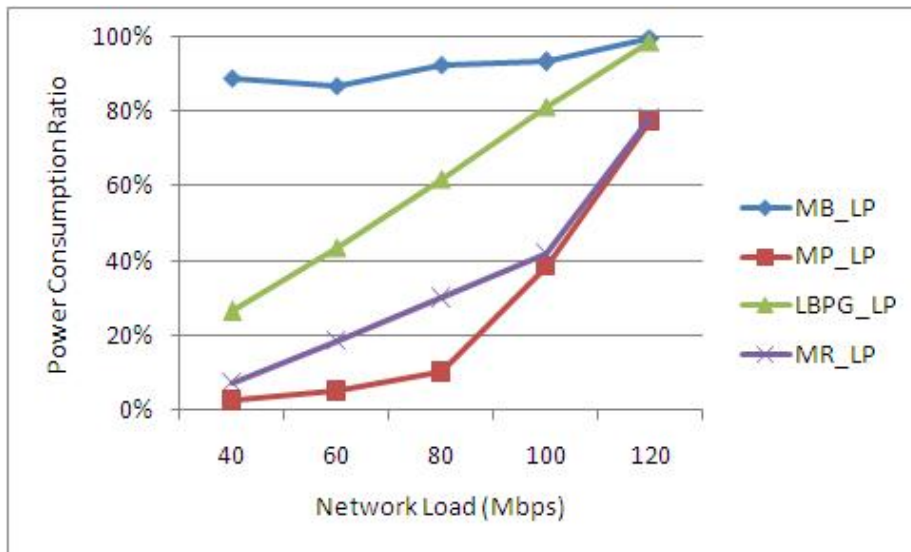


Figure 4.14: Power Cost

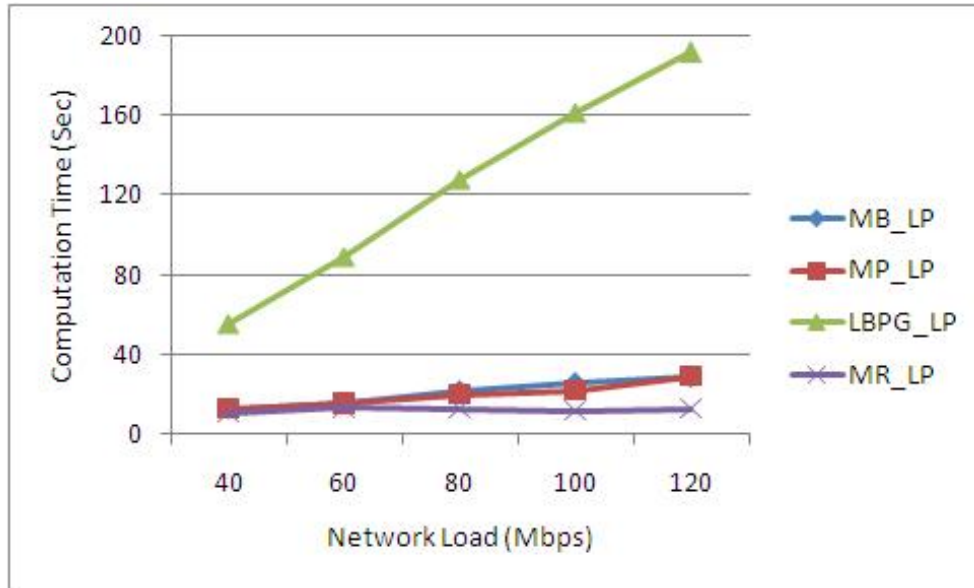


Figure 4.15: Computation Time

According to the simulation results of bandwidth and power allocation performances, I find that solely relying on any one of the four models will not be a good strategy to deal with the different network load in the CoMPNet. Instead, I can select one of the models flexibly according to the network load, whereby the issue of achieving optimal resource allocation can be tackled. The network load is expressed as a percentage which refers to the highest total data rate of network which has randomly allocated users. By observing the result of bandwidth cost and power cost (Figure 4.6 & Figure 4.13 and Figure 4.8 & Figure 4.14), the proposed adaptive RRM scheme for SSs in a CT CO-domain can be described as follows: 1) When the network load is low (less than 40%), the MR_LP model should prevail as it consumes less bandwidth than MB_LP and LBPG_LP yet saves a significant amount of transmission power at the BSs. 2) When the network load is higher (around 60%), LBPG_LP model becomes a good choice due to its balancing capability in consuming both types of network resources, while MR_LP almost exhausts the bandwidth resources. 3) When the network load is very high (higher than 90%), MR_LP and MP_LP are preferable while the bandwidth of the BSs is exhausted.

4.6 Chapter Conclusion

In this chapter, I present a novel optimized framework for adaptive control in terms of RRM for SSs in a CoMPNet, for which four LP models are proposed. Extensive experiments are carried out to analyze the performance behaviors in terms of bandwidth allocation and power consumption. The results show bandwidth savings can be better achieved at the expense of more consumed power. In this chapter, I also suggest a resource allocation scheme which flexibly selects LP model according to the network load. Specifically, when the network load is at a low or middle level, the MR_LP model can save both bandwidth and power resources; however, the LBPG_LP model prevails in case of high load, for it can be used to avoid exhausting the bandwidth resources; if network is in full load, the MR_LP or MP_LP models can save more power than the other two models without increasing the amount of bandwidth utilization.

Chapter 5

CoS Aware RRM Scheme

5.1 Introduction

One of the most challenging issues in the next generation broadband network design is interference management. In this chapter, I will study the RRM scheme with CoS based ICI mitigation mechanisms for OFDM-FMDA based CoMPNet, which aims to achieve larger network capacity, reduce blocking probability and mitigated interference. A novel ICI coordination resource allocation scheme is introduced so as to maximize the reuse frequency via a CoS based subcarrier assignment scheme and a dynamic power control mechanism. At first, I formulate the task of resource allocation under multi-cell collaboration into a mathematical programming problem. Different from the usual conventional optimal resource allocation schemes [56] that consider network throughput as the optimization target, I focus on maximizing the number of accepted users' demands under the throughput constraint of each connection. Due to the huge computation complexity in solving this formulated optimization problem, I introduce a novel heuristic approach that sequentially performs subcarrier assignment and power control for each admitted connection. Specifically, a subcarrier assignment scheme is first invoked for ICI mitigation, where a CoS mechanism provides dynamic scheduling coordination that is assumed so as to determine

the data rate of each user. Then, at the second stage of the heuristic, the transmission power of each user is inspected sequentially and adjusted such that the power is just sufficient to support the specified modulation level. Since the reduction of the transmission power can reduce the interferences on the neighbor cells, thus the SINR of the other cells will be reduced accordingly. The proposed power control scheme goes through multiple iterations in order to approach to the optimal solution.

The chapter focuses on the following three aspects. (1) Formulate the problem of call admission control and resource allocation in cellular networks with ICI by maximizing the number of accepted users' demands. (2) Develop a two-stage heuristic approach to the formulated problem, that is, subcarrier assignment is performed first followed by power control. (3) I show that the proposed strategy can significantly outperform the other conventional spatial reuse schemes.

The rest of the chapter is organized as follows. Section 5.2 describes the system model and propagation model mentioned in this chapter. In Section 5.3, I formulate the optimization problem of resource allocation under multi-cell collaboration with the objective of maximizing the number of accepted users' demands and the constraint of total transmission power. Section 5.4 presents my heuristic solution to the optimization problem as well as my novel CoS RRM scheme. In the end of the chapter, I verify the proposed schemes through extensive simulation, and its effectiveness, fairness, and efficiency will be demonstrated in Section 5.5. Finally, I make the conclusion of this chapter in Section 5.6.

5.2 System Model

I assume OFDM-FMDA as the multiple access technology in the CoMPNet where the network resource is carried with subcarriers, and the instantaneous bandwidth of a user can be determined by the power allocated as well as the modulation scheme with which engaged. The notations of this chapter are listed in Table 5.1.

Each user can only be associated with a single BS at a moment. With BS m and an associated user n , the received signal power in subcarrier s is denoted as $p_{n,m,s}^{Re}$, which can be estimated by a function $f(\Delta)$ of the transmission power at the BS.

$$p_{n,m,s}^{Re} = f(p_{m,s}^{Tr}) \quad (5.1)$$

The interference power to user n in subcarrier s , denoted as $p_{n,s}^I$, is calculated as the summation of the received power from the BSs other than the associated BS m .

$$p_{n,s}^I = \sum_{k=1, k \neq m}^M p_{n,k,s}^{Re} \quad (5.2)$$

The SINR ($\gamma_{n,s}$) of user n which is associated with BS m in subcarrier s can be expressed as follows:

$$\gamma_{n,s} = \frac{p_{n,m,s}^{Re}}{N_0 + p_{n,s}^I} \quad (5.3)$$

With generality, I assume that the ICI imposes the major vicious effect to the quality of received signals of each user, and all the other fading effects, yet those which arise from geographical limitations and malicious/illegal access of the license bands, are not considered. By taking the path loss model in [37] for signal power to user n from BS m , Equation (5.1) can be written as follows:

Table 5.1: Chapter 5 Notations

Symbol	Notation
N	Number of total users
M	Number of total BSs
S	Number of subcarriers in full bandwidth
$P_{n,m,s}^{Re}$	Received signal power of user n from BS m in subcarrier s
$P_{m,s}^{Tr}$	Transmission power of BS m in subcarrier s
$P_{n,s}^I$	Interference power of user n in subcarrier s
$\gamma_{n,s}$	SINR of user n in subcarrier s
$d_{n,m}$	Distance between user n and BS m
α	Path-loss exponent
N_0	Thermal noise power
J	Number of MCS levels
MCS_j	The j th MCS level
Γ_j	Required SINR of the j th MCS
C_j	Data rate of the j th MCS
$c_{n,s}$	Channel data rate of user n in subcarrier s
B	Total wireless bandwidth (Hz)
B_{sc}	Bandwidth (Hz) of single subcarrier
$A_{m,n}$	Associating indicator of BS m and user n
$v_{n,s}$	Allocating indicator of user n in subcarrier s
R_n	Data rate of user n
R_n^{req}	Data rate required by user n
P_m^{Tr}	Max transmission power of BS m
$P_{m,s}^{Tr}$	Transmission power of BS m allocated in subcarrier s
s_n^{req}	Number of subcarriers required by user s
s_n	Number of subcarriers allocated to user s
frg_x	Frequency reuse group x
ρ_s	Transmission power in each subcarrier of FR=3
P_c, P_e	Transmission power for central and edge users
S_c, S_e	Number of subcarriers prepared for central and edge users in each subcarrier of PRF

$$P_{n,m,s}^{Re} = f(P_{m,s}^{Tr}) = P_{m,s}^{Tr} \times \left(\frac{d_0}{d_{n,m}} \right)^\alpha \quad (5.4)$$

