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Simulation and Optimization of Frequency Reuse in OFDMA Networks

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Abstract

Efficient radio resource management is an important aspect when it comes to achieving high bit rates in technologies such as the 3GPP Long Term Evolution (LTE). This thesis aims at understanding existing frequency reuse schemes in OFDMA networks, and to develop an algorithm for frequency allocation for irregular cellular layouts. Previous work done in this field mostly covers schemes for regular cells, whereas in real life cellular layouts are mostly irregular. A comparison of the existing allocation schemes for the users near the boundary of the cells, also known as edge users, with our scheme is presented.

Reuse-1, Fractional frequency reuse-3 with random frequency allocation (FFR3-RFA) (for edge users) and our algorithmic frequency allocation (FFR3-AFA) scheme are simulated and compared. FFR3-AFA algorithm assigns a frequency sub-band to a cell by considering the frequency allocations in the neighbor cell edges and the overlap area between those neighboring cells. Static simulations were performed with one user per base station and constant downlink traffic of 100 Kbits/sec, so that all the resources are utilized and there is maximum interference. This way, the difference between the frequency reuse schemes is much more evident. The throughput for our calculation is the ratio of the total successful packets sent in the network and the total packets sent in the network. Small scenarios are considered with different downlink data rates and the results show that FFR3-AFA has better performance than the other two techniques. There is also room for improvement in the algorithm by introducing other factors into the equation other than overlap area, such as user throughput.

Acknowledgements

We would like to thank our supervisor Prof. Di Yuan for his support and guidance throughout the thesis work. His provided us with all the guidelines and gave us a clear picture on what to aim for this thesis work.

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Regards,
Muhammad Ammar Zafar
Azeem Waqar

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List of Abbreviations

ARMA	Autoregressive Moving Average
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
BS	Base Station
CBR	Constant Bit Rate
CCU	Cell Centre User
CEU	Cell Edge User
CP	Cyclic Prefix
DFT	Discrete Fourier Transform
DSA	Dynamic Sub-carrier Allocation
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FFR	Fractional Frequency Reuse
FFT	Fast Fourier Transform
FSK	Frequency Shift Keying
GSM	Global System for Mobile Communications
ICI	Inter-cell interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISI	Inter-symbol Interference
LOS	Line of Sight
MMPP	Markov-Modulated Poisson Process
NLOS	Non-Line of Sight
NSN	Nokia Siemens Networks
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OpenWNS	Open Wireless Networks Simulator

PP	Point Process
PSK	Phase Shift Keying
QoS	Quality of Service
RISE	Radio Interference Simulation Engine
RNC	Radio Network Controller
SFR	Soft Frequency Reuse
SINR	Signal to Interference Noise Ratio
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
VOIP	Voice over Internet Protocol
Wi-Fi	IEEE 802.11 standard
WiMAC	WiMAX Medium Access Control
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

With the emergence of mobile technologies in the early 1980's no one could have thought that within half a century cellular phones will become such an integral part of our lives. As the technology progressed, so did the demands of the users and the technology had to come out of its shell, of just providing quality voice service, to providing non-traditional services like real-time video and data services. This puts more stress on the radio resources which were always limited. From GSM to 3G and OFDMA systems, the focus has always been on effectively utilizing the frequency spectrum.

The access network in mobile networks is based on the cellular approach because of the limitation on frequency resources. To improve the spectrum efficiency frequency reuse is implemented in these cellular systems. For CDMA systems, frequency reuse factor is equal to 1 i.e. all frequency resources are available in each cell. However, in OFDMA networks, if frequency reuse factor of 1 is used, co-channel interference (CCI) would be introduced because of same resources being simultaneously occupied by different users in adjacent cells, specifically for those users which reside close to the cell boundary. This interference will cause degradation in system performance and service quality for edge users.

To reduce the CCI one technique could be to implement a reuse factor greater than 1 but it reduces the spectrum efficiency and is thus not feasible for OFDMA networks. Several techniques have been developed to overcome this interference problem. The technique that is investigated in this thesis is Fractional Frequency Reuse (FFR). The main idea behind FFR is to logically divide the cell into inner and outer regions and use reuse factor of 1 for the inner region and an increased reuse factor for outer regions. This has the effect of users close to cell boundaries experiencing reduced interference from the adjacent cells and having improved service quality.

1.1 Problem Statement

Related studies on FFR deals with standard hexagonal shaped cell layouts which may be good for theoretical measurements but are far from the cellular layouts used in real network scenarios. Real-life networks have a very irregular cellular layout with high variations in signal propagation, and optimization is required continuously to improve the overall performance of the network. Most of the previous studies of FFR do not provide an optimal solution for real life networks because of irregularity in cell patterns. FFR solutions need to be optimized to enhance the cell edge performance for such irregular networks.

The task of this thesis is to simulate fractional frequency reuse in OFDMA systems and to develop an optimization algorithm to optimize the fractional frequency reuse for realistic cellular layout. The simulation aims at comparing the optimized FFR-3 scheme (FFR3-AFA) with randomly allocated FFR-3 scheme (FFR3-RFA) and the classical reuse-1 scheme for realistic layout of OFDMA cellular networks. The work in a nut-shell consists of selection of the simulation platform, development of simulation scenarios, programming in the selected simulation environment as well as performance evaluation and analysis.

1.2 Thesis Outline

A theoretical background is given in Chapter 2 which goes step by step from single carrier modulation to OFDMA. The concept of frequency reuse is also briefly discussed. This chapter assumes a general understanding of basic modulation techniques and signal processing.

Chapter 3 covers inter-cell interference (ICI) mitigation techniques proposed by major telecommunication vendors. The text explains their proposals briefly.

A brief description of related work on frequency allocation schemes for OFDMA networks is presented in Chapter 4.

An overview of the simulation tool used for simulations is described in Chapter 5. It covers the structural organization and simulation modules of the simulator.

Chapter 6 presents a detailed description of the frequency allocation techniques implemented in the thesis. It also presents the algorithm used to optimize the cell edge performance.

Simulation scenarios and results are presented in Chapter 7, followed by conclusions and possible continuation of work in Chapter 8.

Chapter 2

Technical Background

2.1 Single Carrier Modulation

In single carrier modulation, information signal is modulated on a single carrier using either phase, amplitude or the frequency parameter of the carrier. These techniques are called phase shift keying (PSK), amplitude shift keying (ASK) and frequency shift keying (FSK) respectively. As we move to higher bandwidths in single carrier systems, the symbol/bit duration decreases significantly, thus making the modulated signals more prone to noise, interference and other impairments. The end result is loss of information as the receiver is unable to recover the transmitted information.

2.2 Frequency Division Multiplexing (FDM)

Frequency Division Multiplexing (FDM) is a multi-carrier transmission scheme and is an extension to the single carrier modulated systems. It uses multiple sub-carriers for the same channel i.e. the spectrum (available bandwidth) is divided into different sub-channels and several data streams can be concurrently transmitted over the channel. The individual data rates of each sub-channel taken together gives the overall data rate of the system. One important point to note is that the data which is to be divided into these sub-channels may not be from the same source. Hence, different users can be served simultaneously over the same channel using different sub-channels.

By breaking the bandwidth into small sub-channels, the frequency response of each sub-channel can be considered flat. This flat response helps to simplify the equalizer design and lowers the complexity of the receiver [1]. Different data streams can be transmitted simultaneously without interfering with each other.

If we consider the frequency spectrum of FDM, the main lobes of the sub-channels do not overlap, as shown in Fig. 2.1. In fact, the two sub-carriers are separated by a guard band for minimum interference. These guard bands ease the demands on the cut-off frequencies of the filters in the receiver, and also protect against frequency inaccuracies. Disadvantage of these guard bands is that it lowers the system's spectrum efficiency and effective information rate as compared to a single carrier system with similar modulation.

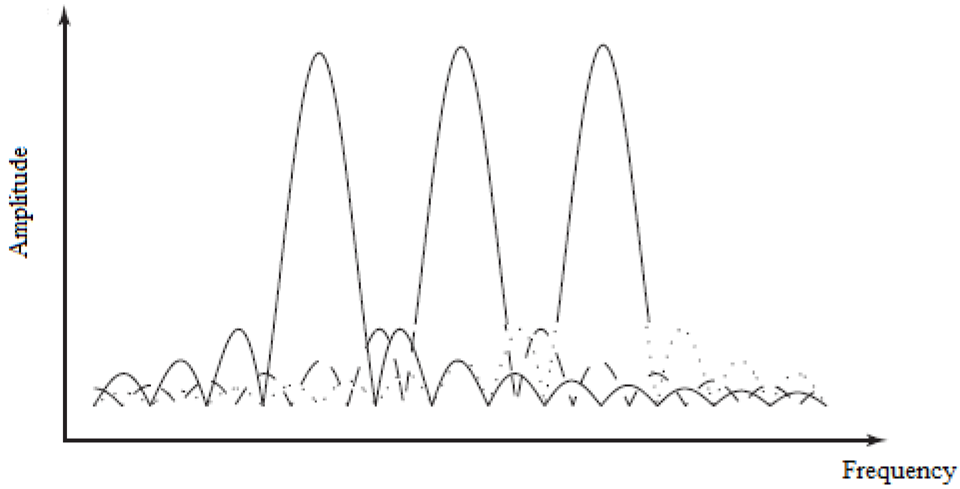

Figure 2.1 FDM sub-carriers.

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The main advantage of FDM over single carrier modulation is the ability to overcome narrowband interference. Since the interference is frequency dependent, only one of the sub-bands will be affected. Additional immunity against impulse noise and frequency reflections is achieved because each sub-carrier has a lower data rate and hence the data symbol period will be longer. Also, we can have separate modulation and demodulation techniques for different data streams (sub-channels).

2.3 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is also a multi-carrier modulation technique and is based on the division of available bandwidth into multiple sub-channels.

OFDM emphasizes that FDM's bandwidth usability can be made much more efficient by allowing overlap between the main lobes of the sub-channels. This is possible by making the overlap in a clever way i.e. using sub-carriers that are orthogonal to each other. By introducing this orthogonality property to the sub-carriers, guard bands that were required for FDM system would no longer be needed. The resulting OFDM signal spectrum is shown in Fig. 2.2.

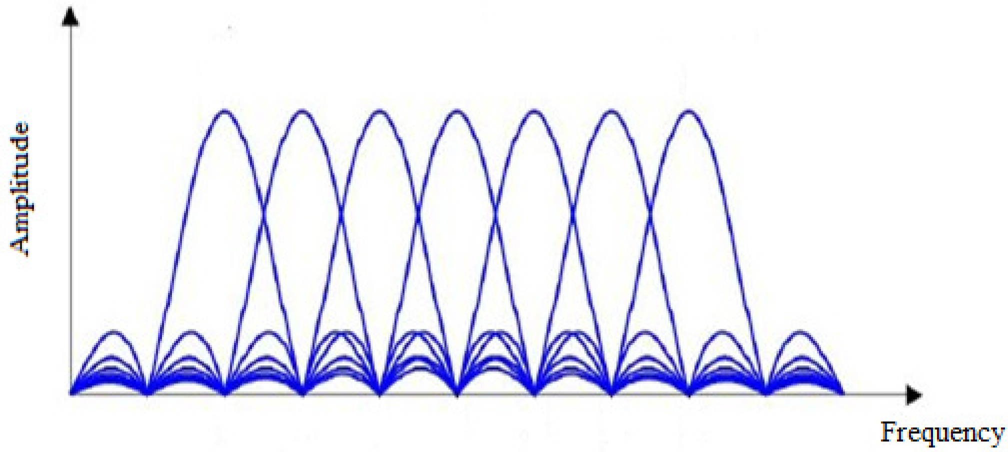

Figure 2.2 OFDM signal with 6 sub-carriers.

