Harmonized co-existence with robust interference management in femto-macro cellular architectures

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TECHNOLOGICAL
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**Harmonized Co-existence with Robust
Interference Management in Femto-Macro
Cellular Architectures**

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School of Computer Engineering

2014

HARMONIZED CO-EXISTENCE WITH ROBUST INTERFERENCE MANAGEMENT IN FEMTO- MACRO CELLULAR ARCHITECTURES

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School of Computer Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2014

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research done by me and has not been submitted for a higher degree to any other University or Institute.

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Date

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Ponnu Jacob

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List of Abbreviations

3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
BS	Base Station
CAC	Call Admission Control
CAPEX	Capital Expenditure
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
CPCFA	Cross-Polarized Complementary Frequency Allocation
CPWA	Cross Polarized Wireless Access
DAE	Distributed Antenna Element
DAS	Distributed Antenna System
FCRA	Femtocell Cluster-Based Resource Allocation
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FemtoBS/FBS	Femtocell Base Station
FemtoUE/FUE	Femtocell User Equipment
FFR	Fractional Frequency Reuse
FRF	Frequency Reuse Factor
HetNets	Heterogeneous Networks
ICT	Information and Communication Technology
IMT	International Mobile Telecommunications
LAN	Local Area Network
LHCP	Left Hand Circular Polarization
LTE	Long Term Evolution
MacroBS/MBS	Macrocell Base Station
MacroUE/MUE	Macrocell User Equipment
NACK	Negative Acknowledgement
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PPP	Poisson Point Process
RF	Radio Frequency
RFA	Reverse Frequency Allocation

RHCP	Right Hand Circular Polarization
RNC	Radio Network Controller
RRC	Radio Resource Control
SFA/SFR	Soft Frequency Allocation/ Soft Frequency Reuse
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
UE	User Equipment
UMA	Unlicensed Mobile Access
VoIP	Voice over Internet Protocol
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
XPD	Cross Polarization Discrimination

Abstract

Today's wireless communication systems are driven by the need for ubiquitous wireless services at high capacity. This has led to the search for a promising solution to provide better user experience by offloading traffic through a supplemental infrastructure to augment the macrocellular network. These growing demands are driving them to use smaller cell sizes to offer better service to higher number of users. Bringing the network closer to the user by reducing the radio transmission range through small cells assures a significant leap in system performance via higher data rates and extended battery life. The HetNets that incorporate different kinds of small cells such as micro, pico, femto, metro cells, relays, and others, all integrated with Wi-Fi, are instrumental in meeting this anticipated performance enhancements.

Considering these deployments, the concept of end-user installed femtocell has become a hot topic since it is the most economical solution with lower upfront costs that assures high quality indoor coverage to home users, while backhauling their traffic over the IP network. If the indoor traffic can be routed into the cellular network using a femtocell base station, the connected users will experience an increase in capacity along with ubiquitous coverage while macrocell base station resources might be spared. This in turn implies a reduction in network maintenance and deployment cost for the operator. At the same time, the key technical challenge of managing inter-tier radio interference inherent in the femto-macro network grabs significant attention. It urges the researchers to devise a viable alternative to support the spectrum sharing strategy in the current deployment in an effective manner.

Keeping these challenges in mind, the main focus of this thesis is on developing advanced co-existence techniques that support inter-cell cooperation and decentralized interference management in two-tier femto-macro network. It aims at devising solutions that can diminish the interference, enhance the system capacity and at the same time encourage mutually beneficial co-existence with the current cellular architectures.

The first contribution mainly aims at improving the current cellular framework in terms of capacity, coverage and dead-zone reduction without bringing in prominent changes in the network architecture. Hence, it introduces the concept of *Femto-Relays* which proposes the coverage extension of existing femtocell network even beyond the home environment through relaying, which not only reduces the load on the macrocell network but also proves to limit the interference significantly. The idea involves the exploitation of under-utilized femtocells to serve high data rate requests of many macrocell user equipments and reduce the probability of their outage with significant energy savings.

Relaying, however demands more operational spectrum which points towards the need for devising a superior inter-tier spectrum sharing strategy resulting in the second contribution - *Reverse Frequency Allocation (RFA)*. RFA is proposed as a key solution to mitigate the cross-tier interference and at the same time enhancing the spectral efficiency and coverage probability by reversing the uplink and downlink transmission frequencies between the femto-macro networks.

Interference mitigation accomplished through incorporation of orthogonal transmission in wireless cellular networks is not a novel idea. However, independent operation of two-tier networks can be facilitated through orthogonal polarized transmission which results in the third contribution aimed at alleviating cross-tier interference in a two-tier femto-macro network. *Orthogonal Polarized Transmission* can be adopted as an effective method to assure network isolation by permitting femtocell network to transmit along right hand circular polarization and macrocell network to transmit along left hand circular polarization, which control interference and thereby enhance the system performance.

Fourth and the last, the much-expected futuristic scenario of *Self-Organized Femtocells* is considered, where each femtocell is expected to be intelligent enough to autonomously integrate into the radio access network without causing any impact on its immediate cellular neighborhood. Hence each femtocell is embedded with a cognitive capability by means of a radio resource allocation algorithm called *Cross-Polarized Complementary Frequency Allocation strategy (CPCFA)* which enables it to select its own operational frequency. Here it exploits both frequency and polarization diversity by incorporating reverse frequency allocation within an orthogonally polarized transmission network to maintain its interference to the macrocell user under a pre-determined threshold.

To summarize, the goal of this thesis is to inspire and motivate the use of advanced co-existence techniques coupled with efficient interference management solutions requiring minimal network overhead in ongoing and future deployment of tiered cellular architectures. It addresses key technical challenges inherent in a femtocell-aided cellular network, with focus on managing radio interference and providing reliable coverage at either tier, for different physical layer technologies.

*Dedicated to GOD Almighty
and
my beloved ones.*

Chapter 1

Introduction

*To raise new questions, new possibilities, to regard old problems from a new angle,
requires creative imagination and marks real advance in science.*

-Albert Einstein

1.1 Overview

The history of wireless communication can be dated back to the pre-industrial age when information was transmitted using smoke, torch signaling, mirror flashing, signal flares etc. Later on, a handful of signal combinations were developed to transmit complex messages using these elementary signals. This mode of communication was further replaced in the 1890s by telegraph and then by telephone. It was in 1895, that Guglielmo Marconi demonstrated the first radio transmission from the Isle of Wight to a tugboat which marked the birth of radio communication. Radio technology rapidly evolved ever since with astonishing pace to enable economically feasible long distance transmissions with better quality and lower power [1]. This included the introduction of wired Ethernet technology in 1970 followed by the development of wireless LANs in 1985. However, by far the most successful and revolutionary invention with the wireless technology was the cellular telephone system, the history of which dates back to 1915 when the first voice transmission was established between New York and San Francisco. Even though, it paved way to the establishment of a number of public telephone booths, the inefficient use of the scarce spectrum and the state-of art radio technology limited the system capacity. It was later in the 50's and 60's that the researchers in AT & T and Bell Laboratories developed the cellular concept as a potential solution to this capacity crunch problem [2].