Thereby the SINR in (5.3) can be calculated as follows:

$$\gamma_{n,s} = \frac{P_{m,s}^{Tr} \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0 + \sum_{k=1, k \neq m}^M P_{k,s}^{Tr} \left(\frac{d_0}{d_{n,k}} \right)^\alpha} \quad (5.5)$$

5.3 RRM Problem Formulation

In this section, the resource allocation task in an OFDM-FMDA system is formulated as a mathematical programming problem with a target of maximizing the number of admitted users while reducing the BS consumed power in a common CO-domain. I denote the number of BSs and users in a CO-domain as M and N , respectively, and suppose the total network bandwidth is B Hz, the number of subcarriers of a BS is S ; therefore the bandwidth of single subcarrier is $B_{sc}(= B/S)$. Assume $n = 1, 2, \dots, N$ as the set of users, $m = 1, 2, \dots, M$ as BSs, and $s = 1, 2, \dots, S$ as subcarriers, respectively.

The total number of modulation/coding levels is denoted as J . In general, a modulation/coding level with a higher rate can only be employed for a larger SINR under a specific bit error rate (BER) threshold, and it requires less subcarriers to achieve a certain throughput. In addition, a minimum γ_j is required to support the transmission with the j -th level of modulation denoted as MCS_j , $\forall 1 \leq j \leq J$, with the rate C_j in the unit of bits per second per hertz (b/s/Hz). The modulation/coding level of user n ($MCS_{n,s}$) is selected based on the SINR ($\gamma_{n,s}$) of the subcarrier s allocated to the user from its associated BS m , and the channel data rate $c_{n,s}$ can be obtained as follows:

$$c_{n,s} = f_{mcs}(\gamma_{n,s}) = C_j = C(MCS_j) \quad (5.6)$$

$$\Gamma_{j+1} > \gamma_{n,s} \geq \Gamma_j$$

In Equation (5.6), the correlative rate of each modulation level is orderly organized so that $C_j < C_{j+1}$, thereby $1 \leq j < j+1 \leq J$, $f_{mcs}(\Delta)$ is the function that returns the rate according to the MCS, and Γ_j is the required SINR for supporting j th-level MCS. Therefore the data rate of the n th user (R_n (bits/s)) can be expressed by:

$$R_n = B_{sc} \times \sum_{m=1}^M A_{m,n} \sum_{s=1}^S v_{n,s} c_{n,s} \quad (5.7)$$

In Equation (5.7), $A_{m,n} = 1$ means that BS m is associated with user n , $A_{m,n} = 0$ are otherwise. $v_{n,s} = 1$ means subcarrier s is allocated to user n , $v_{n,s} = 0$ are otherwise. Therefore, $A_{m,n} v_{n,s} = 1$ indicates that the subcarrier s of BS m is allocated to user n .

Later, the general resource allocation problem for the OFDM-FMDA system investigated in the chapter targets on the objective to maximize the number of accepted connection requests, which is one of the main guidelines of the network capacity, as shown in Equation (5.8).

$$\max \sum_{n=1}^N \sum_{m=1}^M A_{m,n} \quad (5.8)$$

The objective function is subject to the following constraints:

- 1) The data rate requirement of an accepted user's connection must be satisfied.

$$R_n = B_{sc} \times \sum_{s=1}^S v_{n,s} c_{n,s} \geq R_n^{req} \times \sum_{m=1}^M A_{m,n} \quad (5.9)$$

2) One user can only be associated by one BS.

$$\sum_{m=1}^M A_{m,n} \leq 1, \forall n = 1, \dots, N \quad (5.10)$$

3) Capacity constraint: the number of subcarriers that can be utilized by each BS is constrained by an upper limited.

$$\sum_{s=1}^S \sum_{n=1}^N v_{n,s} \leq M \times S \quad (5.11)$$

4) Constraint on the total subcarriers of each BS:

$$\sum_{s=1}^S \sum_{n=1}^N A_{m,n} v_{n,s} \leq S, \forall m = 1, \dots, M \quad (5.12)$$

5) Constraint on each subcarrier of a BS:

$$\sum_{n=1}^N A_{m,n} v_{n,s} \leq 1, \forall m = 1, \dots, M; \forall s = 1, \dots, S \quad (5.13)$$

6) The channel data rate $c_{n,s}$ is obtained by Equation (5.6), which can be rewritten as:

$$c_{n,s} = f_{mcs}(\gamma_{n,s}) = C_j = C(MCS_j) \quad (5.14)$$

$$\Gamma_{j+1} > \gamma_{n,s} \geq \Gamma_j$$

Above SINR $\gamma_{n,s}$ is obtained by Equation (5.5), which is rewritten as:

$$\gamma_{n,s} = \frac{\sum_{m=1}^M A_{m,n} v_{n,s} p_{m,s}^{Tr} \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0 + \sum_{m=1}^M (1 - A_{m,n}) p_{m,s}^{Tr} \left(\frac{d_0}{d_{n,m}} \right)^\alpha} \quad (5.15)$$

7) Transmission power constraint:

$$\gamma_{n,s} \geq \Gamma_j \quad (5.16)$$

8) Variables

$$A_{m,n} \in \{0, 1\} \quad (5.17)$$

$$v_{n,s} \in \{0, 1\} \quad (5.18)$$

$$p_{m,s}^{Tr} \in [0, P_m^{Tr}] \quad (5.19)$$

In the objective function shown in Equation (5.8), $\sum_{m=1}^M A_{m,n} = 1$ means user n is accepted in the network, and a rejection is indicated by $\sum_{m=1}^M A_{m,n} = 0$. Therefore, when the target maximum number of accepted users equals N . The users' QoS requirements are guaranteed by constraint (1). Constraint (2) ensures that each user to be served only by one BS. Constraints (3) and (4) are the upper limits of the number of subcarriers for a network and a BS, respectively. Constraint (5) ensures that each subcarrier of a BS is allocated to one user. Constraint (6) shows the relation between allocated power and modulation schemes. From Equation (5.14), it can be concluded that the SINR ($\gamma_{n,s}$) has to be no lower than Γ_j to support a channel data rate C_j . In (5.15), the SINR ($\gamma_{n,s}$) is controlled by the transmission power from the associated BS and the interference power from other BSs. Constraint (7) defines that the transmission power should yields a receiving SINR (i.e., $\gamma_{n,s}$), which is no less than the minimum required SINR required for the specific modulation/code level.

The above mathematical program is nonlinear and can hardly be exercised for the task of dynamic resource allocation. Therefore, the rest of the chapter focuses on the introduction of

novel heuristics which aim at solving the formulated problem.

5.4 The New RRM Scheme

Although the formulated optimization program can yield a optimal solution, it is not tractable due to its non-linear nature and discrete solution space. Therefore, I turn to the design of a heuristic approach aimed at a systematic approach, that can practically obtain effective solutions. The proposed heuristic approach is performed in two steps. In a nutshell, the first step is for subcarrier allocation, which strategically assigns subcarriers to each user in a BS with the highest possible transmission power, by doing so, the number of accepted calls is in the lower bound; thus, in the second step I try to reduce the transmission power so that each call can be sufficiently supported and possibly accept more calls under the corresponding modulation levels. As a result, an iterative transmission power will be reduced and thereby lead to the following fact: when any BS takes a smaller transmission power, its interferences upon the neighbor BSs are reduced accordingly. Thus, the neighbor BSs can reduce their transmission power, thereby making other BSs capable of reducing their transmissions power.

Based on the above heuristic approach, I design a novel CoMP-based resource allocation scheme, which is denoted as SubOpt and has two stages in total. In the first stage, I enhance the the SFR scheme, and called it Enhanced SFR (SFRE). In the second stage, I try to increase user's SINR by reducing the interference BSs' transmission power, since the user's SINR is increased and a higher MCS is allowed, some subcarriers that were consumed in the first stage can be released and used by the user group that were rejected in the previous stage, at the same time, stage II trims each BS's transmit power to the minimal while supporting the MCS level of each user. The two stages of the proposed heuristic scheme are detailed as follows.

Stage I: Enhanced SFR scheme (SFRE) for subcarriers assignment

Firstly, the proposed heuristic sorts the given calls according to their priorities. The priority

of the calls is determined by the type of service of each user and whether the call is a handover call or a new one. The aim of the first step of proposed heuristic is to accept as many calls in each BS's signal range as possible by estimating the maximum transmission power for each user. Formally, the SINR of user n which is associated with BS m can be calculated by follows:

$$\gamma_{n,m,s} = \frac{P_m^{Tr} \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0 + \sum_{k=1, k \neq m}^M P_k^{Tr} \left(\frac{d_0}{d_{n,k}} \right)^\alpha} \quad (5.20)$$

The channel data rate $c_{n,m,s}$ of user n can be obtained by Equation (5.14). Therefore, the number of subcarriers required by user n can be obtained by follows:

$$s_n^{req} = \left\lceil \frac{R_n^{req}}{B_{sc} \cdot c_{n,m,s}} \right\rceil \quad (5.21)$$

If the total number of subcarriers assigned to all users of a BS is not larger than the number of subcarriers of the BS ($\sum_{n \in m} s_n \leq S$), all users of BS m are accepted, otherwise, some users will be rejected.

The approach adopted in the system tempted to assign subcarriers to each user n ($n = [1, N]$) by the following steps.

Scheme 8 Sub-Optimal CoS Aware Scheme: Stage I

Step 1: Assign user n to BS m with the strongest sensed signal.

