ENHANCED TECHNIQUES FOR INTERFERENCE MANAGEMENT IN LTE FEMTOCELL NETWORKS

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Mahmoud Mohammed Selim

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SUMMARY

Femtocells are low power access points deployed indoor to alleviate indoor coverage problem. The most severe problem related to femtocells is the interference. Interference can be generated either between macrocells and femtocells (cross-tier) or among femtocells (co-tier). This thesis addresses the cross-tier downlink interference problem of LTE femtocell systems. Firstly, the thesis surveys and compares some management schemes proposed in the literature. This comparative survey shows that management schemes based on efficient frequency allocation techniques and Fractional Frequency Reuse (FFR) can be a good solution for managing interference in LTE femtocell systems. Secondly, the thesis describes the cellular system model including cellular layout, indoor area modeling, propagation Pathloss (PL) models, and finally the signal to interference plus noise ratio (SINR) and capacity mathematical analysis used. Thirdly, the thesis proposes some Macro-Femto frequency allocation schemes based on some well-known reuse schemes and FFR variations to allow coexistence of both networks (macrocell and femtocell) and allocate resources efficiently between them. These proposed schemes don’t require any coordination between the two networks. The well-known schemes exploited are: Reuse-1, Reuse-3, Soft Frequency Reuse (SFR), Partial Frequency Reuse (PFR), and Soft Fractional Frequency Reuse (SFFR). Fourthly, the evaluation metrics used to evaluate system performance are described. These evaluation metrics include average users’ capacity as a measurement of throughput, SINR maps and 10%-tile SINR as a measurement of coverage, outage probability as a measurement of Quality of Service (QoS) and finally Jain’s index and fairness ratio as a measurement of fairness. Fifthly, simulation setup and simulation results are provided. A modified version of Vienna LTE simulator is used as a powerful MATLAB simulation tool for simulating this thesis work. Simulation results show that Reuse-1 scheme degrades most of network performance metrics other than throughput for dense deployment of femtocells like coverage, QoS and fairness. Reuse-3 and PFR schemes provide good performance in terms of coverage, QoS, and fairness but poor performance in terms of throughput due to poor spectral efficiency. SFFR scheme provides higher throughput performance rather than Reuse-3 and PFR but lower in
terms of coverage and fairness. SFR scheme provides the best throughput performance in dense deployment of femtocells and good performance for coverage, QoS and fairness. So SFR scheme can represent the best tradeoff among different proposed schemes via different evaluation metrics. Two optimal SFR interior radii are then calculated for two different femtocell deployment densities using exhaustive search. The two calculated radii are found to optimize throughput performance without significant degradation in fairness performance and provide good coverage performance.
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To my beloved parents ..

and my dear sister ..
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<tr>
<td>2G</td>
<td>2nd Generation</td>
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<td>AP</td>
<td>Access Point</td>
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<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<td>BS</td>
<td>Base Station</td>
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<td>CP</td>
<td>Cyclic Prefix</td>
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<td>CQI</td>
<td>Channel Quality Indicator</td>
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<td>CSG</td>
<td>Closed Subscriber Group</td>
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<td>DAS</td>
<td>Distributed Antenna Systems</td>
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<td>DL</td>
<td>Downlink</td>
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<td>DSL</td>
<td>Digital subscriber line</td>
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<td>EDGE</td>
<td>Enhanced Data Rates for GSM Evolution</td>
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<td>eNB</td>
<td>Evolved NodeB</td>
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<td>FAP</td>
<td>Femto Access Point</td>
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<td>FFR</td>
<td>Fractional Frequency Reuse</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>FSC</td>
<td>Femtocell System Controller</td>
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<td>FUE</td>
<td>Femto User Equipment</td>
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<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HeNB</td>
<td>Home Evolved NodeB</td>
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<tr>
<td>HSPA</td>
<td>High Speed Packet Access</td>
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<tr>
<td>ICI</td>
<td>Inter-Cell Interference</td>
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<td>IFI</td>
<td>Inter-Femto Interference</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>ISP</td>
<td>Internet Service Provider</td>
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<tr>
<td>LLS</td>
<td>Link Level Simulator</td>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MATLAB</td>
<td>Matrix Laboratory</td>
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<td>MCS</td>
<td>Modulation and Coding Schemes</td>
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<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
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<tr>
<td>MUE</td>
<td>Macro User Equipment</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<td>PFR</td>
<td>Partial Frequency Reuse</td>
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<td>PL</td>
<td>Path Loss</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PSTN</td>
<td>Public Service Telephone Network</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>ROI</td>
<td>Region of Interest</td>
</tr>
<tr>
<td>Rx</td>
<td>Receive</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single-Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SFFR</td>
<td>Soft Fractional Frequency Reuse</td>
</tr>
<tr>
<td>SFR</td>
<td>Soft Frequency Reuse</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>Single-Input Single-Output</td>
</tr>
<tr>
<td>SLS</td>
<td>System Level Simulator</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmit</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>VOIP</td>
<td>Voice over Internet Protocol</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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“The next significant performance leap will come from small cells such as femtocells and picocells, which bring the network closer to users. Femtos cost-effectively improve coverage and capacity and significantly enhance data rates for users within the femto coverage area. As femtos offload traffic from the macro network, users outside femto coverage also benefit [1]”

1.1 3GPP Release 8 (LTE)

3GPP Release 8 known as Long Term Evolution (LTE) is the evolution of the third generation mobile communications standard, UMTS to the fourth generation technology with increased capabilities of providing voice and other broadband data services. The requirements and main targets of LTE technology are presented in [2] and [3]. LTE standard aims to increase system data rates especially for cell edge zones and improve spectrum efficiency to avoid the problem of scarcity of resources. LTE also allows spectrum flexibility (1.25, 2.5, 5, 10, 15 and 20 MHz) for flexible radio planning. The reduction of packet latency is a crucial target of LTE to allow real-time services like VOIP and video calls. LTE has to reduce the radio access network cost and provides cost-effective migration process from earlier 3GPP releases. LTE network architecture is assumed to be a flat all-IP packet based network architecture which highly simplifies the functionalities done by the system.

The target instantaneous downlink (DL) peak data rate of LTE is assumed to be 100 Mbps using 20 MHz spectrum allocation (5 bps/Hz). While the target instantaneous up-
link (UL) peak data rate is assumed to be 50 Mbps using 20 MHz spectrum allocation (2.5 bps/Hz). LTE exploits Orthogonal Frequency Division Multiple Access (OFDMA) as an access scheme for the downlink, while it exploits Single-Carrier Frequency Division Multiple Access (SC-FDMA) as an access scheme for the uplink. These target data rates are assumed to be achieved using a flexible radio interface based on OFDM technology and MIMO antenna processing [4][5].

1.2 Indoor Coverage Challenge

It has been noticed recently that most of cellular traffic occurs indoor. This traffic is not limited to voice calls but extended to video and high speed data services. Some surveys show that 45% of households and 30% of businesses experience poor indoor coverage problem [6]. A typical usage of outdoor macrocells for serving indoor users will results in some drawbacks such as:

- Indoor users will require higher power from Base Stations (BS) to alleviate high penetration loss which usually comes at the expense of power used for other users which leads to reduced cell throughput.

- The need for large number of outdoor BS sites which represents additive cost for operators especially for densely populated areas.

- The building penetration is a big challenge for networks operating at 2 GHz and above.

- Lower channel conditions will results in lower modulation and coding schemes (MCS) and hence lower data rates for indoor users especially those at cell edges.

Some indoor solutions such as Distributed Antenna Systems (DAS) [7] and Picocells [8] have been proposed to solve the problem of poor indoor coverage in environments like office buildings and shopping centers. These solution are deployed by operators in order to enhance coverage, offload traffic from ordinary macrocells, increase data rates and provide high quality services. These solutions are not cost effective for small environments such as home users
and home offices. A recent low cost indoor solution which is femtocell technology has been proposed and can be easily deployed by users without operator intervention.

Femtocells, also known as home base stations, are cellular network access points (AP) that connect standard mobile devices to a mobile operator’s network using residential DSL, cable broadband connections, optical fibres or wireless last-mile technologies [9]. A more details about femtocell technology will provided in Chapter 2.

1.3 Problem Statement

The deployment of femtocells results in a change in the topology of the ordinary macrocellular network. The new network architecture is composed of two different layers; the macrocell layer and the femtocell layer. This new network architecture is usually called the two-tier network. The presence of femtocells within the same geographic location of macrocells and the possible transmission on the same frequency bands will result in the most severe problem in any telecommunication system which is interference. Dead zones within the macrocell may appear if no interference avoidance techniques are exploited in the two-tier network.