If we denote $\phi(t)$ as sub-carriers, then in time domain we can write the equation for each sub-carrier as

$$\phi_i(t) = \frac{1}{\sqrt{T}} e^{j2\pi f_i t} = \cos(2\pi f_i t) + j\sin(2\pi f_i t) \qquad (2.1)$$

Here the subscript i is for individual sub-carriers and f_i is the centre frequency of a particular sub-carrier. The centre frequency of a particular sub-carrier is given as

$$f_i = f_o + m \cdot \Delta f \qquad (2.2)$$

Here f_o is the base frequency and m is the sub-carrier number and Δf is the sub-carrier spacing.

The orthogonality property which the sub-carriers hold in OFDMA is given as

$$\int_0^\infty L_n(t) L_m(t)\,dt = \begin{cases} 0 & m \neq n \\ 1 & m = n \end{cases} \qquad (2.3)$$

Here $L_n(t)$ and $L_m(t)$ are the two sub-carriers, and m and n are the sub-carrier numbers.

OFDM allows only one user on the channel at any given time. To provide support for multiple users, a multiple access scheme is required with OFDM. TDMA or FDMA could be used but neither of these techniques is time or frequency efficient. A more efficient technique that could be useful for OFDM is Orthogonal Frequency Division Multiple Access (OFDMA).

2.4 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA can be thought of a multi-user OFDM which allows multiple users to access the channel at the same time. In OFDMA, sub-carriers are distributed among different users for intervals of time so that they can transmit and receive within their own channel without experiencing any significant interference from users on other sub-carriers. Each single user can be assigned one or multiple sub-carriers depending on the requested data rate.

OFDMA is considered as a hybrid of TDMA and FDMA because the users can be assigned different sub-carriers at different time intervals or timeslots as shown in Fig. 2.3. The inherited orthogonality among the sub-carriers guards against multiple access interference. By using efficient assignment strategies, resource management within the system can be handled with a great deal of flexibility.

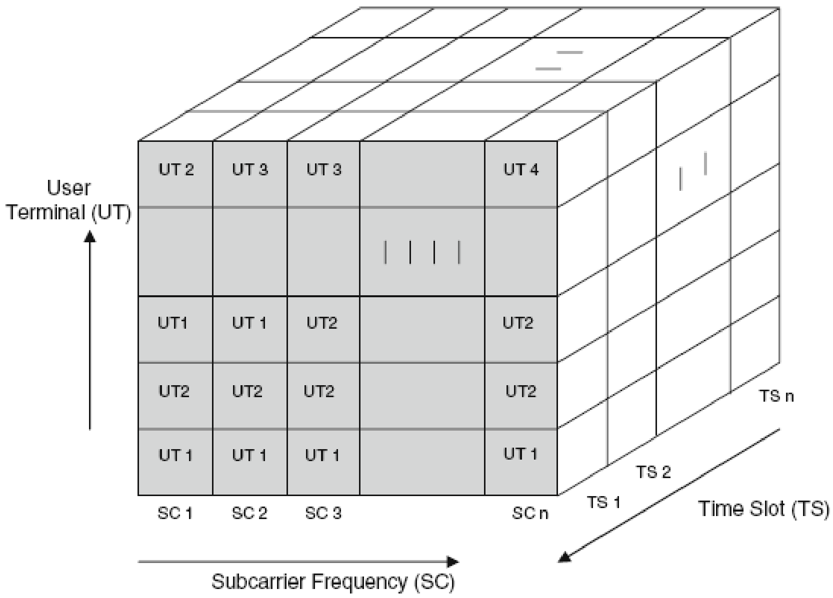

Figure 2.3 OFDMA system with timeslots and sub-carriers.

2.5 The Concept of Frequency Reuse

Frequency reuse is an integral concept of cellular communications which allows the users in different geographical positions to use the same frequency band. By reusing the frequency bands over and over again a cellular network provider can serve a large number of users simultaneously, therefore increasing the capacity of the system [2]. Frequency reuse can considerably increase the spectrum efficiency of the cellular system, but proper planning is required to overcome the interference caused by the common use of the same frequency bands. Because of the closeness of frequency bands, interferences such as adjacent channel interference and co-channel interference can severely degrade the quality of service provided to a mobile user. Efficient frequency allocation techniques have been developed over the years to minimize these interferences and maximize the benefits of frequency reuse. For OFDMA systems, techniques such as FFR and SFR are popular choices.

2.5.1 FFR and SFR

FFR and Soft Frequency Reuse (SFR) are two well-known interference mitigation techniques in OFDMA networks. In both these allocation schemes, the cell is logically divided into inner and outer regions and similarly the users are differentiated as cell-centre users and cell edge users. Both allocation techniques apply reuse factor of one to cell centre. However, cell edge users are served with a reuse factor greater than one with slight difference between the two techniques. In FFR, the given bandwidth is split into two parts, inner and outer. The inner part is allocated to each base station i.e. fully reused by all base stations. The outer part is further divided among base stations with a frequency reuse greater than one trying to maintain that adjacent cells are allocated a different sub-band from the outer part. In SFR, the overall bandwidth is shared by all base stations, but a power bound on certain sub-bands is introduced such that some sub-bands are transmitted with higher power in one cell and some sub-bands in other [3].

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Chapter 3

Inter-Cell Interference Mitigation Techniques

3.1 Interference Mitigation

The cellular concept in mobile communications is faced with issues from inter-cell interference (ICI). This interference arises because of the duplication of signals/resources in the neighboring cells, and has the effect of degrading the service quality of the users. If each base station in the system uses the entire bandwidth resources simultaneously, any mobile station which is close to the boundary of a cell would suffer from interference created by the same resource in the adjacent cell. This interference degrades the QoS of the mobile station located at the cell edge. Users close to the base station, also called Cell Centre Users (CCU), may not be severely affected by this interference because of their distance from the neighboring base stations. At cell edges, because the cells do not have a definite boundary, the frequencies come across each other more which has drastic effects on the cell edge users.

The cellular concept becomes realistic only if efficient solutions can be provided for ICI. Otherwise, there will be large areas within the coverage area of a telecommunication operator where the users cannot be served properly and the concept of efficient resource management is ruined. One solution to this issue is the allocation of alternate resources to cells, i.e. adjacent cells are allocated totally different frequencies such that there is no interference. Ever increasing demand of data services requires the need for increasing data rates and using such schemes is not a solution anymore. Interference mitigation techniques that can maintain a frequency reuse close to 1 (entire bandwidth available to each cell) need to be worked out.

3.2 Proposals by Telecommunication Companies

3.2.1 Ericsson's Proposal

In the allocation scheme proposed by Ericsson only a portion of total resources is made available for allocation to cell edge users with full power, while cell centre users use the whole spectrum with restricted power. The sub-bands used for cell edges are orthogonal between neighboring cells to reduce interference. The cost is reduced bandwidth for cell edge users [4]. An example is shown in Fig. 3.1.

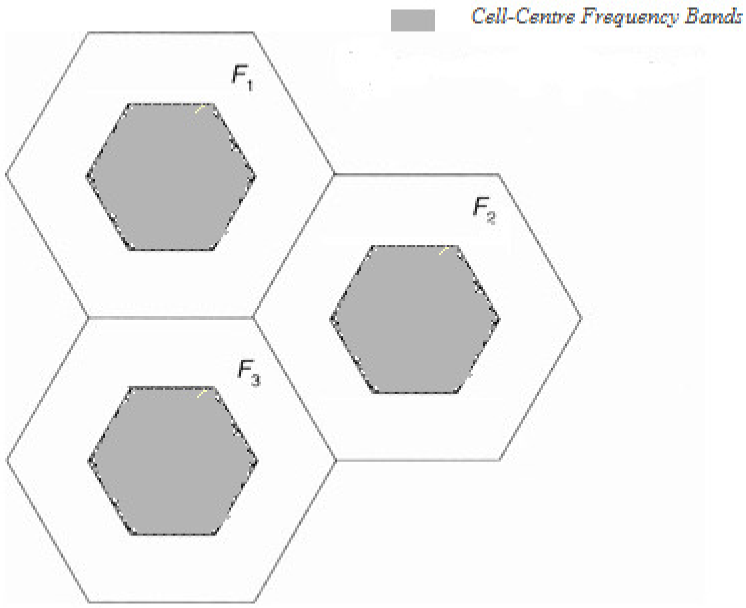

Figure 3.1 Ericsson's proposed scheme with orthogonal cell edge sub-bands F_1, F_2, and F_3 in neighboring cells.

3.2.2 Nokia Siemens Networks' (NSN) Proposal

Nokia Siemens Networks proposed a Soft Frequency Reuse (SFR) technique. It uses a static power profile in each cell. The transmit power is kept constant for a set of sub-carriers, called 'frequency resource units' by NSN. When allocating different sets of sub-carriers to cells, coordination is required such that frequency resource units with higher power in a cell coexist with relatively lower power resource units in the neighboring cells [5]. This assignment of static power profiles to cells reduces the inter-cell interference at cell edges.

3.2.3 Alcatel's Proposal

Alcatel proposed two strategies for inter-cell interference mitigation:

- Interference coordination strategy 1 (network power planning)
- Interference coordination strategy 2 (on demand basis)

In the first method, the frequency spectrum is divided into several subsets. Suppose S is the total number of subsets. The value of S is proposed to be 7 or 9. Each subset is referred by F_n, where n is from 1 to S. Networking planning is done in such a way that always a different frequency subset F_n has reduced power in each sector. So in sector C_n the power of the subset F_n is limited to the cell centre. For example, if a user U_1 (in C_6) approaches sector C_1, as shown in Fig. 3.2, it gets frequency allocation from frequency subset F_1 as F_1 is used with reduced power in C_1. So all users approaching C_1 from the outside are allocated subset F_1 by their respective base stations as long as they remain in the cell edges of their respective cells and before a handover to cell C_1 has taken place. For details on the network power planning scheme the readers are referred to [6].

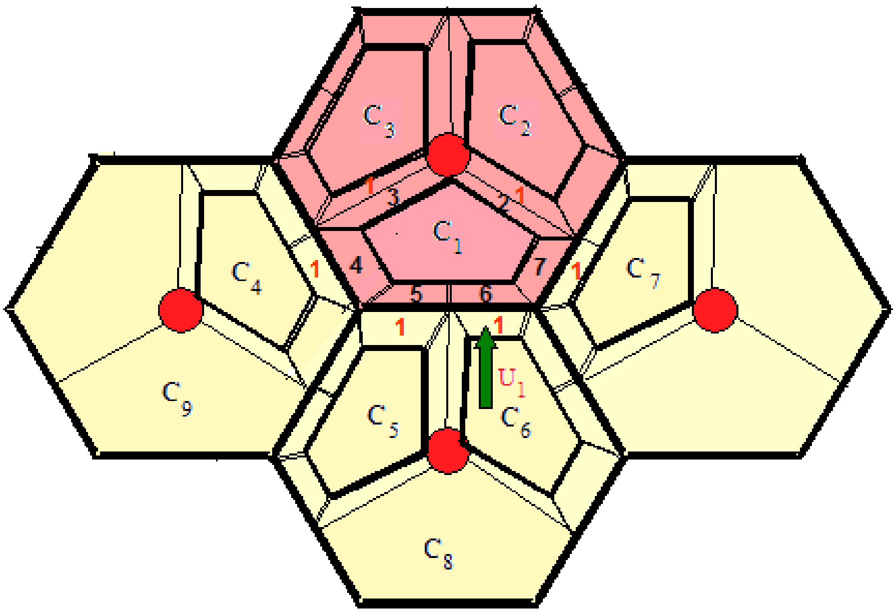

Figure 3.2 Interference coordination strategy 1.

