Optimal Resource Allocation, ACI Effect and Optimal SINR-Threshold in FFR for LTE Uplink

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Rajeev Kumar

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Prof. Krishna Jagannathan

and

Prof. Giridhar K

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INDIAN INSTITUTE OF TECHNOLOGY MADRAS

CHENNAI-600036

CERTIFICATE

This is to certify that the thesis titled **"Optimal Resource Allocation, ACI Effect and optimal SINR-Threshold in FFR for LTE Uplink",** submitted by Mr. Rajeev Kumar, to the Indian Institute of Technology Madras, Chennai for the award of the degree of Bachelor of Technology and Master of Technology, is bonafide record of research work done by him under my supervision. The contents of the this thesis, in full or parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. Krishna Jagannathan
Project Guide
Assistant Professor
Dept. of Electrical Engineering
IIT-Madras, Chennai-600036

Dr. Giridhar K
Project Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, Chennai-600036

Place: Chennai

Date: 8^{th} May 2013

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Abstract

Long Term Evolution (LTE) is a cellular technology development to support diversity of data traffic at potentially high rate. It has improved the performance of wireless communication system. In this thesis, a fairness based weighted resource allocation scheme has been studied in Single Carrier Frequency Division Multiple Access (SC- FDMA) system. SC-FDMA is the uplink multiple access scheme considered in the Third Generation Partnership project-Long Term Evolution (3GPP-LTE) standard. Unlike Orthogonal Frequency Division Multiple Access (OFDMA) resource allocation, SC-FDMA uses *exclusivity* and *adjacency* constraints in PRB allocation. To maximize the weighted system capacity of the network, an optimal solution based on binary linear program along with one sub-optimal allocation based on Hungarian algorithm is implemented for frequency reuse one. Optimal physical resource allocation algorithms are able to achieve a high throughput and spectrum efficiency as compare to random PRB allocation. However, while considering out-of-band or adjacent channel interference (ACI), average throughput decreases significantly, Which can be mitigate using proposed heuristic algorithm to maximize throughput.

Aggressive reuse of frequency spectrum and use of small cell to support high data rate results in an increase in the multi-cell OFDMA networks, especially inter-cell interference. Inter-cell interference can severely degrade system throughput, particularly for cell-edge users. To mitigate the effect of inter-cell interference, inter-cell interference coordination (ICIC) is proposed and well studied in literature. ICIC techniques tackles problem by mean of radio resource allocation or scheduling algorithm. In this thesis effect of fractional frequency reuse and soft frequency reuse for round robin scheduling are studied. For Strict fractional frequency reuse we have obtained an optimal value for SINR-threshold, which maximizes average throughput of the cell. Moreover, effect of number of users in cell on SINR-threshold and throughput is also studied for Strict FFR, where two scheduling scheme– round robin and maxrate is considered. For all the implemented nineteen multi-sector cell with three sectors per cell and fractional power control is considered.

Contents

List of Tables

List of Figures

ABBREVIATION

ACI	Adjacent Channel Interference
BIP	Binary Integer Program
CDF	Commutative Distribution Function
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DFT	Discrete Fourier Transform
DwPTS	Downlink Pilot Time Slot
EDGE	Enhanced Data for GSM
eNodeB	Evolve Node Base Station
FBMC	Filter-bank Based Multi Carrier Transmission
FDD	Frequency Division Duplex
FDMA	Frequency-Division Multiple Access
FFR	Fractional Frequency Reuse
FM	Frequency Modulation
FPC	Fractional Power Control
GPRS	General Packet Radio Service
GSM	Global Systems for Mobiles
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
ICI	Inter Cell Interference
ICIC	Inter Cell Interference Coordination
IDFT	Inverse Discrete Fourier Transform
IMT	International Mobile reference Telecommunication
ITU	International Telecommunication Union
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
OBI	Out-of Band Interference
OFDM	Orthogonal Frequency Division Multiplexing

OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PRB	Physical Resource Block
PSD	Power Spectral Density
PU	Primary User
RR	Round Robin
RS	Resource Set
SC-FDMA	Single Carrier Frequency-Division Multiple Access
SFR	Soft Frequency Reuse
SINR	Signal to Interference plus Noise Ratio
SISO	Single Input Single Output
SU	Secondary User
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time-division Multiple Access
TTI	Transmission Time Interval
UE	User Equipments
UMTS	Universal Mobile Telecommunication System
UpPTS	Uplink Pilot Time Slot

CHAPTER 1

1 INTRODUCTION

1.1 Background

The first-generation cellular wireless communication system was developed to support voice calling using analog communication techniques, and it was mainly built by means of frequency modulation (FM) and frequency-division multiple access (FDMA) techniques. In second-generation cellular wireless communication systems digital communication techniques were used, which improved spectral efficiency significantly. They also improved quality of voice calling and made possible the packet data transmission. Time-division multiple access (TDMA) and code-division multiple access (CDMA) evolve as main multiple access schemes. Evolved 2G systems are GSM (Global Systems for Mobiles), CDMA, General Packet Radio Service (GPRS) and Enhanced Data for GSM (EDGE). GSM and CDMA supports 10 Kbps voice calling, GPRS supports 10 Kbps voice calling and 50 Kbps data rate and EDGE can support 10 Kbps voice calling and 200 Kbps of data rate. To support high data rate for video calling, voice and data 3G systems evolved. The concept of 3G was first brought up in mid-1980s, as International Mobile reference Telecommunication-2000 (IMT-2000) was brought up at International Telecommunication Union (ITU)[1]. IMT-2000 made two standards, as Universal Mobile Telecommunication System/Wideband CDMA (UMTS/WCDMA), which evolved as 3.5G. WCDMA is able to support 384Kbps data rate, evolved 3.5G (HSDPA/HSUPA) is capable to support 5-30 Mbps. Later to support different services like on-line gaming, real time HD tv, voice, data, video calling and many more 3GPP came up with Long Term Evolution (LTE). LTE is capable of data rate of 100 Mbps in uplink and 50 Mbps in downlink. Orthogonal Frequency division multiple access (OFDMA) is chosen as multiple access scheme.

1.2 Motivation

In present scenario wireless communication systems have ambitious requirement for data rate, latency, capacity and spectrum efficiency. Wireless system depends upon concepts and technology innovation in architecture and efficient utilization of spectral resources. In order to fulfill this demand wireless communication system has gone through many generations. To fulfill future demands of users 3GPP has chosen LTE. In established standards of LTE, Orthogonal Frequency Division Multiple Access (OFDMA) is use in downlink but due to high Peak-to-Average Power Ratio (PAPR) DFT-Spread OFDMA (SC-FDMA) is used in uplink. Since there is demand of high data rate in wireless systems and data rate depends upon different type of interferences and channel quality. Proper PRBs allocation is useful to assign good channel to users and also useful in mitigation of interferences. Present work takes this point as inspiration, study focus on interferences and different ways to achieve demand of user.

1.3 Thesis Objective

The objective of this this is to optimize the uplink in LTE by mean of proper allocation of PRBs among the users in the network. Adjacent Channel Interference (ACI) effect on PRBs allocation methods has been also studied . Final part of the thesis study about inter-cell interference mitigation techniques.

1.4 Thesis Scope

The specification for 3GPP Long Term Evolution (LTE) supports advanced antenna system including multiple transmit and receive antennas, that is multiple-input multiple-output (MIMO). LTE uplink supports 1×2 and 1×1 antenna, but for practical reasons the study of this thesis is limited to 1×1 antenna system *i.e* single-input single-output (SISO). MIMO system can achieve better performance due to having multiple receive and transmit diversity, but the aim of thesis to present a relative comparison between methods. 3GPP LTE can be used in both paired (FDD) and unpaired (TDD) spectrum. This thesis focus on FDD. LTE standards are design to support 5MHz-20MHz, in many spectrum bands. This study only deals with 10MHz bandwidth. The scheduling algorithm used by eNodeB is pure time division multiplexing (TDM).

1.5 Assessment Methodology

The implementation and simulation is carried out using multi-cell radio network dynamic simulator in MATLAB. MATLAB built in function `bintprog` is used to find optimal PRB allocation, which is useful in solving binary integer programing. For all the simulation standard power allocation to sub-carrier using fractional power control (FPC) with power control factor $\alpha = 0.8$ is used. Users distribution in the network is consider as uniform having probability distribution function as [2]:

$$\begin{aligned} f_R(r) &= \tfrac{2r}{R^2} \quad 0 \leq r \leq R \\ f_\Theta(\theta) &= \tfrac{1}{2\pi} \quad 0 \leq \theta \leq 2\pi \end{aligned} \tag{1.1}$$

Where, R is the radius of cell site, r is radial distance of UE from base station and θ is angle distance of UE from BS.

Table 1.1: **Simulation Parameters**

Parameter	Value
eNB distribution	Homogeneous (19 cell, 3 sectors)
User distribution	Uniform within cell
Channel fading	Rayleigh fading
Cell radius	Urban (500m)
UE Tx power	23 dBm
UL noise figure	5 dB
Path-loss	PL = -57.92 + 20 log(f_c) + 37.6 log(d) dB
UL antenna configuration	1×1
3-D antenna pattern at eNB	$A_H(\theta) = -min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, 23\right]$ with $\theta_{3dB} = 70°$

Where distance "d" is find as mentioned in [16].

To evaluate the performance of the system, as well as user performance for different PRBs allocation and for computation of cell-edge throughput and cell-center throughput, modulation and coding scheme as mentioned in LTE 10.0.2 [3] is considered. A set of key performance indicator defined as:

Cell-edge throughput: The cell edge user throughput is defined as the 5^{th} percentile point of Cumulative Distribution Function (CDF) of user throughput. It is indicator of coverage performance. In most of the cases 5^{th} percentile point CDF users having SINR values less than 0 dB.

Average throughput: The average per-user throughput is defined as the sum of the average throughput of each user in the system divided by total number of the users in the system.

1.6 Thesis Outlines

Chapter 2: Includes the detail background about SC-FDMA, physical resource block (PRB) allocation in LTE uplink and inter-cell interference mitigation techniques.

Chapter 3: Focus on optimal PRBs allocation using Hungarian algorithm and Binary-Integer Program (BIP) with giving some weight to cell-edge users according to their path-loss. This chapter presents the details of PRBs allocation using FPC $\alpha = 0.8$ and compares the cell-edge throughput and average throughput in all the allocations.