The interference in the two-tier network can be classified into co-layer interference and cross-layer interference. Co-layer interference occurs when both the aggressor and the victim belong to the same layer (femtocell layer). An example of this type of interference is a group of femtocells close to each other such that the transmission of one femto user equipment (FUE) is interfering the reception of a neighbor femtocell (Uplink interference) or the transmission of a femtocell is interfering the reception of a FUE that belongs to different femtocell (downlink interference). This type of interference results in inter-carrier interference (ICI) at the uplink and femtocell coverage holes at the downlink [10].

The other type is the cross-layer interference. It occurs when the aggressor and the victim belong to different network layers. An example of this type of interference at the uplink occurs when a macro user equipment (MUE) is interfering the reception of a neighbor
Figure 1.1: Interference scenarios for both UL and DL in LTE femtocell network

Femtocell or a FUE is interfering the reception of a neighbor macrocell. It also occurs at the downlink when a femtocell is interfering the reception of a neighbor MUE. This type of interference results in inter-carrier interference at the femtocell besides risk of invalidation of macrocell sub-channels at the uplink. It also results in femtocell coverage holes and inter-carrier interference at the macrocell users at the downlink [10]. The different interference scenarios for both Uplink and Downlink are summarized in figure 1.1.

Many interference management schemes have been proposed in the literature which will be discussed in details in Chapter 3. One famous mitigation method is based on the efficient frequency allocation process between the two network layers. While the co-channel allocation (sharing the entire system bandwidth between the two network layers) results in a high spectral efficiency and high total system throughput, the high amount of interference generated in the network results in many coverage holes and low Quality of Service (QoS). The orthogonal channel allocation (dividing the system bandwidth orthogonally between the two network layers) results in limited amount of interference and consequently better cov-
erage and QoS, the system still suffers from poor spectral efficiency and waste of valuable frequency resources. Thus efficient frequency allocation schemes that gather the best of the two allocation methods are needed for efficient interference mitigation. This will be the core of this research work and our proposed frequency allocation schemes are described in details in Chapter 5.

1.4 Research Motivations and Opportunities

Recent research on the topic of femtocells and especially the interference mitigation schemes in the two-tier networks is assumed to be crucial for the following reasons:

- 2/3 of calls and about 90% of data services occur indoor.
- A large deployment of femtocells is expected in the near future [11].
- The capability of providing data services for indoor users using femtocells and consequently more revenues for operators.
- Offloading more traffic from macrocells and consequently less number of macrocell sites is needed which means lower cost for operators.
- Wide deployment of femtocells should be preceded by efficient resource management process which is a very hot topic in most recent research work.

1.5 Outline of Master Thesis

This master thesis is divided into 7 chapters:

- Firstly, Chapter 1 provides a brief introduction about 3GPP LTE Technology, small-cell technologies, problem statement, and research motivations and opportunities.
- Chapter 2 provides an overview about the technology of femtocells and a brief description of the LTE femtocell network.
• Chapter 3 provides a literature survey on the management schemes used for interference avoidance in the two-tier networks.

• Chapter 4 provides a detailed description of system model assumed in this thesis work.

• Chapter 5 provides a detailed description of proposed frequency allocation schemes used in the process of frequency resources allocation between macrocells and femtocells.

• Chapter 6 provides a detailed description for the evaluation methodology used for evaluating proposed frequency allocation schemes, the simulation setup done, and finally the simulation results and comments on these results.

• Chapter 7 summarizes the concluding remarks of this master thesis work and proposes the future work to be done in order to continue the investigation of this research topic.
CHAPTER 2
FEMTOCELL TECHNOLOGY: AN OVERVIEW

This chapter gives a brief overview on the femtocell technology in terms of definition, deployment techniques, importance, access strategies and the network architecture.

2.1 Femtocell Definition

As mentioned in the previous chapter, femtocells are cellular network wireless access points that connect standard mobile devices to the network of a mobile operator via residential DSL, cable broadband connections or optical fibres as shown in figure 2.1 [9]. The first product of home base station was firstly announced by Motorola at 2002. The Small Cell Forum [11] is responsible for the standardization and deployment of femtocells worldwide. Femtocell Networks are expected to play an important role in the network architectures of
upcoming 3GPP releases. Femto access points (FAP) can be found for different cellular technologies such as 2G technologies (e.g. GSM/GPRS/EDGE), 3GPP technologies (e.g. UMTS/HSPA/LTE) and non-3GPP technologies such as mobile WiMAX.

2.2 Femtocell Deployment

Femtocells are assumed to be self-deployed by users rather than operators. The femtocells should have the capability of automatic configuration as they are regarded as consumer electronics. The automatic configuration is achieved via two processes; the sensing process in which the femtocells sense the surrounding environment for assessment and the auto-tuning process in which the femtocell adjusts its configuration parameters like downlink Tx power and sub-channel allocation. The femtocell deployment can also be classified based on the capacity into; home femtocells which are capable of supporting 3-5 simultaneous users and enterprise femtocells which are capable of supporting 8-16 users [12].

2.3 Femtocell Advantages

Femtocells can provide a lot of advantages for both operators and subscribers as follows.

2.3.1 Operator’s advantages

- Offloading traffic from macrocells and hence less macrocell sites are needed.

- Simplifying Radio Frequency (RF) planning process.

- Improving service quality and wideband data services and hence more revenues.

- Providing coverage for places where macrocell implementation is very difficult.
2.3.2 Subscriber’s advantages

- Gathering all voice, video and high speed data services in one consumer electronics device.
- Making use of bundled services which are very cost-effective.
- Saving user equipment (UE) power.

2.4 Femtocell Access Control Strategies

There are three access control modes in which a femtocell could be operated: open, closed, and hybrid [13]. The description of these different access modes is shown below.

2.4.1 Closed Access Mode

It is also called Closed Subscriber Group (CSG) in 3GPP terminology. In this access mode, only a set of UEs are allowed to use the services of the femtocell based on a list of subscribed UEs to this femtocell. No other UEs are allowed to use the femtocell except for emergency calls when no other cell is available.

2.4.2 Open Access Mode

In this access mode, any UE in the coverage area of the femtocell can camp on it without any preferential access.

2.4.3 Hybrid Access Mode

This access mode is similar to closed access mode except that UEs that are not part of the list of the subscribed UEs may camp and acquire some level of service but the subscribed UEs still have preferential access.
2.5 Femtocell Network Architecture

Figure 2.2: Simplified Femtocell Network Architecture

Figure 2.2 shows a sample network architecture of the femtocell deployment. The homes are expected to have a broadband modem connection (i.e. cable, or fiber) through their internet service provider (ISP) to the internet. The cellular specific data will be transferred to the femtocell gateway for access back into the cellular network. For the 3GPP network, the gateway would interface to the core network; this interface is called $I_{u-h}$. We have also shown the cellular core network accessing the public service telephone network (PSTN) for voice services and a broadband interconnect for data services. As the core network evolves into a packet network, all traffic will be IP based, thus allowing for a convergence of services [12].
The interference problem has been discussed briefly in Section 1.3. It has been stated that the interference in two-tier networks has two types; \textit{co-tier interference} and \textit{cross-tier interference}. Both types of interference may occur either in the uplink or downlink transmission. Due to the unplanned and random deployment of femtocells, interference can be a severe problem in two-tier networks if it is not well managed.

Interference is managed via two different approaches which are \textit{interference cancelation} or \textit{interference avoidance} [14]. Interference cancelation aims to reduce interference at the receiver end by means of signal processing using some prior knowledge about interfering signal. It has been found that interference cancelation is not preferred practically in two-tier networks as it mostly requires antenna array systems and signalling overhead which may not be suitable especially for downlink. Interference avoidance aims to allow intelligent transmission to avoid or reduce interference as much as possible. In this chapter we provide a brief survey on some of the approaches and schemes used for providing interference avoidance in two-tier OFDMA femtocell networks.

Some of the approaches proposed for interference avoidance in two-tier OFDMA femtocell networks are mentioned below.
3.1 Spectrum Splitting

Spectrum splitting has been proposed in [15] to solve the problem of Co-tier interference. The spectrum is divided into two portions; one of them is assigned to the operation of macro-cell users while the other one is assigned for the operation of femtocell users. While cross-tier interference is substantially eliminated, co-tier interference still exists. Spectrum splitting usually tends to reduced spectral efficiency but it may be needed in some scenarios such as dense deployment of femtocells with dominant cross-tier interference that is difficult to manage in any other way.