The second interference coordination strategy is a dynamic technique and does not require network planning to deal with cell edge users or users which are approaching the cell boundary. When a user approaches the cell boundary between two cells, it will experience interference from other cells. The user reports this interference to its serving base station. The serving base station coordinates with its neighboring (interfering) base station and a power restriction is placed on a set of frequency bands in the neighbor and those bands are granted to the serving base station. Thus, a resource is restricted in the neighbor and is assigned to the serving station [6]. The result is improved service for the cell edge users. The method is shown in Fig. 3.3.

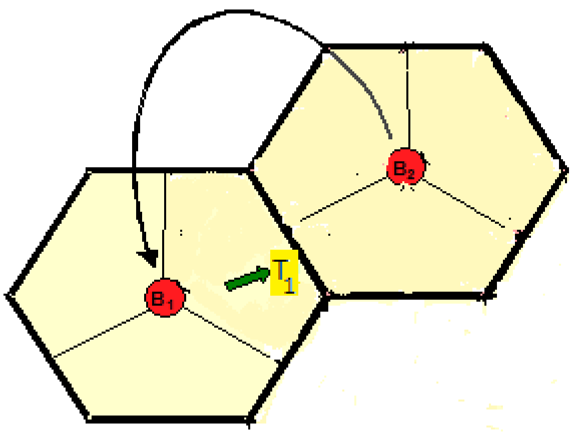

Figure 3.3 As user T_1 moves closer to the edge, resource in neighboring station B_2 is restricted and assigned to serving base station B_1.

3.2.4 Samsung's Proposal

Samsung proposed a flexible FFR technique. The frequency set is divided into different logical resource sets. A logical unit is a group of sub-carriers either distributed or contiguous, and one or more resource units are combined to constitute a resource set. A preferred resource unit is allocated to each cell. In cases of partial loading, the cells use resources from this source. Once the resource unit is fully utilized or the cell is fully loaded and more resources are required, the cell can use frequency resources from its neighboring cells following some pre-defined strategy implemented on the base station [7].

The example in Fig. 3.4 shows three cells being allocated three resource blocks A, B and C. The total sub-carrier frequencies are divided into three in this case and each segment is allocated to a cell. The allocation of resource units to users in a cell is done in ascending order i.e. A1 first, then A2 and so on for cell A. Now, if cell A has allocated all its resource blocks to users and require more resources, it can allocate resource blocks from cell B and cell C alternatively. From Fig. 3.4, if cell A is out of resources then it will allocate resources to its users in the reverse order as B5, C5, B4, C4, and so on. This technique effectively mitigates inter-cell interference when the cells are not fully loaded, and interference on only some resource blocks occurs for fully loaded system.

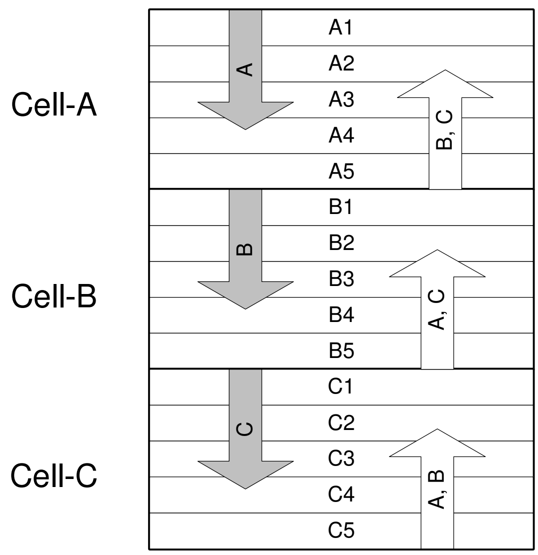

Figure 3.4 Flexible FFR proposed by Samsung.

Chapter 4

Literature Study

Design and development of efficient resource/frequency allocation techniques have been given significant attention as a research topic in recent years. The main aim is to achieve an optimal frequency reuse technique to serve the demands of higher data rates and better quality of service. In this chapter, related work regarding different frequency reuse techniques is covered.

The concept of cell splitting is used in many frequency allocation techniques for OFDMA networks. The cells are divided logically into two regions, the cell centre and the cell edge regions. These regions are shown in Fig. 4.1. The cell edge region can be assigned dedicated frequency sub-bands to improve the service quality to the cell edge users. The way these dedicated resources are assigned to the cell edge users can differ for different allocation schemes.

A frequency reuse scheme for multi-cell OFDMA systems for co-channel interference reduction is proposed in [8]. Each cell is partitioned into three sectors. All the available sub-carriers in each cell are divided into two groups. One group, called the super group, is reused in the central region of the three sectors. Another group, called the regular group, is divided into three parts with regards to the outer region of the three sectors. The sub-carrier a user can use depends on the location or the received SINR of the user. Thus, intra-cell interference is avoided and inter-cell interference is minimized. The allocation of super and regular groups is shown in Fig. 4.1 for three cells. All the sub-carriers may use the same transmit power in this scheme. Results show that this scheme can bring higher system throughput and lower co-channel interference (CCI) and it can also increase the data rate at the cell's edge.

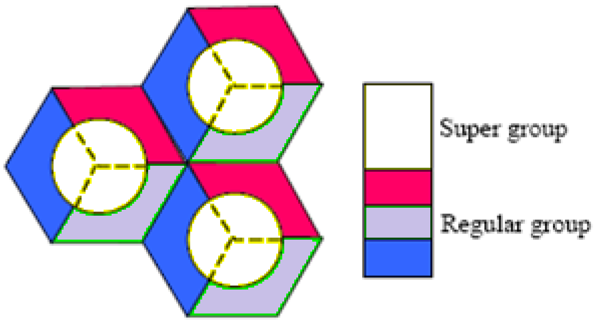

Figure 4.1 Super and regular group allocation.

Sub-carrier allocation to the inner or outer part of the cell can be done statically or dynamically. The authors in [8] used dynamic allocation. Assigning a fixed set of sub-carriers in each cell to a set of users is likely to give low system throughputs in case of systems with varying user distributions. So the sub-carrier allocation used by the authors is dynamic, adjusted according to the distribution and the Quality of Service (QoS) of the users. If there is no user in the cell edge, all the available sub-carriers can be used in the central cell region. The threshold proposed to distinguish between inner and outer cell regions is either a distance of *800m*, or a SNR value of *0 dB*. Users with SNR values greater than the *0 dB* threshold get resources from the resource block reserved for center users, having a reuse factor of 1. Users experiencing SNR values below *0 dB* are treated as edge users and given resources correspondingly. The authors work with dividing the total available resources into two equal blocks. Giving 50% of the total to the center and dividing the remaining 50% between the edge groups (divided by 3, for three sector cells in this case). Their results show improvements in comparison with the conventional scheme, i.e. with frequency reuse factor in all cells equal to 1.

Another dynamic technique for frequency allocation in OFDMA networks is presented in [9]. In this work, a method for dynamic channel allocation and opportunistic scheduling for multi-cell OFDMA networks is presented. As an alternative to the static FFR scheme, the authors propose a dynamic FFR architecture where a cell area is partitioned into two regions. The first region is called a super group and the user sub-carrier pairs in the group experience interference from all the neighboring cells. The second region is called the regular group which is physically partitioned into sectors, as shown in Fig. 4.1. The user sub-carrier pairs for this group experience reduced interference. The system architecture supports full frequency reuse. By covering the whole cell area, both groups include all the cell users which results in increased trunking gain. The novel dynamic sub-carrier allocation (DSA) scheme makes best use of the FFR architecture. Algorithms at the Radio Network Controller (RNC) and the base station are implemented. At the RNC, sub-carriers to the groups are allocated so that the system performance is increased while satisfying the sum of the minimum performance requirement of those groups. At the base station, opportunistic scheduling decisions are made and sub-carriers are assigned to the users.

The research work in [10] provides an analysis of the inter-cell interference coordination in multi-cellular OFDMA system. The work is based on the FFR technique i.e. partitioning the cell into two regions (inner and outer). The regions have different frequency reuse factors. The resource allocation and interference coordination are considered jointly. The problem is formulated as a combined integer and linear continuous optimization problem and solved by the Prima Dual Interior Point Method. The best configuration was found in reserving 32 chunks to the interior cell region, and 18 chunks to be shared among the three neighboring cells (out of the total 50 chunks). The optimal interior cell region radius is determined to be equal to 2/3 of the overall cell radius. Also the resource distribution is such that 64% of the resources are kept for the inner cell users and 36% to be divided between the outer cells.

A graph based framework for dynamic FFR in multi-cell OFDMA networks is proposed in [11]. The dynamic feature provides the capability of adjusting the spectral resources to varying cell load conditions. The adaptation is accomplished via a graph approach in which the resource allocation problem is translated to a graph coloring problem. The aim of the dynamic allocation is to deliver higher cell throughput and service rate in asymmetric cell load conditions.

A non-conventional technique for frequency allocation for OFDMA networks is proposed in [12]. The authors stress the fact that previous research done on FFR has focused on relatively small networks and standard hexagonal shaped cell layouts. For real life networks, with highly irregular cell layout variation in radio propagation, using a conventional approach is inadequate. The authors propose an FFR scheme for irregular cellular structure in OFDMA networks. They also point out that FFR-3 is not an optimal solution for irregular cells as the number of neighbors for each cell could be different. Furthermore, an allocation algorithm has been devised for the number of sub-bands for the edge users of every cell. Using data from real networks of Lisbon and Berlin, it is demonstrated that better throughputs are achieved for cell edge users, and it is sometimes optimal to split the cell edge band into more than the standard three sub-bands.

Chapter 5

Simulation Platform

5.1 Choice of Simulation Tool

There are a number of different simulation platforms available for simulating wireless networks and the analysis of different protocols. However, these simulation tools provide little support for the simulation of different techniques for frequency reuse on a system level. We have considered tools such as NS-2, OPNET modeler and MATLAB for the simulation purposes before choosing the Open Wireless Network Simulator (OpenWNS).

NS-2 is an object-oriented event-driven network simulation tool. It is an open source tool and its main core is based on C++. The programming language used as a front end for simulation configurations is oTCL. NS-2 can be used for protocol design, traffic studies, protocol comparison etc. A variety of IP networks can be simulated in NS-2. A large number of applications, network elements, network types and traffic models are supported by the tool. Several transport and MAC layer protocols along with different types of traffic sources, queue management mechanisms are also supported. Scenarios based on various telecommunication technologies like General Packet Radio Service (GPRS) [13], Multiprotocol Label Switching (MPLS) [14], AdHoc networks [15], and IPv6 [16] can be implemented and analyzed.