Step 2: Initiate interference BSs group \mathbb{I} for each user, which contains all BSs besides the associating BS m , $\mathbb{I} = \{1..i..M | i \neq m\}$. Initiate non-interference BSs group $\mathbb{H}\mathbb{i} = \Phi$. The number of non-interference BSs in the group is 0, $\psi = 0$.

Step 3: Estimate SINR of user n using following equations, which are obtained from Equation (5.20). Suppose the BS m is in the frg_x ($m \in frg_x$)

IF n is an edge user $d_{n,m} > D_c$, $s \subset frg_y$:

$$\gamma_{n,m,s} = \frac{P_e \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in frg_y \& k \in \mathbb{I}} P_c \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha + \sum_{k \notin frg_y \& k \in \mathbb{I}} P_e \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} \quad (5.22)$$

IF n is a central user $d_{n,m} \leq D_c$:

$$\gamma_{n,m,s} = \frac{P_c \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in frg_x \& k \in \mathbb{I}} P_c \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha + \sum_{k \notin frg_x \& k \in \mathbb{I}} P_e \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} \quad (5.23)$$

Step 4: Obtain the channel data rate per subcarrier of user n by $c_{n,m,s} = C_j = C(MCS_j) = f_{mcs}(\gamma_{n,m,s})$. Then, calculate the number of subcarriers to be required to satisfy the data rate requirement of user n by (5.21).

Step 5: Find the highest interference BS i to user n in the interference BSs group \mathbb{I} . Renew the group \mathbb{I} by removing the BS i , $\mathbb{I} = \mathbb{I} - i$. Then add the BS i into non-interference BSs group $\mathbb{H}\mathbb{i} = \mathbb{H}\mathbb{i} \cup i$. Renew the number of non-interference BSs by $\psi = \psi + 1$.

Step 6: Estimate a new SINR ($\gamma'_{n,m,s}$) of the user n from the BSs in the renewed interference BSs group \mathbb{I} by (5.22) and (5.23).

Step 7: According $\gamma'_{n,m,s}$, the channel data rate per subcarrier of user n is obtained by $c'_{n,m,s} = C_j = C(MCS_j) = f_{mcs}(\gamma'_{n,m,s})$. Then, calculate the new number of subcarriers s'_n to be required to satisfy the data rate requirement of user n by (5.21).

Step 8: Compare the subcarriers cost (s_n and s'_n) as follows: Let

$$SC_{\text{cost}} = \frac{s_n^{\text{req}}}{s'_n} \quad (5.24)$$

If

$$SC_{\text{cost}} \geq \psi + \delta, \delta \in [0.7, 1] \quad (5.25)$$

Then $s_n^{\text{req}} = s'_n$ and Goto *Step 5*, Else Goto *Step 9*

Step 9: Check whether BS m has sufficient available subcarriers ($sreq_n$). IF the user is an edge user, SWITCH to Step 9.1. IF the user is a central user, SWITCH to Step 9.2.

Step 9.1: For edge user. Check whether the BS m has enough available subcarriers of frequency group $frgy$. If YES, then GOTO Step 10. If NO, check whether all the frequency groups of the BS m edge have been tried; If YES, then the user will be rejected, If NO, GOTO Step 2, try to use next frequency group.

Step 9.2: For central user. Check whether the BS m has enough available subcarriers. If YES, then GOTO *Step 10*; If NO, set n as an edge user then GOTO *Step 2*.

Step 10: Check whether all non-interference BSs in group \mathbb{H}_i have sufficient available subcarriers (s_n^{req}), AND these available subcarriers must be at same positions.

- YES, then the user will be accepted by BS m . The network updates the subcarriers usage information of the BSs.
 - NO, For edge user: check whether all the frequency groups of the BS m edge have been tried; If YES, then the user will be rejected, If NO, GOTO Step 2, try to use next frequency group. For central user. Set n as an edge user then GOTO Step 2.
-

The first stage yields a tentative solution which can be far from optimal, because some users are granted with more capacity than required. In the second step, all the BSs cooperatively adjust their transmission powers on every subcarrier to reduce the ICI and then accept more users, therefore the rest of the BSs may be able to select higher modulation levels due to reduced ICI. As a result, these BSs can save some free subcarriers for accepting more users who have been rejected in Stage I.

Stage II: Power adjustment and subcarriers reassignment

The above subcarriers assignment stage that estimates maximum transmission power at each BS, certainly achieves the maximum transmission range yet also the maximum interference to adjacent BSs. Therefore it is important to minimize the transmission power to each user in each subcarrier so that the SINR of the corresponding MCS level at the subcarrier can be just supported. With the reduced transmission power at a BS of a subcarrier, the other users that are not associated with the BS may become subject to less interferences at the subcarrier, whereby the users can possibly adopt a higher level of MCS. Alternatively, some rejected users' requirement in Stage I Step 9 can be fulfilled by reassigning the saved subcarriers.

The power adjustment and subcarriers re-assignment process is described as follows:

Scheme 9 Sub-Optimal CoS Aware Scheme: Stage II

Step 1: Initiate a BS group \mathbb{P} , put the BS(s), which have accepted all their associating users, into the group \mathbb{P} . M' is number of BSs in the \mathbb{P} . If $M' = 0$, put a BS, which rejects the least number of demands, into group \mathbb{P} , then $M' = 1$.

Step 2: Reset the transmission power of all BSs in \mathbb{P} . Let j -th MCS is allocated on subcarrier s of BS m ; the minimum SINR to support j -th MCS is Γ_j , which requires minimum transmission power (P^{REQ}). Then the transmission power of BS m allocated to subcarrier s , denoted as $p_{m,s}^{Tr}$, can be reset by following:

- 1: **for all** BS $m \in \mathbb{P}$ **do**
- 2: **for all** subcarrier s of BS m **do**
- 3:

$$P^{REQ} \leftarrow \frac{(1 + \theta)\Gamma_j \times \left(N_0 + \sum_{k=1, k \neq m}^M p_{k,s}^{Tr} \left(\frac{d_0}{d_{n,k}} \right)^\alpha \right)}{\left(\frac{d_0}{d_{n,m}} \right)^\alpha} \quad (5.26)$$

4:

$$p_{m,s}^{Tr} \leftarrow \begin{cases} P^{REQ} & p_{m,s}^{Tr} - P^{REQ} > \epsilon \\ p_{m,s}^{Tr} & \text{otherwise} \end{cases} \quad (5.27)$$

- 5: **end for**
- 6: **end for**

Step 3: If the transmission power on any subcarrier is updated at *Step 2*, then repeat *Step 2*.

Step 4: Try to accept the rejected users of BS m in Stage I:

- 1: **if** $M' = M$ **then**
- 2: FINISH Stage II.
- 3: **else**
- 4: **for all** BS $m \notin \mathbb{P}$ **do**
- 5: **for all** user n associated with BS m **do**
- 6:

$$\gamma_{n,m,s} = \frac{p_{m,s}^{Tr} \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0 + \sum_{k \in \mathbb{I}} p_{k,s}^{Tr} \left(\frac{d_0}{d_{n,k}} \right)^\alpha} \quad (5.28)$$

$$p_{m,s}^{Tr} = \begin{cases} P_e & s \subset \text{edge frequency groups} \\ P_c & s \subset \text{central frequency group} \end{cases}$$

$$p_{k,s}^{Tr} = \begin{cases} P_e & k \notin \mathbb{P}, s \subset \text{edge frequency groups} \\ P_c & k \notin \mathbb{P}, s \subset \text{central frequency group} \\ p_{k,s}^{Tr} & k \in \mathbb{P} \end{cases}$$

7:

$$c_{n,m,s} = C_j = C(MCS_j) = f_{mcs}(\gamma_{n,m,s})$$

8:

$$s_n^{req} = \left\lceil \frac{R_n^{req}}{B_{sc} \cdot c_{n,m,s}} \right\rceil$$

9: **if** $s_m^{rest-frag} \geq s_n^{req}$ **then**
10: user n is accepted;
11: $s_m^{rest-frag} \leftarrow s_m^{rest-frag} - s_n$;
12: **else**
13: user n is rejected;
14: **end if**
15: **end for**
16: **end for**
17: **end if**

$s^{rest-frag}$ means the number of remaining available subcarriers of the frequency group, which the subcarrier s is belonged to.

Step 5: Renew the group \mathbb{P} . Check whether there is some new BS(s) which have accepted all users in Step 4.

- IF YES, put the BS(s) into \mathbb{P} .
- IF NO, put a BS, which rejects least number of demands, into \mathbb{P} .

Update M' , then GOTO Step 2.

5.5 Simulation Results

5.5.1 Simulation Environment

In this section, the performance of the proposed resource allocation scheme are evaluated and compared with the four benchmark schemes. In order to better evaluate the enhanced performance of my subcarriers allocation scheme (SFPE), I introduce the performance of my CoMP resource allocation scheme without and with the power control step respectively. The scheme

Table 5.2: Simulation Parameters Setting

Parameters	T	B (MHz)	P_m^{Tr} (W)	N_0 (W)	α
Value	250	20	20	1×10^{-9}	2.5

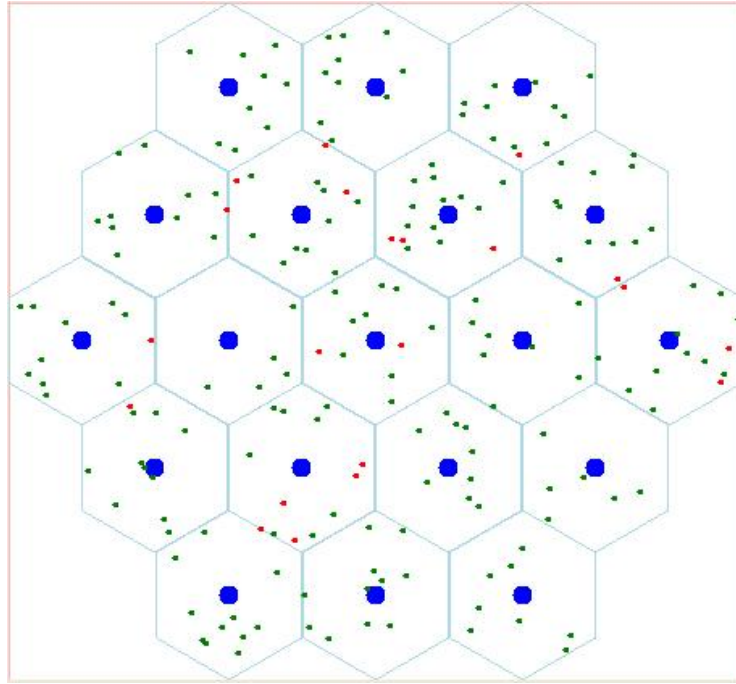
The thermal noise power (N_0) is assumed equivalent at any point in the network.

is denoted as SFPE and SubOpt if without and with power control step respectively. The first and second benchmark schemes are conventional frequency reuse schemes FR1 and FR3, which take the frequency reuse factors (FRF) as 1 and 3 respectively. The third scheme is the partial frequency reuse scheme (denoted as PFR), and the fourth one is the soft frequency reuse scheme (denoted as SFR).