Chapter 4: Focus on effect of Out-of Band interference or Adjacent Channel Interference on these PRBs allocation without any weigh to cell-edge user.

Chapter 5: Focus on inter-cell interference mitigation techniques. In this section, soft-frequency reuse (SFR) and fractional-frequency reuse (FFR) techniques is used to mitigate (ICI). An optimal threshold for round robin and maxrate scheduling algorithm has been implemented to evaluate optimal performance of network, while setting optimal SINR-threshold.

Chapter 6: presents the results obtained in the study of chapter 2, chapter 3 and chapter 4. In this section, simulation results of all these PRB allocation and effect of ACI on throughput considering PRB allocations is studied.

Chapter 7: Includes conclusion.

CHAPTER 2

2 SC-FDMA DESCRIPTION and FRAME STRUCTURE

3GPP has proposed LTE to improve the UMTS mobile phone standard for future requirements. Beside high throughput and spectral efficiency, LTE includes spectrum management, protocol latency and power consumption as major design goal. An improved specification LTE-advanced has been launched to achieve the goals of 4G wireless communication system. LTE uses OFDMA in downlink but due to high PAPR ratio SC-FDMA has been chosen in uplink.

2.1 OFDMA and SC-FDMA Description

In cellular systems, biggest advantage of OFDMA is its robustness in presence of multi-path signal propagation [1]. OFDMA system transmit information on M orthogonal frequency carrier, each operating at $\frac{1}{M}$ bit rate of information signal. Simultaneous data transmission and reception handled almost independently. On the other hand, OFDMA waveform exhibits very pronounced fluctuations which results in high peak-to-average power ratio (PAPR). Signals having high PAPR requires highly linear power amplifier to avoid excessive inter modulation distortion. To achieve linearity amplifiers have to operate at large back-off from their peak power, thus OFDMA is low power efficient.

To overcome from this problem 3GPP has introduced DFT-spread OFDMA technique in uplink [4],[5],[6], where the time domain data signal transformed into the frequency domain by DFT before going through conventional OFDMA modulation. The transmitter in SC-FDMA uses different orthogonal sub-carrier to transmit information symbol sequentially. Figure 2.1 shows transmitter and receiver structure in SC-FDMA and compare it with OFDMA. SC-FDMA first convert a binary input signal to sequence of modulated sequence. Transmitter next maps the modulated symbols into blocks each contains N symbols. Then the symbols modulated by N-point DFT to produce frequency domain equivalent of the input signals. Then it maps to sub-carrier by different ways followed by IDFT to get back signals in time domain to transmit. Due to single carrier modulation at transmitter, SC-FDMA has lower PAPR.

There are two type of sub-carrier mapping in SC-FDMA, 1) Distributed Mapping: distributed SC-FDMA is called interleaved SC-FDMA (IFDMA), where the occupied sub-carriers are equally spaced over the entire bandwidth [7], 2) Localized Mapping: In localized mapping, the DFT outputs are mapped to a subset of consecutive subcarriers thereby confining them to only a fraction of the system bandwidth. Figure 2.2 is showing sub-carrier mapping for QPSK symbols.

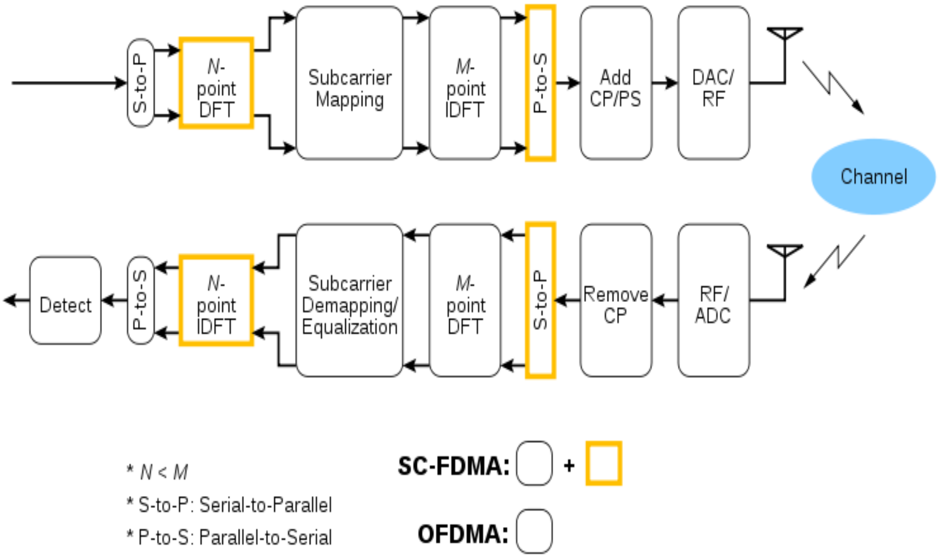

Figure 2.1: **Transmitter and receiver structure of SC-FDMA and OFDMA**

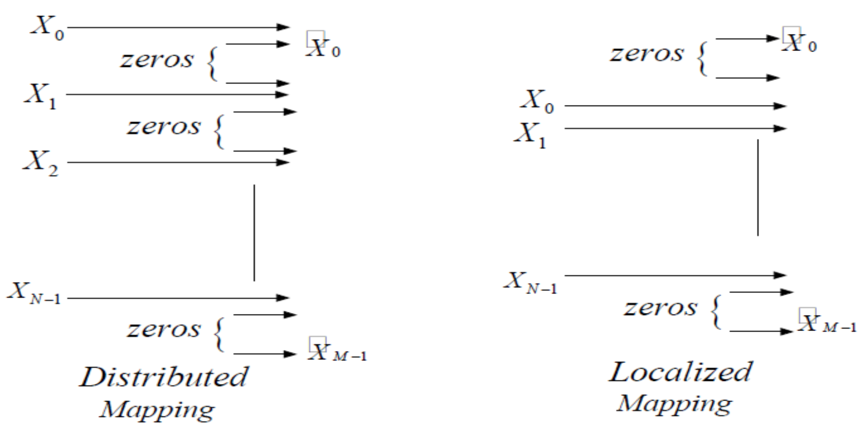

Figure 2.2: **Sub-carrier mapping**

SC-FDMA offers frequency diversity gain over the standard OFDM, as well information data is spread over multiple subcarriers by DFT mapper. However distributed SC-FDMA is more robust with respect to frequency selective fading and offers more diversity gain , as information is spread over whole bandwidth. Localized SC-FDMA in combination with channel dependent scheduling offers multiuser diversity. But due to complexity in distributed SC-FDMA localized SC-FDMA has been preferred over distributed mapping in uplink.

2.2 LTE Frame and Slot Structure

2.2.1 Frame Structure Types

LTE uplink uses same generic structure as downlink, in FDD. The width of PRB and subcarrier spacing are same in uplink and downlink. Two radio frame structure is supported in LTE: type1, FDD and type2, TDD. Frame structure type1 is supported in both full duplex and half duplex FDD. Each radio frame is consist of 20 slots numbered from 0 to 19. A sub-frame is defined as two consecutive slots and called transmission time interval (TTI). For FDD 10 frames are available for downlink transmission and 10 are available for uplink transmission. uplink and downlink transmission are separated in the frequency domain. In half duplex simultaneous reception and transmission are not allowed. Type 1 frame is used for this thesis.

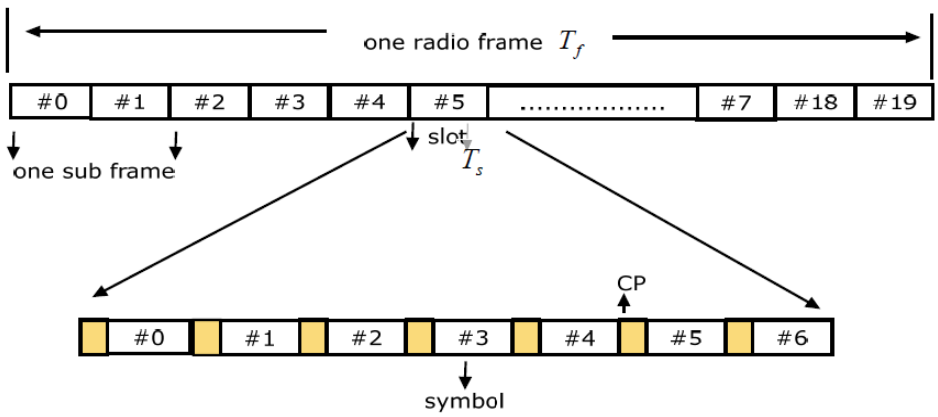

Figure 2.3: **Frame structure type1**

Type 2 frame is applicable to TDD of length $T_f = 307200 * T_s$ ms consist of two half frame of length 5 ms each. Each half frame is consist of 5 sub-frame of length 1 ms. Each sub-frame is define as two consecutive slots of length 0.5 ms. Sub-frame 0 and 5 and DwPTS is reserve for downlink transmission. UpPTS and sub-frame immediately following the special sub-frame are always reserve for uplink transmission.