NS-2 is more concentrated on the protocol analysis and design of protocols and on the overall systems. Although it is possible to have control over the mobility patterns and propagation models, the implementation of OFDMA at the modulation level is very simple. NS-2 does not focus in detail on the assignment of frequency sub-bands to cells. Also, the logical division of cells into inner and outer regions having different frequency bands is not supported. Only frequency reuse-1 can be modeled by default. NS-2 add-on for IEEE 802.16 model supports multi-cells to have different frequencies in different cells but still logical division of cells to inner and outer regions is not possible.

OPNET is another popular choice for modeling and simulation of communication networks, devices and protocols. It is a commercial tool and is based on object-oriented modeling approach and graphical editors. Higher OSI layers are the focus of this tool and the lower layers such as the physical layer and the transmission characteristics are modeled quite simply. Although a special model is available in the OPNET modeler for WiMAX simulations (WiMAX uses OFDMA) which supports multiple cellular networks, multi-sectored base stations, path loss modeling, scheduling for uplink and downlink connections but it is not possible to logically define inner and outer regions in cells. Also, OPNET is not open source so to additionally include this functionality is not possible. By default, the OPNET modeler supports hexagonal cells and support for irregular cells is not provided.

After thorough search for research papers on FFR, OpenWNS was found to be one open-source simulation tool in which some simulations on soft frequency reuse were performed recently [17]. OpenWNS has a separate module for OFDMA network simulations with some example scenarios as well. Fine control over the base station parameters, their antenna transmission powers and azimuth, allocation of sub-bands to base stations is provided. As it is an open source tool, changes can be made to modify the module according to one's own requirements. Also, an important factor in choosing OpenWNS was the possibility of creating irregular cell patterns over the service area.

5.2 Open Wireless Network Simulator (OpenWNS)

The simulation platform used to perform desired simulations in this thesis is Open Wireless Networks Simulator (OpenWNS) which is available at [18]. It was developed at the Department of Communication Networks (ComNets) at RWTH Aachen University. It is an event driven simulation tool for the simulation of various networks and technologies. The core programming language is C++ while python is used for configurations and simulations. Fig. 5.1 shows the OpenWNS framework.

For the simulations we required a tool which can allow us to make irregular cellular patterns and allow allocation of frequency sub-bands to cells. The tool also needed to provide propagation models, mobility models and traffic models to simulate real-time environments. Most of the required features are available in OpenWNS, and some of the changes were made to the simulator to incorporate the functionality necessary for the simulations. For example, OpenWNS does not support the feature of frequency allocation to inner and outer cell regions (required for FFR) which had to be added in the simulator.

5.2.1 Event Scheduler

Both real time and non-real time schedulers are provided in OpenWNS. Real time scheduler is for building demonstrators and for implementing interaction with the simulation host. Non-real time scheduler, used for the simulations in our case, is a two layered map data structure. For a distinct simulation time, a map entry is created. In every map entry, there is a queue of all the events that are scheduled to run at that time.

5.2.2 Configurations

As previously stated, Python language is used for scenario simulations. Scalability is one of the important reasons for using a programming language instead of data representation language like XML. Scalability is very important as the configuration mechanisms need to be capable of handling large scenarios and complex simulation models.

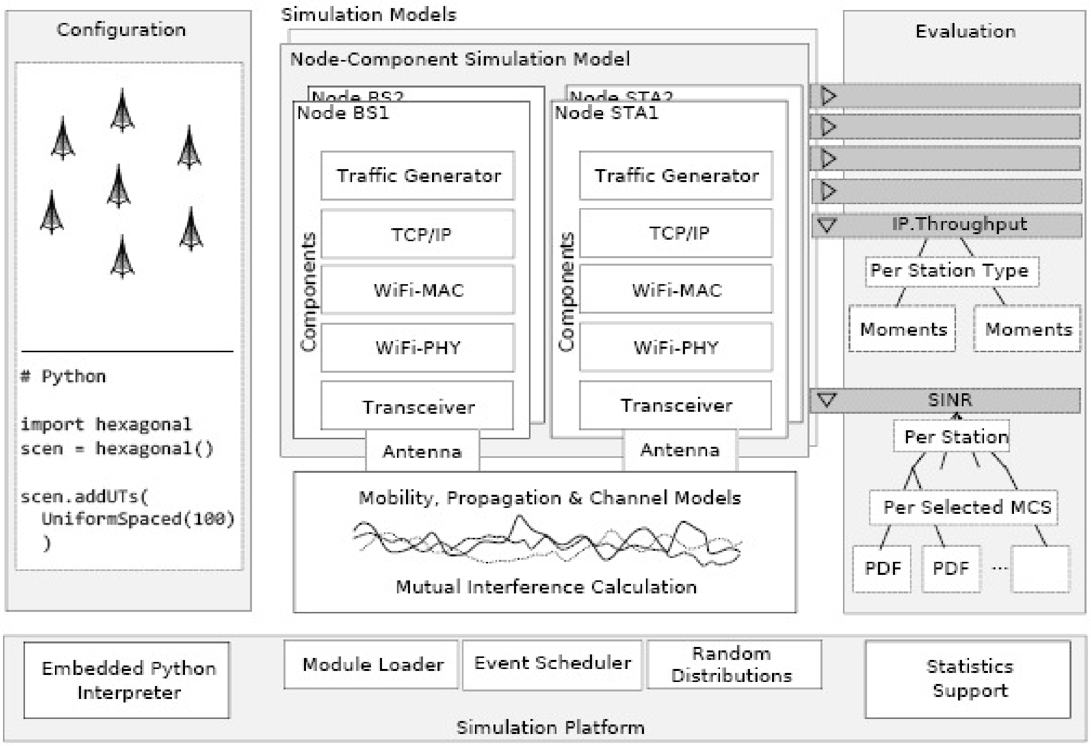

Figure 5.1 OpenWNS structural organization.

5.2.3 Evaluation

The evaluation subsystem of OpenWNS, as shown on the right part of Fig. 5.1, provides ways to sort measurements according to a measurement context and also compresses the data by means of statistical processing during runtime.

When configuring simulation scenarios, measurement parameter can be chosen from a number of different kinds of evaluations as desired by the simulation. For example, an evaluation of the signal to interference noise ratio (SINR) measurement could be configured.

5.2.4 Simulation Modules

OpenWNS provides support for various technologies standards. For the data link layer, WiMAX and WiFi are available in the simulator. OpenWNS allows for multi-standard nodes which can operate concurrently below the IP layer. TCP and UDP are the available standards for the transport layer. Traffic models are also available which can operate on top of either transport, network or data link layer.

One of the main simulation modules is RISE (Radio Interference Simulation Engine). It manages node mobility and interference calculations. The total received signal strength for every transmission is calculated by the channel model using the formula in (5.1)

$$P_R = P_T - L_{path} - L_{shadow} - L_{FastFading} + G_T + G_R \qquad (5.1)$$

Here P_R is the received power, P_T is the transmitted power, L_{shadow} is the loss due to shadowing, L_{Path} is the path loss, $L_{FastFading}$ is the loss due to fast fading, G_T is the transmit antenna gain and G_R is the received antenna gain. The parameters are measured in dB/dBm scale.

Antenna models are also an important part of the simulation modules. Two main types of antennas are notable i.e. omni-directional and beamforming antennas. Omni-directional antenna is defined by its gain in all directions, and beamforming antenna allows the user to dynamically adjust antenna's directivity by varying the vertical angle θ and azimuth angle φ of the antenna.

A. Path loss Models

Several path loss models add to the feature of calculating path loss between the transmitter and receiver in the OpenWNS simulator. Constant, free space, single slope and multi slope models are available. Constant path loss model is not an accurate model for real scenarios but is sometimes used for very short or very far distance for which the loss can be assumed constant.

Free space is the term used for mediums in which the signal can propagate without obstruction between the transmitter and receiver. The free space model is a good approximation for satellite communication systems and for microwave LOS links, when the transmitter and receiver are high above the ground. Friis Formula gives the free space loss as

$$L_{Path} = \left(\frac{\lambda}{4\pi d} \right)^2 \quad , \tag{5.2}$$

where L_{Path} is the free space loss, λ is the wavelength and d is the distance between transmitter and receiver. We can see from (5.2) that doubling the distance or carrier frequency increases the path loss by four times or 6 dB.

The single slope model is defined as

$$L_{Path} = \left(\frac{\lambda}{4\pi d} \right)^\eta \quad , \tag{5.3}$$

where L_{Path} is the path loss, d is the distance between the transmitter and receiver, λ is the wavelength and η is the propagation constant. When η = 2, it is same as the free space model.

The multi slope model is defined by using a path loss factor η_1 after some distance d_0 and up to a critical distance d_c, after which the power falls with path loss factor η_2. P_t is the transmit power and K is the antenna gain of both transmitter and receiver side.

$$P_r(d)dB = \begin{cases} Pt + K - 10\eta_1 \log_{10}(d/d_0) & d_0 \le d \le d_c \\ Pt + K - 10\eta_1 \log_{10}(d_c/d_0) - 10\eta_2 \log_{10}(d/d_c) & d > d_c \end{cases} \tag{5.4}$$

(5.4) gives the path loss in dB scale. Multi-slope model can be extended to more than two regions [19].

B. Traffic Model

The OpenWNS traffic model is named Constanze. Traffic generators create data packets and can be connected to any of the transport, network or data link layers. Available traffic models in OpenWNS are Simplistic Point Process (PP), Markov-Modulated Poisson Process (MMPP) and Autoregressive Moving Average (ARMA).

PP models include Constant Bit Rate (CBR) and Poisson traffic. CBR traffic model is very basic and is used for connections that transport traffic at a constant bit rate. It is well suited for any data type for which the end systems require predictable response time and a specific bandwidth is available for the duration of the connection. This model can be used for simulating video conferencing, telephony or any on-demand service such as interactive video and audio. In this model, time synchronization between the source and destination is considered.

Poisson traffic model is based on the memory-less Poisson distribution and is used to model traditional telephone networks. In this model, the number of incoming data packets follow the Poisson distribution.

The formula for the Poisson probability function is given as:

$$P(x,\lambda) = \frac{e^{-\lambda}\lambda^{x}}{x!} \qquad for\ x = 0,1,2...,\tag{5.5}$$

Here λ is the average rate of packet arrival in a given time interval, x is the number of occurrences of an event and $P(x, \lambda)$ is the probability of the occurrence. Two characteristics of Poisson generated data is that the arrivals occur in an orderly manner i.e. no two occurrences can be simultaneous and secondly, each occurrence is independent from the previous one.

MMPP is a Poisson process with variable rate. Its current rate λ_i is controlled by a continuous-time Markov chain. Research has shown that classical Poisson methods are insufficient for large scale networks, which is where MMPP comes in handy [20]. It is able to model traffic activity well, keeping the approximations scalable [21]. Further, MMPP can model traffic bursts and arrival streams more accurately than other models.

MMPP can be represented by two matrices P and Λ where P is the generator matrix of Markov process and Λ is a diagonal matrix giving the arrival rate for each state of the Markov process.

$$P = \begin{bmatrix} -w_{00} & w_{01} & \cdots & w_{0m} \\ w_{10} & -w_{11} & \cdots & w_{1m} \\ \vdots & \vdots & \ddots & \vdots \\ w_{m0} & w_{m1} & \cdots & -w_{mm} \end{bmatrix} \tag{5.6}$$

$$\Lambda = Diag\begin{bmatrix}\lambda_0 & \lambda_1 & \dots & \lambda_m\end{bmatrix} \tag{5.7}$$

Here w_{ij} gives the state transitions from one state to another and λ_i is the current arrival rate. For detailed study of MMPP, the readers are referred to [22].