Cellular system operation is based on the fact that the attenuation of transmit power with distance enables spectrum reuse in cells with spatial separation. This helped in accommodating more users since the cells could effectively reuse the frequency spectrum with minimum interference. The tremendous growth of the cellular industry resulted in explosive demands from the users, which further caused the shift from analog technology to digital communication better known as the second

generation (2G) of cellular systems. This migration in technology was driven by its higher capacity, affordable cost, tremendous speed and improved power efficiency of digital hardware. The prodigious market potential for 2G systems was accepted globally when it evolved to support data services in addition to the voice services. This ultimately paved way for extensive proliferation of services like email, internet access and VoIP which unified onto a single computing platform among the users. It necessitated the initiation of third generation (3G) services in data dongles, tablet computers with 3G radio modules, smart phone etc. and accelerated social change. The aforementioned rapid evolution and technological convergence in the field of wireless communication resulted in unrelenting demand for better quality of service (QoS) which ultimately triggered the researchers to design and develop newer and advanced cellular standards such as WiMAX- (IEEE 802.16e), the 3GPP's High Speed Packet Access (HSPA) and Long Term Evolution (LTE) standards, and 3GPP2's Evolution Data Optimized (EVDO) standard. With 1G, 2G and 3G operating on FDMA, TDMA and CDMA respectively, the fourth generation (4G) communication system evolved with OFDMA as the physical layer technology. The specific aim of OFDMA was to improve the 3Cs of communication namely cost, capacity and coverage, i.e. to offer better coverage with higher capacity at lower cost. OFDMA guarantees this by exploiting frequency diversity along with multi-user diversity [3].

As network operators are determined to satisfy the exponentially rising data rate demands, new network paradigms are sought to enhance spectrum reuse and scale additional capacity in an economically viable fashion. Indeed, the growth in wireless capacity is exemplified by the observation from Martin Cooper of Arraycomm: "The wireless capacity has doubled every 30 months over the last 104 years". This translates into an approximately million-fold capacity enhancement since 1957 [4]. This capacity explosion is apparently the contribution from wider spectrum (25x), spectrum slicing (5x), advanced modulation techniques (5x) and finally network densification by reducing the size of cells-small cells (1600x). The colossal gains earned from smaller cell sizes arise from efficient spatial reuse of spectrum, or alternatively, a higher area spectral efficiency [3, 4]. In addition to this, studies on wireless usage highlights that more than 50% of all voice calls and more than 70% of data traffic originates indoors [5]. While voice calls are engineered to tolerate low signal quality, data networks require much higher signal quality in order to satisfy the multi-Mbps data demands of the users. For indoor devices, particularly at higher carrier frequencies likely to be deployed in many wireless broadband systems, high signal quality and high data rates are difficult to be accomplished due to attenuation losses. Poor signal strength in the indoor environment results in customer discontent which will encourage them to either switch operators or maintain a separate wired connection whenever indoors. It was to address these

challenges that the concept of compact self-optimizing home cell-site was proposed in 1999 by Alcatel which aimed at combining fixed-line broadband access with cellular telephony [6]. The system model was re-designed and made use of the Cordless Telephony Standard. Although demonstration models were assembled and proven to operate through a standard POTS phone line, the enormous equipment expense was far too high to make it commercially viable. The focus then shifted to the unlicensed mobile access (UMA) standard which functioned on Wi-Fi access points with a UMA capable handset and a UMA network controller (UNC) to connect into the mobile operator's core network. During this period, the market dominating network operators used the built-in Wi-Fi functionality in a variety of handsets to offer low cost long-distance calls over Wi-Fi and VoIP. These schemes were mainly targeted at saving call charges, especially when roaming abroad, than addressing coverage or capacity issues. Various research projects continued to focus on home cell-site concept, with Motorola engineers in Swindon claiming to have built the first complete 3G home base station in 2002 [7]. Around 2005, the term *femtocell* was adopted for a standalone, self-configuring home base station. Later in 2007, a non-profit membership organization named *Femto Forum* was formed by different vendors, operators and research organizations with the aim to promote the standardization and large scale deployment of femtocells around the world [7].

1.1.1 The Femtocell Concept

Figure 1.1: Typical femtocell deployment scenario [8]

Femtocells, also known as femtoBS are short range, low power access points (APs) that provide a cost effective means of achieving ubiquitous indoor connectivity along with quality data reception.

As evident from Figure 1.1, they are ‘plug and play devices’ installed by the end-users to communicate with the network over a broadband connection such as Digital Subscriber Line (DSL), cable modem or an independent wireless backhaul. They use the same physical layer technology as the cellular networks and hence eliminate the need for a separate user equipment (UE). Femtocell, by virtue of its revolutionizing concepts of small size, low cost and high performance is a potential paradigm shift in radio access technology in cellular networks. Their small size implies that the achievable spectrum efficiency is much greater than that of macrocells while their low cost explains that they rely on the same network resources and data transport infrastructure as that of the classical cellular network. This significantly reduces capital expenditure (CAPEX) and operational expenditure (OPEX) of the network operator in terms of macro cell site installation and new spectrum acquisition [8]. Their high performance translates to minimal coordination with macrocell network and almost-zero loss to the end-user, in many cases owing to the improved link budget and services [4]. Due to the short transmitter-receiver separation, femtocells rely on lower transmit power and assure prolong handset battery life along with higher signal-to-interference-plus-noise ratio (SINR). Thus femtocells are capable of solving the existing problems of indoor coverage, better quality reception, higher data-rate, greater spectral efficiency, attractive services and affordable pricing options. However, unlike the planned macrocell network, femtocell deployments are ad-hoc and unplanned, which brings along with it a baggage of several key challenges that needs to be cleverly addressed so as to enable a mutually beneficial femto-macro co-existence [9].

1.2 Motivation and Objectives

Classical cellular systems employ network planning, transmit power control, spatially separated frequency reuse etc. to ensure interference free operation. The placement, configuration and operation of classical networks are meticulously planned and optimized with the help of simulation tools and measurement reports derived from drive testing. However, femtocell being a ‘plug and play device’ is deployed within the macrocell in an ad-hoc fashion and can be randomly moved from one place to other. This makes the conventional mode of testing commercially not feasible. In addition, the unplanned deployment of femtocells in the network is steadily increasing on a day-to-day basis. This demands the need for a different deployment methodology and network adaptive operation especially with self-configuration and self-optimization capabilities [10].

Even though the network densification through femtocells has benefits in terms of capacity, coverage and QoS [11], it also brings forth potential problems and new design challenges [12, 13]. Primarily, this ultra-dense femtocell network is not utilized to its fullest potential, resulting in chances for excess power consumption, unwanted spectrum occupancy and network interference.

Secondarily, the frequency allocation and access strategies has an inevitable impact on the legacy macrocell network. The femtocell users occupy the same radio spectrum as that of the macrocells which enables smooth transition of the user from one tier to the other. Though commercially viable, this frequency reuse in the co-existing femto-macro network which increases the spectral efficiency, results in heavy cross-tier interference that degrades the performance of both tiers. Due to these potential challenges, it is imperative for the network operator to focus on the optimal usage of the deployed femtocells along with appropriate mitigation and control of interference to enhance the system performance. However, interference management in co-existing femto-macro architecture has bottlenecks arising from lack of coordination between the macrocell base station (macroBS) and femtocell base station (femtoBS) mainly due to issues in security, scalability, and limited availability of backhaul bandwidth [14], which prohibit the network operators from exploiting the full potential of femtocells. Also, it results in a complex problem for the network operator to manage the radio resources dynamically by meeting the demands of both the tiers. Evidently, dedicated spectrum usage supports interference free co-existence, but is less efficient and overpriced owing to the uneconomical pricing of the radio spectrum. Similarly, shared spectrum usage with frequency reuse permits spectrally efficient operation but demands public access and poses interference threats to the macrocell network. Partially shared spectrum usage is proposed as a solution to overcome these shortcomings. It can solve the aforementioned problems to a great extent by allowing the femtocells to have restricted access on the macrocell spectrum, but it questions the spectral efficiency of the system. It is to solve this problem of efficient spectrum usage that pragmatic solutions need to be formulated to fully exploit the profits of spectrum allocation strategies and limit their impact on the legacy macrocell network.