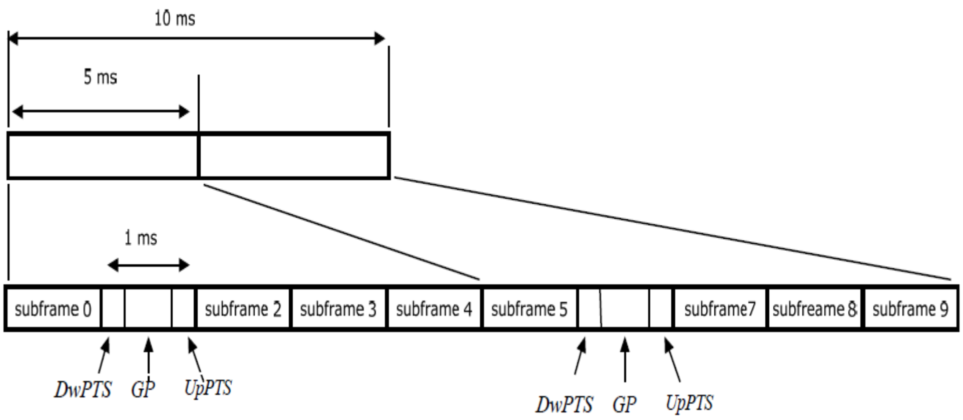

Figure 2.4: **Frame structure type2**

2.2.2 Slot Structure

The transmission signal in each slot is described by resource grid of $N_{RB}^{UL} N_{SC}^{RB}$ subcarrier and N_{symb}^{UL} SC-FDMA symbol, where N_{SC}^{RB} is the resource block size in the frequency domain, N_{RB}^{UL} is the uplink bandwidth configuration and N_{symb}^{UL} is the number of SC-FDMA symbols in an uplink slot. Each element in the

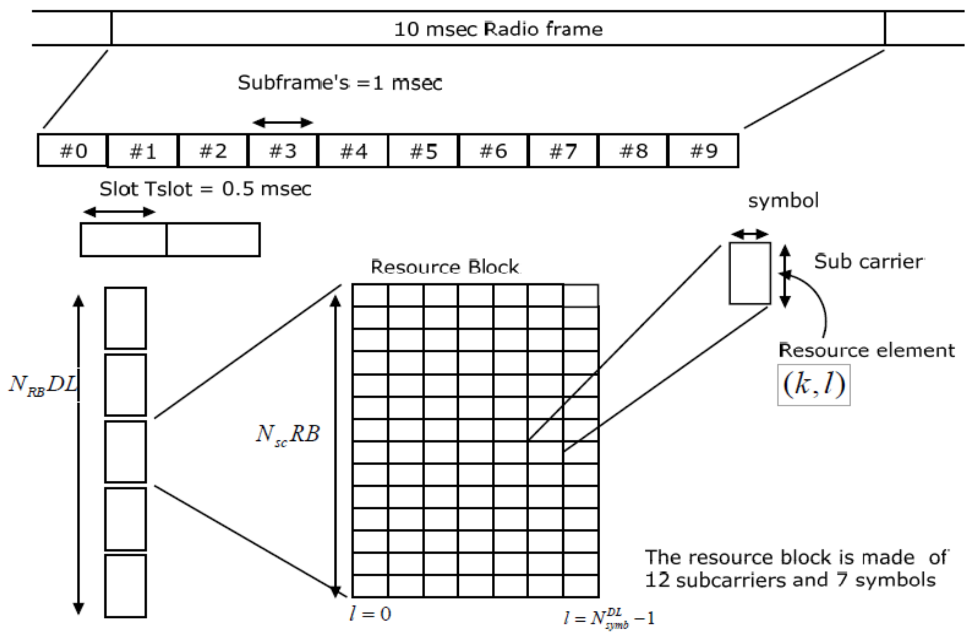

Figure 2.5: **Resource gride structure**

resource grid is called resource element and is defined by the indices k, l, where k, l are indices in the frequency and time domain respectively. Figure 2.5 illustrate resource grid structure and table 2.1 shows the set of allowed values for resource block numbers, occupied subcarrier, CP length and transmission bandwidth.

Table 2.1: **SC-FDMA Uplink Parameter**

Parameters						
Channel bandwidth(MHz)	1.4	3	5	10	15	20
Number of resource block	6	15	25	50	75	100
Number of sub-carriers	72	180	300	600	900	1200
FFT size	128	256	512	1024	1536	2048
Sampling frequency(MHz)	1.92	3.84	7.68	15.36	23.04	30.72
CP length	9	18	36	72	108	144

CHAPTER 3

3 OPTIMAL RESOURCE ALLOCATION IN SC-FDMA

A nineteen cell architecture for resource allocation in a multiuser wireless communication system in SC-FDMAis considered, in which each cell is divided into three sectors. On the top of PRB allocation adjacent channel interference effect has been consider to study real life scenario which is further suppressed by mitigation techniques to achieve a better performance in terms of average throughput and cell-edge throughput. Assume that there are total number of users as M indexed by set $\mathcal{M} \equiv \{1, \cdots, m, \cdots M\}$ are assigned to observation sector, and total bandwidth B is divided in to K PRBs indexed by $\mathcal{K} \equiv \{1, \cdots, k, \cdots K\}$. In localized Uplink there are two resource allocation constraint present: (1) *exclusivity*, implies at most one user can be assign to a PRB. (2) *adjacency*, implies users can have multiple of PRB assigned only if they are adjacent to each-other. SC-FDMA resource allocation problem involves determining the resource block that maximizes the total user-weighted system capacity, with user weights denoted by w_m. The user weights signify by fairness in resource allocation depending upon their path-loss. Fraction Power Control (FPC) with ($\alpha = 0.8$)is considered as power allocation algorithm for SINR calculation. The uplink SINR for user m on PRB k is given by [8]

$$SINR_{(m,k)} = H_m(k) \times \frac{P_{tx}(m) \times PL_{(m,j)}}{BN_0 + I_j(n)} \tag{3.1}$$

where BN_0 is thermal noise power on one PRB, $P_{tx}(m)$ is power transmitted by user m on one PRB, BS serving to user m is indexed by j, and $PL_{(m,j)}$is total path-loss between user m and BS j. $I_j(n)$ in (1) represents the interference created by users from other cell on PRB n, and expressed as

$$I_j(n) = \sum_{l \epsilon U(n), l \neq m} P_{tx}(l) \times PL_{(l,j)} \tag{3.2}$$

where $U(n)$ set of users transmitting on PRB n in the other cell, $P_{tx}(m)$ and $PL_{(m,j)}$ is the transmit power of user and total path-loss to BS j respectively.

Let PRB allocated to user m is denoted by $\mathcal{K}_m$. Capacity is a non-decreasing function of SINR, the resource allocation problem reduces to determining the sub-channel allocation $\mathcal{K}_m$ subject to *exclusivity* and *adjacency* constraints, written as

$$\max_{\{\mathcal{K}_1,\cdots\mathcal{K}_m\}\epsilon\mathcal{K}} \sum_{m\epsilon\mathcal{M}} w_m \sum_{k\epsilon\mathcal{K}} R_{m,k} \tag{3.3}$$

$$s.t. \;\; \mathcal{K}_m \bigcap K_{m'} = \varnothing, \forall m \neq m^{'}, m, m^{'}\epsilon\mathcal{M}$$

where

$$R_{m,k} = log_2(1 + SINR_{(m,k)}) \tag{3.4}$$

is the capacity for PRB k of user m, and $\mathcal{K}$ is the set of all possible PRB allocation which satisfying constraints. where weight matrix is define as:

$$w_m = \theta \times PL_{(m,j)}\,(dB) \tag{3.5}$$

where θ is fairness factor which decides the fairness of resource allocation depending upon path-loss data. In this method some compensation to the cell-edge users is provided to achieve a higher cell-edge throughput.

3.1 SC-FDMA Resource Allocation Algorithm

3.1.1 Optimal Resource allocation for SC-FDMA

Our Optimization problem (3.3) is a combinatorial optimization problem. To check the complexity of search space, let us assume exactly μ users are to share K PRBs. Due to adjacency constraint, require to divide K PRBs into μordered sets, such that each set has k_i adjacent PRBs, i.e $\mathcal{K} = k_1 + \cdots + k_\mu$. Number of composition of K into μ parts is given by $\binom{K-1}{\mu-1}$, number of possible ordered set of μ elements from the set of M users is given by $\binom{M}{\mu}\mu!$. Total PRB allocation when μ users out of total user M are using K PRBs is $\binom{K-1}{\mu-1}\binom{M}{\mu}\mu!$, on addition from 1 to M total feasible search space is $\sum_{\mu=1}^{M}\binom{K-1}{\mu-1}\binom{M}{\mu}\mu!$. In our case number of users($\mathcal{M}$)

is 10 and PRBs ($\mathcal{K}$) is 50, require $9.26X10^{15}$ PRB allocation in search space. Straight forward approach having high complexity, so binary-integer program is used to formulate problem as set partitioning problem having generic form:

$$\underset{x}{max}\, c^T x \tag{3.6}$$

$$s.t.\;\; Ax = 1_r \quad and\, x_j \epsilon \{0, 1\} \;\; \forall j$$

where $A\ r \times c$ is a constraint matrix of zeros and ones, c is a weighted system capacity vector, $1_r = [1, \cdots, 1]^T$ is a r-length vector where r is the number of constraints and x is the c-length decision vector of optimization variables which can take values zero or one. Each element in our decision vector x correspond to a particular PRB allocation a pattern and each element in c is weighted-sum capacity corresponding to a particular PRB allocation. The constraint matrix A enforce the adjacency and exclusivity constraints. To understand better let us consider 3 PRBs and 2 Users. Let us assume that PRB allocated to a particular user is donated by 1, and if not allocated then denote by 0, PRB allocation matrix A_m to user m is denoted by:

$$A_m = \begin{bmatrix} 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \tag{3.7}$$

which will be same for all users. Here, row indicates a particular PRB and column indicates a particular PRB allocation pattern. Let us assume user 1 assigned 5^{th} column the user 2 has to select 4^{th} pattern as its PRB allocation. When multiple PRB assigned to a user it should be adjacent to each-other. When a user is assigned $t > 0$ PRB then there are only $K-(t-1)$ possible PRB allocation. Hence, total numbers of column is $C = \sum_{t=1}^{K}(K-(t-1)) = \frac{1}{2}K^2 + \frac{1}{2}K + 1$ which is 7 for example case. We associate each possible PRB allocation for a user m with a binary-decision variable $x_{m,j} \epsilon \{0, 1\}, j = 1, \cdots, C$, which indicates weather a particular PRB allocation pattern is chosen or not with MC decision vector as $x = [x_1, \cdots, x_M]^T$ where $x_m = [x_{m,1}, \cdots, x_{m,c}]^T$. Fairness is considered reward vector $c_{m,j}$ for each possible PRB allocation. In our case it is simply a weighted capacity to provide cell-edge users fairness for constant power allocation to user m when PRB allocation pattern j is being used, given by:

$$c_{m,j} = w_m \sum_{k \epsilon \mathcal{K}_{m,j}} log_2(1 + SINR_{m,k}) \tag{3.8}$$

where $\mathcal{K}_{m,j} \equiv \{k\epsilon\mathcal{K} : A_m(k,j) = 1\}$ is the set of used PRB indices corresponding to allocation pattern j of user m. Lets $c = [c_{1,1}, \cdots, c_{M,C}]$ is reward vector of same dimension as x. Hence our objective function is $f = c^T x$ which is mean to maximize subject to constraints on x.