ARMA model can be used to generate random data sequence with a given autocorrelation or power spectral density. It can also be used to predict into the future about network traffic. Given a time series of data, the ARMA model is a tool for understanding and predicting future values in the series. ARMA is composed of two parts, an autoregressive (AR) part and moving average (MA) part, as shown in Fig. 5.2.

The AR model is an all pole model and MA is an all zero model, which makes ARMA a pole and zero model. Mathematically, ARMA can be written as

$$X_t = c + \varepsilon_t - \sum_{i=1}^{p} \phi_i X_{t-i} + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} \tag{5.8}$$

Where ϕ_i $(i = 1,2...p)$, θ_i $(i = 1,2...q)$ are the parameters of the ARMA(p,q) model, c is a constant, ε_t and ε_{t-i} are white noise, and X_t is the data sequence.

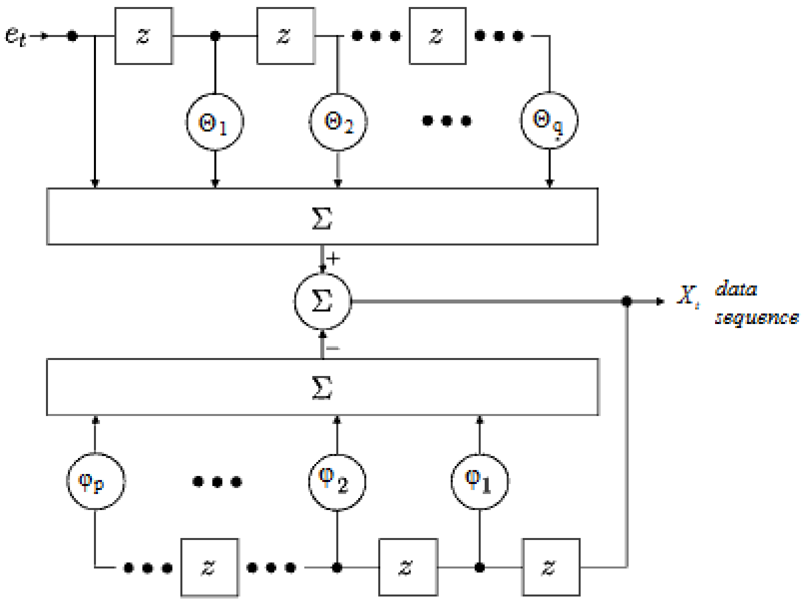

Figure 5.2 ARMA model.

In addition to all the above mentioned models, OpenWNS also provides separate modules for the simulation of Wi-Fi (IEEE 802.11), WiMAX (IEEE 802.16) and TCP/IP. Also, another module named WiMAC (WiMAX Medium Access Control) exists which supports the OFDMA and hence is the module used to run the simulations for this thesis.

Although all these modules are available in OpenWNS for users to configure and analyze their desired wireless scenarios, but a major hurdle in using these models is the lack of available documentation. Till now, OpenWNS has a very limited documentation set which gives difficulties to the users in properly understanding and using all the available models.

Chapter 6

Optimization of FFR for Irregular Cellular Structure

6.1 Frequency Reuse Schemes

The frequency reuse schemes simulated in this thesis are:

- Frequency Reuse-1
- Fractional Frequency Reuse-3 with Random Frequency Allocation (FFR3-RFA)
- Fractional Frequency Reuse-3 with Algorithmic Frequency Allocation (FFR3-AFA)

6.1.1 Frequency Reuse-1

In frequency reuse-1 scheme or simply reuse-1 scheme, the total system bandwidth is available to be allocated in each cell. In traditional GSM systems, reuse-1 is almost impossible to achieve because the users would come up against severe adjacent channel and co-channel interferences. In OFDMA networks, as the subcarriers are orthogonal to each other, interferences from other subcarriers are alleviated but inter-cell interference at cell edge is higher which results in weak signal strength for users at the cell edge. This means, users close to the base station may get very high data rates with minimum interference, but the users close to cell edges experience degraded quality because of the same frequency sub-bands being used in the neighboring cells by other users.

6.1.2 FFR-3 with Random Allocation

In FFR-3, each cell is logically partitioned into center and outer areas based on fixed distance threshold or signal to noise ratio (SNR) threshold. The edge users of neighboring cells are assigned different frequency sub-bands so that they do not interfere with each other. Three sub-bands are reserved for allocation in cell edges. 30% of the total bandwidth is reserved for the edge users. The 30% is divided into three groups. Hence each sector's edge has 10% of the total bandwidth. For the simulations, the region beyond the 2/3 of the cell radius is considered as the outer region or the cell edge. Since the irregularity of the cell is achieved by changing the power and the antenna tilt of the sectors, users are placed by looking at the coverage of each sector. In this allocation scheme, the three frequency sub-bands were randomly assigned to cell edges of each cell sector without considering neighbor relation or overlap between coverage of cell sites. Random allocation is used to clearly demonstrate the difference between a poor frequency allocation to cell edges and the algorithmic allocation, to be presented in the next section.

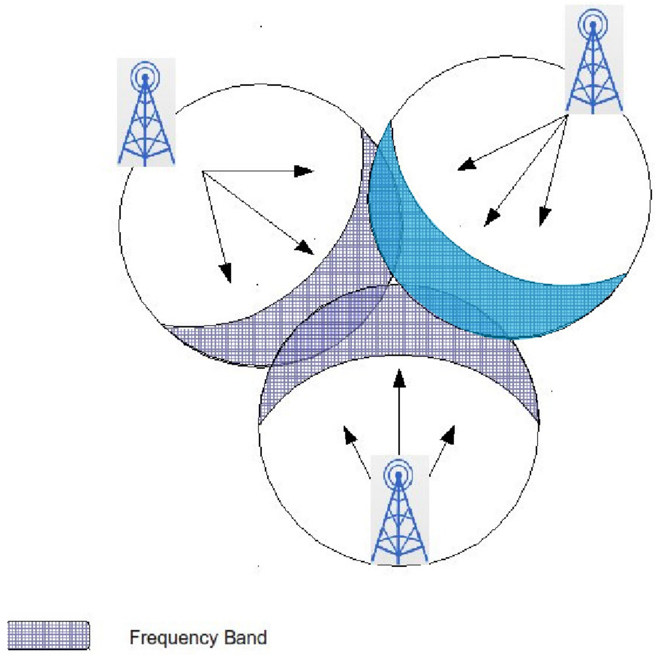

Figure 6.1 Same sub-bands in neighboring cells in FFR3-RFA.

Fig. 6.1 shows sectors for three separate cells getting assigned frequency bands randomly. As seen from the figure, the random allocation could result in a situation where two neighboring cell edges are assigned the same frequency band. This will not lower the interference for the cell edge users in such cells.

6.1.3 FFR-3 with Algorithmic Allocation

The second frequency allocation scheme that we used for the simulations is FFR-3 with algorithmic frequency allocation. The algorithm's objective is to optimize the cell edge performance. The main idea is that instead of randomly allocating sub-bands, cell edges are assigned frequency sub-bands by taking into consideration the allocated sub-bands to cell neighbors as well as the degree of overlap between the neighboring cells. By introducing these constraints, close to real-life scenario for frequency allocation was attempted.

The optimization procedure aims to further improve the throughput achieved by cell edge users. In other words, the frequency sub-bands are allocated to cell edges in such a way that same sub-bands are kept as far as possible. To emphasize the need for optimization, let us consider an example. Suppose we have a large cell A which has many smaller cells as its neighbors. If only three frequency sub-bands are available for allocation to cell edges, there is a possibility that one of the neighbors of cell A will end up having the same frequency at its edge as the large cell A's outer region. This is where optimization comes into play because we know that a collision is inevitable. We can shift this collision such that the overall damage is minimum. For example, cell C, a smaller cell neighboring to A, has been allocated the same cell edge frequency as that assigned to the cell edge of cell A. We assume that cell C and cell A have a large overlap area. It would be a better solution to assign the conflicting sub-band to some other neighbor of cell A that has a lesser overlap area than the overlap area of cell A and cell C. This will lead to less interference for users in the overlap regions of cells A and C, and hence improved overall throughput for the system.

In the algorithm considered in this thesis, the optimization procedure assumes the amount of cell overlap as a factor for re-allocation of frequency sub-bands to edge users, instead of directly considering user throughput at cell edges. This is done due to the limitations of the simulation tool (OpenWNS). Cell overlap directly affects the user throughput because if the overlapping part of two cells have same frequency sub-band then the users within the overlap area will most likely have degraded signal quality. The algorithm tries to make sure that cells with significant overlaps do not end up having the same frequency allocation.

Fig. 6.2 shows a Matlab representation of cells to give an idea about the overlap and cellular structure used. The figure clearly shows the overlap between cells with different colors for each cell. Because of the irregular cell patterns in real-life networks, coverage holes within the cellular network may also exist where there is no coverage at all. Expert cell planning is required to reduce these holes to a minimum. The cell boundaries shown in Fig. 6.2 are not exact because for real networks there is no definite boundary of a cell.

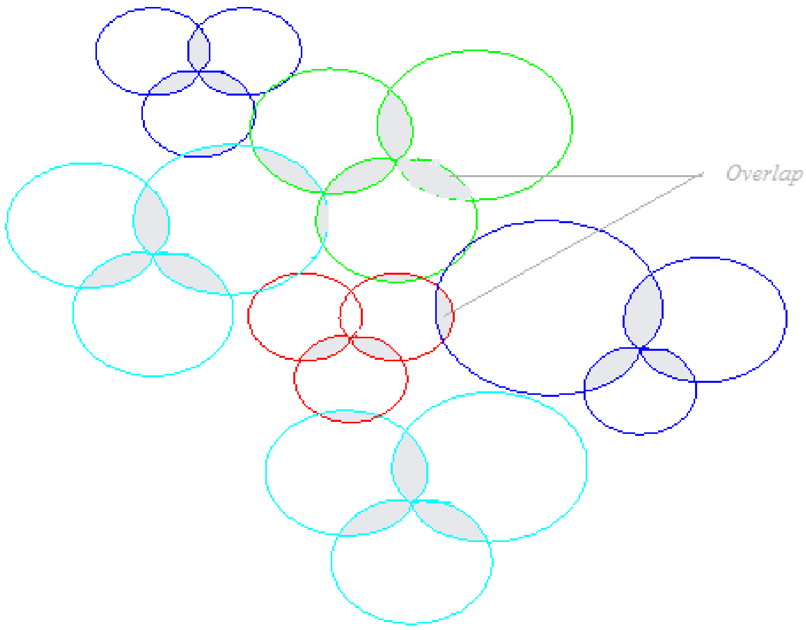

Figure 6.2 Cell overlap.