The motivation of this thesis is to propose potential solutions to optimize the utilization of femtocell network and at the same time minimize its performance degrading impact on the existing macrocell network. It aims at devising decentralized radio interference management strategies to regulate the cross-tier interference and promote the harmonious co-existence of femto-macro network to enhance the overall system performance. With growing femtocell density in the network, the solutions devised should assist smooth integration of the femtocells into the macrocell network with minimal signaling overhead and system impact. In fact, it should be the foremost obligation of the network operator to ensure that the macrocell users are unaffected by the underlay femtocell network so that their desired QoS is always met despite the interference from neighboring entities and that the additional complexity brought in by the introduction of femtocells should not overshoot the benefits reaped from the same. The macrocell network being modelled as the primary infrastructure with “anytime anywhere access” even for users without hotspot access should be

guaranteed preference in all network operations. The reason being the large volume of subscribers served by the macrocell in comparison to femtocells which are deployed for their selfish motives. Also, it must be ensured that the femtocells should aid in enhancing the macrocell performance by offloading the macrocell traffic wherever possible, offering access to macrocell users in regions of limited coverage, and above all enable the users to achieve their target QoS by assuring minimal impact due to femtocell co-existence.

Due to reasons of scalability, limited backhaul availability, bandwidth restrictions and increasing deployment of small cells, the macroBS and femtoBS may not be able to coordinate their transmissions (for example, using a centralized scheduler or centralized power assignments to users) for minimizing cross-tier interference. The implication is that the macroBS and femtoBS should not only provide reliable coverage to their own users, but ensure that they do not cause intolerable interference to users in the other tier in a distributed fashion. By distributed, we mean that there is only the indispensable signaling exchange between the macroBS and femtoBSs or between femtoBSs to minimize complexity due to additional signaling overheads. This motivates employing decentralized interference management schemes, which is the main focus of this thesis for ensuring better performance at both tiers.

1.3 Thesis Statement

The main focus of this thesis is to highlight the fact that, densification of macrocell network with femtocells without addressing the challenges of spectrum allocation, interference management and optimal utilization will likely be self-defeating due to the additional complexities that may override its benefits. Keeping these factors in mind, this dissertation deals with developing methods that support inter-cell cooperation and decentralized radio interference management in two-tier femto-macro network. It aims at addressing these challenges through a combination of solutions that can minimize the interference, enhance the system capacity and at the same time encourage a harmonious co-existence of the current cellular architectures. Although, downlink communication is the main focus of this thesis, channel reciprocity makes the downlink methodologies applicable to the uplink case to a great extent.

1.4 Contributions

With the demand for mobile broadband growing at an exponential rate, network operators are compelled to increase network capacity and coverage through low-cost home base stations like femtocells. The current wireless operation has reached a stage with one femtocell in each home. However, the utility factor of these femtocells are not fully exploited since a large portion of them

remains under-utilized for a long period of time. Since bandwidth under-utilization is equivalent to bandwidth wasted, this thesis aims at using the idle femtocells to offload the macrocell traffic and at the same time offer better QoS to the macrocell users. The concept of relaying through femtocell users is explored for this purpose which enables the macrocell user equipment (macroUE) to determine a potential *femto-relay* capable of serving its requests. While the model initially relies on macroUE to initiate the relay request, the challenge of limited battery life for the UE encourages to explore the possibility of femtoBS broadcasting its availability to the nearby network entities. This has led to the development of energy efficient self-organizing femto-relay framework.

Although the theory of relaying contribute towards conservation of power and enhancement of capacity, it demands frequency resources for transmission along short hops. This has led towards the investigation of spectrum allocation strategies in two-tier femto-macro networks. Limited availability of the heavily priced spectrum prohibits the use of dedicated frequency resources for each tier. Even though frequency reuse with spatial separation helps in accommodating more users, it limits the spectral efficiency to a larger extent. It is to address this bottleneck in the spectrum allocation strategy that the *reverse frequency allocation* methodology is explored in this thesis. Reverse frequency allocation aims at achieving unity frequency reuse factor in each cell along each tier. In fact it doubles the spectral efficiency by re-allocating the uplink and downlink frequencies of macrocell network to the femtocells by reversing the direction of their transmission.

Improving the spectral efficiency helps in enhancing the system performance, however, restraining the cross tier interference appears to be indispensable to achieve better capacity. This steered towards investigating the possibility of isolating the network tiers through *cross-polarized transmission*. Even though the use of cross polarized transmission for satellite communication dates back to the 20th century, its application in multi-cellular network is quite novel mainly due the challenges involved in non-line of sight transmission. This thesis evaluates the application of orthogonally polarized transmission for enhancing the SINR in multi-tier cellular networks and projects the significant performance improvement that is achieved through it, via multi-cell system level simulation and mathematical analysis.

The aforementioned strategies unquestionably demonstrated noteworthy enhancement in the multi-tier network performance. However, the practical feasibility of integrating these technologies into the state-of-art cellular architecture may be questionable. This pushed forward the need to come up with the most embraced futuristic scenario of self-organized femtocell network with cognitive capabilities that could respond intelligently to the unpredictable situations. Hence, each femtocell is embedded with a pre-programmed intelligence by means of a radio resource allocation algorithm called *Cross-Polarized Complementary Frequency Allocation strategy* (CPCFA) which enables it

to dynamically choose its own operational frequency without causing any network imbalances. Here it exploits both frequency and polarization diversity by incorporating reverse frequency allocation within an orthogonally polarized transmission network to maintain its interference to the macrocell user under a pre-determined threshold.

The solutions proposed in this thesis will allow for a smooth integration of femtocells into the legacy macrocell network with demand driven control over spectrum allocation process, leading to an increased overall network capacity as well as a fairer distribution of capacity. In contrast to the unmanaged situation, a minimum acceptable performance can be offered by each femtocell through the self-organizing self-selection capabilities embedded within them. In essence, these solutions ensure a seamless interaction between large number of femtocells within a macrocell coverage area without significant service disruptions.

1.5 Organization of the Thesis

To facilitate a coherent understanding of the concepts presented, the thesis is structured as follows:

Chapter 1 is an introduction discussing how femtocells evolved to occupy a significant part in the history of present and future wireless communication systems. It also enlightens on how the network operator is still obligated to enhance the performance of the classical cellular network and hence the need for basic technical challenges to be addressed while introducing femtocells into this legacy macrocell network.

Chapter 2 aims to highlight the fundamental background on the development of this thesis by evaluating the progressive evolution of heterogeneous networks and contextualizing the research till date in promoting a harmonious coexistence of multi-tier femto-macro networks. It also includes a discussion of the state-of-art and the positioning of this work in relation to the existing research, related problems and possible solutions.

Thereafter, the technical contributions of this dissertation are covered in Chapters 3 through 6. *Chapter 3* introduces the concept of Femto-relays as a means of coverage extension and capacity enhancement through interference mitigation. It emphasises how femtocell user equipments (femtoUEs) can be used as relays to serve the macroUE data requests through which the network interference can be controlled and the macrocell traffic can be offloaded. Finally it is extended as an energy efficient self-organizing framework where the femtoBS notifies the macroUEs regarding its interest in serving the data-requests and get rewarded for the same.

It is in *Chapter 4* that the concept of Reverse Frequency Allocation for femtocells is proposed as a means to improve the spectral efficiency of the system without seizing the macrocell radio

spectrum. The proposed scheme better balances the requirements of greater inter-cell orthogonality and reduced inter-cell interference by reversing the frequency spectrum allocation between the femtocells and macrocells. It also assures a reasonably high spectral efficiency and the well-known benefit of reduced outage probability throughout the network, especially for the cell-edge users. This work analytically quantifies and assesses the impact through simulation results which guarantee greater overall network throughput in the downlink and lower co-channel interference irrespective of the distance of the femtocell from the macrocell base station.