Then, a constraint matrix on x is formed to enforce the exclusive PRB assignment constraint for PRB k, i.e. only one PRB allocation pattern containing a 1 in the k^{th} column should be chosen. These K constraints can be further written as:

$$[A_1, \cdots, A_M] = 1_K \tag{3.9}$$

Apart from this, M constraint has been enforced so that only one pattern in A_m can be choose, i.e. $\sum_{j=1}^{C} x_{m,j} = 1 \ \forall m\epsilon\mathcal{M}$. Stacking all these M constraint in matrix form, we have

$$\begin{bmatrix} 1_C^T & 0_C^T & \cdots & 0_C^T \\ 0_C^T & 1_C^T & \ddots & 0_C^T \\ \vdots & \ddots & \ddots & 0_C^T \\ 0_C^T & \cdots & 0_C^T & 1_C^T \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix} = 1_M \tag{3.10}$$

combining (3.9) and (3.10) we have $K + M$ constraints. Now our original problem in (3.3) is converted in general set partitioning problem, which is widely study in airline crew scheduling. It is very complex to find optimal solution manually, we simply used the built-in MATLAB function `bintprog` to solve this problem, which uses a linear programming (LP)-based branch-and-bound algorithm to solve binary integer programming problems. It significantly reduces the complexity of the problem.

3.1.2 Suboptimal Hungarian Algorithm

Optimal solution has a very high complexity in solving set partitioning problem. To reduce the complexity of the assignment used Hungarian Algorithm. Instead of assigning *adjacency* constraint in a complex way, Resource set (RS) is formed which consist of a set of continuous PRBs. The number of PRB forming a resource set is equal for all the RSs, which is computed by dividing PRBs by numbers of users in the network. If number of PRBs are not divisible by number of users then remaining PRBs assigned to last RS. To compute the effect on SINR by forming resource set, an average on PRBs is taken:

$$SINR'_{(m,rs)} = \frac{1}{S} \sum_{n=i,\cdots,S+i} SINR_{(m,k)} \tag{3.11}$$

where i is the index of first PRB on the RS, and S is the number of PRBs in RS. Then, a weighted matrix to calculate fairness is developed as in (5). To assign RSs to different users, *Hungarian Algorithm* is used which is similar to one used in Job assignment problem in Operational Research to reduce cost of the organization. Here, this algorithm is used to maximize weighted-system capacity and we end up on the same optimization problem as in optimal assignment problem with *exclusivity* constraint. In the optimal assignment problem Hungarian algorithm is used to assign RS's to users such that it maximizes system capacity and so throughput using one-to-one assignment problem. Table 3.1 shows the throughput after our optimal and suboptimal allocation and compare it with random PRB allocation. To compute throughput, modulation and coding scheme mentioned in LTE 10.0.2 has been used. The number of user has been considered as 10 and number of PRB has been considered as 50 for this calculation.

Table 3.1: **Throughput for different PRB allocation**

Allocation Scheme	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
Random Allocation	0.3171	2.3875	1.7809
Suboptimal Allocation	0.5715	2.4543	2.3621
Optimal Allocation	0.5835	3.5997	3.5334

CHAPTER 4

4 ADJACENT CHANNEL INTERFERENCE

4.1 ACI Effect on PRB Allocations

In this section, the effect of out of band leakage or Adjacent channel leakage on overall system has been studied. Out-of-band interference or adjacent channel interference arise due to imperfection of transceiver. Presence of hardware imperfection destroy orthogonality of sub-carrier due to having frequency offset and phase noise[17], as a result of that UE signal starts leakage and interfere to other UE's signals. In practical scenario due to mobility of user, imperfection of hardware and miss-alignment of antenna create different frequency offsets to UEs which leads to inter-user interference or ACI. The power spectral density of received signal also vary due to different modulation and coding scheme, power control methods and inter-cell interference[18]. Signal leakage from the adjacent UEs with higher PSD can leads to a significant degradation of the system performance. To study ACI in uplink, cognitive radio network model has been considered. In the analysis, the interferer user is taken as secondary user and the convicted user as primary user. From the Figure 4.1 one can conclude that each OFDM sub-carrier includes interference to at most 8 sub-carrier of adjacent UEs. In order to computer how much interference is created by primary user (PU) on Secondary user (SU), PSD of SU in CR systems have been used. If $s(t)$ is transmitted signal on k^{th} sub-carrier in secondary user m and filter is rectangular then power spectral density of OFDM based CR system can be written as [9]:

$$\Phi_{ss}^{OFDM}(f) = P_{i,k}T_s\left(\frac{sin\pi fT_s}{\pi fT_s}\right)^2 \tag{4.1}$$

where $P_{i,k}$ is power transmitted on i^{th} sub-carrier of secondary user k and T_s is total OFDM symbol length including guarded time. In order to calculate the interference from secondary users to PU band, we should find the out of band interference of each secondary user sub-carrier in PU band. Interference introduce on k^{th} sub carrier by m^{th} secondary user is given by as [9]:

$$\triangle_{SU_{(k,m)}\rightarrow PU}(n) = \frac{1}{P_{tot}} \int_{(n\triangle f - \frac{B}{2})}^{(n\triangle f + \frac{B}{2})} |\gamma_{k,m}|^2 \Phi_{ss}(f) df \tag{4.2}$$

In [10], OFDMA interference table has been obtained when transmitting with power equal to "1" on k^{th} frequency slot. The interference vector of OFDM with CP length $\frac{T}{8}$ [11] are defined as:

$$V^{ofdm} = \begin{array}{l} [8.94 \times 10^{-2},\ 2.23 \times 10^{-2},\ 9.95 \times 10^{-3},\ 5.60 \times 10^{-3}, \\ 3.58 \times 10^{-3},\ 2.50 \times 10^{-3},\ 1.84 \times 10^{-3},\ 1.12 \times 10^{-3}] \end{array} \tag{4.3}$$

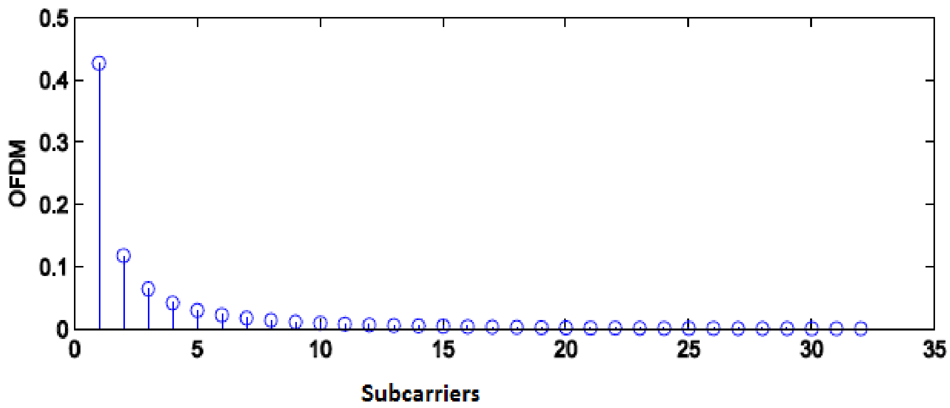

Figure 4.1: **Interference distribution of sub-carrier in OFDM, Source: Hosseinali Jamal, "A Fair Radio Resource Allocation Algorithm for Uplink of OFDM/FBMC Based CR System," KSII Transactions on internet and information systems vol. 6, no.6 June 2012.**

The Out-of-Band interference or ACI can be express in the mathematical form [12] as follows:

$$I_f^k = \begin{cases} \sum_{n=f}^{N} P_p^{k_l} G_p^{k_l} V_n, & f = 1, 2, \cdots N \\ \sum_{n=F_k-f+1}^{N} P_p^{k_r} G_p^{k_r} V_n, & f = F_k - N + 1, \cdots F_k \\ 0, & others \end{cases} \tag{4.4}$$

Where $P_p^{k_{l(r)}}$ is the transmit power of Primary user (PU) located in the left (right) of K^{th} sub-carrier, $G_p^{k_l}$ is the channel gain of Primary user (PU) located in the left (right) on K^{th} sub-carrier and V_n is ACI vector. Using (4.3) and (4.4) and modulation and coding scheme mentioned in LTE 10.0.2, the effect of adjacent channel interference on throughput is calculated. Table 4.1, Table 4.2 and Table 4.3 respectively compare ACI effect on throughput in case of random PRB allocation, PRB allocation by Hungarian algorithm and PRB allocation by binary-linear program. For simplicity, number of users has been considered as 50 and number of PRBs has been considered as 50.

Table 4.1: **ACI effect on throughput Random Allocation**

Random Allocation	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
With ACI Consider	0.2268	2.0217	1.2726
Without ACI Consider	0.2787	2.2948	1.6702

Table 4.2: **ACI effect on throughput Hungarian Allocation**

Hungarian assignment	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
With ACI Consider	0.2430	2.1024	1.3159
Without ACI Consider	0.3133	2.4190	1.7957

Table 4.3: **ACI effect on throughput Optimal (BIP) Allocation**

Optimal Assignment	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
With ACI Consider	0.2497	2.2498	1.4117
Without ACI Consider	0.2951	2.4902	1.8449

4.2 Optimal Throughput considering ACI

In LTE downlink to mitigate near far effect if the allocation of users in PRB is done such that users with low SINR values are together and users with SINR values are together, then one will be able to get high cell-edge throughput and average throughput while considering adjacent channel interference. Thus we are able to mitigate adjacent channel interference by such allocations of users in PRBs in downlink, but interference in uplink is not similar to downlink and hence such allocation of users in uplink is not able to achieve optimal solution for average throughput while considering adjacent channel interference in uplink. To maximize throughput of the network, the effect of adjacent channel interference has to be minimized. Complexity of achieving optimal solution for this problem in case of uplink is very high. A heuristic algorithm to maximize the average throughput of cell edge users has been proposed.