For the algorithm, the input is the cellular network's information. Network information includes the overall cellular configuration and the degree of overlap among the cells. The cellular configuration will give us the neighbor relationships for each cell and the degree of overlap will aid the optimization procedure for frequency allocations. This information is in the form of two matrices of size *NxN* where *N* is the number of cells. Each row of the matrices gives the information of a cell's neighbors and non-neighbors. The first matrix is the connectivity matrix which gives the neighbor relationship of each cell. A "*0*" represents no neighbor connection and "*1*" represents a neighbor. An example for this matrix for a three cell network is shown in Fig. 6.3 where A, B and C are the three cells. In this case, the neighboring cell of A is only B as it has a *1* at B's position. An element a_{ij} in the matrix for $i=j$ will always be zero because a cell cannot have itself as a neighbor, with i referring to rows and j referring to columns in the matrix.

$$\text{Connectivity matrix} \longrightarrow a = \begin{array}{c} \begin{array}{ccc} A & B & C \end{array} \\ \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \end{array} \begin{array}{c} \\ A \\ B \\ C \end{array}$$

$$\text{Overlapping matrix} \longrightarrow a = \begin{bmatrix} 0 & 15 & 0 \\ 10 & 0 & 5 \\ 0 & 25 & 0 \end{bmatrix}$$

Figure 6.3 Input matrices for the algorithm.

The second matrix is the overlapping matrix which tells us the degree of overlap between the neighboring cells. In the algorithm, the degree of overlap is defined by integers between *0* and *100,* where *0* means no overlap or no neighbor overlap and *100* is full overlap i.e. two cells on top of each other. All other values will lie within this range according to the overlap among two cells. The values between *0* and *100* are easier to set because we can relate these values to the percentage of areas (based on signal strength) being overlapped for each cell.

The overlapping matrix is also shown in Fig. 6.3 with sample values. The value of *10* at position a_{21} means that 10% of the total coverage area of cell B is overlapped with cell A. This does not mean that cell A is also overlapped with cell B by the same amount. The overlap area is relative to the cell size. This is clear from the overlapping matrix that the value at position a_{12} is *15*, meaning that because of the overlap between cell A and B about 15% region of cell A is in overlap with cell B. In our case, connectivity and overlapping matrices are kept in a text file and from there read into the program routine.

Apart from these two input matrices, the number of frequency sub-bands which are to be divided among the cells can also be taken as an input. For simulating FFR-3 with optimized allocation, the frequency set consists of three sub-bands and is implemented as an array with three values each referring to a sub-band, as given in (6.1).

$$f = [1 \quad 2 \quad 3] \tag{6.1}$$

The algorithm can take more number of sub-bands as input, but it is not studied in this thesis. Once the inputs are defined, we move onto the frequency allocation part. The frequency allocation is done in two steps. First, there is a random allocation of sub-bands to cell edges and then the edges which require optimization are treated further. The steps are as follows:

Initially, all the cells are assigned a frequency sub-band value of *-1.* A random frequency band f_i is assigned from the frequency set f to cell k. For cell k, we find all the cells that are connected to it by going through the k^{th} row of the connectivity matrix and locating all the ones in that row. Frequency bands of all the neighbor cells are then checked. Initially, because of the arbitrary value assigned to each cell, cell k will have a different frequency band allocated than its neighbors, but as the algorithm proceeds and more and more cells are assigned frequency bands, it is likely that adjacent cells have same sub-band due to random allocation. If one or more neighbors have same frequency sub-band allocated as k then the cell k is assigned another frequency sub-band from the frequency set f. If that band is also allocated to some neighbor then the next frequency sub-band from the set is assigned and checked for the interference. If there is no frequency sub-band that has not been allocated to the neighboring cells, the frequency sub-band that was last assigned is kept and would be changed, if required, when considering the overlapping between cells in the next step. These frequency allocations are stored in a matrix whose rows are equal to number of cells and each column position gives the allocated frequency sub-band for that cell.

After this first allocation, each cell is re-visited again; neighboring cells are located from the overlapping matrix along with their corresponding overlapping values. If for a particular cell, there is no neighboring cell with the same frequency sub-band, we move onto the next cell. Once a cell k is reached whose neighbor j has the same frequency sub-band assigned, overlapping factor value a_{kj} from the overlapping matrix is checked. If that value is larger than a *threshold value,* we need to change the frequency sub-band for cell k. For the thesis, a threshold value of *10* is used i.e. if the cell overlapping is 10% or more then we change the allocation for cell k. We assign that frequency sub-band of the neighboring cell for which cell k has minimum overlapping value. This process is repeated for each cell, and all cells are tested against their neighbors considering their overlapping values. Each cell is visited a number of times to make sure that cells with high overlap value never have the same frequency sub-band. As frequency sub-bands are limited, two lightly overlapped cells could end up having the same frequency sub-band in their cell edges. The end result of the algorithm is a matrix which gives the revised allocation of frequencies.

The pseudo-code for the algorithm is given below:

```
FFR(number of cells, number of sub-bands available for outer cells)
Load connectivity matrix from file
Load overlapping matrix from file
For each cell
    Assign a dummy value (suppose -1) of sub-band
End for
For each cell
      Assign a random sub-band from the frequency set f
      FindNeighbor(current cell k)    // identify neighbors for each  cell
      For each neighbor
            Check the sub-band of the neighbor
               If (neighbor has same sub-band allocated)
                  Assign another sub-band from the frequency sub-set f and
check again
            End if
           If (all sub-bands are allocated to neighbors)
                 Do nothing i.e. the last assigned sub-band is kept
           End if
      End for
End for
For I = 5 iterations
    For each cell
       If(no neighbor cell has same sub-band allocated)
            Do nothing
       End if
       Else // neighbor has same sub-band
            If(overlapping  factor  value  for  that  neighbor  >  threshold
value)
          sub-band of the current cell = sub-band of the neighboring cell
                                 with least overlapping factor
            End if
       End else
   End for
End for
END FFR
```

One important point to note is that in the second loop of the pseudo-code, the values assigned to a cell are fixed in the progression of the loop. Any changes made in the neighboring cells of an already assigned cell c, does not change the value of cell c.

Setting the threshold value can have significant effects on the frequency allocation. If this value is set too high then it is possible that many overlapping cells with same frequency sub-band are skipped and are not optimized. As a result, cell edge users of many cells could still experience degraded service. On the other hand, if the threshold value is set too low there will be more cells which would require optimization. Because of the limitation on the number of frequency sub-bands, it would not be possible to enhance performance for all such cells. Optimized results are not expected if most of the cells in the network are heavily overlapped.

To locate all the neighboring or connecting cells for a given cell, the *FindNeighbor* method simply finds the non-zero value in each row of the NxN matrix (where the neighbor information is stored).

If we consider increasing the number of sub-bands, although the inter-cell interference between the cells will certainly be reduced but it will also have its consequences. With increasing number of sub-bands, bandwidth of each sub-band will be reduced and this reduced bandwidth can have the effect of lowering the throughput for cell edge users. And also with large number of sub-bands for cell edges, there is a possibility of not utilizing the full resources because of the fact that frequency reuse factor will be much higher for cell edge users in that case.

Chapter 7

Simulation Setup and Results

7.1 Simulation Model and Parameters

The simulation parameters are summarized in Table 7.1.

Parameter	Value
System Bandwidth	20 MHz
No. of Base Stations	21
System configuration	OFDMA
OFDMA Symbol duration	102.858 µsec
Packet Size	2400 bits
Downlink Traffic	100 Kbps and 1 Mbps , CBR
Frame Length	10 ms
Cell Radius	Variable
FFT size	2048
Sub-carriers	96

Table 7.1. Simulation parameters.

The simulation model consists of 21 base stations each with its own coverage pattern. The cells formed are non-hexagonal. Irregular cells were created by varying the transmit powers of base stations. For the simulations, transmit power ranges from *20 dBm* to *45 dBm*. The coverage patterns for cell sites are shown in Fig. 7.1. Users were made to traverse the whole scenario, and then their SNR and serving base station were studied to plot the radiation pattern. The dots, in Fig. 7.1, are the users having received signal strength above a threshold value and the different colors indicate the different sectors. The received signal strength of -*95 dBm* is taken as the threshold value (cell boundary). The white lines were added later on to make the sectors and the shape of the cell clear. Transmit powers 30-40-30 means that the transmit power is *30 dBm* in the first sector, *40 dBm* in the second sector and *30 dBm* in the third respectively. Apart from transmit power; down tilt and azimuth of antennas are two other parameters which could be used to introduce irregularity to cells. The azimuth angles for antennas were set to 30^{o}, 150^{o} and 270^{o}. Changes to the azimuth angle and the down tilt of the antennas results in different irregular cell patterns.

OpenWNS does not support the feature of frequency allocation to inner and outer cell regions by default, and this functionality had to be added to the simulator. Frequency ranges are masked out depending on the FFR scheme being used. Masking out frequency ranges meant that the range would be made unavailable for the base station to use.

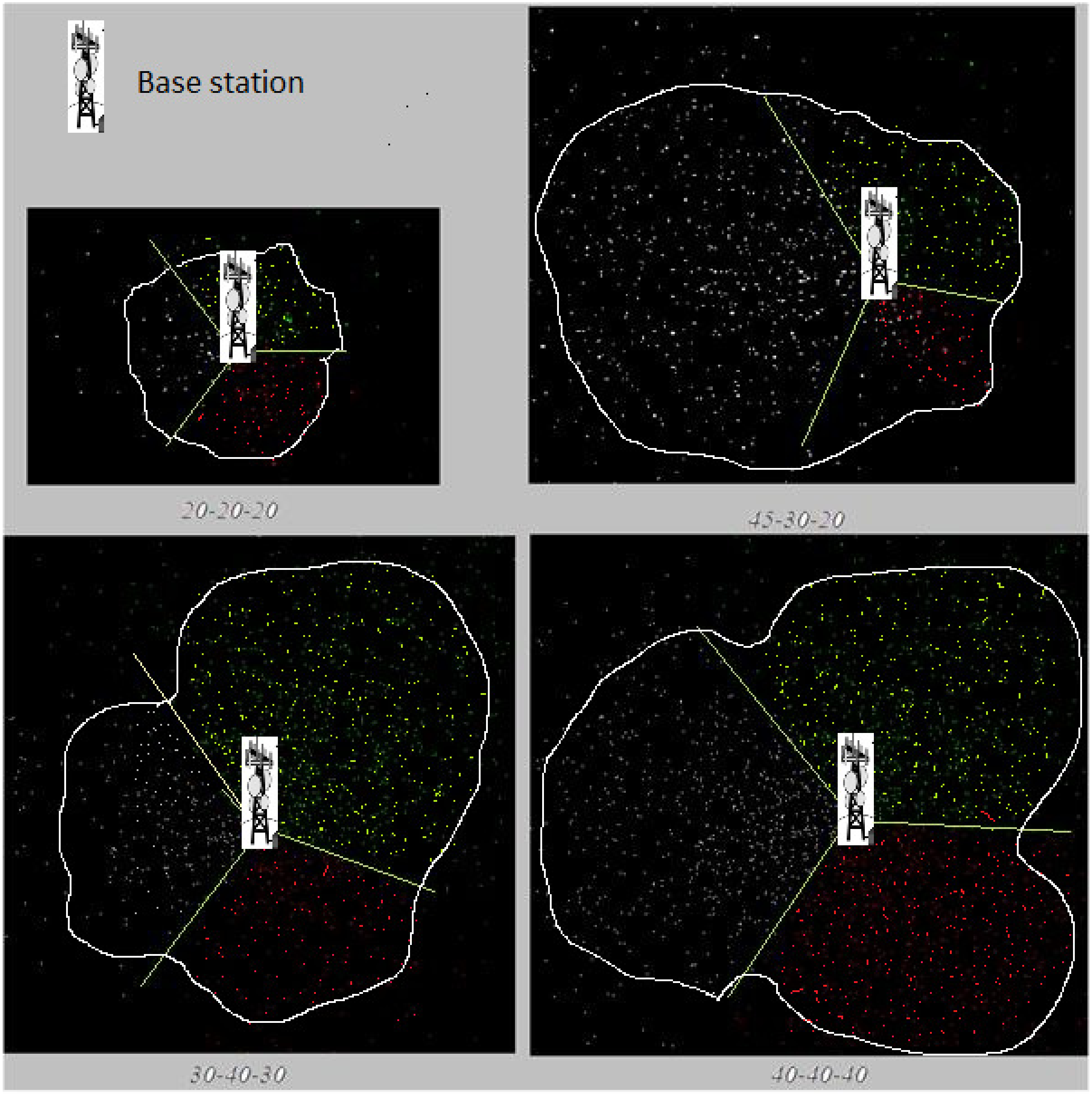

Figure 7.1 Cell radiation patterns for four base stations with transmit powers of 20-20-20, 45-30-20, 30-40-30 and 40-40-40. *Note: sector-1 is on left hand side, sector-2 is at top right and sector-3 at bottom right.*

Frequency division for FFR-3 is shown in Fig. 7.2. In our simulations, the transmit power of the base station is the total power used for both the center and the edge.