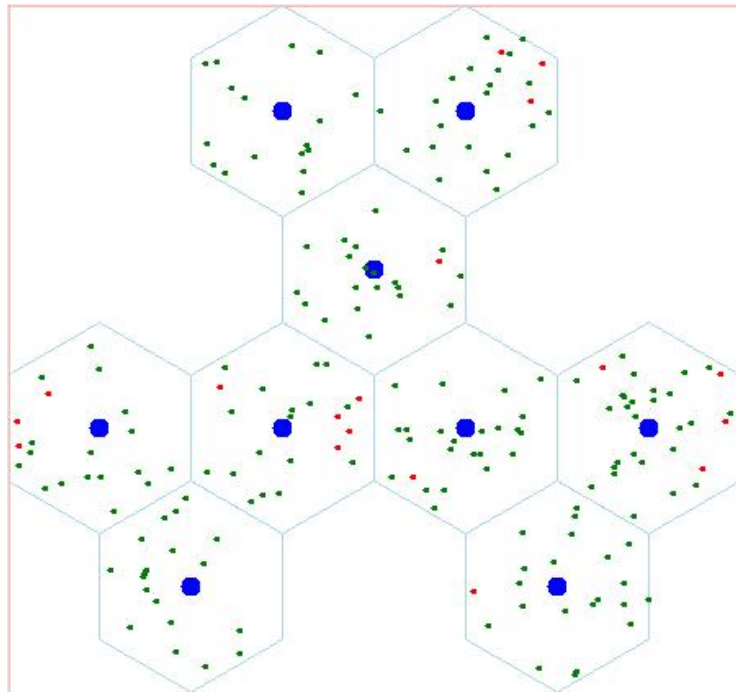
The simulation program was coded in C#, and the simulation was conducted on a computer with Intel Pentium T2390 (1.86 GHz) CPU and 2 GB memory. The performance metrics of interest in the evaluation of the six schemes include the total capacity in terms of the number of rejected demands, total channel usage of each BS, total power usage of each BS, and the computation time to obtain feasible solutions. Without loss of generality, two CO-domain contains 19 cells ($M = 19$) and 9 cells ($M = 9$) with an equal distance of 1000 meters between every pair of adjacent cells as illustrated in Figure 5.1.

The simulation parameters are summarized in Table 5.2. The frequency reuse factors of PFR, SFR, and SFPE are set to 3 to make sure that no conjoined cells are using same frequency sub-band. The assignments of frequency sub-bands are shown in Figure 5.2.

According to Table 5.3, 10 levels of MCS are involved in the simulation. For each simulation trial, the CO-domain is randomly placed with 200 users ($N = 200$), and all the users have a common data rate requirement, which is one of 0.5, 0.75, 1, 1.25, or 1.5 (Mbps). Each data value was obtained by averaging the results of 50 trials based on a resource allocation scheme under a specific scenario of data rate requirement. Figure 5.1 illustrates the user distribution in a simulation trial, the big spots represent the BSs and the small ones represent the users.

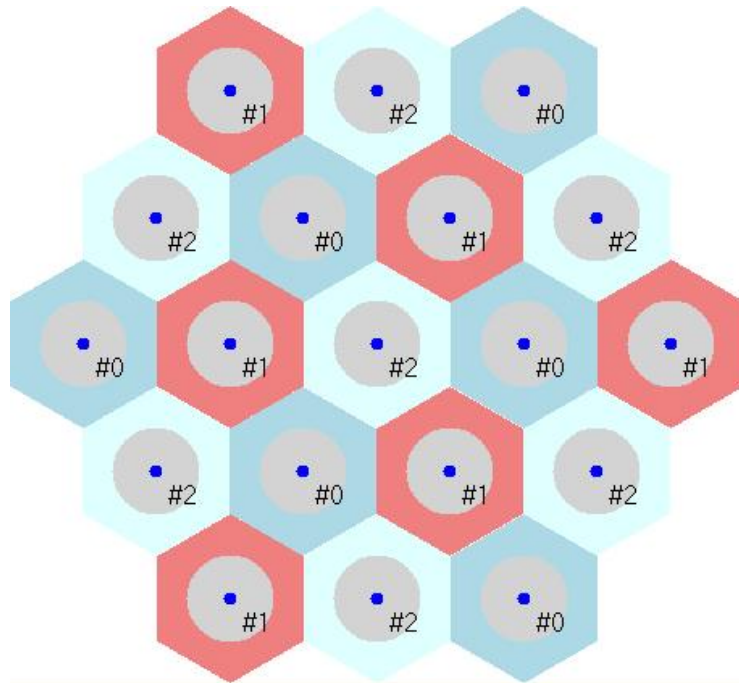


(a) 19 cells

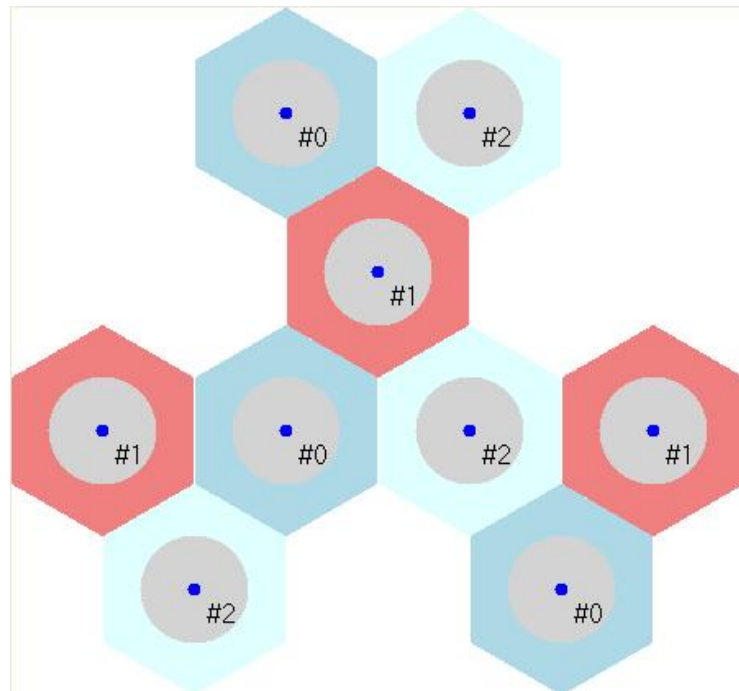


(b) 9 cells

Figure 5.1: A snapshot on the mobile user distribution in the two test networks



(a) 19 cells



(b) 9 cells

Figure 5.2: Assignments of Frequency Sub-bands

Table 5.3: MCS Levels and Related SINR

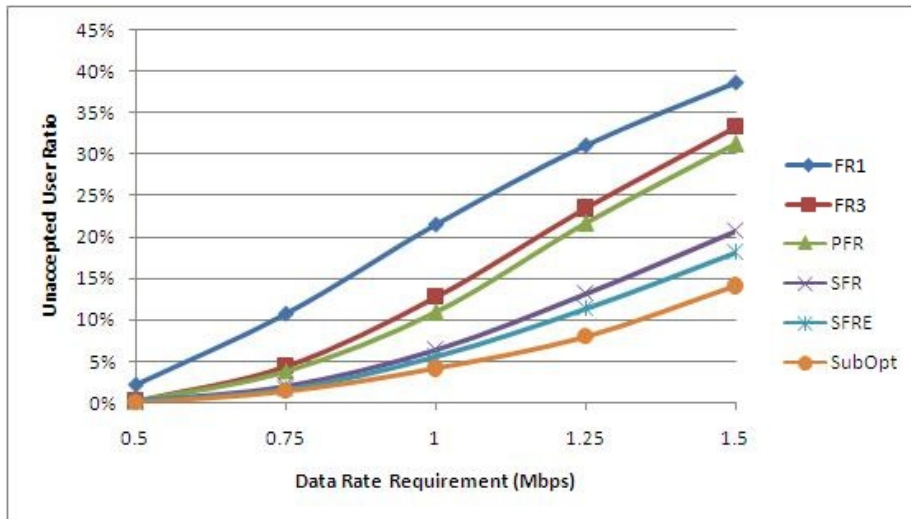
C_j	MCS levels	Rate	SINR
C_1	QPSK 1/2 R6	0.128	0.32
C_2	QPSK 1/2 R4	0.192	0.48
C_3	QPSK 1/2 R2	0.384	0.96
C_4	QPSK 1/2	0.768	1.93
C_5	QPSK 3/4	1.152	4.23
C_6	QAM16 1/2	1.536	7.19
C_7	QAM16 3/4	2.304	18.48
C_8	QAM64 2/3	3.072	48.61
C_9	QAM64 3/4	3.456	62.63
C_{10}	QAM64 5/6	3.84	97.00

The bit error is less than 1×10^{-6} .