Assume that there are total number of users as M indexed by set $\mathcal{M} \equiv \{1, \cdots, m, \cdots M\}$ are assigned to observation sector, and total bandwidth B is divided in to K PRBs indexed by $\mathcal{K} \equiv \{1, \cdots, k, \cdots K\}$. The proposed heuristic algorithm follow steps as:

Table 4.4: **Algorithm to mitigate ACI effect**

1:	For PRB 1^{st} and K^{th}
2:	find user m and n.
3:	s.t. if (n at 1 and m at 2) or (n at 50 and m at 49)
4:	we have: $max\,(log_2(1 + SINR_n))\ \forall m,\, n\,\epsilon\mathcal{M},\, m \neq n$
5:	for PRB=2:49
6:	find m, n, p having PRB $k-1$, k, $k+1$ s.t.
7:	we have: $max\,(log_2(1 + SINR_n))\ \forall m,\, n,\, p\epsilon\mathcal{M},\, m \neq n \neq p$
8:	for $\forall m$ we have: $\underset{\{\mathcal{K}_1,\cdots\mathcal{K}_m\}\epsilon\mathcal{K}}{max} \sum_{m\epsilon\mathcal{M}} \sum_{k\epsilon\mathcal{K}} log_2(1 + SINR_{(m,k)})$

4.2.1 Implementation Methodology

The above heuristic optimization algorithm is implemented based on the user preference of adjacent users, such that they can produce minimum interference as compare to others. A best match for each user has been found and the match which has higher SINR value is given as higher preference. In matching it is taken care that there should not be any circle. After getting match for each user depending upon the SINR value, string is formed until the end has no other match. After we reach at the end of strings and there is no match, optimization is used s.t. $\underset{\{\mathcal{K}_1,\cdots\mathcal{K}_m\}\epsilon\mathcal{K}}{max} \sum_{m\epsilon\mathcal{M}} \sum_{k\epsilon\mathcal{K}} log_2(1 + SINR_{(m,k)})$.

CHAPTER 5

5 INTER CELL INTERFERENCE MITIGATION

The inter-cell interference (ICI) mitigation techniques can be classified into three categories: ICI randomization, ICI cancellation and ICI coordination or avoidance.

In ICI randomization, the interfering signals are randomized enabling interference suppression at receiver due to processing gain. Randomization of interfering signal done by applying pseudo-random scrambling after channel coding.

ICI cancellation aims at interference suppression at receiver beyond what can be achieved by just exploiting the processing gain. This Scheme requires channel knowledge and PRB allocation pattern of interfering user from other cells. The LTE system does not support such type of signaling hence this scheme can not be performed.

ICI Coordination scheme performed by applying certain constraints on resources used in different cells in a coordinated way. These restrictions can be in the form of restrictions to what time-frequency resource are available to resource manager or restriction on transmit power that can be applied to certain time-frequency resource. These type of restriction provide the possibility for improvement in SINR and cell-edge throughput in corresponding time-frequency in neighbor cells. The ICI coordination sometimes require certain inter-eNodeB (BS) communication in order to achieve the scheduling goal. Two ICI coordination techniques - Fractional frequency reuse and Soft frequency reuse are studied.

5.1 Frequency Reuse

5.1.1 Fractional Frequency Reuse

A Fractional Frequency reuse (FFR) scheme is based on the concept of reuse partitioning [13]. In reuse partitioning, the user with highest signal quality uses a lower reuse factor while the user with low SINR value uses a higher reuse factor. A reuse factor 1 is used for cell-center as Cell-center users has higher signal quality and experiencing higher SINR value while reuse factor 3 is used for cell-edge user experiencing low SINR value. Figure 5.1 shows that fractional frequency reuse scheme uses a universal (reuse of one) frequency reuse for cell-center while reuse of three is used for cell-edge.

The total frequency resource is divided into 4 segments (f_1, f_2, f_3, f_4). The frequency resource (f_1) is used by cell-center to serve users having higher SINR values. A frequency reuse of three is implemented on remaining three segments. Frequencies is assigned to the cells in such a manner so that they have low interference thus improvement in SINR value. There is wastage of bandwidth as for all the three cases shown in Figure 5.1 two segments are going to be unused.

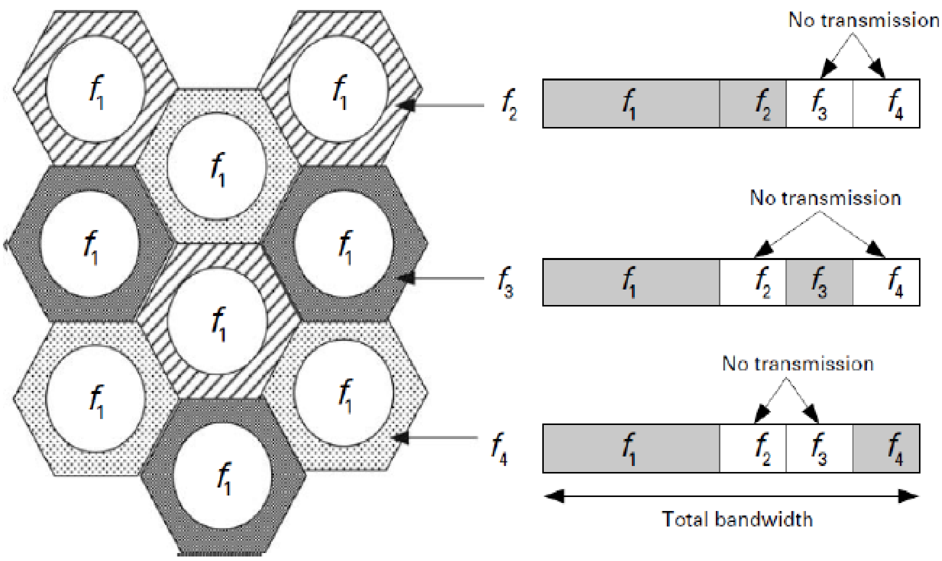

Figure 5.1: **An example of fractional frequency reuse**

Table 5.1 shows the capacity improvement achieved by cell-center user and also overall performance with SINR target for cell-edge user is set as 0 dB.

Table 5.1: Throughput improvement in fractional frequency reuse

cases	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
Without FFR	0.4819	2.6847	1.9883
After FFR	3.6123	2.6847	2.1410

5.1.2 Soft Frequency Reuse

It has been noticed that in fractional frequency reuse scheme, the frequency resource used for cell edge users in neighboring cell left empty in given cell. Soft frequency reuse (SFR) is designed with a goal to overcome this wastage of bandwidth and come with better performance for cell-edge user and overall system performance. In soft frequency reuse all the frequency used in each cell. Figure 5.2 illustrate the soft frequency reuse technique.

In SFR, whole bandwidth divided into three segments. One third PRBs are reserved for cell-edge and others for cell-center users. Cell-edge users are allowed to occupy only those PRBs, which are reserved for them while cell-center should occupy PRBs allocated to them but they can occupy cell-edge PRBs too. Since all the frequency is used in all the cell, cell-edge user experience high interference like universal reuse one. In order to reduce inter-cell interference, SFR assign a high power to cell-edge users and relatively lower power to cell-center user satisfying power constraints in uplink. Lets assume total power is same for frequency reuse one

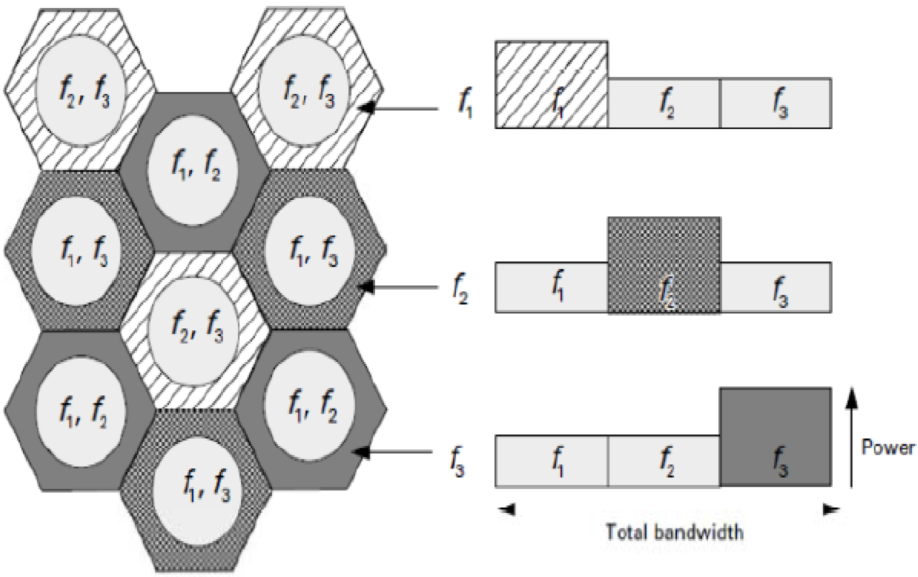

Figure 5.2: **An example of soft frequency reuse**

and SFR as mentioned in [19]. Power per PRB in FR one is given by $\frac{P_{total}}{K}$, where P_{total} is total transmit power used in FR one and K is the numbers of PRBs. In SFR, if the average power assigned to edge user is P_{edge}, the average power per PRB for center user is assigned as αP_{edge}, where $0 < \alpha < 1$ is denoted as power ratio. P_{edge} can be determine from the equation

$$P_{edge} \times \frac{K}{3} + \alpha P_{edge} \times \frac{2K}{3} = P_{total} \quad (5.1)$$

and hence

$$P_{edge} = \frac{3P_{total}}{K(1+2\alpha)} \quad (5.2)$$

This type of Power allocation scheme improves cell-edge user performance while degrades cell-center performance. The expectation is that since cell-edge users as lower SINR values, the throughput increase almost linearly with SINR. While cell-center user has higher SINR value hence throughput will degrade logarithmic. Table 5.2 shows effect of SFR on cell-edge user and cell-center users for $\alpha = 0.7$

Table 5.2: **Throughput improvement in soft frequency reuse**

cases	cell-edge thr/BW (bps/Hz)	cell-center thr/BW (bps/Hz)	average thr/BW (bps/Hz)
Without SFR	0.4815	2.6302	1.9502
After SFR	0.6794	2.6230	1.9751

5.2 Optimization of Fractional Frequency reuse

In this section, the throughput and SINR-threshold of static FFR using round robin (RR) and maxrate scheduling strategies has been studied. In [15] optimal distance threshold for static FFR has been studied in case of downlink. But scenario are not same for uplink as interference distribution is not same as downlink and one can not achieve a optimal distance. However, optimal throughput and optimal SINR-threshold in uplink scenario can be found.

5.2.1 Scheduling Strategies

Round robin (RR) and Maxrate scheduling strategies has been considered in frequency domain to investigate the impact of scheduling strategies on SINR threshold.

The RR scheduling strategy select users for each PRB with equal probability, which guarantees absolute fairness among multiple users. Lets assume $\widetilde{m}_n$user is assigned to the n^{th} PRB, then

$$Pr\{\widetilde{m}_n = m\} = \frac{1}{M_s},\ m\epsilon M_s,\ n\epsilon F_s \tag{5.3}$$

where, $Pr\{\cdot\}$ denotes the probability function, S denotes the cell-center or cell-edge region, F_s denotes PRB set and M_s denotes the total number of users belong to cell-center or cell-edge.