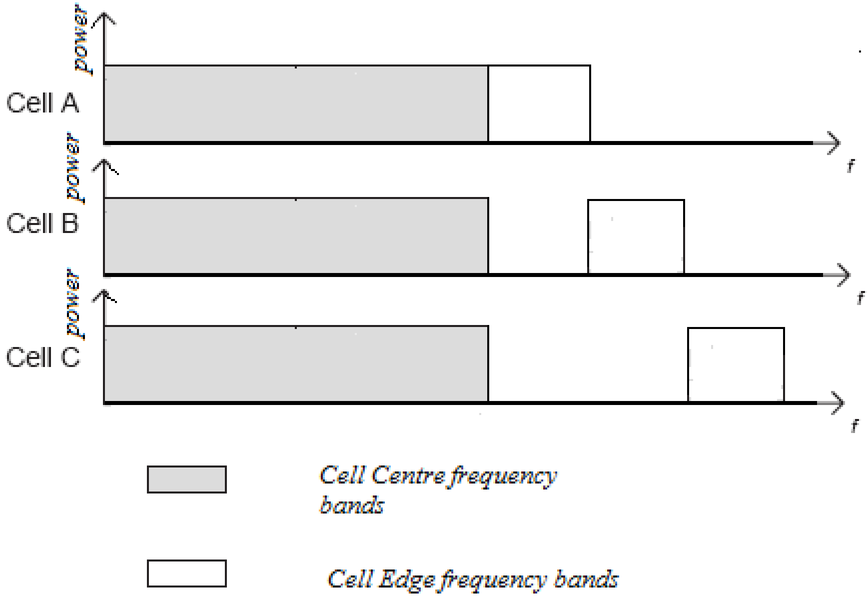

Figure 7.2 Frequency division between cell centre and cell edges.

7.2 Choosing Cell Edge

Based on the work performed by Assaad in [10], the area beyond 2/3 of the total cell radius is considered as cell edge no matter what the size of the cell. Work done in [10] shows that the optimal interior cell region radius is determined to be equal to 2/3 of the overall cell radius. In our simulations we are not considering or generating traffic for users closer to the base station than the 2/3 cell mark. All the users are placed manually beyond that point. Adding users to the center regions will not affect the performance of the edge users as they have different frequency chunks assigned to them. There is also an option to set an SNR threshold to establish cell edge but it is not used since one user per base station is simulated, and also it is easier to place the user at a position beyond the 2/3 region than to find the correct position in the cell where the received SNR of the user is below the threshold. One user per sector is simulated for a number of reasons. Firstly, this way the location of the interferers is known and secondly, simulating with a large number of users was resulting in a very large simulation time.

7.3 Analysis of Results

7.3.1 Number of Users and Placement

The number of edge users is relatively low in total, for 21 base stations there are 21 users. But the downlink traffic from their base stations is such that the complete bandwidth is utilized. The users are placed closer to the edge of the cells, sometimes ending up in the overlap region between two cells. They are not mobile as this makes it easier to know which cell the user is connected to and understand the results. Random mobility introduces ambiguity as many users could end up in the same cell, whereas some cells could be left completely empty. There was one user per cell edge region for each base station. The number of users could be increased but it would not affect the overall trend of the results.

7.3.2 Packet Throughput

The throughput is calculated as a ratio of packets received to the packets sent at the listener. The results are in form of percentages which tells us the percentage of successfully received packets by the user as compared to total number of packets sent. This is comparable to throughput which is the average rate of successful packets/bits delivered over a communication channel. The allocation is focused on improving the overall throughput of the system and individual user throughput is not directly considered. As mentioned earlier, the link is tried to be fully utilized so that there are no free resources. This gives the system high interference, and hence makes the difference between the different allocation schemes clear. Results are given in Table 7.2. In case of random allocation, as predicted, the similar sub-bands in neighboring cells interfere and result in lower throughput values.

7.3.3 Effects of Irregular Cells

In regular hexagonal cells scenarios each sub-band is reused at constant distances from each other and hence the interference created for the users is almost the same throughout the scenario. Irregular cells results in varying interference over the cell area. This changes the dynamics of frequency allocation.

7.3.4 Implications with Regards to Real Network Scenarios

In real scenarios it is very rare that there is a perfect hexagonal cellular structure. While using frequency reuse techniques the cellular structure makes a difference. As seen from the results, smart frequency allocation shows significant improvements with regards to throughput in such irregular scenarios. Introducing more factors into the frequency allocation assignment method can give better results for larger and more complex network.

In the different simulation runs, the user positions were changed slightly and the results were studied. When the frequency sets are allocated by considering the neighboring cell edge sub-bands and overlap conditions of the network, a clear increase in throughput compared to the other two schemes for the edge users is observed in Table 7.2. The increase in throughput for FFR with algorithmic allocation is due to the fact that the scenario is irregular and high interfering base stations are kept as far from each other as possible in sub-band allocation. This results in better throughput for the edge users. In the FFR schemes, although the bandwidth at cell edge is less than the reuse-1 scheme but the interference is much more significant in reuse-1. That is why user data rates for reuse-1 are considerably less than the FFR-3 schemes for cell edge users. In the reuse-1 scheme, the cell edge users are much more interference-sensitive than bandwidth-sensitive. At low downlink data rate, FFR-RFA and FFR-AFA have similar results. To see the difference clearly between the two allocation schemes, high downlink data rate of 1 Mbit/sec were tested. The overall throughput was lower but the difference between them is more evident. The reasons why the two schemes have same similar results at low data rates are explained later on.

Run	**Reuse-1**	**FFR3 with Random Allocation**	**FFR3 with Algorithmic Allocation**
1	50.12%	65.44%	66.83%
2	49.75%	64.55%	66.60%
3	49.95%	64.80%	66.12%

Table 7.2.a Throughput for edge users with 100 Kbit/sec downlink.

Run	**Reuse-1**	**FFR3 with Random Allocation**	**FFR3 with Algorithmic Allocation**
1	28.45%	31.44%	37.83%
2	28.76%	31.55%	37.60%
3	28.83%	31.80%	37.12%

Table 7.2.b Throughput for edge users with 1 Mbit/sec downlink.

7.4 Scenarios

Fig. 7.3 shows the simulation scenario with algorithmic allocation. The three different colors represent the three frequency sub-bands used for cell edges in different sectors of the cells. The dark regions are the overlapping areas between the neighboring cells.

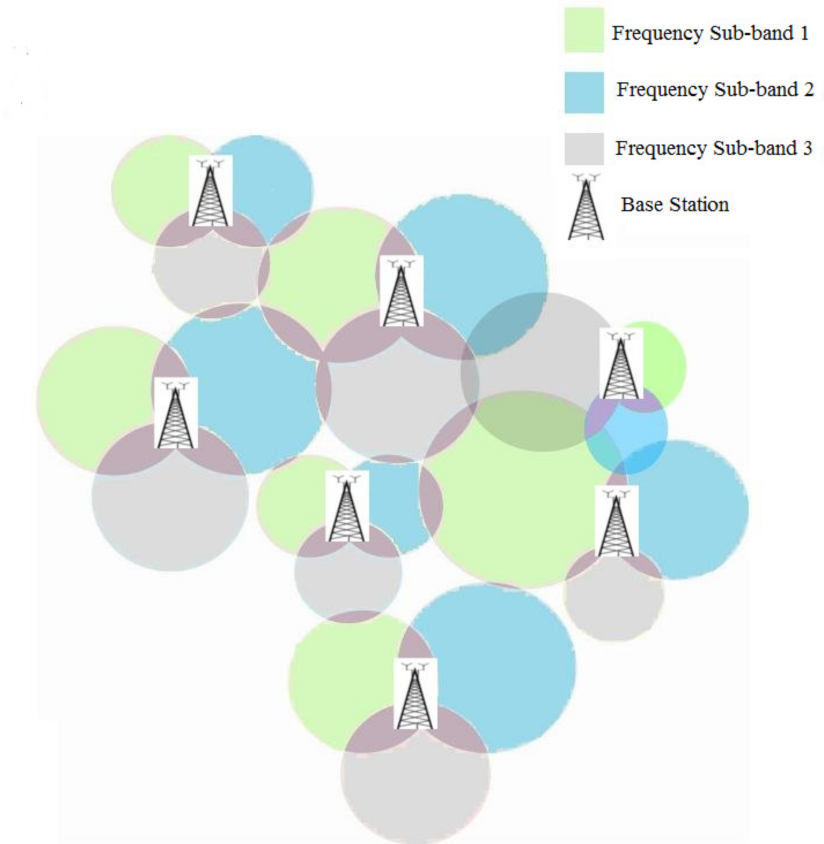

Figure 7.3 Simulation scenario.

Fig. 7.4 shows how the allocation of each sub-band is kept as apart as possible. This is mainly done by checking the neighbors and finding a sub-band not allocated to the neighboring cells.

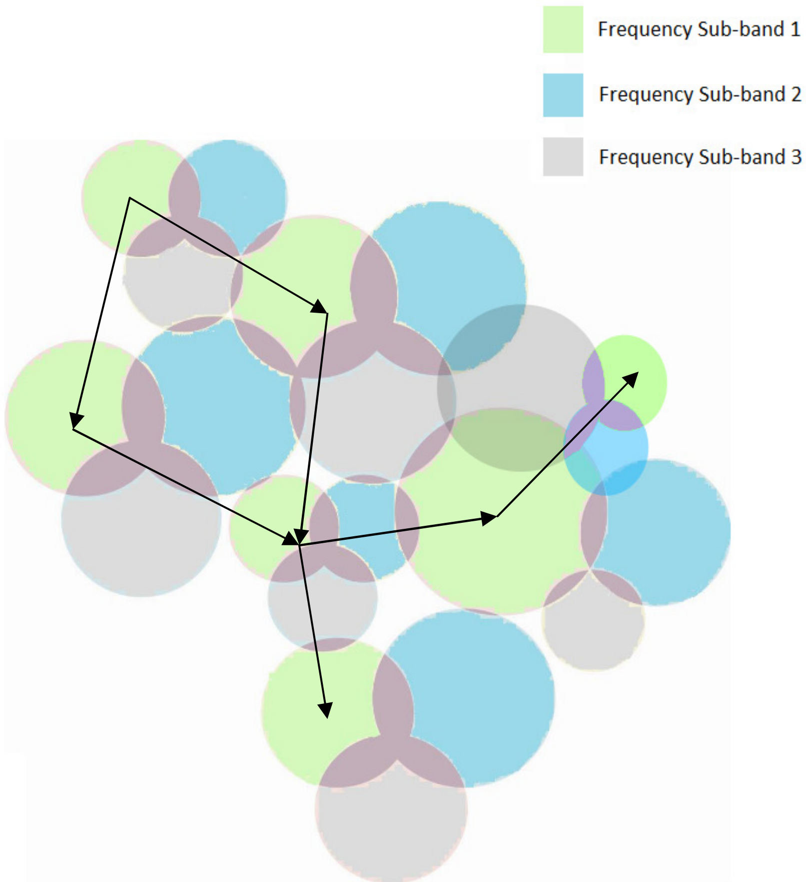

Figure 7.4 Allocations of each sub-band is kept as far away as possible as the algorithm goes through the scenario.