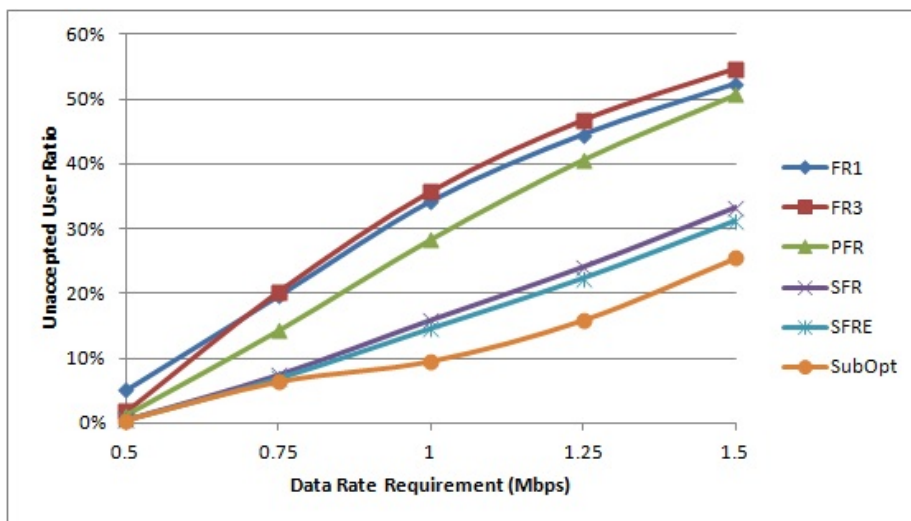
5.5.2 Capacity Performance

In Figure 5.3, I use the percentage of the rejected demands to show the capacity performance of the six schemes. The best performance scheme should reject the least number of demands; in the other words, it can accept the requirements of the largest number of users' thereby the network can yield the highest capacity. By observe Figure 5.3, I find the new resource allocation scheme (SubOpt) rejects the least amount of demands, therefore, it can be concluded that SubOpt has the best capacity performance among the six schemes. In addition, both new schemes outperform the other four existed frequency reuse schemes, FR1 adopts universal frequency reuse strategy thereby can maximum using the bandwidth resource in each cell, yet it causes maximum ICI especially for the users at the cell edge, which reduces the whole network capacity seriously; FR3 sets FRF as 3, which can make sure that each cell has no ICI among all its neighbor cells so that the cell capacity is increased, however, each cell in the network can only occupy 1/3 bandwidth. PFR and SFR are improved from FR schemes, PFR fails to involve some sub-band frequency for ICI mitigation to edge user, therefore it doesn't use full spectrum. However SFR uses fixed power control and frequency planning for the edge user, so full available frequency is used. Figure 5.3 shows that SFR outperforms PFR, which is result from the fact that SFRE is

improved from SFR by adding a dynamic coordinate ICI mitigation mechanism among the BSs, so more users can be accepted than SFR. At the same time, as shown in Figure 5.4, SFRE costs the least subcarriers among the six schemes, the SubOpt scheme uses SFRE in Stage I and a dynamic power control scheme in Stage II, as a result, SubOpt not only efficiently use spectrum, but also decline the effect of ICI, therefore it has the best capacity performance. However, in order to accept more users, it costs more subcarriers than the SFRE scheme.

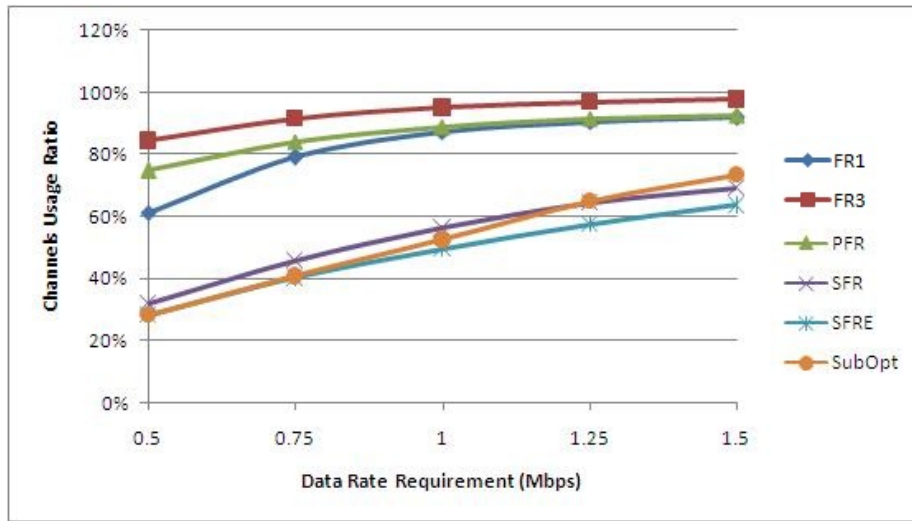


(a) 19 cells

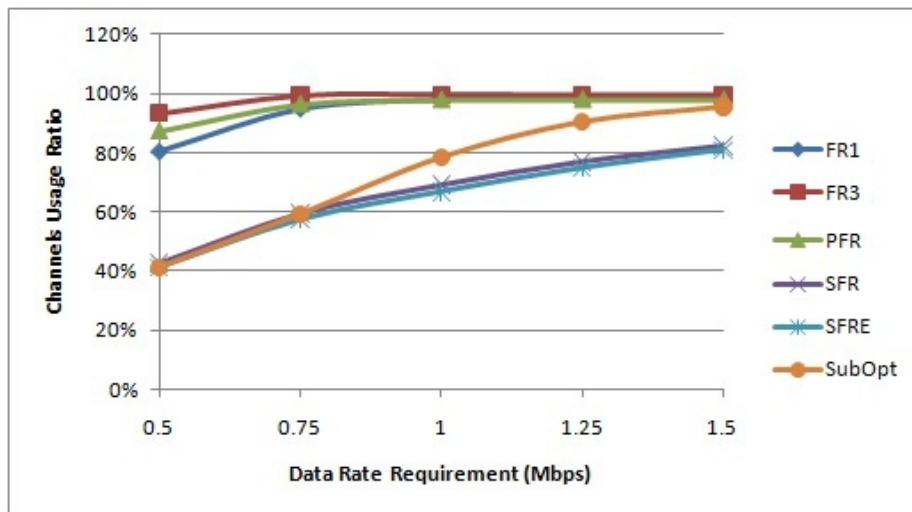


(b) 9 cells

Figure 5.3: Percentage of Rejected Demands



(a) 19 cells



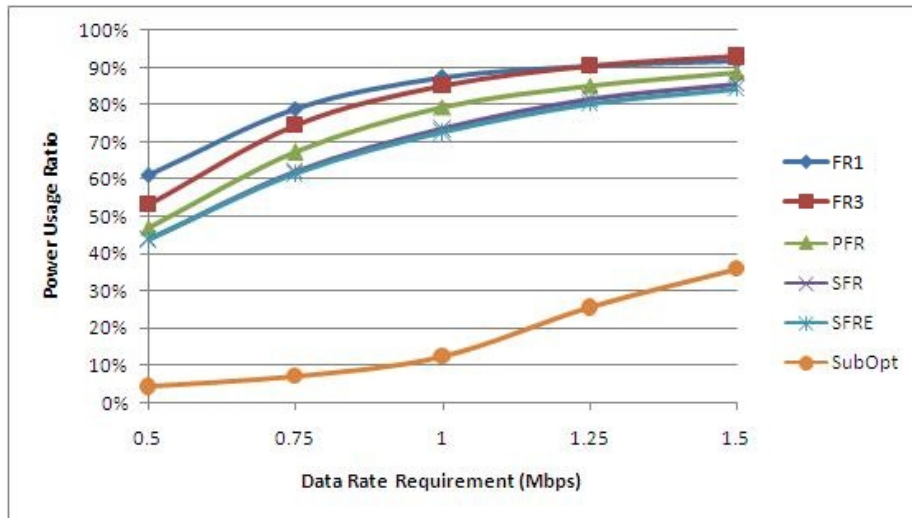
(b) 9 cells

Figure 5.4: Percentage of Subcarriers Usage

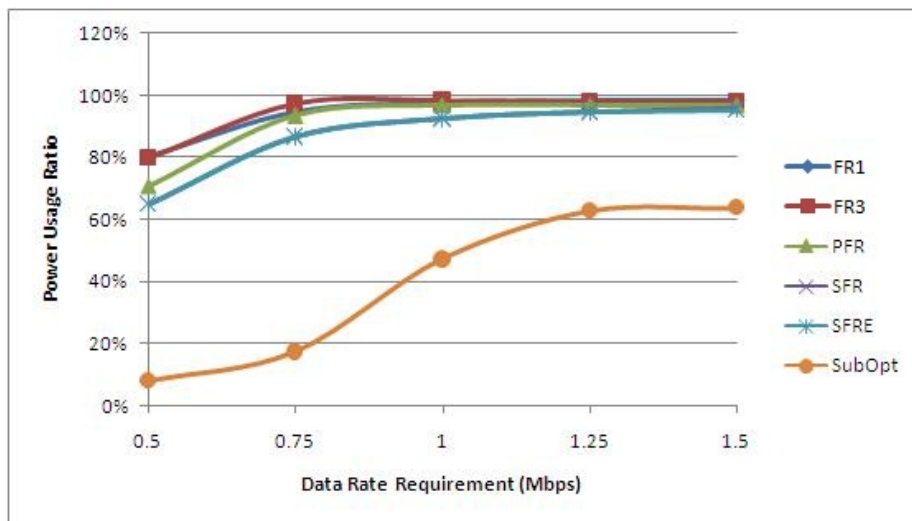
5.5.3 Power Usage Performance

By observing Figure 5.5, it can be concluded that the power usage performance of SubOpt is much better than other five schemes, as SubOpt employs a power control stage, which has effectively reduced the transmission power usage by more than 60%. In contrast, the other five

schemes adopt fixed transmission power, and their power consumptions are proportional to their subcarrier consumptions.