3.2 Femto-aware spectrum arrangement scheme

This approach has been proposed in [16] to solve the cross-tier interference problem in uplink. The spectrum is split into two portions; one of them is dedicated for macrocell operation and the other is shared between macrocells and femtocells such that this allocation process is configured by the network operator and known for macrocells. The macrocell prepares a list of MUEs that represent a threat for nearby femtocell so that they will be assigned resources from the portion dedicated for macrocells to avoid interference.

3.3 Clustering of femtocells

This scheme has been proposed in [17] to avoid both co-tier and cross-tier interference in downlink transmission. The scheme depends on assigning a central node called *Femtocell System Controller (FSC)* which is responsible for gathering all system configuration done by femtocells and performing computations. Similarly like the previous approach, spectrum is divided into two parts; one is dedicated for macrocells while the other is shared. A clustering algorithm is used to allocate femtocells into different frequency reuse clusters and FUEs of different femtocells in the same cluster use the same sub-channels allocated from the shared frequency band. Based on the geographical locations of the femtocells, the threshold
distance for clustering interference is calculated. If the Euclidean distance between any two femtocells is less than the threshold distance, then they are assigned to different clusters to avoid co-tier and cross-tier interferences.

### 3.4 Power Control

Power control schemes are used to mitigate cross-tier interference by reducing transmission power of femtocells. The main advantage of power control schemes is the possibility of using the entire bandwidth by a method of interference coordination. Adjusting femtocell power can be done either by measurement results of a femtocell alone or based on coordination with macrocells. A hybrid method is proposed in [18] where a femtocell switches power adjustment technique between either a lone or based on coordination depending on the deployment scenario. For a cluster basis scenario, the sensing process required in adjustment of power control is done either by centralized method by the help of macrocell or distributed method where each femtocell works in an individual manner. Game theory models can be also used in power control interference mitigation schemes [19].

### 3.5 Cognitive Radio

The concept of cognitive radio is used in the process of distributed spectrum sensing in a downlink co-tier interference management scheme [20]. The co-tier interference is estimated by each femtocell during the sensing phase using path-loss information. Using the femtocell gateway, the information obtained by each femtocell about carriers used by neighboring femtocells are shared among femtocells. Femtocells are then capable of accessing carriers that are not used by neighbor femtocells to minimize interference as much as possible. If all carriers are used by neighbor femtocells, then it use the carriers used by the furthest femtocell to minimize interference as much as possible.
3.6 Fractional Frequency Reuse (FFR)

The concept of Fractional Frequency Reuse (FFR) depends on dividing the macrocell into center region and edge region such that different reuse factors are used at each region mainly to enhance cell edge performance. FFR has two types; static and dynamic. A static FFR scheme is used in [21] to mitigate cross-tier interference in co-channel allocation scenario. Femtocells sense the spectrum during turn on to discard operation on sub-bands with largest received signal strength to enhance signal-to-interference and noise ratio (SINR) of MUEs and overall network throughput. Another static FFR scheme is used in [22] to mitigate cross-tier interference in downlink. This scheme divides macrocell into center zone with reuse factor of 1 and edge zone with reuse factor of 3. The spectrum is divided into two parts; one of them is assigned for center region while the other is divided equally between the three sectors of the macrocell. The femtocells at each sub-area of the macrocell use the sub-bands that are not used by macrocell operation at this sub-area.

The other type is the dynamic FFR. An adaptive FFR scheme is used in [23] to mitigate cross-tier interference in downlink. Resource partitioning process is varied in both time and frequency (dynamic) and the allocation process depends on the density of femtocells and the location of each one (center or edge). If the femtocells are in a dense scenario in center region, femtocells use orthogonal sub-channels to minimize interference otherwise they use arbitrarily sub-channel.

3.7 Comparison Evaluation of Surveyed Schemes

The interference management schemes mentioned above are compared and evaluated via different approaches. These approaches include type of interference considered, transmission mode, complexity, efficiency, access strategy, coordination between macrocell and femtocell(s). This comparison is summarized in Table 3.1.
<table>
<thead>
<tr>
<th>Scheme</th>
<th>Transmission Mode</th>
<th>Cooperation</th>
<th>Access Mode</th>
<th>Complexity</th>
<th>Efficiency</th>
<th>Type of Interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femto aware spectrum</td>
<td>Uplink</td>
<td>Required</td>
<td>Closed</td>
<td>Moderate</td>
<td>Low</td>
<td>Cross-tier</td>
</tr>
<tr>
<td>management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clustering of femtocells</td>
<td>Downlink</td>
<td>Required</td>
<td>Closed</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Co-tier and Cross-tier</td>
</tr>
<tr>
<td>Power control</td>
<td>Downlink</td>
<td>Not Required</td>
<td>Closed</td>
<td>Moderate</td>
<td>High</td>
<td>Cross-tier</td>
</tr>
<tr>
<td>Cognitive radio</td>
<td>Downlink</td>
<td>Required</td>
<td>Closed</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Cross-tier</td>
</tr>
<tr>
<td>Fractional Frequency</td>
<td>Downlink</td>
<td>Not Required</td>
<td>Closed</td>
<td>Low</td>
<td>High</td>
<td>Co-tier and Cross-tier</td>
</tr>
<tr>
<td>Reuse (FFR)</td>
<td></td>
<td></td>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of Different Interference Management Schemes

In our research work we rely and focus on interference management schemes that depend on frequency allocation and resource partitioning with special focus on those schemes relying on FFR as will be described later in details in Chapter 5.
CHAPTER 4
SYSTEM ANALYSIS

In this chapter we provide a full description and analysis of LTE femtocell system applied in our research work. We start firstly by giving an overview of the Vienna LTE Simulator [24] used as a powerful LTE System Level Simulator (SLS). We then describe the LTE cellular system Layout and how we can model indoor area. We also describe the propagation pathloss (PL) models used between BSs and UEs in addition to different types of antenna patterns used. We provide an SINR and Capacity analysis for Downlink (DL) between BSs and UEs.

4.1 Vienna LTE Simulator

System Level Simulators are very crucial tools to evaluate the performance of new mobile technologies like LTE. Vienna LTE Simulator is a MATLAB computationally efficient LTE System Level Simulator (SLS). The simulator can be used to evaluate the performance of downlink (DL) shared channel for different transmission modes (e.g. SISO, MIMO, and Transmit diversity with different antenna configurations) [24].

The Vienna LTE Simulator package has two types of simulators: LTE Link Level Simulator (LLS) and LTE System Level Simulator (SLS). The LTE Link Level Simulator is used to simulate the Physical Layer procedures and analyze the link level related issues like receiver structures and coding schemes while the LTE System Level Simulator is used to measure the whole network performance after abstracting the Physical Layer from Link Level results.
The core part of the System Level Simulator is divided into link measurement model and link performance model. Link measurement model is used to abstract the measured link quality used for link adaptation and resource allocation based on signal to interference and noise ratio (SINR) as a metric. The aim of this step is to reduce run-time computational complexity by pregenerating and storing the results of these heavy computations to be reused during simulation time. While the link performance model is used to determine throughput and error rates at a reduced complexity. One of the most important purposes of such simulation tool is measuring the quality and performance of new scheduling algorithms in LTE Systems.

4.2 System Model

4.2.1 Cellular Layout

Our wrap-around LTE cellular layout is composed of 7 macrocells. A base station (BS) located at the center of each macrocell is used to provide service for macro user equipments (MUEs) attached to this BS. Base Stations for LTE cellular systems are given the name evolved NodeB (eNBs) in 3GPP standard [25]. Each macrocell consists of 3 hexagonal-sector sites such that each hexagonal sector is served by a different directional antenna. The beam directions of different sector antennas are separated by 120° from each other.

MUEs are randomly dropped in the macrocell and can be classified into outdoor MUEs located in free space area and indoor MUEs located inside offices, enterprises, houses ... etc. Indoor MUEs are served by ordinary eNBs unless they are authorized to access femto BSs located in their coverage area. The cellular layout of ordinary LTE cellular system is shown in figure 4.1.
4.2.2 Modeling Indoor Area

Mac ROCell Coverage area in our system model is classified into outdoor coverage area (e.g. Free Space) and indoor coverage area. Indoor coverage area is represented by uniformly distributed randomly dropped square houses of size $15m \times 15m$. One femto BS is randomly dropped inside each house. Figure 4.2 shows one example of randomly dropped houses where femto BS could be located in one of the 9 possible locations inside each house.