In the scenario shown in Fig. 7.5 an interesting case occurs. Base station numbered 4 has neighbors of all three sub-bands. In this case the overlap plays an important role. We see the region outlined in black has the maximum cell overlap. Overlap between base station 1 and base station 4 is lesser and the overlap between base station 2 and base station 4 is the smallest. Therefore, the algorithm allocates the same sub-band to base station 4 and base station 2. This also results in base stations 6 and 7 having the same sub-band. If base station 6 was given the green sub-band, it would cause greater overlap with base station 3. Hence it is assigned the blue sub-band causing lesser overlap with base station 7. The algorithm automatically converges itself to this situation.

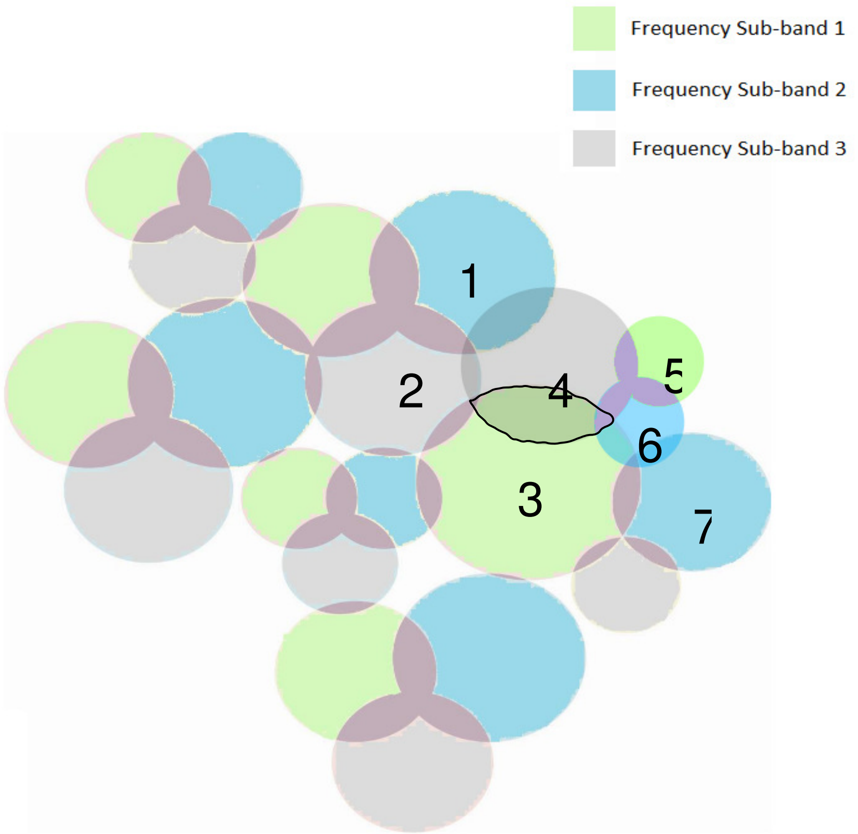

Figure 7.5 The impact of overlap while allocating sub-bands. The black out-lined area is the maximum overlap area.

Fig. 7.6 shows the user placements. In cell sectors marked 3 and 4, the users are in the overlap region. This will cause more interference in case neighboring cell sectors have similar sub-bands allocated to them. In case of random allocation, cell sectors 3 and 4 have the same sub-band. Since we are simulating one user per base station, it is important to know where and how they are placed, especially in the cells where overlap is an important factor in the allocation of the sub-bands. Users in sectors 2, 3 and 4 are placed around the 2/3 mark. The users in sectors 3 and sector 4 are in the overlap region as shown in the figure. Only the frequency allocation to cell sector numbered 4 is changed. Cell sectors 3 and 4 have the same frequency for that simulation.

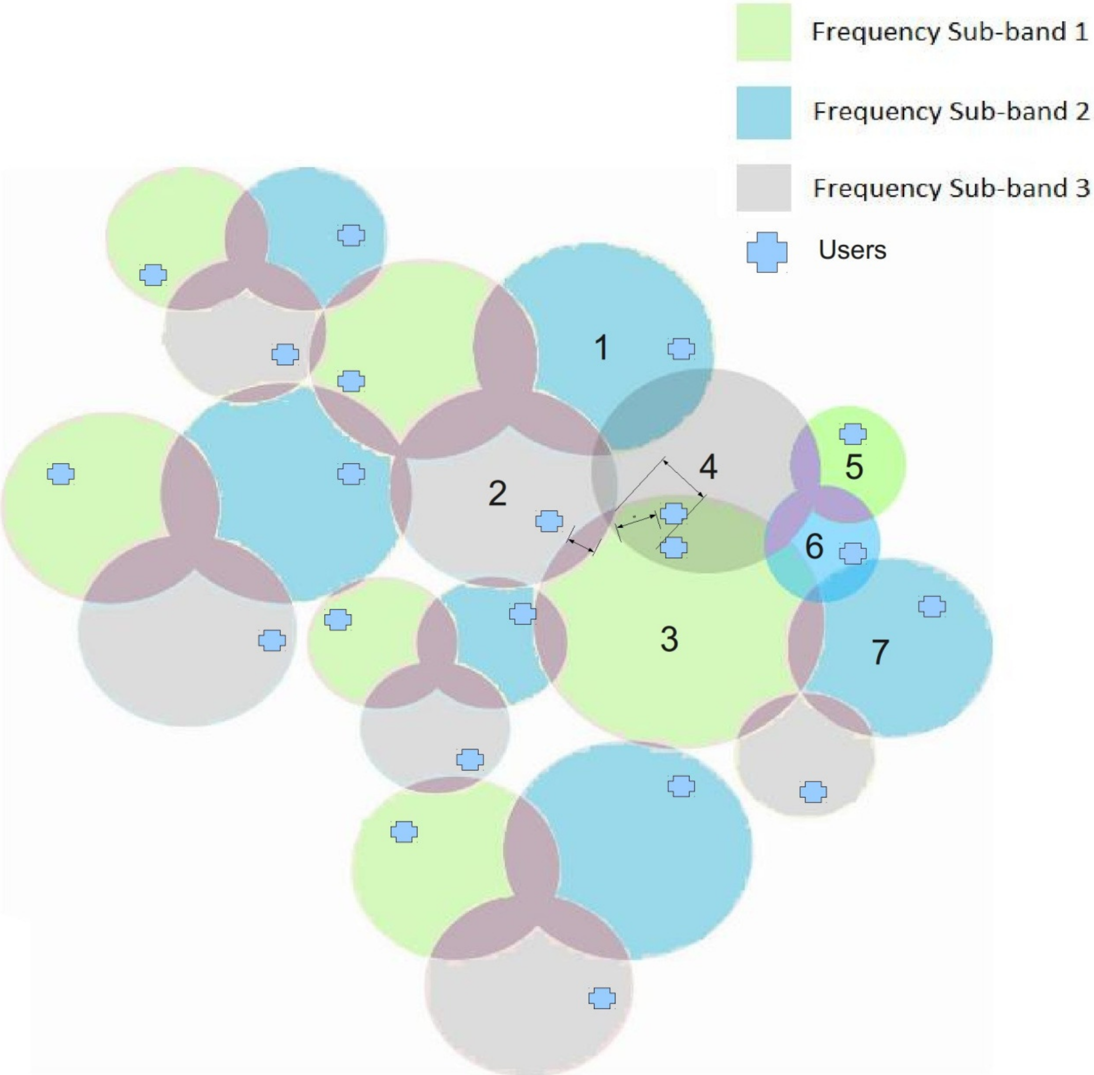

Figure 7.6 Scenario with user placement.

Data rate of 1 Mbit/sec was used in the downlink for all scenarios. It was essential because at lower rates both users in the overlap region could end up being connected to the same base station and not create any interference to each other. This is also why FFR-RFA and FFR-AFA have similar results at lower downlink data rates. In a high downlink data rate, if both users try to connect to the same base station they will have to compete for resources, and if they connect to separate base stations they will create interference for each other.

Chapter 8

Conclusions and Future Work

8.1 The Algorithm

The algorithm used for allocating the frequency bands achieved better results than the other allocation schemes, although a larger scenario would be more desirable to demonstrate the frequency allocation process. However, five interferers for each frequency band are sufficient to get reasonable interference and results. A literature study was done regarding search methods that could be used in the algorithm. Our algorithm was made specifically for scenarios with irregular cells and with cell overlap regions of varying sizes. This algorithm can be enhanced by adding other factors into the equation such as cell size. Also the work can be expanded further to dynamic frequency allocation.

8.2 Choosing a Tool

Choosing a simulation tool was also an important part of our work. There were no off-the-shelf solutions available for our problem. We chose to work with an open source tool, so that we could make changes to the code and customize it. But as a drawback there was little help available regarding the tool.

8.3 The Scenario

The base station positions in the scenario had to be carefully specified to achieve the desired overlapping effect in the simulator. It was important to have a cell with more than three neighbors. This would allow us to see the effect of the algorithm on the performance results. Creating a customized scenario does not mean though that the algorithm will not work for other scenarios.

8.4 Effect of User Placements

The user placement was done manually in locations with known received SNR so that they were using the cell edge sub-bands. Since few users were simulated it was important to place them in the proximity of other users, otherwise the difference in the results for the different schemes was lesser.

8.5 Results

The results obtained were coherent with our expectations. Better throughputs were achieved for frequency allocation based on our algorithm. Schemes which resulted in minimum interference resulted in better results. Interference was caused by base stations using the same frequency sub-bands. It was essential to have a balanced traffic load in the downlink, so that enough resources were utilized to cause sufficient interference. The results showed that poor allocation (non-algorithmic) in scenarios of irregular shaped cells with different overlap regions lead to lower overall throughputs. Similarly for reuse-1 scheme, the high interference experienced by the edge users significantly reduces the system performance. By using an algorithmic approach to such a scenario, where cell shape and the overlap between them is non-consistent, leads to much improved results. This shows that for such scenarios factors such as cell overlap, user throughput and base station transmit power could be important to consider while using fractional frequency reuse. These results are specific for FFR-3.

8.6 Future Work

More work is needed in simulating frequency reuse schemes for irregular cell networks. Larger scenarios can be simulated with various kinds of propagation conditions. In irregular cell networks factors other than cell overlap can be used to make a frequency reuse scheme, such as frequency allocation based on user throughput. Also simulations with different numbers of sub-carriers can also give interesting results. There is also room to test FFR-5, FFR-7 or FFR-11 schemes in irregular cellular scenarios. It was beyond the scope of our work due to time limitations.

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