Chapter 5 discusses the possibility of applying orthogonally polarized signals in either tier of the femto-macro network to ensure isolation, minimize interference and hence enhance the capacity. It investigates a scenario where femtocell network makes use of right hand circular polarization (RHCP) and macrocell network makes use of left hand circular polarization (LHCP) for simultaneous transmissions even when using the same frequency spectrum. The practical feasibility of this system is also evaluated and theoretical analysis to the simulated results are provided.

Chapter 6 finally explores the benefits of simultaneously exploiting frequency diversity along with polarization diversity through Complementary Frequency Allocation in Cross-Polarized femto-macro network. It is analysed as a potential solution for maximizing spectral efficiency and minimizing interference in the existing heterogeneous networks. The results of analytical and simulation studies furnish a proof for an easily implementable and remarkable opportunity in the context of two-tier femto-macro network that can substantially increase the system capacity as well as cell coverage without additional network complexities.

Chapter 7 summarizes the major contributions of the work, and also recommends future research directions and still-to-be explored impact areas.

Chapter 2

Co-existence of Femtocells in Macrocell Network-A Roadmap

Learn from yesterday, live for today, hope for tomorrow.

The only important thing is not to stop questioning

-Albert Einstein

This chapter gives an overview of femtocells along with their potential benefits and architecture, and explains in detail the state-of-art research developments to promote constructive co-existence of femto-macro networks. In addition to this, it examines key challenges encountered in the practical deployment of femtocells within the macrocell network with specific attention on multi-tier interference in spectrum allocation strategies and the potential solutions proposed for the same. Finally, it reviews the significant interference management techniques envisaged till date for the holistic performance enhancement of femto-macro networks.

2.1 Femtocell Architecture

Unlike the classical single-tier planned cellular architectures with a centralized-controller, femtocell networks rely on an additional underlay tier with different operational parameters, without a centralized controller. Figure 2.1 represents the LTE femto-macro network architecture in which multiple femtoUEs are attached to the femtoBS, which are in turn connected to the mobile core network (MCN) through a controller known as Femto-Gateway (FGW) [15]. FGW is a network entity, which acts as an access router that aggregates traffic from a large number of femtoBSs via the Security Gateway (Se-GW) and manages the signaling and data connections along with global information of femto-interference for femtoUEs attached to its access points [16]. It also provides the interface scalability and acts as the concentrator for the control plane [17]. The macroUEs on the other hand are connected to the core network via its own Serving Gateway (SGW), which controls the macroBSs attached to it. The SGW supports user data and provides routing and

forwarding functionality between macroBS or femtoBS and the Packet Data Network (PDN). It also acts as the mobility anchor during handovers between LTE and other 3GPP systems [18]. All base stations-macroBS and femtoBS connect to the MCN and the PDN through the respective gateways for control signaling. The Mobility Management Entity (MME) connected to these gateways is the key control node for LTE access network. It delivers the control plane functionality, which takes care of the seamless mobility between LTE and other access networks, and is responsible for choosing and authenticating the right SGW for a UE. Both FGW and SGW are connected to the MME as well as the MCN via bi-tunnel.

Figure 2.1: Co-existing LTE femtocell-macrocell network architecture

Femtocells have emerged as the most promising solution to offer high capacity wireless link with the following benefits [4-7]:

- *Fast data with high call quality*

The improved coverage enables femtoUEs to work at the peak of their capability enabling them to achieve the highest possible data rates and call quality. This permits the customers to make better use of their phones and other mobile enabled devices, especially to depend on them for the most important business related calls and rely on them as their primary personal entertainment and network connectivity device.

- *Power saving*

With an upsurge in number of mobile users, there is a huge load on the macrocells. So, the deployment of femtocell can cause a significant portion of the macrocell traffic to be diverted to them, thereby reducing the load on the macrocells. This helps in establishing an effective network equilibrium, with the end users efficiently utilizing macrocells when they are outdoors and femtocells when they are indoors. The coverage of femtocells is restricted to a smaller area, which falls within the limits of a home environment or an office. The limited radio transmission range of femtocells lead to lower power consumption and higher received signal strength. Also, the mobile phone associated with a femtoBS, experience increase in battery life when compared to that connected to a macroBS due to lower transmit power requirement.

- *Unlimited data service and femtozone call tariffs*

Network operators are likely to offer better quality data services on femtocells, which have comparatively higher usage limits or are even uncapped, at a subsidized rate, thereby, enabling customers to use these services without anxiety of associated charges. This will also encourage the customers to overcome their initial barrier towards network access and ultimately adopt these services even beyond the home environment. Some femtocell operators even offer special tariffs for calls made or received on the femtocell, including a lower rate and a hefty bundle of minutes per month compared to the fixed-line rates. A wide range of tailored pricing options are also possible, differentiated based on the type of user, time of utilization, call destination and other such dimensions. Some of these benefits may also be available to users when granted access to femtocells from the same operator in their friends' or colleagues' homes.

- *Easy Installation and Simplicity of Operation*

It is essential for femtocells to possess simple installation, configuration and operation techniques. No special expertise is required and it delivers service with an absolute minimum intervention by the customer. There is no requirement for special security settings or to access any device (e.g. a computer) other than the femtocell and the customer's mobile device. This 'zero-touch' facet of femtocells is vital for any femtocell deployment. During the 10-minute configuration period, the femtocell is engaged in some very sophisticated activities, including:

- Contacting the mobile network and establishing a secure, fully encrypted communication tunnel.

- Mutually authenticating with the network and establishing the user's credentials, service options and location.
- Sensing the surrounding radio environment and configuring itself to operate within parameters set by the operator so as to deliver good quality service with minimal interference.
- *Seamless handover*
Mobile phones associated with the femtocell automatically switch to the femtocell from the macrocell upon arrival into their home environment.

2.2 Relevant Channel Models

It has been widely accepted that the performance of the wireless communication system is greatly influenced by the characteristics like increased data rate, bandwidth, mobility, adaptivity, QoS, etc. These have an obvious impact on the system performance and complexity of future broadband systems. As a result, the radio channel models chosen for the simulation purpose is expected to be more versatile and accurate. Keeping this in mind, the Wireless World Initiative New Radio (WINNER) II channel model [19] considered in the forthcoming analysis corresponds to a combination of path-loss and log-normal shadowing within a ubiquitous radio access system adaptable to a comprehensive range of mobile communication scenarios from short range to wide area. This channel model follows a geometry-based stochastic channel modelling approach, for link level and system level simulations of local area, metropolitan area, and wide area wireless communication systems. The radio interface optimises the use of spectral resources (e.g. through the exploitation of actual channel conditions and multiple antenna technology) and supports challenging requirements of systems beyond 3G. It is scalable in terms of carrier bandwidth and carrier frequency range and covers propagation scenarios like indoor office, large indoor hall, indoor-to-outdoor, urban micro-cell, bad urban micro-cell, outdoor-to-indoor, stationary feeder, suburban macro-cell, urban macro-cell, rural macro-cell, and rural moving networks. Taking into consideration all these factors, the WINNER II model establishes its appropriateness for indoor and outdoor multi-tier femto-macro systems. The path loss models are typically of the form:

$$L = A \log_{10}(d) + B + C \log_{10}\left(\frac{f_c}{5.0}\right) + X \quad (2.1)$$

where d is the distance between the transmitter and the receiver in meters, f_c is the system frequency in [GHz], the fitting parameter A includes the path-loss exponent, parameter B is the intercept, parameter C describes the path loss frequency dependence, and X is an optional, environment-specific term (e.g., wall attenuation scenario). For indoor environment the constants are defined as

$A=36.8$, $B= 43.8$, $C=20$ and $X= 5(n_w-1)$ where n_w is the number of walls between the UE and BS [19].