The Maxrate scheduling fully exploits multiuser diversity and does not concern about user's fairness. It assigns the users with maximum SINR to each PRB,

$$\widetilde{m}_n = arg\,\underset{m\epsilon M_s}{max}\{SINR_{m,n}\},\ n\epsilon F_s \tag{5.4}$$

CHAPTER 6

6 SIMULATION RESULTS

For simulation, nineteen cell sites with 3 sectors-per-site in a hexagonal grid has been considered. Network consists of inter-site distance as 500m, a Bandwidth of 10MHz, a penetration loss of 10 dB and carrier frequency of 2.0 GHz. An adaptive modulation an coding scheme is used for all the simulation as mentioned in LTE 10.0.2 based on the SINR estimations over the allocated bandwidth. The Scheduled user sets its total transmission power using following [14]

$$P = min\{P_{max},\ 10 \cdot log_{10}M + P_0 + \alpha \cdot PL + \triangle_{mcs}\} \tag{6.1}$$

Where P_{max} is the maximum transmit power from the user, P_0 is power to be contained in one PRB, α is path loss compensation factor, PL is path loss, M is number of PRBs assigned to the user and $\triangle_{mcs}$ is modulation and coding dependent value Obtained from base station. Where P_0 is calculated by

$$P_0 = \alpha \cdot (SINR_0 + IN) + (1 - \alpha) \cdot (P_{max} - 10logM_0) \tag{6.2}$$

6.1 Performance Simulation of Optimal Allocation

Following Figure 6.1 shows that optimal resource allocation is able to having highest SINR value. On the other side PRB allocation by Hungarian algorithm is slightly bad than optimal allocation but better than random PRB allocation. It is expected that when number of users in the network will equal to number of PRB, it will achieve optimality. It is also observed that due to giving weight to cell-edge users they are able to have better SINR values and hence better performance for cell-edge users.

Figure 6.2 shows the throughput in all the three different cases of PRB allocation. From the figure, it can be observed that our optimal allocation is able to achieve highest throughput value. On the other hand Hungarian algorithm is also able to achieve a higher throughput for different users according to their SINR values. It can also be observed that throughput obtained for binary-integer program PRB allocation and Hungarian algorithm is much better than random allocations of PRBs. Which is the effect of weight for cell-edge users and better resource set selection for users in Hungarian Algorithm and better adjacent PRBs selection in Optimal PRB allocation. For simulation purpose we have taken $\triangle_{mcs} = 0$.

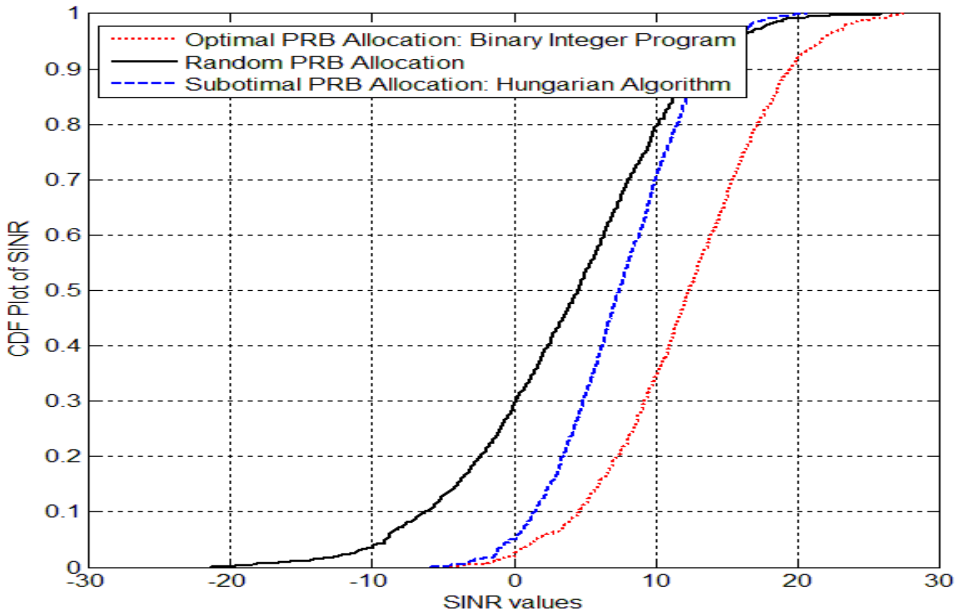

Figure 6.1: **CDF plot of SINR in different PRBs allocation**

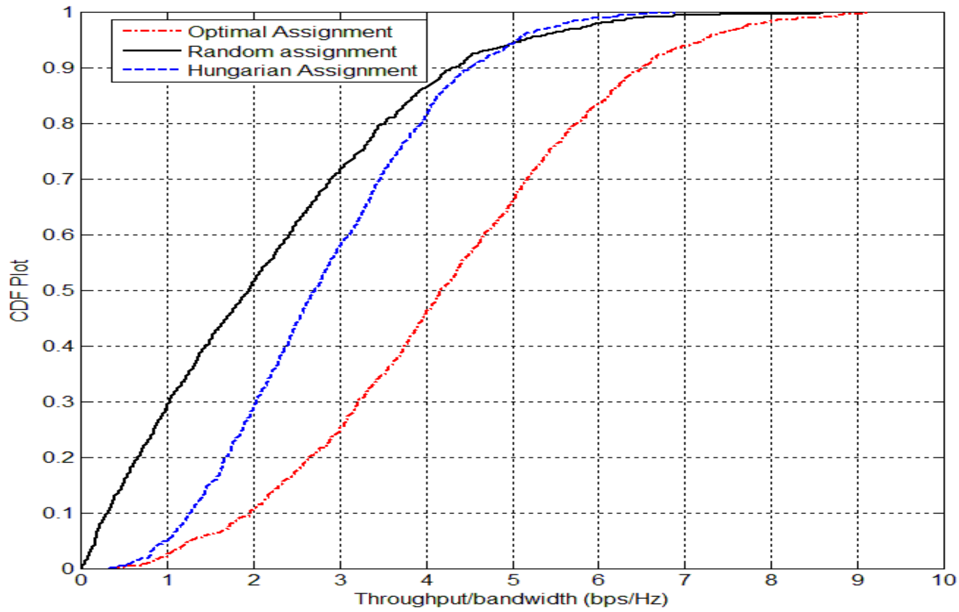

Figure 6.2: **CDF Plot of throughput in different PRB allocation**

6.2 Adjacent channel effect on PRB allocation

In this section for simplicity of analysis and simulation, the number of users and PRBs has been considered as 50. Figure 6.3 shows the effect of out-of Band interference or adjacent channel interference in case of random PRBs allocation. It can be observed that due to leakage from adjacent bands orthogonality of OFDM get disturbed and creates interferences to each-others. Due to these interferences SINR value of each user gets slightly degraded. It is expected that if a user with low signal quality is adjacent to user with higher signal quality then degradation will be high. If a cell-edge user is adjacent to a user with high signal quality degradation in SINR will be observe high.

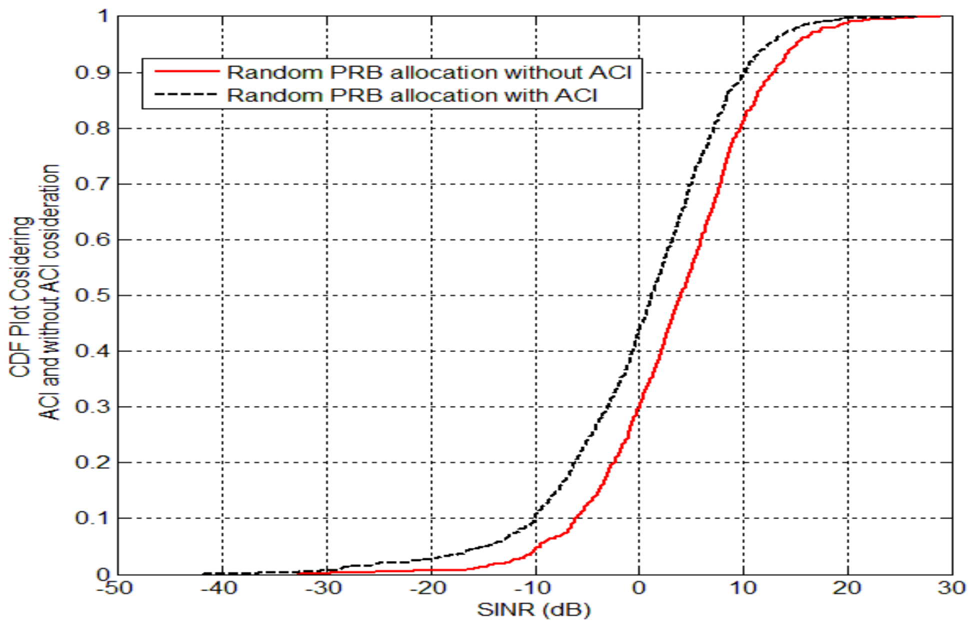

Figure 6.3: **ACI effect on SINR in random PRB allocation**

Figure 6.4 and Figure 6.5 shows effect of adjacent channel interference on Hungarian allocation and optimal allocation respectively. Like ACI effect on random allocation, it can be observed that due to leakage from adjacent bands orthogonality of OFDM get disturbed and creates interferences to each-others. Due to these interferences SINR value of each user gets slightly degraded. It is expected that if a user with low signal quality is adjacent to user with higher signal quality then degradation will be high.