The femtocell coverage area is defined by a specific radius centered by the location of the femto BS inside each house. The number of active femto BSs at a time is not set to a fixed number but set as a variable parameter to study performance in different femtocell deployment densities. Unlike MUEs that can be located anywhere with macrocell coverage.
area, FUEs existence is only limited to the predefined femtocell coverage area otherwise it will handoff to macrocell and be a MUE. Figure 4.3 shows an example of a macrocell providing access for ordinary MUEs (outdoor and indoor) overlaid by femtocell network providing access for only limited number of subscribed UEs (FUEs).
4.2.3 Propagation Pathloss (PL) Models

Figure 4.4: Different Connection Links of Hybrid Macro-Femto Network

Suburban deployment scenario is assumed in our research work. Propagation pathloss (PL) models are the reference formulas used to describe the propagation loss encountered in the downlink between Tx (macro BSs or femto BSs) and Rx (MUEs or FUEs). Pathloss formulas are valid for Tx-Rx separation larger than 1 m. Pathloss (PL) model formulas can be summarized as follows [26]:

**UE to Macro BS**

1. **UE is outside:**
   
The following PL model expressed in equation 4.1 is used when the transmitter is a macro BS and the receiver is either outdoor MUE or a FUE located outside the house
such as link 1 and 2 respectively in figure 4.4.

\[ PL(dB) = 15.3 + 37.6 \log R \]  \hspace{0.5cm} (4.1)

2. **UE is inside a house:**

The following PL model expressed in equation 4.2 is used when the transmitter is a macro BS and the receiver is either indoor MUE or a FUE located inside such as links 3 and 4 respectively in figure 4.4.

\[ PL(dB) = 15.3 + 37.6 \log R + L_{ow} \]  \hspace{0.5cm} (4.2)

**UE to Femto BS**

1. **UE is inside the same house as femto BS:**

The following PL model expressed in equation 4.3 is used when the transmitter is a femto BS and the receiver is either indoor MUE or a FUE located inside the house such as link 5 and 6 respectively in figure 4.4.

\[ PL(dB) = 38.46 + 20 \log R + 0.7d_{2D,indoor} \]  \hspace{0.5cm} (4.3)

2. **UE is outside:**

The following PL model expressed in equation 4.4 is used when the transmitter is a femto BS and the receiver is either outdoor MUE or a FUE located outside the house such as link 7 and 8 respectively in figure 4.4.

\[ PL(dB) = \max(15.3 + 37.6 \log R, 38.46 + 20 \log R) + 0.7d_{2D,indoor} + L_{ow} \]  \hspace{0.5cm} (4.4)

3. **UE is inside a different house:**
The following PL model expressed in equation 4.5 is used when the transmitter is a femto BS and the receiver is either MUE or FUE located inside a different house other than that of femto BS such as link 9 in figure 4.4.

\[ PL(dB) = \max(15.3 + 37.6 \log R, 38.46 + 20 \log R) + 0.7 d_{2D, indoor} + L_{ow,1} + L_{ow,2} \]

(4.5)

where

- \( R \) is the distance between Transmitter and Receiver.
- \( L_{ow,1} \) and \( L_{ow,2} \) are the penetration losses of outdoor walls, which are 10dB.
- \( d_{2D, indoor} \) is the distance inside each house in the case of UE located inside the same house or the total distance inside two houses if it is located in a different house.

### 4.2.4 Antenna Patterns

As described in subsection 4.2.1 each hexagonal sector is served by a directional antenna such that the main beams of the three antennas used in each macrocell are separated by 120° from each other. Based on [27] the antenna gain encountered at any point in the macrocell as a function of the angle from the reference main beam direction of this antenna \( \theta \) can be formulated in equation 4.6 below.

\[ A(\theta) = -\min[12(\frac{\theta}{\theta_{3dB}})^2, A_m] \]

(4.6)

where \( \theta_{3dB} = 65^\circ \) and \( A_m = 20 \) dB.

The antenna patterns of both types of UEs and femto BSs are assumed to be omnidirectional.
4.2.5 Shadowing Models

Log-normal shadowing is assumed in our research work. The standard deviation for log-normal shadowing is assumed to be 4 dB for links between femto BSs and its associated FUEs. Standard deviation of 8 dB is used for all other links including interference links.

4.3 SINR and Capacity Analysis

4.3.1 SINR Analysis

In this part of the chapter we analyze signal to interference and noise ratio (SINR) encountered by different types of UEs (e.g. MUEs and FUEs) in LTE cellular system for any of the different frequency allocation schemes described in details in Chapter 5.

As described in section 4.2 MUEs are categorized into outdoor and indoor UEs and can be located anywhere within the coverage area of each macrocell while FUEs can only be located within coverage area of each femtocell. The analysis used for calculating SINR encountered by any MUE in the macrocell can be found below.

Each MUE is assigned to a macrocell where its BS is responsible for providing service for this UE. This UE is interfered by both neighboring macrocells and femtocells operating on the same frequency sub-bands assigned to its serving BS. While the intracell interference is almost eliminated due to the characteristics of OFDMA provided by LTE system [28], inter-cell interference (ICI) still exists and represents an important issue especially for Reuse-1 operation and small-sized macrocells. The downlink signal to interference and noise ratio (SINR) for any MUE can be formulated as shown below in equation 4.7.

\[
SINR_{MUE} = \frac{P_{S,B}^{B}}{\sigma^2 + \sum_{b=1}^{7} \sum_{i=1}^{3} P_{R}^{s,b} + \sum_{f=1}^{N_f} P_{R}^{f}}
\]  

(4.7)
where $P_{R}^{S,B}$ is the received power from Sector $S$ of serving macrocell $B$, $P_{R}^{s,b}$ is the received power from interfering Sector $s$ associated with macrocell $b$, $P_{R}^{f}$ is the received power from interfering femtocell $f$ using the same sub-bands, $N_f$ is number of femtocells, and $\sigma^2$ is the thermal noise power in watts. The power received $P_R$ can be directly calculated using equation 4.8 shown below.

$$P_R(dBm) = P_T(dBm) - P_{TL}(dB)$$ \hspace{1cm} (4.8)

where $P_T$ is the macrocell transmission power in dBm and $P_{TL}$ is the total loss encountered by the signal in dB such that

$$P_{TL}(dB) = P_L(dB) - G_T(dB)$$ \hspace{1cm} (4.9)

where $P_L$ is the macroscopic pathloss encountered by the signal in dB and $G_T$ is the transmitting antenna gain in dB. The receiver antenna gain $G_R$ is set to 0 dB since the UEs antenna pattern is set to be omnidirectional.

Each FUE is attached to its associated femtocell which is responsible for providing service for this UE. If FUE becomes unauthorized for femto access, it will directly handoff to nearest macrocell. Similarly like MUE, each FUE is interfered by all neighboring macrocells and femtocells operating on the same frequency sub-bands like its serving femto BS. The downlink SINR for any FUE can be calculated using equation 4.10 below.

$$SINR_{FUE} = \frac{P_F^R}{\sigma^2 + \sum_{b=1}^{7} \sum_{s=1}^{3} P_{R}^{s,b} + \sum_{f=1}^{N_f} P_{R}^{f}}$$ \hspace{1cm} (4.10)

where $P_F^R$ is the received power from serving femtocell $F$, and $P_{R}^{s,b}$ and $P_{R}^{f}$ are zero if the corresponding cell is utilizing another sub-band.


4.3.2 Capacity Analysis

We assume in our work that one MUE is connected to each macro BS at a time such that this MUE is capable of using all available frequency resources assigned to this macro BS. The same is assumed for femtocells, one FUE is connected to each femtocell at a time such that this FUE is capable of using all available frequency resources assigned to its associated femto BS. Our methodology depends on changing the location of both MUE and FUE continuously in the x-y domain of our assumed cellular network in order to cover all possible locations where MUEs and FUEs can be located within coverage area of macrocells and femtocells respectively. One other important assumption in our work that all neighboring BSs are assumed to be always transmitting with full power over all their available frequency sub-bands so worst-case interference scenario can be simulated and studied.

The theoretical user capacity (bps) can be calculated for any UE (macro or femto) using equation 4.11 below (assuming a static additive white gaussian noise AWGN scenario).

\[
C_{\text{MUE/FUE}} = W \log_2(1 + \text{SINR}_{\text{MUE/FUE}})
\]  

(4.11)

where \( W \) is the total bandwidth of the sub-bands available for this UE in Hz. This procedure is used to evaluate SINR and theoretical user capacity for both MUEs and FUEs at all possible locations in our cellular network which will be used later in Chapter 6 for calculating our evaluation metrics for measuring system performance.
CHAPTER 5

PROPOSED FREQUENCY ALLOCATION SCHEMES

In this chapter we describe in details our proposed frequency allocation schemes in LTE femtocell system. Frequency allocation schemes mean the procedures and algorithms used to allocate the limited frequency resources for both macrocells and femtocells in LTE femtocell system. The aim of any frequency allocation scheme is to enhance the overall system performance and increase the spectral efficiency of the limited frequency bandwidth.