Assuming f_c to be 2.5 GHz and $n_w = 1$, the corresponding indoor path loss is given by:

$$L_{in}(d) = 36.8 \log_{10}(d) + 37.8 \quad (2.2)$$

For outdoor environment, the path loss is given by:

$$L_{out}(d) = (44.9 - 6.55 \log_{10}(h_{BS})) \log_{10}(d) + 31.46 + 5.83 \log_{10}(h_{MS}) + 23 \log_{10}\left(\frac{f_c}{5.0}\right) \quad (2.3)$$

where h_{BS} is the height of the base station antenna and h_{MS} is the height of the mobile station antenna.

Taking $h_{BS} = 25\text{m}$, $h_{MS} = 1.5\text{m}$ and f_c to be 2.5 GHz:

$$L_{out}(d) = 35.74 \log_{10}(d) + 35.68 \quad (2.4)$$

The interference between femtoBS and macroUE is analyzed using Indoor-to-Outdoor (L_{in_out}) and Outdoor-to-Indoor (L_{out_in}) Path loss models given by:

$$L_{in_out}(d_{out}, d_{in}) = L_{out}(d_{out} + d_{in}) + 14 + 15 (1 - \cos(\theta))^2 + 0.5 d_{in} \quad (2.5)$$

$$L_{out_in}(d_{out}, d_{in}) = L_{out}(d_{out} + d_{in}) + 13.8 + 0.5 d_{in} \quad (2.6)$$

where d_{out} is the distance between the outdoor terminal and the wall that is nearest to the indoor terminal, d_{in} is the distance from the wall to the indoor terminal, θ is the angle between the outdoor path and the normal on the wall. In the simulation we assume θ to be zero.

In addition to the path loss models described above we have also included Rayleigh fading and shadowing in the transmission paths. Outdoor and indoor shadowing was also considered to obtain realistic results.

2.3 Challenges Faced by Co-existing Femto-macro Networks

The integration of femtocells into the meticulously planned macrocell network introduces several bottlenecks into the system like unplanned network management and radio access issues, which needs to be rightly addressed. The former category explores and analyzes the traffic load balancing problems between the macrocell and femtocell tiers [20, 21], the mobility management issues [22, 23], or the backhaul congestion management techniques [24, 25]. The latter class, on the other hand, investigates and addresses the core technical challenges of the physical and the medium access control layers, such as radio resource management and interference mitigation. In this thesis,

we deal with the latter class of problems, while we direct the interested reader to refer [26-28] for additional details on infrastructure related aspects.

From this standpoint, it must be noted that the topology of femtocell networks significantly differs from classical macrocell architecture. Since the femtoBSs can be installed any-time anywhere by the subscribers, the positioning of the femtoBS is random with several coverage overlaps. In addition, femtoBSs based on the link connectivity may resort to different modes of backhaul operation (wired or wireless), resulting in unpredictable delays on the control plane. Finally, the colossal increase in femtoBS population within the macrocell coverage area will render the centralized coordination mechanisms almost impossible, especially in a multi-operator environment. As a result, the arbitrariness of femtocell deployments and their uncoordinated nature intensifies the complexity of optimization procedures involving network integration and coverage [29, 30], interference management [31-33] and radio resource efficiency [34, 35].

In the context of harmonious co-existence of femto-macro network, one can identify three main open issues: offloading the macrocell load by optimizing femtocell usage, enhancing spectral efficiency with minimized interference, boosting network performance through cognitive, self-organization capabilities. The following sections discuss each of these aspects in detail.

2.3.1 Offloading the Macrocell Load by Optimizing Femtocell Usage

With fourth-generation wireless technologies introducing a new dimension in our life, the next-generation mobile communication systems are well geared to lead the technology march. Today's society is driven by ever-growing data demands stemming from the rapid proliferation of smart phones, laptops, tablet PCs and other in-built cellular access systems, which trigger the instant need for ubiquitous and very high speed wireless communication networks. Hence, confronting the new technologies is the challenge of providing flexible, reconfigurable architectures capable of catering to the dynamics of the network and at the same time facilitating the optimized usage of current cellular architectures to achieve high data rates with better energy savings. It should also enable the network providers to guarantee minimal interference to the co-existing technologies and to meet the tremendous growth in mobile traffic demand with relatively flat revenues per bit. The market is always on the look out for such technologies that can satisfy all these demands with minimal overheads whether it be in terms of money or resources.

As part of addressing these demands, various technical studies, research experiments and business models have revealed the outstanding potential of underlay networks comprising of small cells like femtocells in terms of enhancing the network performance, saving energy resources and providing benefits on a social and economic scale. Hence, the classical macrocellular networks are

currently undergoing a major restructuring, where they are forced to rely more on low-power, low cost, energy efficient, mobile underlay networks to handle a significant part of their data traffic to be in pace with their subscriber demands. The key necessitating factors for this dependence of macrocells on the femtocell network includes:

2.3.1.1 Energy Efficiency

It is quite startling that the overall energy consumed by ICT industry, which includes cellular networks, already constitutes about 2% of global carbon emissions and is predicted to shoot up further in the coming years [36]. Because of this, energy efficiency is considered as a significant parameter for designing future communication systems in this green radio environment since reduction in energy consumption of base stations and user equipment can directly translate into controlling CO₂ emission. Moreover, the increasing network operational expenses (OPEX) coupled with the spur of government led regulatory initiatives have spawned numerous research projects worldwide [37] with specific targets to drive down the energy expenditure in all aspects of cellular networks. Extensive research and surveys have estimated that a whopping 80% of the energy consumption in cellular networks arise from operations and functionality of the base stations in the radio access network (RAN) while the remaining energy is expended in the switching and core networks [38]. Collectively, these factors have heightened the necessity to focus on energy efficient resource management solutions that are capable of minimizing the energy expenditure while at the same time maintaining and enhancing the QoS assured to the subscribers.

Considering the fact that deploying more number of high power macroBSs is neither energy efficient nor economical, the only way to enable energy efficient cellular operation is to offload the traffic from a high power-consuming tier to a low-power operated tier, so as to make it commercially and technologically viable. In fact, judicious use of free and under-utilized femtocells to redirect the macroBS-macroUE transmission to the femtoBS-macroUE link will help to reduce the bandwidth utilization of macro cell network, limit the high power transmissions in the network which in turn minimizes the interference, and thereby offering better QoS to all users in either tier with minimum OPEX for the network operator. This problem to minimize the energy consumption within the cellular network while achieving the target capacity can be formulated as:

$$\begin{aligned} & \min \sum_{b \in BS} \int_t^{t+D} E_b A_b(t) dt \\ & \text{subject to } \int_t^{t+D} C_b A_b(t) dt \geq C_{min} \quad \forall b \in BS \end{aligned} \quad (2.1)$$

where BS corresponds to the set of total number of femtocell and macrocell base stations in the network, E_b correspond to the energy consumption of the base station b to achieve capacity C_b in

time t , C_{min} is the minimum guaranteed capacity of the base station by the network operator and $A_b(t)$ corresponds to the operational status of the base station given by $A_b(x) \in \{0,1\}$, $\forall x \in (t, t + D)$. This ultimately strives towards achieving better energy efficiency (EE) in the system (ie. maximizing network throughput over the energy consumption within a given period of time) whose dependence on different network parameters is represented as [214]:

$$EE \propto \frac{F(P_{mb}, P_{fb}, B, IUR, IBD)}{F(P_{mb}, P_{fb})} \quad (2.2)$$

where $P_{mb}, P_{fb}, B, IUR, ISD$ represent the macrocell transmit power, femtocell transmit power, system bandwidth, indoor user ratio and inter-base station distance respectively. The denominator term basically corresponds to the inter-cell and intra cell interference in the network which need to be minimized for better EE . In essence, it is evident from equation (2.2) that the EE of the system can be enhanced by increasing the percentage of indoor users and minimizing the interference in the network which validate the necessity of offloading the macrocell traffic to the femtocell network.