(a) 19 cells

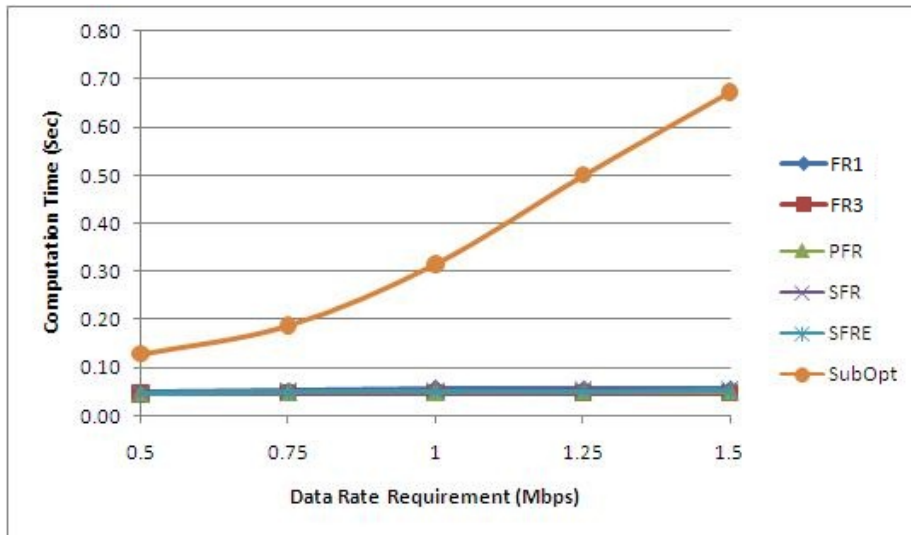


(b) 9 cells

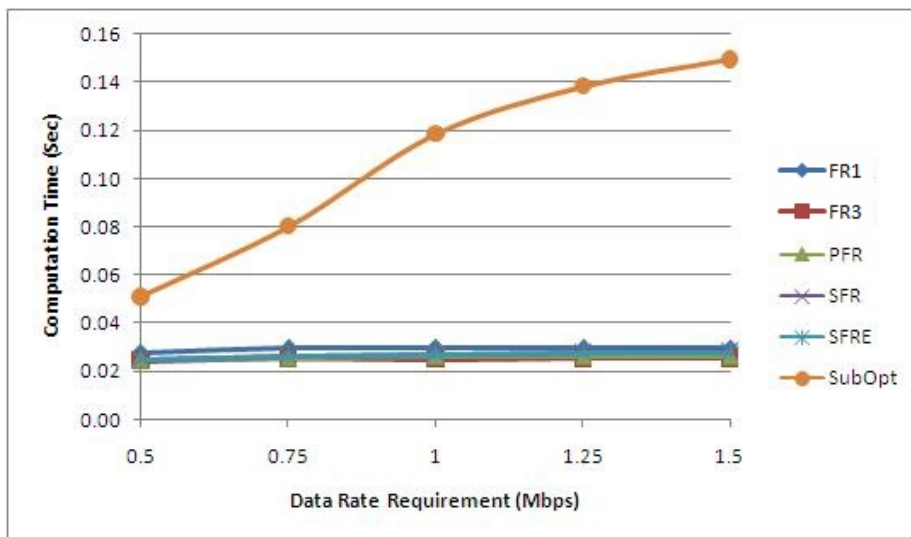
Figure 5.5: Percentage of Power Usage

5.5.4 Computation Time

The performance of computation efficiency for each scheme is shown in Figure 5.6. The observation results are summarized as follows. 1) The SubOpt scheme involves slight more computation time than the other five schemes due to its power control stage. 2) The computation complexities of all the other five schemes, including FR1, FR3, PFR, SFR, and the new SFRE scheme, are similar. 3) From Figure 5.3 and Figure 5.6, it can be found that when the data rate requirement increases, the rejected number of demands increases, thereby the computation time of SubOpt also increases. The reason for the above results is that the Stage II of SubOpt would take more time in the consideration of admitting those originally rejected demands, if the number of rejected demands increases. Overall, the proposed SubOpt scheme can yield a valid solution to the proposed resource allocation problem in a short time, and it is subject to very low computation complexity for supporting numerous users in a CO-domain.



(a) 19 cells



(b) 9 cells

Figure 5.6: Computation Time

5.6 Chapter Conclusion

This chapter has investigated resource allocation for OFDM-FMDA cellular networks with fully exploring ICI mitigation. Firstly I formulated the proposed resource allocation problem into a nonlinear optimization problem which is nonetheless subject to very high computation complexity. Then I turned to heuristic approach, through which the resource allocation problem can be divided into two sub-tasks referred as subcarrier assignment and AMC-based power control. The two tasks are solved sequentially and iteratively until convergence is achieved, thereby the complex relation between the two tasks can be effectively resolved. Based on the heuristics, I present a new heuristic CoMP resource allocation scheme for OFDM-FMDA wireless networks. Simulation results showed that the network capacity can be significantly increased by compare the new scheme with four conventional schemes, FR1, FR3, PFR, and SFR. Specifically, the transmission power of each BS can be significantly reduced in the power control stage, which therefore effectively reduces the inter-cell interference. Overall, I conclude that the proposed scheme is expected to contribute to real-time resource allocation operations in practical cellular networks.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

RRM scheme is a critical component of next generation mobile broadband network for efficiently utilizing the limited wireless network resources. In addition, the CoMP technology is a key technology of next generation mobile broadband network for extending coverage, increasing capacity, and improving spectral efficiency. This thesis has investigated the problem of radio resource management issue for CoMPNet, in which inter-cell CT technology or CoS technology is incorporated.

Firstly, I have investigated CT aware RRM schemes. I have provided three new CT aware RRM schemes for the OFDM-TDMA based CoMPNet, and studied how the mobility of users affects the RRM. I have proposed three CT aware RRM schemes for three different kinds of users with three different moving speeds. I have introduced a novel optimization frame-work for adaptive control in terms of RRM for SSs in the OFDM-FDMA based CoMPNet. I have compared the performance of the proposed RMM schemes against that with conventional NCT technology. The simulation results have shown that network capacity and resource usage efficiency can be increased with the CT aware RRM schemes. It has also been found that the new RRM schemes

can be conducted adaptively at the CO so that network resource utilization can be achieved in a cost-effective manner.

Secondly, I have investigated the CoS aware RRM schemes. I have formulated the resource allocation into non-linear programming under multi-cell collaboration with the objective to maximize network capacity. For OFDM-FDMA mode, I have presented a new heuristic CoS aware RRM scheme with subcarrier assignment stage and AMC-based power control stage. Simulation results show that the network capacity can be significantly increased with the new CoS aware RRM scheme compared with the conventional FR schemes without CoS technology. Because of the AMC based power control mechanism, my new scheme can save more than 50% transmission power.

6.2 Future Work

For future research, the resource utilization efficiency of the next generation mobile broadband network can be improved if a full CoMP aware RRM scheme is designed, considering CT with CoS together rather than separately. The main challenge of the design of the full CoMP aware RRM scheme is how to adaptively choose CT or CoS, based on different CSI and user's requirements.

The next generation mobile broadband network adopts smart antenna technology [57] [58], such as MIMO and beamforming, to increase spectral efficiency. Since the CoMP technology is independent of the smart antennas technologies, the CoMP aware RRM schemes can be directly used in a next generation mobile broadband network with the smart antennas technologies. However, to fulfill network level simulation and evaluate the RRM schemes close to the real network, I have to practically implement the algorithms considering smart antenna technologies, multiple sectors network structure, and the antenna pattern of direction antennas in my future work.

The effect of adopting the proposed schemes in a specific application, such as file transfer,

VoIP, and IPTV, will certainly be promising and critical to the design of more dynamic and short-term scheduling schemes, which will also be one of the research topics in my future work.

APPENDICES

Appendix A

Non-CT RA Schemes

A.1 Multi-user Optimization Model for Non-CT (NCT_LP)

The non-CT multi-user model is aimed to minimize the total time slot consumption of the BSs in a conventional wireless access networks, in which the CT technology is not preferred. The objective can be expressed through the following formula:

$$\text{minimize } \sum_{m=1}^M \sum_{n=1}^N T p_{mn} \quad (\text{A.1})$$

which is subject to the following constraints:

1) Total time slot constraint

$$\sum_{n=1}^N T p_{mn} \leq 1, \forall m = 1 \dots M \quad (\text{A.2})$$

2) Data rate requirement of each user

$$R_n \geq R_n^{\text{Req}}, \forall n = 1 \dots N \quad (\text{A.3})$$

R_n can be obtained from equations (3.1) to (3.4), and (3.8), which can also be expressed as follows:

$$R_n = B \times T p_{mn} \times \log \left(1 + \frac{P_{mn}^r}{N_0 + \sum_{k=1, k \neq m}^M P_{kn}^r} \right) \geq R_n^{\text{Req}} \quad (\text{A.4})$$

$$\forall n = 1 \dots N$$

3) Non-CT Constraint, that only one BS associates a user

$$\sum_{m=1}^M A_{mn} = 1 \quad (\text{A.5})$$

$$A_{mn} - T p_{mn} \geq 0$$

4) Variables

$$T p_{mn} \in [0, 1] \quad (\text{A.6})$$

$$A_{mn} \in \{0, 1\} \quad (\text{A.7})$$

Constraint (A.2) ensures that the total allocated time slot to each user is no larger than the total time slot of one BS. Constraint (A.3) makes sure that the data rate requirement of each user must be satisfied. Constraints (A.5) and (A.1) limit one user can only be associated by one BS. Constraints (A.6) and (A.7) state the boundaries of the decision variables. Due to the nonlinearity of equation (A.4), the formulation is a mixed integer nonlinear program (MINLP), which cannot

be solved by any systemic approach, therefore, I reformulate it with a linearization approach (A.17), as expressed as follows:

$$R_n = \sum_{m=1}^M (T p_{mn} \times (B \times LOG_SINR_{mn})) \geq R_n^{\text{Req}} \quad (\text{A.8})$$

$$\forall n = 1 \dots N$$

$$LOG_SINR_{mn} = \log \left(1 + \frac{P_{mn}^r}{N_0 + \sum_{k=1, k \neq m}^M P_{kn}^r} \right) \quad (\text{A.9})$$

A.2 Single User Optimal Model for Non-CT (H_NCT_LP)

The goal of first single user optimal scheme is to minimize the time slot consumption to satisfy the new arrival user in a conventional wireless network. The objective can also be formulated as follows:

$$\text{minimize } \sum_{m=1}^N T p_{mn} \quad (\text{A.10})$$

Constraints: 1) The associating BS should have enough free time slot

$$T p_{mn} \leq F_m \quad (\text{A.11})$$

2) Data rate requirement of the new user

$$R_n = \sum_{m=1}^M (T p_{mn} \times (B \times \text{LOG_SINR}_{mn})) \geq R_n^{\text{Req}} \quad (\text{A.12})$$

3) Non-CT Constraint, that only one BS associates a user

$$\sum_{m=1}^M A_{mn} = 1 \quad (\text{A.13})$$

$$A_{mn} - T p_{mn} \geq 0$$

4) Variables

$$T p_{jn} \in [0, 1] \quad (\text{A.14})$$

$$x_{jn} \in \{0, 1\} \quad (\text{A.15})$$

The user will be rejected, if LP is no solution.