In each scheme we exploit a well-known frequency allocation method for macrocell operation with focus on those depending on the concept of Fractional Frequency Reuse (FFR) that was firstly proposed in [29] for GSM networks as it proves to solve the problem of poor coverage at edge zone that represents a big issue in any mobile cellular system [30]. We then propose techniques for allocating frequency resources for femtocells such that these techniques cope with those of macrocell operation to enhance the overall system performance. We ensure that all of our proposed schemes are static and don’t require any signalling between macrocells and femtocells. The well-known frequency allocation schemes exploited in our research work are: Reuse-1, Reuse-3, Soft Frequency Reuse (SFR), Partial Frequency Reuse (PFR), and Soft Fractional Frequency Reuse (SFFR). All of these schemes are described in details in the remaining part of this chapter.
5.1 Reuse-1 Scheme

We study the Reuse-1 scheme in our research work for comparison purpose with other schemes. The universal reuse scheme (or Reuse-1) assigns the entire frequency resources to be reused by all macrocells and femtocells existing in the system. The main advantage of Reuse-1 scheme is the possibility of using all available frequency resources and hence increasing the spectral efficiency of scarce bandwidth. This usually comes at the expense of the amount of interference generated in the system. Since all macrocells and femtocells share the same bandwidth at the same time to provide service for their attached UEs, the amount of inter-cell interference ICI becomes very high especially for small-sized macrocells. The Reuse-1 scheme also results in a coverage problem due to poor SINR for those MUEs far from their serving BSs at the edge of macrocell due to the interfering transmission of nearby macrocells [31]. Reuse-1 scheme also results in a severe problem for indoor MUEs that are very near to active transmitting femto BSs.

In figure 5.1 we describe the operation of Reuse-1 scheme where all macrocells use the entire frequency bandwidth at the same time slots with reference transmission power $P_M$. The femtocells also apply the concept of Reuse-1 such that they use the same entire frequency bandwidth simultaneously with macrocells but with limited transmission power $P_F$. 

![Figure 5.1: Reuse-1 Scheme](image)
5.2 Reuse-3 Scheme

Higher reuse factors than Reuse-1 have been proposed in order to solve the problem of poor coverage at edge zone [32]. Reuse-3 has proved that it can provide the best performance among different reuse factors as shown in [33]. In Reuse-3 scheme the entire frequency band is divided equally into three sub-bands such that each cell is assigned only one of the available sub-bands and the frequency bandwidth is reused every three cells rather than every cell like Reuse-1 case. We can notice that the amount of inter-cell interference ICI has been highly decreased due to limiting most of dominant interferers by operating on a different sub-bands while at the same time the spectral efficiency of the limited frequency resources also decreased by wasting most of them to avoid interference.

In figure 5.2 we describe the operation of Reuse-3 scheme. Each macrocell is divided into three different sectors and each sector is served by a different directional antenna. The three sectors are assigned the three different sub-bands such that the interference is only limited to one sector (instead of 3 in Reuse-1 case) that operates on the same sub-bands in neighboring macrocells. The transmission power level in each sector is set as $3P$ where $P$ is the reference power level used in Reuse-1 transmission [34]. For femtocell operation we propose that femtocells at each sector operate on the two remaining sub-bands not used by macrocell. This procedure provides almost complete frequency separation between macrocell and femtocell networks but at the expense of spectral efficiency.
5.3 Soft Frequency Reuse (SFR) Scheme

It can be noticed that Reuse-1 alone results in a big amount of interference and Reuse-3 alone results in poor spectral efficiency and waste of frequency resources. A mix of Reuse-1 and Reuse-3 has been proposed in [35] such that the composite scheme is a compromise between the two different schemes. This scheme is called Soft Frequency Reuse (SFR) and can be described as follows.

Figure 5.3: SFR Scheme

Figure 5.3 describes the frequency allocation process for both macrocells and femtocells applied in SFR scheme. SFR scheme divides the coverage area of macrocell into interior (center) region and edge region as shown in figure 5.3. The definition of center region is defined by the radius from the center of macrocell where macro BS is located. The optimal radius that maximizes system throughput has been calculated in [36] and found to be 63% of cell radius. Based on dividing the macrocell into center region and edge region, consequently MUEs are classified into center MUEs and edge MUEs based on their location in the macrocell.

The LTE frame is divided into two time slots [37]. The first time slot in SFR scheme is reserved for access of center MUEs where they can use freely the entire frequency bandwidth during this time slot (Reuse-1 operation). The second time slot is reserved for access of edge MUEs. The entire frequency bandwidth in the second time slot is divided equally into three sub-bands such that edge MUEs at each sector of each macrocell can access only one of
the three available frequency sub-bands (Reuse-3 operation) as shown in figure 5.3. The transmission power level of the edge region is set to be three times the transmission power level of center region [38].

We then propose an allocation scheme for femtocells that copes with macrocell allocation procedure that was described in previous paragraph and doesn’t require neither synchronization nor signalling between the two types of networks. Femtocells will be also categorized into center femtocells and edge femtocells according to their location in the macrocell as shown in figure 5.3. Let the entire frequency bandwidth is divided equally into three sub-bands A, B, and C. Center femtocells at each sector will operate only on one sub-band such that this sub-band is not accessed by edge MUEs at this sector and different from the frequency sub-bands used by center femtocells in neighboring sectors on the same macrocell. Edge femtocells at each sector can use the two sub-bands not accessed by edge MUEs at this sector. In general the sub-bands accessed by edge MUEs at each sector is prohibited for access by femtocells to avoid strong interfering transmission. For example, if macrocell uses sub-band A to serve edge region at sector 1, then center femtocells will use either sub-band B or C and edge femtocells will use both sub-bands B and C.

We assume that this procedure for both macrocell and femtocell allocation provides an efficient mutual Macro-Femto interference management scheme due to the following reasons:

1. The Macro-to-Femto interference in the center region only exists during the first time slot.

2. Femto-to-Macro interference in center region is attenuated to 1/3 as femtocells only transmit on 1/3 of the allocated Bandwidth and hence can be tolerated by center MUEs as they have a high received power from their serving macro BS.

3. Macro-to-Femto interference over FUEs associated with edge femtocells is minimized due to relatively large distance from the center interfering macro BS.
4. Femto-to-Macro interference occurred by edge femtocells is only limited to center MUEs and is negligible due to low femtocell power.

5.4 Partial Frequency Reuse (PFR) Scheme

One variation of the concept of Fractional Frequency Reuse (FFR) is called Partial Frequency Reuse (PFR). PFR has been proposed in [39] as a technique for resource allocation in macro-cellular networks. The concept of PFR is somehow similar to SFR as it also divides the macrocell coverage area into center region and edge region based on the same optimal radius used in section 5.3.

Figure 5.4 describes the macrocell frequency allocation process in PFR scheme. The entire system bandwidth is divided into 6 sub-bands as shown in figure 5.4. Three of these sub-bands (called common sub-bands) are reserved for access of center MUEs at any sector. The three remaining sub-bands are reserved for access of edge MUEs of the three different sectors such that each sector is assigned on sub-band for its UEs’ access. Based on [40], the transmission power level over the sub-bands used by edge MUEs is 2/3 of the total transmission power assigned for macro BS while the transmission power level over sub-bands used by center MUEs is 1/3 of total transmission power.

We propose a femtocell allocation process as described in figure 5.4. Center femtocells at each sector will operate on sub-bands not used neither by center MUEs nor by edge MUEs.
Edge femtocells will operate on the same sub-bands like center femtocells in addition to common sub-bands. Since edge femtocells are far enough from center macro BS, the amount of interference power level received becomes very limited.

If the entire system bandwidth is divided into 6 sub-bands A, B, C, D, E, and F. Common sub-bands A, B, and C are reserved for center MUEs while sub-bands D, E, and F are reserved for edge MUEs located at the three different sectors. If we assign sub-band D for edge MUEs at sector 1, then sub-bands E and F will be used by center femtocells. Edge femtocells will use the same two sub-bands E and F in addition to common sub-bands (A, B, and C). Like Reuse-3 scheme, PFR can almost provide complete separation in frequency between the two different networks of LTE femtocell system.

5.5 Soft Fractional Frequency Reuse (SFFR) Scheme

Soft Fractional Frequency Reuse (SFFR) is another variation of FFR proposed firstly in [41]. Similar to SFR and PFR, SFFR also divides the macrocell coverage area two distinct regions; center region and edge region. The optimal radius of center region is also set to 63% of cell radius as calculated in [36]. The concept of SFFR is very similar to PFR except for one variation as will be described below.