Table 2.1: Energy consumption profile of femtocells

HARDWARE COMPONENT	ENERGY CONSUMPTION (WATTS)
Microprocessor	1.7
Associated Memory	0.5
FPGA	2.0
Associated Memory	0.5
Other Circuitry	2.0
RF Transmitter	1.0
RF Receiver	0.5
RF Power Amplifier	2.0

Though the transmit power is comparatively small, femtocell deployment comes at the expense of fixed BS hardware related power consumption as given in Table 2.1. Hence, to justify the efficiency of femtocell deployment, the achieved capacity improvement must compensate for the energy loss at the femtoBS level in order to maintain a net gain over the energy efficiency. One of the earliest insights into leveraging the potential of existing cellular networks in an energy aware manner is explained in [39] where it is explored from the perspective of the BS hardware, the transmission link and the network layer. Also, there exists an optimal number of femtocells for a reference cell area that maximizes the energy efficiency beyond which, any further addition of BSs does not provide any significant capacity gain [40]. Owing to these factors, it is inefficient to promote the existence of idle femtoBSs in a multi-tier system. Hence, redistributing the macroUEs

to the idle femtoBS is also a potential solution for improving the energy efficiency of the system as a whole.

A network controlled handover strategy based on the used load factor is discussed in [41] where users are handed over from the macroBS to femtoBS to attain higher energy efficiency. Here the energy efficiency metric considers not only the energy costs attributed to transmissions but also the energy expended at the UE for network scanning and feedback. The study shows that, in environments with dense femtocell deployment, performing energy aware handover will result in most users to switch over to femtoBS, especially when the macroUEs are located far away from the macroBS. Finally, [42] analyses an energy efficient, context aware scheme, which takes into account the network conditions along with the user's QoS requirement before re-routing the macroUE to the femtoBS. Here, the multiple decisions obtained from the fuzzy logic unit (based on bandwidth, reliability, cost) are combined with the estimated energy consumed upon handover to determine the most appropriate network to be associated with. To encapsulate, handing over macroUEs to idle femtoBS with significant channel quality can assure better QoS by maintaining adequate network energy efficiency, which acts as the motivation for the present work.

2.3.1.2 Coverage Extension through Relays

The exponential increase in the number of mobile users in this high speed communication era has led to a tremendous escalation in user data traffic in the macrocell network. However, the current capacity of outdoor macrocells are not sufficient to satisfy this ever-increasing demand. In addition, capacity enhancement achieved through coverage optimization by means of adequate power control, may leave behind severe interference signature in the network. As a result, from the viewpoint of mobile network operators, traffic offloading from the macrocell network to the underlay tier is a key solution to meet the user demands. This is demonstrated in Figure 2.2. For the same reason, the implementation of cooperative techniques among various network elements consisting of either different BSs or intermediary relay stations have been demonstrated to project the tremendous improvement in cellular network's performance [43]. This has paved way towards utilizing femtoBSs to serve the data requests of the macroUEs, which helps in minimizing the load on the macrocell backhaul and offer better throughput to the macroUEs. It also strives towards minimizing the network power consumption, acquiring rewards for femto-users in terms of pricing options or data usage from network operator and ultimately drive the macroBS to be dependent on the femtoBS to serve regions of limited coverage. However, the access policies of femtocells and the limited coverage radius acts as a hindrance in serving the macroUEs. While open access femtoBS can serve any outside user, closed access or hybrid access femtoBS restricts connectivity to non-registered

users. Also, the privacy issues emerge as a major concern when privately-owned femtoBSs are accessed by macroUEs to route their data through the femtoBS owner's private backhaul [44]. To address these concerns, the potential of cooperation across tiers must be exploited due to their ability to induce an efficient organization of the available network resources, or, to smoothly coordinate complex phases of transmission in a decentralized manner. The existing literature assembles several multi-tier cooperative solution models with specific focus on interference mitigation and coverage extension. Among them, one of the potential solutions is the deployment of relay nodes between BSs and UEs, which is highlighted as one of the most practical and cost effective solutions to minimize the impact of high path loss while meeting the downlink data rate requirements [45, 46]. In fact, radio coverage optimization through relaying is an effective cooperative transmission scheme that aims at improving the transmission diversity and the transmission reliability for femtocell users [47].

Figure 2.2: Offloading macrocell traffic through coverage extension in femto-macro network

While coverage extension through the densification of network with new base stations involves substantial expenditure owing to the infrastructure costs and subsequent maintenance cost for the dedicated wired/microwave point to point backhaul, relays use wireless backhaul, due to which the capital and operational expenses are largely subsidized. In addition, relays offer network connectivity even beyond the cell boundary which is beneficial in rural and sparsely populated areas. Also, they help to cover the dead zones in densely populated regions. Relays, in certain cases also provide multipath diversity for NLOS users within heavily populated cell coverage areas. The BS can decide to transmit to the user simultaneously using both the direct one-hop link as well as the two-hop links through a relay node based on the traffic parameters and channel quality. Such a configuration helps in increasing the link capacity, although it does not contribute significantly to

an improved network coverage. Lastly, multi-hop relays can also offer network connectivity and coverage extensions in remote areas like hilly regions or highways where it is impractical to provide continuous infrastructure for a full-fledged base station [48].

Taking into consideration the commonly used wireless propagation model, assuming the received signal power to attenuate with distance d to some power of the path loss exponent n , without loss of generality, the required power P_{ij} to support a wireless link at a given data rate R between node i and node j is given by:

$$P_{ij} = d_{ij}^{-n} \times \left(1 + \sum_{k \in N} P_t \times \frac{1}{d_{kj}^{-n}} \right) \times R \quad (2.3)$$

where P_t is the transmitting power at node k and N is the set of concurrent relay nodes in the network. It is clear from equation (2.3), that for the same transmit power P_t , the signal can reach farther when compared to a single hop in an interference-limited network. This concept essentially support the incorporation of relaying in femtocell network for coverage extension and thereby serve more number of users with limited transmit power [49].

The context of serving outdoor UEs by means of indoor base station is proposed in [50, 51]. However, this scenario can be realized only with open access femtocells so as to overcome access policy violations and mobility management issues such as optimization of inter-femtocell handover. At the same time, [52] explores the possibility of utilizing mobile equipment as relay nodes in assisting users far away from the base station. Similar analysis is carried out in [53] where the femtocell backhaul is used to aid the macrocell backhaul when the latter is congested, whereas [54] proposes a rate-splitting approach where macroUEs can share their load between the direct macrocell link and an open-access femtocell using internet-based backhaul. In both these cases, the relaying femtoBS forwards both its own and the served femtoBS's traffic on its wired backhaul, as in Radio over Fibre (ROF) [55]. It is in [56] that the concept of signal decoding at macroBS is introduced in which the data is routed to the macroBS from the open-access femtocell, which is accessible to both femtoUEs and macroUEs. Later on the combination of relay-nodes with femtocell backhaul was identified as a solution to improve mobility and enhance system performance in [57]. However, all these concepts are devoid of techniques for optimizing the usage of idle femtocells with inter-tier cooperation, which ultimately results in impairing the system performance through additional signalling overheads and complexity. In this context, the present work tries to enhance the system performance through self-organizing femto-relays whose operation is based on multi-tier cooperation and assures significant energy savings with limited signalling overheads. However, multi-tier cooperation and inter-tier communication in femto-relay networks, always demand spectral resources, the unplanned sharing of which can end up in interference. This calls for the need

for an extensive assessment of the impact of spectral allocation across-tiers and the resulting interference challenges.