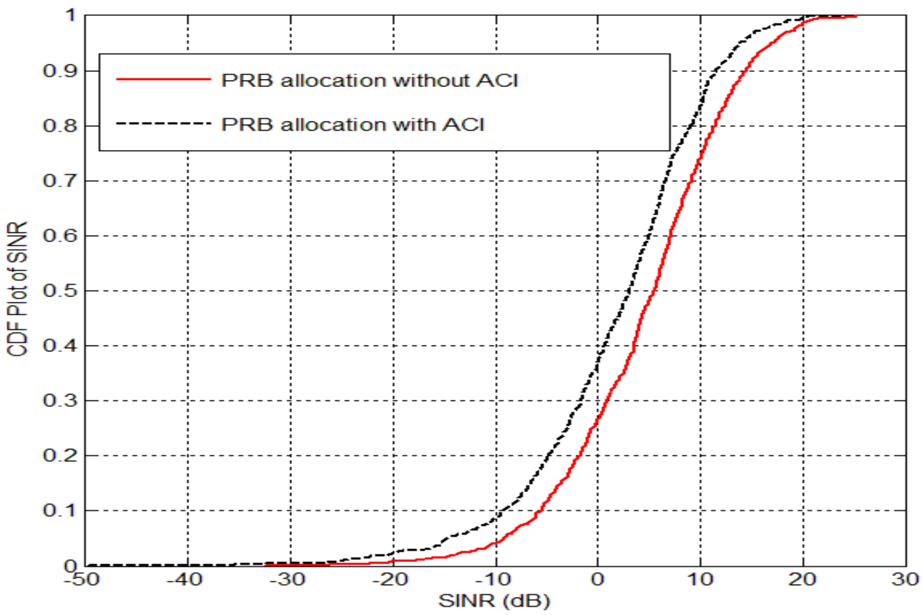

Figure 6.4: **Effect of ACI on SINR values: Hungarian allocation**

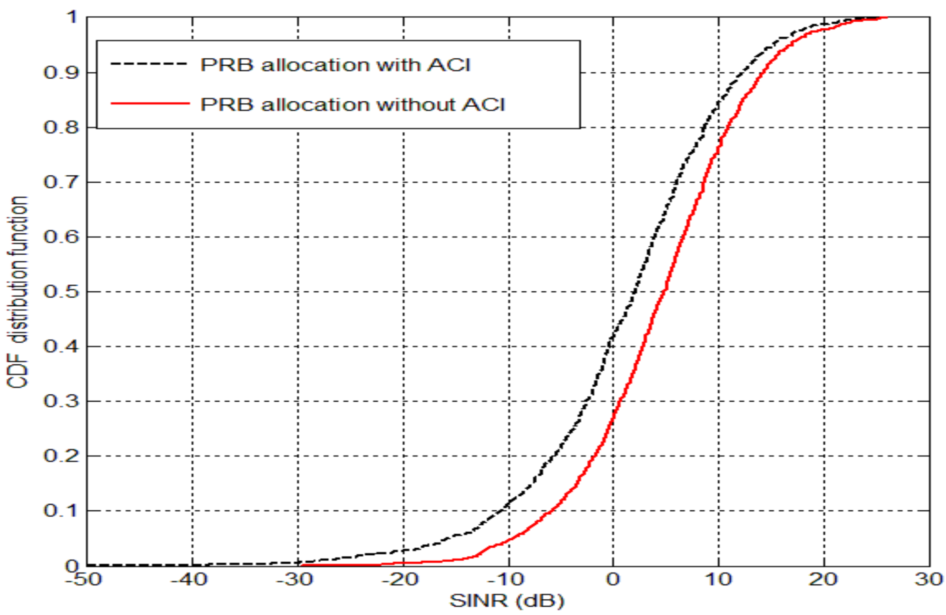

Figure 6.5: Effect of ACI on SINR values: optimal allocation

Figure 6.6, Figure 6.7 and Figure 6.8 shows user throughput in random allocation, Hungarian allocation and optimal allocation respectively. One can observe the degradation of user throughput due to adjacent channel interference. For simulation purpose we have taken $\triangle_{mcs} = 0$.

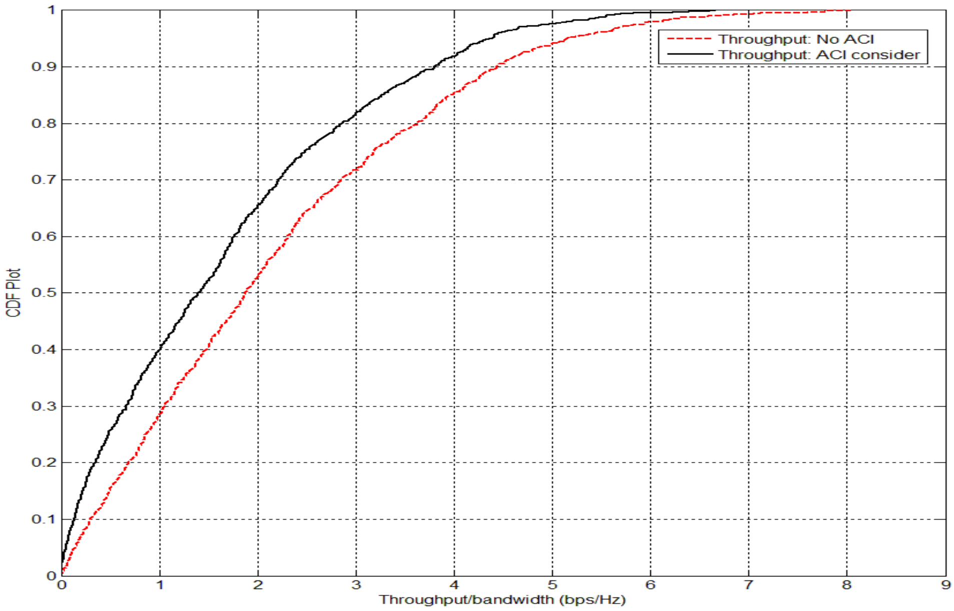

Figure 6.6: **CDF Plot of throughput in random PRB allocation**

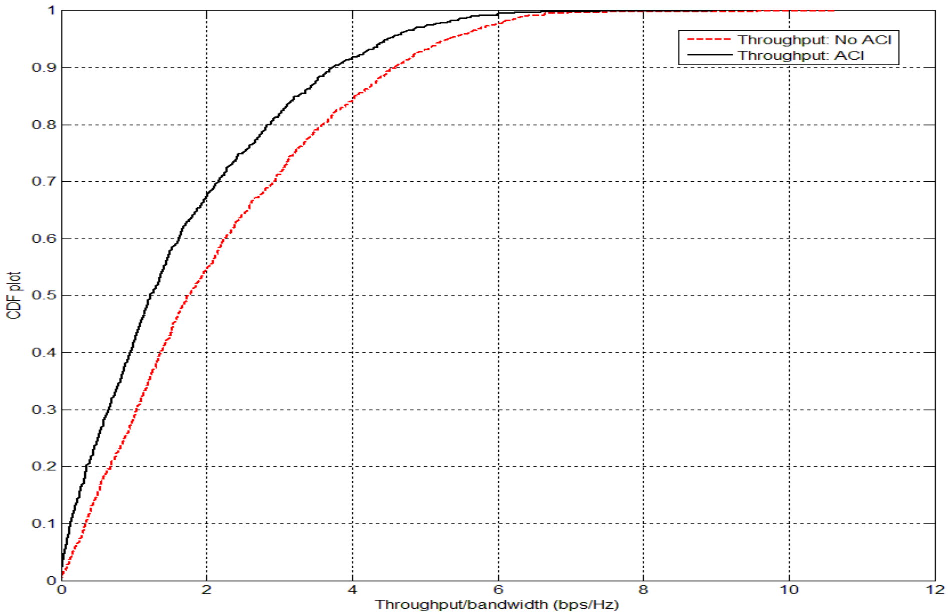

Figure 6.7: CDF Plot of throughput in Hungarian PRB allocation

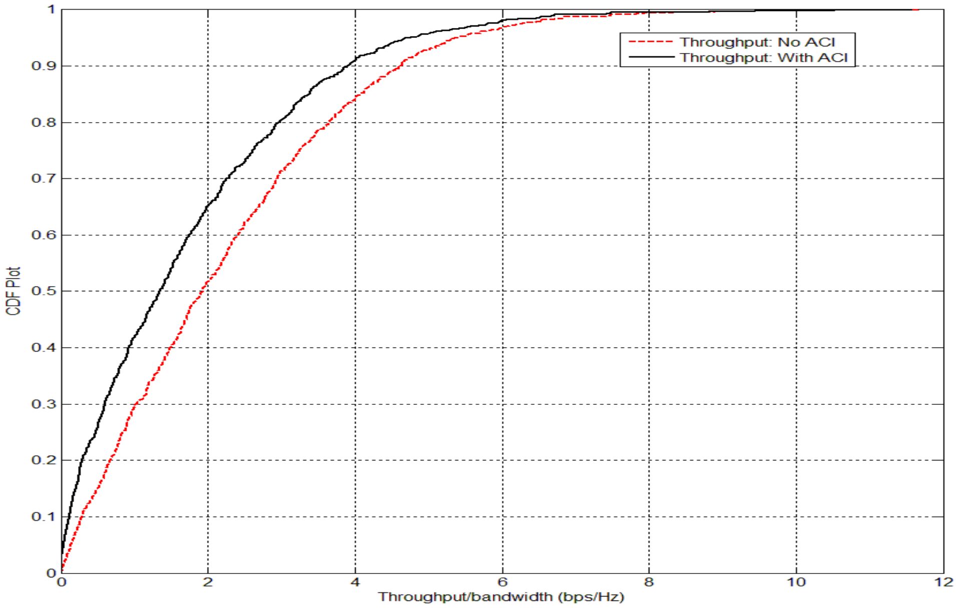

Figure 6.8: **CDF Plot of throughput in optimal PRB allocation**

6.2.1 Optimal Throughput considering ACI

In Figure 6.9 and Figure 6.10, we investigate the impact of our heuristic algorithm on the throughput. From Figure 6.9, it can be observed that a better PRB allocation for cell center users has been achieved but it causes degradation of cell edge users. From figure 6.10, it can be seen that using our heuristic algorithm, we can mitigate the effect of ACI significantly.