![Diagram of SFFR Scheme](image)

**Figure 5.5: SFFR Scheme**

Figure 5.5 describes the macrocell frequency allocation process used in SFFR scheme. Similar to PFR, the entire system bandwidth is also divided into 6 sub-bands. Three of them
are reserved for center MUEs access \textit{(common sub-bands)} and the remaining three sub-bands are distributed over the three different sector for edge MUEs access (one sub-band each). The only difference between PFR and SFFR is the capability of center MUEs at any sector to access two additional sub-bands assigned for edge MUEs access of the two other sectors but with limited transmission power to minimize interference as much as possible. This enhancement is assumed to increase spectral efficiency performance over that of PFR. For example, if sub-band D is reserved for edge MUEs access at sector 1, center MUEs at sector 1 can access common sub-bands A, B, and C with a specific power level while they can also access sub-bands E and F but with limited power level to minimize interference level. A quarter of the total transmission power assigned to macro BS is reserved for transmission over common sub-bands. The ratio of transmission power level over edge region sub-bands to the transmission power level over the two additional sub-bands of center region is set to be [10:1] [42].

Figure 5.5 shows that the femtocell allocation process in SFFR scheme is the same like that of PFR scheme without any change. In general, we can see that PFR scheme is a specialized case from the general SFFR scheme by setting the power of additional sub-bands of center region to zero power.
CHAPTER 6

EVALUATION METHODOLOGY & SIMULATION RESULTS

In this chapter we describe the evaluation metrics used in evaluating the performance of our LTE femtocell system and our proposed frequency allocation schemes described in details in Chapter 5. These evaluation metrics are targeting the evaluation of different aspects of the network such as throughput performance, coverage performance, Quality of Service (QoS) performance and finally the fairness performance of LTE femtocell system. The simulation setup and system parameters are described in details in this chapter. Then we show the simulation results of our research work and give comments and conclusions based on these results. The second part of this chapter provides an optimization analysis for one of our proposed frequency allocation schemes which is Soft Frequency Reuse (SFR) in order to enhance the overall system performance of both network types. Simulation results of this optimization analysis are then provided and comments are given on these results. We start with describing evaluation metrics used as will be shown below.

6.1 Evaluation Metrics

6.1.1 Coverage Performance

The coverage performance in LTE femtocell network is measured via two main metrics.

1. $\text{SINR maps}$
The region of interest (ROI) of our LTE femtocell network is divided into small-squared pixels such that the area of each pixel is $5m \times 5m$. Each pixel is localized by cartesian coordinates in ordinary x-y domain. The x-y coordinates help to calculate distance from different pixels to either fixed-located macro BSs or randomly dropped femto BSs in the network. Each pixel is assumed to represent the location of a FUE if it is located within the coverage area of a femtocell, the location of indoor MUE if it is located inside a house, or the location of an outdoor MUE elsewhere.

Using the SINR equations stated in section 4.3.1 and for the different frequency allocation schemes described in Chapter 5, we can easily calculate SINR values for both MUEs and FUEs at all pixels of ROI based on the location of the pixel and the allocation process used. We can easily translate these calculated values into SINR maps plotted in x-y domain that describes the distribution of SINR values for both MUEs and FUEs for each frequency allocation scheme.

2. 10%-tile SINR

Coverage performance is usually a crucial issue for UEs suffering from poor SINR. For LTE femtocell networks, those UEs with poor SINR values could be indoor MUEs, MUEs located at cell edges, FUEs far from their serving femto BS, or MUEs/FUEs subjected to strong interfering transmission. We use the 10%-tile SINR as metric for measuring coverage performance of all UEs available in the network. The 10%-tile SINR is calculated for different frequency allocation schemes and for different active femtocell deployment densities.

6.1.2 Throughput Performance

The second aspect evaluated in our research work is the system throughput. Our methodology for evaluating system throughput depends on measuring users capacity. Using equation 4.11 in section 4.3.2 we can easily evaluate the user capacity for any UE (MUE or FUE) in our LTE femtocell network. The calculated user capacity for any UE represents the maxi-
mum data rate that this UE can achieve based on the assumption that one UE at a time can use all the available resources assigned for its serving BS. By calculating the users capacity achieved by all UEs available in the network, we can easily calculate two average values which are; average value of users capacities of MUEs and average value of users capacities of FUEs. Finally we can express the overall average user capacity of all UEs available in the network by using weighted average of those two values using equation 6.1.

\[
C_{overall} = \frac{N_{MUE} \cdot C_{avg}^M + N_{FUE} \cdot C_{avg}^F}{N_{MUE} + N_{FUE}}
\]  

(6.1)

where \(N_{MUE}\) and \(N_{FUE}\) are the number of MUEs and FUEs available in the network respectively. \(C_{avg}^M\) and \(C_{avg}^F\) are average user capacities of MUEs and FUEs respectively. We assume that this overall average user capacity can express average throughput performance of the whole network. We calculate this overall average user capacity for different frequency allocation schemes and for different active femtocell deployment densities.

### 6.1.3 Quality of Service (QoS) Performance

The quality of service (QoS) performance of our LTE femtocell network is measured via outage probability \(P_{outage}\). Outage Probability \(P_{outage}\) is defined as the probability of all UEs (MUEs + FUEs) having SINR values below a predefined SINR threshold. Suppose \(\gamma\) is a vector containing all calculated SINR values for both MUEs and FUEs based on analysis in section 4.3.1 such that \(\gamma = [\gamma_1 \ \gamma_2 \ldots \gamma_M \ \gamma_{M+1} \ \gamma_{M+2} \ldots \gamma_{M+F}]\) where \(M\) and \(F\) are number of MUEs and FUEs in the network respectively. The outage probability can then be expressed mathematically as follows.

\[
P_{outage} = Pr(\gamma < \gamma_{th})
\]  

(6.2)

where \(\gamma_{th}\) is the threshold SINR value.

The explanation of using SINR values to evaluate QoS comes from that SINR values usually reflect channel quality indicator (CQI) values. CQI values are sent as feedback by
UEs to the serving base station (BS) to determine the modulation and coding scheme (MCS) used in LTE network [43]. The MCS determines the transmission rate and hence QoS in the network. The outage probability is calculated for a range of SINR threshold values and for different proposed frequency allocation schemes.

6.1.4 Fairness Performance

Fairness is a very crucial requirement for any cellular network. It is not sufficient to have a system with high throughput with no guarantee of fair distribution of system resources. Fairness performance of our LTE femtocell network is evaluated via two main metrics.

1. Jain’s index

Jain’s index is a very famous parameter used for measuring fairness [44]. Suppose we have a vector $C$ containing all user capacity values calculated based on analysis of section 4.3.2 for both MUEs and FUEs available in the network such that $C = [C_1, C_2, \ldots, C_M, C_{M+1}, C_{M+2}, \ldots, C_{M+F}]$ where $M$ and $F$ are numbers of MUEs and FUEs respectively. The jain’s index calculated for this user capacity vector can be expressed in equation 6.3 below.

$$J(C_1, C_2, \ldots, C_M, C_{M+1}, \ldots, C_{M+F}) = \frac{\left(\sum_{i=1}^{M+F} C_i\right)^2}{(M+F) \sum_{i=1}^{M+F} C_i^2} \quad (6.3)$$

Jain’s index is calculated for different proposed frequency allocation schemes and for different active femtocell deployment densities.

2. Fairness Ratio

We define another metric for measuring fairness performance of LTE femtocell network. This metric is called Fairness Ratio [45]. Fairness Ratio is defined as the ratio of 5%-tile capacity calculated from vector $C$ used in Jain’s index calculation to the

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overall average user capacity calculated in section 6.1.2. This definition can be expressed mathematically in equation 6.4 below.

\[
\text{Fairness Ratio} = \frac{5\text{-tile Capacity}}{C_{\text{overall}}} \quad (6.4)
\]

Fairness Ratio is calculated for different proposed frequency allocation schemes and for different active femtocell densities.

### 6.2 Simulation Setup

Our LTE cellular network is composed of 7 macrocells, and femtocells are randomly dropped over the macrocells. The number of active femtocells is varied from 30 to 180 to study the effect of varying femtocell deployment density on the whole network performance. MUEs and FUEs are located within all possible locations of macrocells and femtocells coverage areas respectively. Either MUE or FUE at a time is allocated all available resources assigned to its serving macro or femto BS respectively. Three sector antennas are installed at each macro BS to serve the three different sectors such that the maximum allowed transmission power for each sector antenna is 20 W. All femtocells are assumed to use a limited transmission power of only 20 mW. AWGN channel model is assumed and the pathloss models are calculated as explained in section 4.2.3. SINR and capacity values are then calculated for all UEs and hence used for calculating evaluation metrics explained in section 6.1 above. The simulation system parameters are summarized in Table 6.1.