A.3 Single User Heuristic Model for Non-CT (H_NCT))

The following are the three steps for a conventional wireless network associate a new user:

Step 1: Find the associating BS m which has the minimum distance (d_{min}) to the user.

Step 2: Calculate the amount of time slot ($T p_n$) to be allocated to the user by following formula.

$$T p_n = \frac{R_n}{B \times LOG_SINR_{mn}} \quad (A.16)$$

LOG_SINR_{mn} is obtained by (A.9).

Step 3: If BS m has enough time slot ($F_m \geq T p_n$), then the n th user will be associated by the m th BS successfully, the time slot usage information is updated as follows:

$$T S_m = W_m + T p_n \quad (A.17)$$

$$F_m = F_m - T p_n \quad (A.18)$$

On the other hand, the requirement of the user n will be rejected if BS m doesn't have enough time slot ($F_m \leq T p_n$).

Appendix B

Frequency Reuse Subcarriers Allocation Schemes

Frequency reuse based resource allocation schemes are the traditional ICI mitigation solutions for resource allocation problem, and most dynamic resource allocation schemes are based on the frequency reuse schemes. The first step of my scheme is improved from soft frequency reuse (SFR) scheme. Here 4 kinds of frequency reuse subcarriers allocation schemes will be reviewed for OFDM-FMDA system. The four schemes are universal frequency reuse scheme (FR=1), reuse 3 scheme (FR=3), partial frequency reuse (PFR), and soft frequency reuse (SFR).

B.1 Traditional Frequency Reuse (FR=X)

Full bandwidth (B) is divided into X ($X \in [1, M]$) sub-band ($B_X = B/X$), which means the frequency reuse factor (FRF) is X . Each BS is assigned one of the sub-band. The BSs using the same sub-band are defined in the same frequency reuse group (frg_x), therefore, there are X frequency reuse groups in a FR= X frequency reuse scheme. The interference only exists among the BSs in the same frg_x . Generally, neighbor BSs belongs to different $frgs$ for making sure there

is no interference between the neighbor cells. Suppose BS m is in the frg_x , denoted as $m \in frg_x$, and the subcarrier s in the sub-band of frequency group x is denoted as $s \in frg_x$. Following are the steps of traditional FR resource allocation scheme.

Step 1: Assign user n to its closest BS m .

Step 2: Estimate the SINR of the user n by (B.2) which is obtained from (5.3). The BS m uses maximum transmission power (P_m^{Tr}). The transmission power is evenly allocated to all the available subcarriers in a frg . So I have equation (B.1); $\frac{S}{X}$ is the number of subcarriers in the sub-band of frg_x .

$$p_{m,s}^t = \rho_s = P_m^{Tr} / \left(\frac{S}{X}\right) \quad (\text{B.1})$$

And assume the user is interfered by the maximum transmission power from other BSs in the same frg_x , $p_{k,s}^t = \rho_s, \forall k \in frg_x$, I can get following:

$$\gamma_{n,m,s} = \frac{\rho_s \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in frg_x} \rho_s \left(\frac{d_0}{d_{n,k}}\right)^\alpha} \quad (\text{B.2})$$

Step 3: According the SINR, the correlative rate per subcarrier of user n is obtained by $c_{n,m,t} = C_j = C(MCS_j) = f_{mcs}(\gamma_{n,m,s})$. Then, calculate the number of subcarriers (s_n^{req}) to be required to satisfy the data rate requirement of user n by (5.21).

Step 4: Check if the associating BS m has enough available subcarriers. If YES, then the user will be associated by the BS m , update subcarriers usage information of the BS at CO; if NO, the user's requirement will be rejected.

The simplest frequency reuse scheme is to use a reuse factor of 1 (FR=1) shown in Fig. B.1a, i.e. to assign all subcarriers to each cell, which is also call universal frequency reuse. In the universal FR scheme, the SINR of the user n can be estimated by (B.3), however, high inter-cell

interference is observed especially at cell edges from (B.3).

$$\gamma_{n,m,s} = \frac{\rho_s \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0 + \sum_{k=1, k \neq m}^M \rho_s \left(\frac{d_0}{d_{n,k}} \right)^\alpha} \quad (\text{B.3})$$

Another scheme is a non-reuse approach, i.e. $FRF = M$. According to this scheme, any subcarrier in one CO-Domain can only be allocated one time. The SINR of the user n can be obtained by (B.4), so that each subcarrier of a BS has no interference from any other BS. This scheme leads to low interference within a CO-domain, however it costs a price of a large capacity loss since $1/M$ spectrum resources can only be used in each cell.

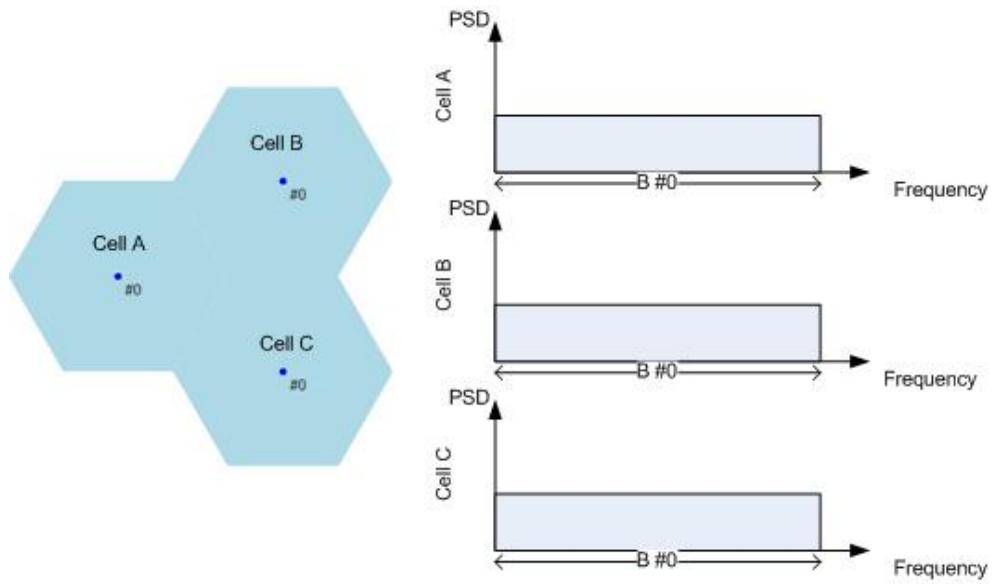
$$\gamma_{n,m,s} = \frac{\rho_s \left(\frac{d_0}{d_{n,m}} \right)^\alpha}{N_0} \quad (\text{B.4})$$

In the cellular network, the classical interference avoidance scheme is a tradeoff of above two schemes, called reuse 3 scheme ($FR=3$), which divides the frequency into 3 equal sub-bands. As shown in Fig. B.1b, the reuse 3 scheme can promise that all adjacent cells can always use different frequencies, so that no interference will be existed between any two neighbor cells.

The reuse 3 scheme has been used as a benchmark of my schemes. The following two improved FR schemes, PFR and SFR, are also based on the reuse 3 scheme.

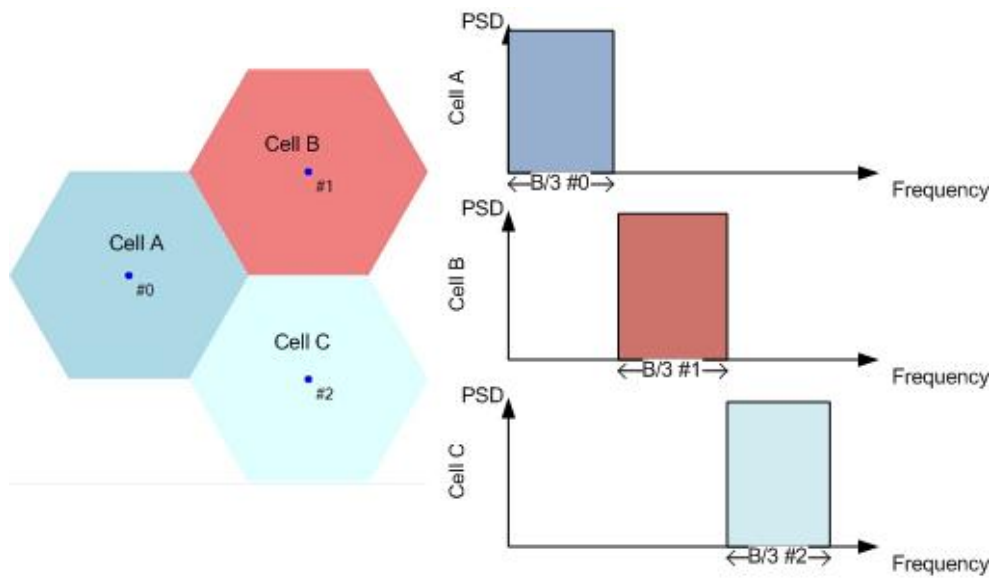
B.2 Fractional Frequency Reuse

Fractional frequency reuse (FFR) is a kind of enhanced frequency reuse (FR) scheme, which involves partitioning the network spectrum into a number of sub-bands and assigning a given sub-band to each cell after carefully designed frequency planning and transmission power allocation that minimize intercell interference. Two improvement versions of FFR, soft frequency reuse



FRF=1

(a) FR=1



FRF=3

(b) FR=3

Figure B.1: Traditional Frequency Reuse Schemes

(SFR) and partial frequency reuse (PFR) are elaborated below.

B.2.1 Partial Frequency Reuse (PFR)

Partial Frequency Reuse (PFR), a variation of FFR, employs zone-based reuse factors in central and edge areas, shown in Fig. B.2. The full system bandwidth is also divided into general sub-band and special sub-band. The general sub-band can only be used by central users and the reuse factor is 1, in contrast, reuse factor of special sub-band is $X (X > 1)$, normally $X = 3$. As a result, each cell can only use $1/X$ special sub-band, and the edge users can only use special sub-band.