2.3.2 Enhancing Spectral Efficiency with Minimized Interference

Figure 2.3: Co-tier and cross-tier interference scenarios

Figure 2.4: Possible scenarios of interference in femto-macro network

One of the major challenges in a co-existing femto macro architecture is the optimal allocation of available spectral resources by limiting the interference generated in the network. The network

operator always prefers co-channel deployment of femtocells to sufficiently improve spectral efficiency as well as system capacity. However femtocells sharing the same radio spectrum as that of the macrocell results in frequency interruptions to each other, which affects the received signal quality and hence ironically deteriorates the system capacity [58]. Hence confronting cellular operators will be the two major problems of radio interference mitigation and efficient spectrum distribution in femtocell-aided cellular networks. Indeed interference management in cellular networks is a time-honoured topic [59], [60], [61] on which monumental contributions has been made. Nonetheless, studying the interference in two-tier femto-macro networks is quite puzzling than in conventional cellular networks since femtocell network comprises of both operator and user deployed base stations, with minimum intervention and planning from the network operator. As a result, the network topology is characterized by randomly scattered, uncoordinated femtoBSs where the interference alleviation demands ground-breaking solutions capable of scaling down signal processing capabilities as well. Nonetheless the efficiency of an interference management scheme depends on several attributes like:

- Ability to mitigate all types of interference
- Promotion of coordination among network entities
- Need for minimal signaling overhead
- Scalability and robustness
- Applicability to all types of access modes
- Optimized reusability of existing architecture
- Autonomous decision making capacity.

To begin with, the interference signature in the two-tier femto-macro network can be categorized into two types, *co-tier* and *cross-tier interference* [58]. In co-tier interference, the interfering network elements belong to the same tier, e.g., unwanted transmissions between femtocells as given in Figure 2.3. Since unplanned, dense femtocell deployments typically lead to overlapping coverage areas, severe co-tier interference arises more often, which becomes difficult to manage [33]. In cross-tier interference, the interfering network elements originate within different tiers, e.g., macroBS downlink/uplink transmissions interfering with femtoBS downlink/uplink transmissions. While the co-tier interference is relatively small due to lower transmit power and penetration losses, the near-far effect due to uneven spatial distribution of network elements operating on the same spectrum acts as the main contributor of cross-tier interference. The femtocell access modes also have a direct influence on the interference categories in the system which makes the selection of modes a vital decision. The impact of co-tier interference is severe in case of closed access mode

which is usually preferred by the customers who resist from sharing the billed resources with others. Open access mode unlikely to be used by the customers provide better coverage but at the same time raise security concerns. A trivial solution is the hybrid access mode which considers a trade-off between the impact on the subscriber's QoS and the network access offered to non-subscribers. It thus allows specific un-authorized customers to access the femtoBS based on user traffic, bandwidth availability and QoS requirements. The detailed explanation on access modes and its impact on the interference management is furnished in [62-64]. Figure 2.4 illustrates the various possible scenarios of co-tier and cross-tier interference experienced in different access modes in a two-tier femto-macro network which is summarised in Table 2.2.

Table 2.2: Interference scenarios in a two-tier femto-macro network

SCENARIO		DESCRIPTION
A	MacroBS DL interference to femtoUE	A femtoUE connected to the femtoBS at the edge of its range and located close to the apartment window is in the direct bore sight of rooftop macroBS and faces DL interference from the macroBS.
B	MacroUE UL interference to femtoBS	A femtoBS with a femtoUE connected to it and located in a weak coverage area of macroBS experiences UL interference from the macroUE that has a call established at full power from the macroBS.
C	FemtoBS DL interference to macroUE	MacroUE connected to the macroBS at the edge of its range and located in the same room as the femtoBS experiences DL interference from the femtoBS.
D	FemtoUE UL interference to macroBS	A femtoUE located next to the apartment window, is in direct bore sight of a rooftop macroBS. FemtoUE connected to the femtoBS at the edge of its range, transmitting at full power causes UL interference to the macroBS.
E	FemtoBS DL interference to femtoUE	A femtoUE visiting the neighboring apartment and in the edge of coverage of its own femtoBS, will face DL interference from the femtoBS of the neighboring apartment.
F	FemtoUE UL interference to femtoBS	A femtoUE connected to a femtoBS and transmitting at full power can cause UL interference to a closely located neighboring femtoBS.

Formulating as a problem, the received SINR at a femtoUE i can be modelled as:

$$SINR_i = \frac{P_{fb}\varphi_i\|d\|^{-n}}{\sum I_{co-tier}^i + \sum I_{cross-tier}^i + Noise} \quad (2.4)$$

where P_{fb} is the femtoBS transmit power, $\|d\|$ is the distance between the femtoBS and the femtoUE i denoted by the Euclidian norm $\|\cdot\|$, φ_i represents the parameter which takes care of log normal shadowing and fading effects and n being the path loss exponent. $I_{co-tier}^i$ and $I_{cross-tier}^i$ represent the co-tier (nearby femtoBSs) and cross-tier (nearby macroBSs) downlink interference to the femtoUE i due to signal transmission along the same frequency sub-carrier as that of the serving femtoBS. Equation (2.4) clearly projects that the user throughput can be significantly enhanced by limiting the interference from the neighboring macroBSs and femtoBSs. This can be enabled by either ensuring transmission along orthogonal sub-carriers within the immediate neighbourhood of

the serving femtoBS or by devising methods to keep the interference to the serving femtoBS at tolerable levels without any performance degrading impact.

Extensive review on various interference signatures are already available in the literature. The most discussed among them is the cross-tier and co-tier interference among which former draws more attention due to the avalanche of impact it has on the legacy cellular network. The influence of cross-tier interference generated by co-channel femtocells co-existing with legacy macro cellular network on call drop probability is investigated in [13, 20, 65]. Similarly, the impact of cross-tier interference on the coverage radius of a co-channel femtoBS is studied in [66, 67] which proposes a carrier selection scheme based on the coverage area. Several hardware-based solutions have addressed the interference footprint and its limitations in the design of femtoBS. In particular, the use of sectorized antenna [68] and beam forming [69] have been recommended as an effective solution for minimizing the interference between neighboring cells. In addition to this, the dynamic selection of predefined antenna patterns is suggested as a means to reduce unwanted power leakage in [70]. However, hardware-based approaches are essentially followed by complex circuit designs and higher production expenses. On the other hand, alternative solutions such as intelligent spectrum allocation with adequate power control support the exploitation of wireless transmission parameters in an economically feasible manner [71]. In this context, adaptive power control techniques are proposed in [60, 72-74] which depend on lower transmit power for base stations to mitigate interference. This approach was further extended with dynamic or adjustable power setting specifically for application in femtocells, which again can be performed in either open loop power control mode or closed loop power control mode [33]. This finally led to the application of opportunistic power control for femtoBS on a cluster level based on the number of active members in the cluster [75]. This could be initiated with a centralized sensing from the macroBS or a cooperative distributed sensing among the femtoBSs themselves. However, since the power regulated techniques have a direct impact on the total system throughput, they are often accompanied by controlled-power, bandwidth allocation schemes [66, 76, 77] or cell coverage expansion techniques [78], or methods for QoS differentiation [33, 79]. Hence in addition to power control, solutions for both co-tier and cross-tier interference management (avoidance and cancellation) have been proposed in [80-83]. However, the efficiency of an interference cancellation methodology is dependent on the strength of the received unwanted signal and hence it is susceptible to errors in low SINR regimes. Also, the ad-hoc nature of femtocell deployment prohibits a centralized controller from efficient interference management. In this context, a preferred solution is the intelligent allocation of spectrum with specific focus on interference avoidance.