### 6.3 Simulation Results

We plot some SINR maps as explained in Section 6.1.1 to evaluate coverage performance of the whole network.

Figure 6.1 shows Macro-Femto SINR coverage map with focus only on the target center macrocell for different proposed frequency allocation schemes with 60 deployed femtocells.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LTE System Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Inter-site Distance</td>
<td>1732 m</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>Sub-urban</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>FFT Size</td>
<td>512</td>
</tr>
<tr>
<td>Sub-carrier Spacing</td>
<td>15 KHz</td>
</tr>
<tr>
<td>CP Type</td>
<td>Normal</td>
</tr>
<tr>
<td>Thermal Noise</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Shadow Fading SD</td>
<td>8 dB</td>
</tr>
<tr>
<td><strong>eNB Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Number of eNBs</td>
<td>7</td>
</tr>
<tr>
<td>Number of Sectors per eNB</td>
<td>3</td>
</tr>
<tr>
<td>Max Tx Power</td>
<td>20 W</td>
</tr>
<tr>
<td>Max Sector Antenna Gain</td>
<td>15 dB</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>$A(\theta) = -\min[12\left(\frac{\theta}{65\pi}\right)^2, 20]$</td>
</tr>
<tr>
<td>Minimum Coupling Loss</td>
<td>70 dB</td>
</tr>
<tr>
<td><strong>HeNB Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Number of HeNBs per macrocell</td>
<td>30 ~ 180</td>
</tr>
<tr>
<td>Femtocell Radius</td>
<td>20 m</td>
</tr>
<tr>
<td>HeNB Tx Power</td>
<td>20 mW</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>0 dB</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Minimum Coupling Loss</td>
<td>40 dB</td>
</tr>
<tr>
<td><strong>UE Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>0 dB</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Rx Noise Figure</td>
<td>9 dB</td>
</tr>
</tbody>
</table>

Table 6.1: Simulation Parameters
The entire map represents the SINR performance of MUEs at all possible locations except the locations that belong to femtocells’ coverage areas that represent SINR performance of FUEs. Figure 6.1 addresses the different proposed frequency allocation schemes in addition to the case when all femto BSs are turned OFF and Reuse-1 is operated. Figure 6.1(a) shows that Reuse-1 scheme coverage performance is suitable for those MUEs that are close to cell center as they receive good signal strength from their associated macro BS however there is a coverage hole generated at the cell edge encountered by edge MUEs due to poor signal strength and high level of ICI. Figure 6.1(b) shows that the presence of femtocells enhanced the coverage performance of FUEs close to their associated femto BSs however the coverage hole encountered by edge MUEs still exists and new coverage holes are generated at the edge of femtocells due to unmanaged interference between macrocells and femtocells, interfering transmission of nearby femtocells, and poor signal strength received from femto BSs at the cell edge of femtocells. Figure 6.1(c) and (e) show the SINR coverage performance of Reuse-3 and PFR schemes respectively. Both schemes substantially eliminate the coverage problem at both macrocell edge and femtocell edge due to complete frequency separation between macrocell and femtocell networks. Figure 6.1 (d) and (f) show the SINR coverage performance of SFR and SFFR schemes respectively. Both schemes also eliminate macro coverage hole at cell edge and coverage holes generated at cell edge of edge femtocells. However SINR performance at cell edge of center femtocells is somehow lower due to sharing some sub-channels with macrocell transmission for center MUEs.

Figure 6.2 shows Macro SINR coverage map for different proposed frequency allocation schemes with 60 deployed femtocells. The entire map here represents the all possible locations for MUEs only and the locations within the coverage area of femtocells are assumed to be indoor MUEs rather than FUEs like the previous case. We can notice that the performance of indoor MUEs is highly degraded with Reuse-1 scheme as shown in Figure 6.2(b) due to large amount of ICI and interfering transmission of very close femto BSs while the performance is the best for Reuse-3, and PFR schemes. The performance of center indoor
MUEs related to SFR and SFFR schemes are somehow lower; but still very good compared to Reuse-1 scheme; due to sharing some sub-channels with femtocell operation.

We address the SINR coverage map for another femtocell deployment density. Figure 6.3 shows Macro-Femto SINR coverage map for different proposed frequency allocation schemes with 150 deployed femtocells in addition to the case when all femto BSs are turned OFF with Reuse-1 operation. With dense deployment of femtocells, the interference problem becomes very severe as shown in Figure 6.3(b) as the co-layer interference between femtocells becomes very significant. We can notice that the proposed frequency allocation schemes have treated the cross-layer interference issue and still provide acceptable levels of SINR coverage performance however there are some scenarios of very dense femtocell deployment in a small geographic area where the co-layer interference becomes the dominant type of interference which results in coverage holes at the edge of femtocells. The co-layer interference problem needs to be addressed with different management schemes.

Similarly we address the indoor MUEs performance for the 150-femtocell deployment scenario in Figure 6.4. Figure 6.3(b) shows the very poor performance of indoor MUEs to very high interfering transmission of nearby femtocells. The indoor performance of MUEs have been highly enhanced by different proposed schemes especially Reuse-3 and PFR schemes. The performance of SFR and SFFR schemes are lower due to sharing some sub-channels with femtocell operation and large amount of Inter-Femto Interference (IFI) generated at this dense deployment scenario.
Figure 6.1: Macro-Femto SINR coverage map for different allocation schemes (60 deployed femtocells)
Figure 6.2: Macro SINR coverage map for different allocation schemes (60 deployed femtocells)
Figure 6.3: Macro-Femto SINR coverage map for different allocation schemes (150 deployed femtocells)
Figure 6.4: Macro SINR coverage map for different allocation schemes (150 deployed femtocells)
The other metric used for measuring coverage performance as explained in Section 6.1.1 is 10%-tile SINR. Figure 6.5 shows the 10%-tile SINR (dB) of all network UEs (MUEs + FUEs) against number of active femtocells deployed in the network for the different proposed frequency allocation schemes. Reuse-1 scheme provides very poor 10%-tile SINR values and hence very poor coverage especially for large number of active femtocells where the performance dramatically decreases as shown. Other proposed frequency allocation schemes like Reuse-3 and PFR can highly enhance the coverage performance and provide almost stable performance as the number of active femtocells increases. This can be explained as these schemes (e.g. Reuse-3 and PFR) provide almost complete frequency separation between Macro and Femto networks. The two other proposed frequency allocation schemes; SFR and SFFR also provide acceptable level of 10%-tile SINR coverage performance but lower than Reuse-3 and PFR.

The evaluation metric used for measuring throughput performance is the overall average user capacity as explained in Section 6.1.2. Figure 6.6 shows the overall average user capacity (Mbps) against number of active femtocells deployed in the network for the different proposed frequency allocation schemes. Reuse-1 scheme can outperform all other proposed
schemes for only a small number of active deployed femtocells. This can be explained as the amount of interference power is still limited and can be tolerated by different types of UEs. SFR scheme provides the best performance as the number of active femtocells becomes much higher as shown. Due to the poor spectral efficiency, other proposed schemes like Reuse-3, PFR, and SFFR provide lower throughput performance than Reuse-1 and SFR schemes. Figure 6.6 shows that while the total system throughput increases by deploying more femtocells, average user capacity may decrease with large number of femtocells like Reuse-1 and SFR schemes.

The evaluation metric used for measuring Quality of Service (QoS) performance is the outage probability as explained in Section 6.1.3. Figure 6.7 shows the outage probability against a predefined SINR threshold. The number of active deployed femtocells is set to 90. The predefined SINR threshold is varied from -5 dB to 30 dB by a step size of 5 dB. The Reuse-1 scheme has very high outage probability compared to the other proposed frequency allocation schemes. The Reuse-3 scheme, as expected, the best in term of QoS performance due to the complete frequency separation between the Macro and Femto Networks and hence most of the cross-layer interference that represents the dominant factor of interference is
eliminated. The other proposed frequency allocation schemes (e.g. SFR, PFR, and SFFR) provide almost the same level of outage probability that is highly reduced from that of Reuse-1 and near to that of Reuse-3 for small SINR threshold values up to 5 dB.