PFR assigns general sub-band channels first, then the special sub-band channels for the central users. On the other hand, for the edge users, only special sub-band is assigned automatically, yet he general channels can be assigned to the edge users, if there are redundant general sub-band channels left after accepted all central users.

A fixed power control scheme can be employed in the PFR scheme. Specifically, allocate the lower transmission power to the general sub-band and the higher power to the special sub-band.

Step 1: Assign user n to its closest BS m . If the distance between n and m ($d_{n,m}$) is no more than the range of BS central area (D_c) ($d_{n,m} \leq D_c$), n is set as a central user; otherwise ($d_{n,m} > D_c$), n is set as an edge user.

Step 2: Estimate the SINR of the user n by (B.5). All BSs transmit signal by edge transmission power (P_e) on each subcarrier to the edge user; and use central transmission power (P_c) for the central user

$$\gamma_{n,m,s} = \begin{cases} \frac{P_e \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in \text{frg}_x}^M P_e \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} & \text{edge user: } d_{n,m} > D_c \\ & m \in \text{frg}_x \\ \frac{P_c \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k=1, k \neq m}^M P_c \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} & \text{central user: } d_{n,m} \leq D_c \end{cases} \quad (\text{B.5})$$

Step 3: According to the SINR ($\gamma_{n,m,s}$), I can get which the MCS order can be used for the user n and get the normalized data rate by $c_{n,m,s} = C_j = C(MCS_j) = f_{mcs}(\gamma_{n,m,s})$. Then, calculate the number of subcarriers to be required to satisfy the data rate requirement of user n by (5.21).

Step 4: Check whether the BS m has enough available central subcarriers. If YES, then the user will be accepted by the BS m , update subcarriers usage information of the BS; if NO and n is a central user, set it as an edge user then GOTO step 2; OTHERWISE rejects the user n .

Notice: suppose the number of subcarriers of a BS prepared for edge users is S_e , the number of subcarriers per BS prepared for central users is S_c ; and the frequency reuse factor is X . Then I have following equations.

$$S = S_c + X \times S_e \quad (\text{B.6})$$

$$P_m^{Tr} = S_e \times P_e + S_c \times P_c \quad (\text{B.7})$$

B.2.2 Soft Frequency Reuse

Contrary to PFR, the idea of the soft frequency reuse (SFR) is to use all of the resources so that the whole spectrum can be used in every cell; it also employs zone-based reuse factors in the cell-centre and the cell-edge areas. In addition, it uses the FR3 scheme in the cell-centre area and the rest frequency in the cell-edge area, as shown in Fig. B.3.

Secondly, lower power is used for the centre users, who are affected by lower ICI, and at the same time it causes lower ICI to the neighbor cells; on the other hand, the edge users have higher power, which is required to resist higher ICI.

Step 1: Assign user n to its closest BS m . If the distance between n and m ($d_{n,m}$) is no more than the range of BS central area (D_c) ($d_{n,m} \leq D_c$), n is set as a central user; otherwise

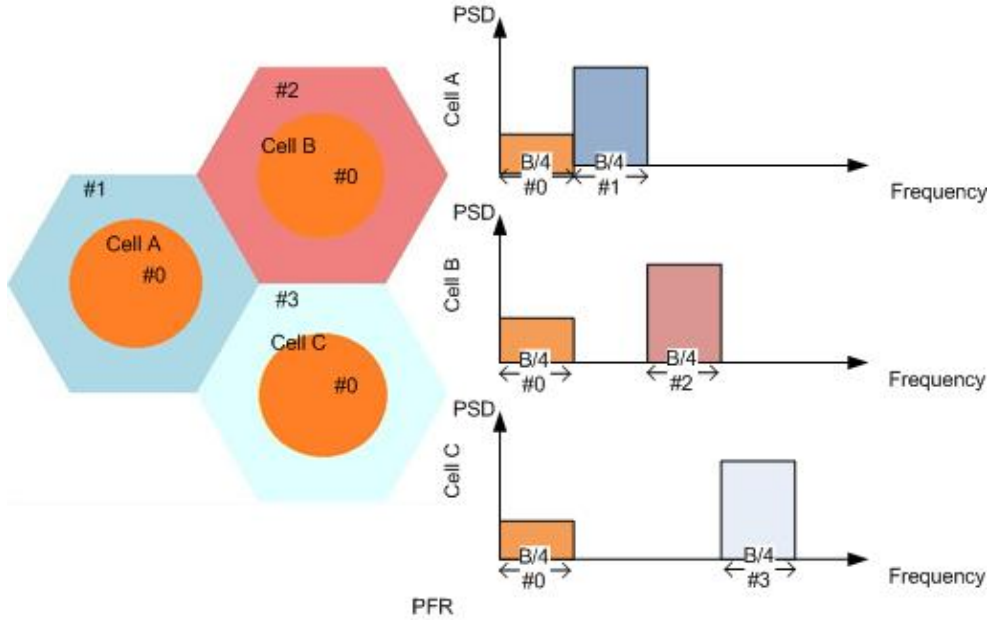


Figure B.2: Partition Frequency Reuse (PFR)

$(d_{n,m} > D_c)$, n is set as an edge user.

Step 2: Estimate the SINR of the user n by (B.8). Suppose the BS m is in the frg_x ($m \in frg_x$), which means the central users of BS m is using the sub-band of frg_x . For the central user, all BSs use the central transmission power (P_c) on each subcarrier. For the edge user, BS transmits signal by edge transmission power (P_e). And there are two kinds of interference signals, according to the subcarrier selection. Suppose the selected subcarrier is included in the frequency reuse group frg_y ($s \in V$), and $frg_y \neq frg_x$; then the interference transmission power from the BS k , which is in the group V ($k \in V$), is the central transmission power (P_c), and the interference power from the BS (k), which is not in the group V ($l \notin V$), is the edge transmission power (P_e)

$$\gamma_{n,m,s} = \begin{cases} \frac{P_e \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in frgy} P_c \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha + \sum_{k \notin frgy} P_e \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} & \begin{array}{l} \text{edge user:} \\ d_{n,m} > D_c \\ s \subset frgy \end{array} \\ \frac{P_c \cdot \left(\frac{d_0}{d_{n,m}}\right)^\alpha}{N_0 + \sum_{k \in frgx} P_c \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha + \sum_{k \notin frgx} P_e \cdot \left(\frac{d_0}{d_{n,k}}\right)^\alpha} & \begin{array}{l} \text{central user:} \\ d_{n,m} \leq D_c \end{array} \end{cases} \quad (\text{B.8})$$

Step 3: According to the SINR ($\gamma_{n,m,s}$), I can get which the MCS order can be used for the user n and get the normalized data rate by $c_{n,m,s} = C_j = C(\text{MCS}_j) = f_{mcs}(\gamma_{n,m,s})$. Then, calculate the number of subcarriers to be required to satisfy the data rate requirement of user n by (5.21).

Step 4: IF the user is an edge user, SWITCH to Step 4.1. IF the user is a central user, SWITCH to Step 4.2.

Step 4.1: For edge user. Check whether the BS m has enough available subcarriers of frequency group V . If YES, then the user will be accepted by the BS m , update subcarriers usage information of the BS; If NO, check whether all the frequency groups of the BS m edge have been tried; If YES, then the user will be rejected, If NO, GOTO Step 2, try to use next frequency group.

Step 4.2: For central user. Check whether the BS m has enough available subcarriers. If YES, then the user will be accepted by the BS m , update subcarriers usage information of the BS; If NO, set n as an edge user GOTO Step 2.

Notice: suppose the frequency reuse factor is F . All subcarriers are evenly allocated to each frequency reuse group. Then I have following equations. S_{frg} is the number of subcarriers of a frequency reuse group

$$S_{frg} = S/F \quad (\text{B.9})$$

$$P_m^{Tr} = (F - 1) \times S_{frg} \times P_e + S_{frg} \times P_c \quad (\text{B.10})$$

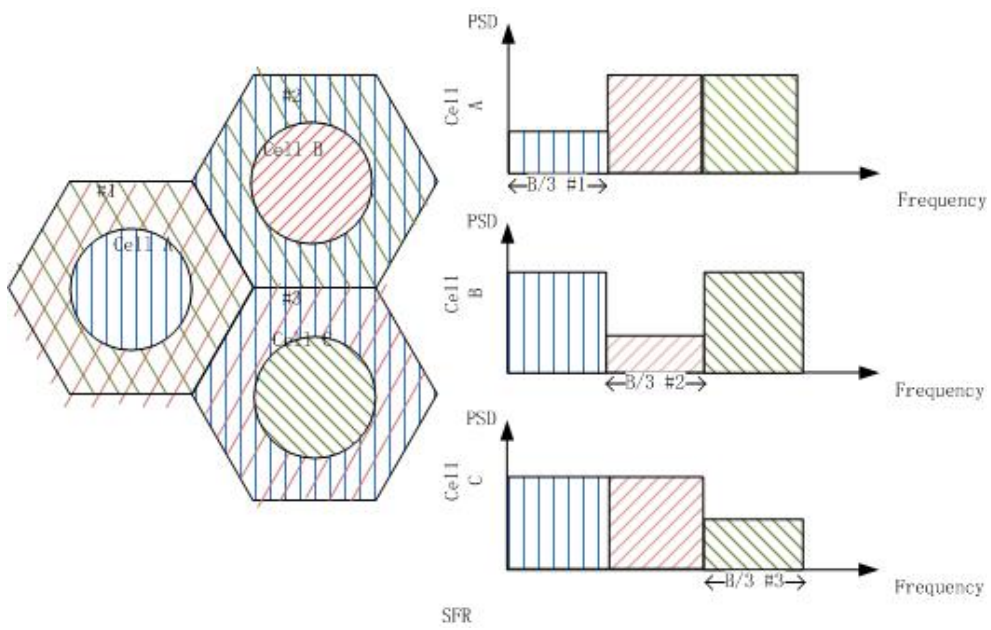


Figure B.3: Soft Frequency Reuse (SFR)

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