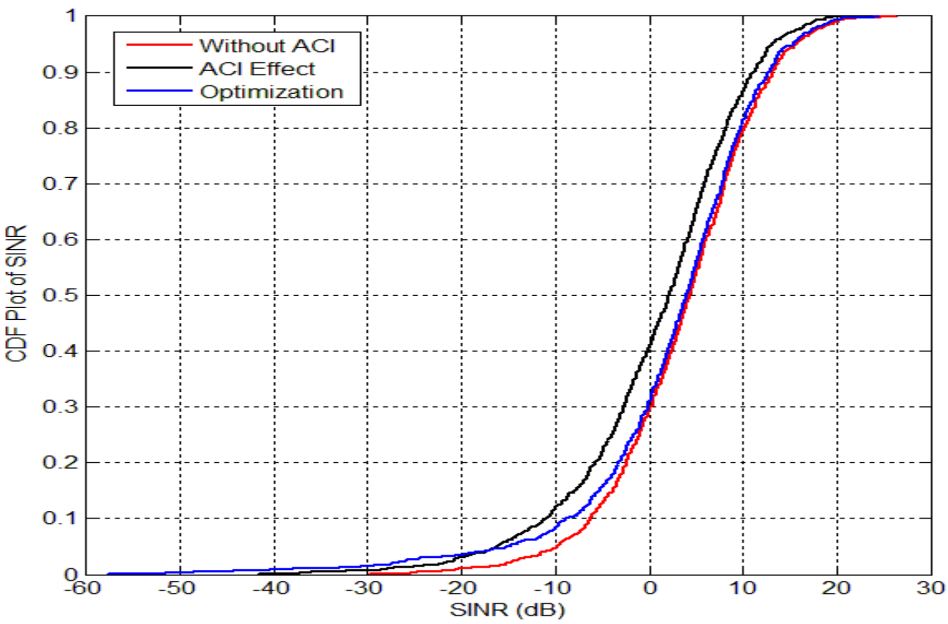

Figure 6.9: **CDF plot of SINR for proposed heuristic algorithm**

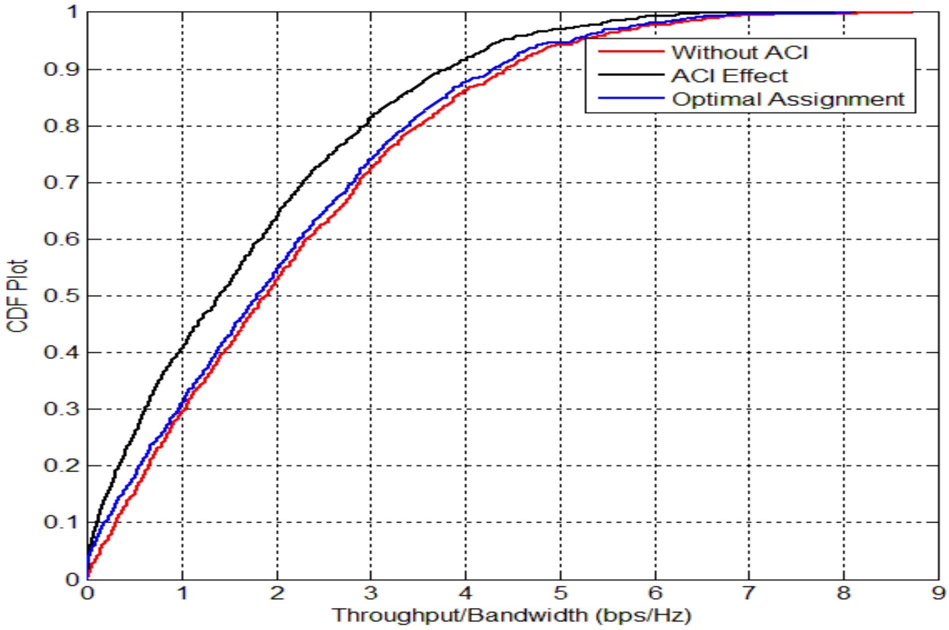

Figure 6.10: **Throughput/Bandwidth forproposed heuristic algorithm**

6.3 Throughput and optimal threshold for FFR

6.3.1 Round Robin Scheduling:

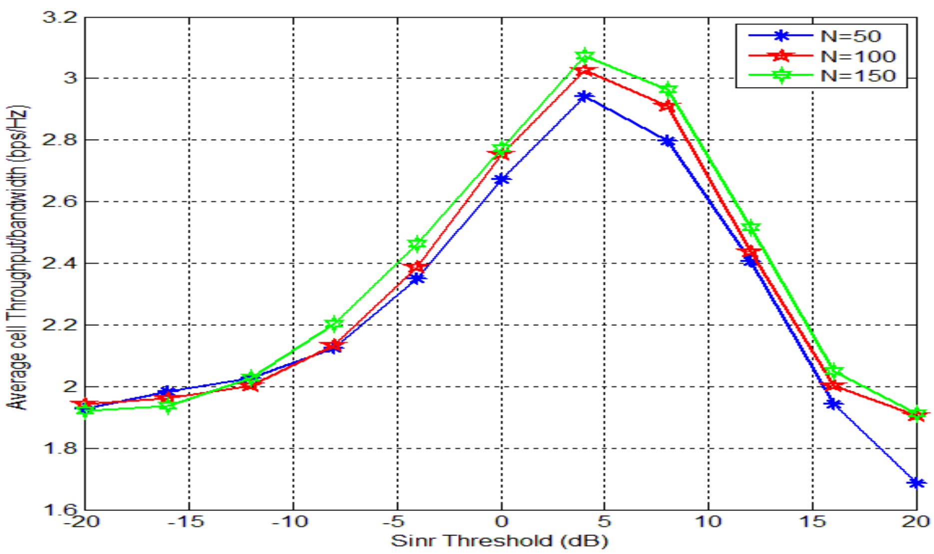

Figure 6.11: **Average throughput for Round Robin scheduling strategy**

In round robin scheduling one can observe that by setting different SINR threshold value, average throughput achieves an optimal value. It can also be observed that for different number of users optimal threshold value is achieved at the same point.

6.3.2 Maxrate Scheduling:

In Maxrate scheduling, one can observe that by setting different SINR threshold value average throughput achieves an optimal value. It can also be observed that with number of users getting increased, the optimal threshold value is also increasing.

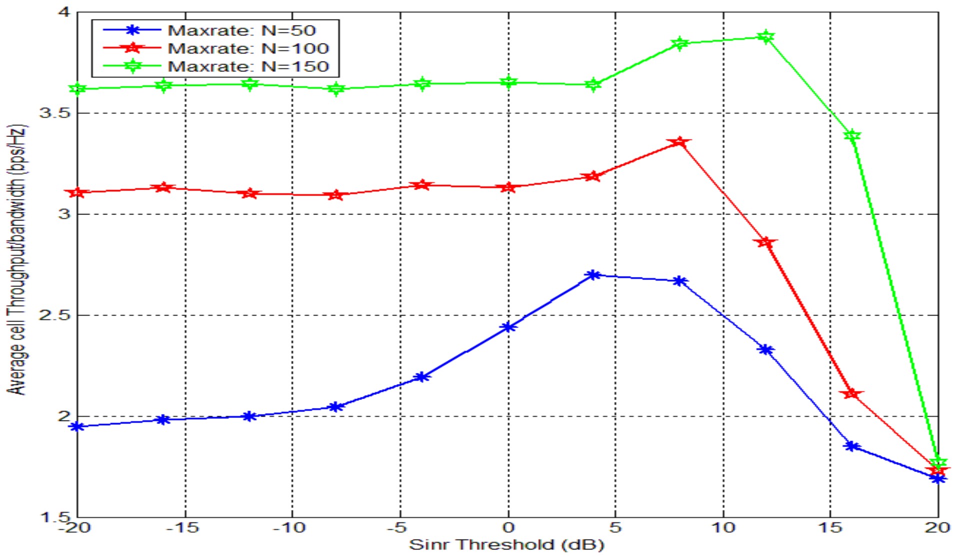

Figure 6.12: **Maxrate scheduling strategy**

6.3.3 Comparison of RR and Maxrate SINR-threshold

One can observe that with number of users getting increased in case of maxrate, average throughput gets increased. As maxrate does not give fairness to cell-edge users so it is able to achieve higher throughput in as number of users getting increased.

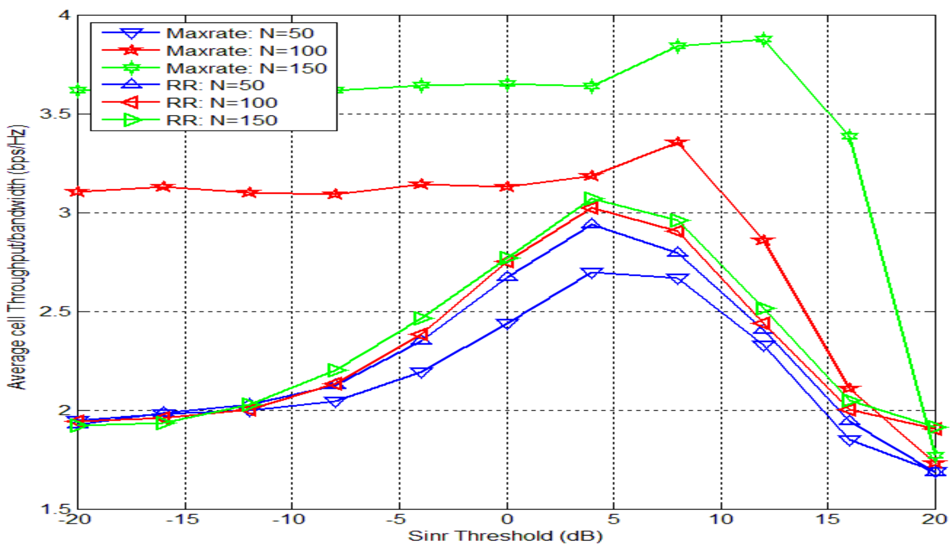

Figure 6.13: **Comparison of RR and Maxrate**

CHAPTER 7

7 CONCLUSION

In thesis, an optimal PRB allocation based on binary linear program is implemented to maximize average throughput of the cell for frequency reuse one. Along with maximization of cell center throughput some fairness to cell edge user depending upon there path-loss is also considered.The optimal SC-FDMA resource allocation improves average throughput significantly but has relatively high complexity. To minimize the complexity of the allocation, an sub-optimal Hungarian algorithm with low complexity for PRB allocation is used. The effect of adjacent channel interference or out-of Band interference on these allocations has also been studied. Results shows that throughput of the users decreases significantly due to ACI. To mitigate the effect of ACI effect we have proposed a heuristic algorithm to optimize throughput of the cell. Proposed heuristic algorithm is able to mitigate ACI effect on users with high SINR values at the cost of increase of interference on users with low SINR values.

As Alone PRB allocation can not increase throughput significantly due to very less improvement in cell-edge users throughput, a fractional frequency reuse to increase cell edge throughput has been considered. By setting different SINR target, the average throughput in strict FFR has been optimized. We have achieved an optimal SINR-threshold which maximizes average throughput. Analysis and simulation results have demonstrated that the throughput increases and the SINR-threshold increases with the number of users in case of maxrate scheduling. While, throughput increases and the SINR-threshold remain constant with the number of users in case of round robin scheduling. We have also observed substantial gain in cell throughput with the optimal distance threshold over that with a fixed threshold.

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