The first metric used for measuring Fairness is the Jain’s index of users capacity values as explained in Section 6.1.4. Figure 6.8 shows the Jain’s index against number of active femtocells deployed for different proposed frequency allocation schemes. Proposed Reuse-3 and SFR schemes are the best in terms of fairness performance while both of them slightly decrease as number of active femtocells increases. The other proposed schemes (e.g. Reuse-1, PFR, and SFFR) have lower fairness performance as shown in Figure 6.8. It can be also noticed that the rate of Jain’s index decrease of Reuse-1 scheme as number of active femtocells increasing is much higher than the rate of decrease of the other two schemes.

The second metric used for measuring Fairness is the Fairness ratio as explained in Section 6.1.4. Figure 6.9 shows the fairness ratio against number of active femtocells deployed for the different frequency allocation schemes. Similarly like the results of Jain’s index performance, Reuse-3 and SFR are the best in terms of fairness performance with almost flat performance as number of active femtocells increases. PFR and SFFR schemes also provide
flat performance against number of active femtocells but with lower fairness ratio values than those of Reuse-3 and SFR schemes. Finally as expected, the fairness of the Reuse-1 scheme is highly degraded at higher femtocell densities due to the unmanaged interference.

In order to choose the best proposed frequency allocation scheme from those mentioned above, we depend on a tradeoff between fairness performance and throughput performance based on calculated evaluation metrics. Figure 6.10 and 6.11 show this tradeoff between fairness and throughput for two femtocell deployment scenarios. The medium femtocell deployment scenario is shown in figure 6.10 where 90 active femtocells are deployed within each macrocell. The heavy femtocell deployment scenario is shown in figure 6.11 where 150 active femtocells are deployed within each macrocell. Figure 6.10 and 6.11 show that Reuse-3 and PFR schemes can provide high level of fairness at the expense of throughput. Reuse-1 scheme can provide high level of throughput at the expense of very poor fairness and QoS. We can notice that SFR scheme can provide the best throughput performance with an acceptable level of fairness which is not too much far from those of Reuse-3 and PFR schemes.
6.4 Optimizing Interior Radius of Soft Frequency Resue (SFR) Scheme

We have concluded at the end of Section 6.3 that our proposed SFR scheme can provide a good tradeoff between fairness and throughput performance in our LTE femtocell network.
Thus we try at this section to optimize the interior region radius of the SFR scheme using exhaustive search method for the best possible performance as shown below.

The impact of changing the SFR interior region radius on the overall average user capacity is shown in Figure 6.12. We set the SFR interior radius as a variable parameter during simulation changing from 50% to 90% of cell radius with step size of 5%. Two femtocell deployment scenarios are simulated; the relatively low deployment scenario represented by 60 active deployed femtocells and the relatively high deployment scenario represented by 150 active deployed femtocells. Figure 6.12 shows that the optimal interior radius that maximizes overall average users’ capacity and hence average throughput performance is found to be 76% of cell radius for the relatively low deployment scenario. The same figure also shows that the optimal interior radius that maximizes overall average users’ capacity and hence average throughput performance is found to be 65% of cell radius for the relatively high deployment scenario. We can observe that the optimal interior region radius is a factor of the deployment density and decreases as number of active femtocells increases. As the SFR interior radius decreases, more of the active femtocells are then considered Edge fem-
tocells that can use more frequency sub-bands than Center femtocells and thus have higher throughput.

We also study the impact of changing SFR interior radius on the fairness performance. Using the same two deployment scenarios mentioned above and over the same range of SFR interior radii, figure 6.13 shows the fairness ratio of the two deployment scenarios against the SFR interior radius. Figure 6.13 shows that for the relatively low deployment scenario the fairness ratio doesn’t decrease significantly as the SFR interior radius increases. On the other hand, the same figure shows that the fairness ratio decreases dramatically for the relatively high deployment scenario due to the increased amount of interference. We can also notice from this figure that at the two optimal radii points of 76% and 65% calculated in the previous paragraph, there is a very slight decrease in the fairness ratio by only 5% and 15% for the two deployment scenarios respectively. These results give a conclusion that the two calculated optimal SFR interior radii of 76% and 65% of cell radius can provide a good performance for both throughput and fairness.

We finalize with a comparison of SINR map distribution in figure 6.14 between the Reuse-1 scheme with 60 active femtocells deployed and the proposed SFR scheme with
also 60 active femtocells deployed and using the calculated optimal SFR interior radius. Figure 6.14(a) shows that the Reuse-1 scheme suffers from coverage holes at the edge regions of both macrocells and femtocells besides coverage holes due to overlapping femtocell coverage regions. Figure 6.14(b) shows that the proposed SFR scheme with optimized interior radius has solved the problem of coverage holes at edge regions of both macrocells and femtocells. The problem of coverage holes due to neighbor femtocells still exists. However, it can be alleviated by deploying inter-femto interference (IFI) mitigation schemes.
Figure 6.14: Macro-Femto SINR coverage map for Reuse-1 and SFR scheme with optimized interior radius (60 deployed femtocells)
CHAPTER 7

CONCLUSION & FUTURE WORK

In this chapter we summarize the concluding remarks of our research work in this thesis and the future work to be done.

7.1 Conclusion

This thesis addressed a very important research topic which is interference management in LTE femtocell networks. The importance of this research work comes from the importance of the femtocell technology itself as it is expected to be a very crucial part of the network topology of modern mobile cellular networks such as LTE-Advanced. A brief overview of the femtocell technology and femtocell network architecture was provided in this thesis work. Wide deployment of femtocells will not be available until the severe problem of mutual interference between the macrocell layer and femtocell layer is well managed.

The interference problem addressed by our research work has been defined and interference scenarios have been analyzed into two main categories; cross-layer interference and co-layer interference. The focus of this research work was oriented to the first type which is cross-layer interference. A survey has been done on some of the pre-prosed interference management techniques in the literature used for OFDMA femtocell networks. We analyzed these schemes based on type of interference addressing, complexity, efficiency, coordination required and transmission mode. We came to a conclusion that interference management schemes based on efficient frequency allocation techniques especially those exploiting the
concept of *Fractional Frequency Reuse (FFR)* can be the best choice for interference management process.

We built our own system model by modifying the *Vienna LTE Simulator* to accept the presence of the new network element which is the femtocell. We used the standardized parameters for LTE cellular system, macro BS, femto BS, MUEs and FUEs. We provided a mathematical analysis for both MUEs and FUEs performance in the network based on SINR analysis and users capacity analysis.

We then proposed some frequency allocation schemes used for allocating resources for both macrocells and femtocell to allow coexistence of both networks and minimize interference as much as possible. These allocation schemes exploit some of the well-know allocation schemes used for macrocell operation such as Reuse-1, Reuse-3, SFR, PFR and SFFR schemes. The main advantages of theses proposed schemes are being very simple for practical implantation and nonnecessity of coordination between the two network types. We evaluated the different proposed schemes via different metrics such as throughput performance, coverage performance, QoS performance and fairness performance.

Simulation results showed that Reuse-1 scheme degrades network performance in terms of coverage, QoS and fairness especially for large number of deployed femtocells. Reuse-3 scheme is the best in terms of coverage, QoS and fairness, but throughput performance is very poor due to poor spectral efficiency. PFR scheme is very good in terms of coverage and provided acceptable performance levels in terms of QoS and fairness. Similar to Reuse-3 scheme, PFR provided very poor performance level in terms of throughput due to poor spectral efficiency. SFFR scheme increased spectral efficiency rather than PFR scheme and hence higher throughput performance but lower performance in terms of coverage and fairness. SFR scheme increased spectral efficiency and hence provided very high throughput performance that exceeded Reuse-1 in dense deployment of femtocells. It also provided very good performance level in terms of fairness and acceptable levels in terms of coverage and QoS. Thus we concluded that SFR scheme can be the best tradeoff among different proposed schemes via different evaluation metrics. We also optimized SFR interior radius using ex-
haustive search for both optimal throughput and fairness performance for two deployment scenarios. The two calculated SFR interior radii have been found to be the optimal in terms of throughput and fairness. They also preserved the good coverage performance obtained by the SFR scheme.

7.2 Future Work

A number of items have been proposed as a future work to complete the investigation of this important research work as follows.

- Evaluating the system via other important metrics such as total system throughput and packet latency.
- Investigating the impact of changing traffic type and load size on network performance.
- Investigating the impact of using famous types of scheduling algorithms such as round robin, proportional fair, max CQI,...etc.
- Implementing new scheduling algorithms and evaluating them in our cellular system model.
- Investigating the co-layer interference problem or so called inter-femto interference (IFI) problem especially by management schemes depending on femto power control.
- Combining co-layer interference management schemes and cross-layer interference management schemes and evaluating the whole network performance.
- Studying dynamic FFR schemes and proposing new allocation schemes based on dynamic FFR as it is very crucial in some deployment scenarios.
REFERENCES