Intelligent spectrum allocation can always help in mitigating interference and at the same time assure system capacity and spectral efficiency [84]. The first basic proposal in this direction was the concept of spectrum splitting [85] also known as dedicated spectrum reuse approach. In this case, the macrocell radio spectrum is partitioned into two sub-bands and each one of them is independently accessed by macrocell and femtocell users. This ensures that either of them remains unaffected by the other tier transmissions, which simplifies the cross-tier interference management. This leaves the scope limited to co-tier interference which is almost nil in the case of macrocell and negligible in the case of femtocell. However, owing to the high pricing of the spectrum and its scarcity, explicitly devoting a portion of the radio spectrum to femtocell users can potentially lead to spectral inefficiency. Also, while major licensed bands are mostly allocated for communication, television-radio broadcasting or military applications, the unlicensed bands are overcrowded by the numerous devices and technologies from cordless phones, wireless LANs to microwave ovens and home entertainment products. Thus, reusing the limited available spectrum within the designated band for communication emerged as an essential need. Hence, to overcome these challenges, another approach known as the shared spectrum reuse was proposed, in which the femtocells are given full access to reuse the macrocell spectrum. In this approach, the macrocells are affected by interfering co-channel transmissions from the femtocells and vice-versa. To address this challenge and enhance the spectral efficiency, femtocells are required to sense, identify and dynamically access the unoccupied macrocell spectrum and thereby control the interference. For this purpose, a femto-aware spectrum arrangement scheme was developed in [86], in which the macroBS creates an interference pool comprising of all macroUEs that pose a threat to the nearby femtocells. The macroUEs from this interference pool is further assigned a dedicated spectrum for its operation while the rest of the macroUEs share the spectrum with the femtoUEs. This approach is akin to the cognitive radio network paradigm whose main advantage is its versatility. Here, the femtoBSs are virtually granted permission to reuse the whole macrocell spectrum, and the bandwidth assignments follow a decentralized distribution pattern. The complexity of such an approach essentially lies in the implementation of highly dynamic mechanisms, which can sense the variations in the interference scenario, and thereby modify the transmission parameters accordingly. However, the increase in femtoUE density near to the macroBS weakens this strategy.

In context of the aforementioned challenges and complexities [51, 87, 88], aggressive spectrum reuse is considered as a main enabler for achieving better spectral efficiency in multi-cell networks. Although in traditional macrocell networks, such operations can be planned by the network operator in a centralized fashion, in femtocell networks where the base stations are installed in an ad-hoc manner with no prior planning, the spectrum reuse demand effective orthogonalization to ensure

interference free operation. The state-of-art orthogonalization approaches can be classified as follows:

2.3.2.1 Frequency Orthogonalization

Figure 2.5: Frequency orthogonalization

Figure 2.6: Static Frequency orthogonalization methods

(a) FFR-Fractional Frequency Reuse

(b) SFR-Soft Frequency Reuse

Frequency orthogonalization basically involves the concept of orthogonal sub-band partitioning and allocating these orthogonal sub-bands for femtoUEs and macroUEs for simultaneous transmission. This is explained in Figure 2.5. This approach is further developed to effectively capture the benefit of both unity frequency reuse and orthogonalization. Here both the uplink and downlink spectrum are partitioned into disjoint frequency resource blocks called sub-bands which make use of different reuse patterns. UEs close to the BS, experience minimal interference and are

allotted frequency reuse of 1 whereas those far away facing heavy interference are allotted higher frequency reuse factors. Although this approach is applicable to any multi-carrier system, it is comparatively easy to implement in OFDMA systems which by default utilizes spectrum blocks. Frequency orthogonalization can be broadly classified as *Static Frequency Orthogonalization* (SFO) and *Dynamic Frequency Orthogonalization* (DFO).

In SFO, the frequency spectrum is partitioned between groups of the member tiers of the multi-cellular network. This enables the complete elimination of co-channel interference between tiers. This non-overlapping spectrum partitioning strategy helps in interference mitigation in a well-planned cellular network. However, it may result in spectral inefficiency, if the traffic load on either tier is varying randomly. SFO is further classified into Fractional Frequency Reuse (FFR), and Soft Frequency Reuse (SFR). FFR which was first proposed for GSM (Global System for Mobile Communication), is one way of statically orthogonalizing frequency usage [89]. It basically involves the spatial partitioning of the macrocell service area into cell centre region and cell edge region, followed by the allocation of each partition with non-overlapping frequency bands as illustrated in Figure 2.6 (a). A frequency reuse factor of 1 is applied to the cell-centre region whereas the cell-edge region is allotted a higher frequency reuse factor. This prevents interference between cell-center region users and cell edge region users, which in turn assures an acceptable signal quality to the cell-edge region users by subsequently reducing outage probability and increasing capacity [89]. SFR is a variant of FFR, which is illustrated in Figure 2.6 (b). Here, the cell-center region UEs are allowed to reuse the cell-edge region sub-bands of the neighboring cells within the same cluster which makes SFR more bandwidth efficient when compared to FFR. However, in a multi-tier scenario, one of the shortcomings of SFR is that, it cannot ensure efficient interference mitigation as that of FFR.

In DFO, the spectrum partitioning is not permanent and the co-existing tiers of the network dynamically access the spectrum. In [90-91], a DFO algorithm for autonomous component carrier selection is proposed, in which each femtoBS allocates radio bandwidth based on the real-time traffic and the interference signature in the network. It even illuminates how autonomous carrier selection can enhance the macrocell edge-user performance without compromising the overall system data rate. This work was further extended for carrier selection based on interference relations [92-93], selfish and altruistic motives [94] and self-configuration capabilities [95]. It is also established in [96] that combining power control techniques with adaptive resource allocation methodologies can help in mitigating the interference. Following this, joint solutions for bandwidth and power allocation problems were proposed in [97-98].

DFO can be generally classified under *random-based* and *sensing-based* orthogonalization [99]. In random based approach, access to the spectrum by each base station is random, which results in higher probability for collision. Each base station divides the bandwidth into a number of sub-bands based on the neighbor-size which is then randomly chosen by each one of them. The selection can be done based on a hashing function [100]. If the randomly selected sub-band do not collide with that of a strong interfering neighbor, the femtocell reserves such sub-band for subsequent transmission. Frequency hopping [101] in which the sub-band is not reserved can be considered as one variation of random-based DFO. The hopping artificially makes the interference scenario to fluctuate along the transmission of a reference user which leads to an interference diversity gain. When used in OFDMA-based femtocell, the probability of persistent channel collision between neighboring femtocells and macrocells is further reduced. Sensing based DFO involves several techniques like network listening, message sharing and measurement report collection [99]. *Network listening-based* spectrum access is a sensing-based approach in which femtoBSs sense the air-interface and identify the cells and channels that are active within its vicinity. This enables the femtoBS to configure and access the remaining channels for its operation. In *message sharing-based* spectrum access, femtoBSs exchange messages with neighboring femtoBSs about their channel usage and traffic load. This information exchange, helps the femtoBS to be aware of the neighboring entity's present actions and future intentions, the knowledge of which helps it to decide on its mode of operation. *Measurement report-based* spectrum access relies on the measurement reports that are periodically exchanged between a femtoBS and its associated users. The report contains information on the received signal strength and active channels of the serving and strongest neighboring cells (both macrocell and femtocell). If post-processed, interference relationships and forbidden channel list can be established based on which interference-free operational spectrum can be determined.

Though spectrally efficient, DFO brings along larger signalling overhead between the macro cell and the femtocell tiers, and thus increases the network complexity. In addition, due to the real-time variations in the multi-tier environment, additional adaptive techniques need to be combined to effectively meet the users' QoS requirements. This motivates the combined use of SFO in planned macrocell network and DFO in unplanned femtocell network so as to enhance the system performance.

2.3.2.2 Time Orthogonalization

The basic concept of time orthogonalization is explained in Figure 2.7 where the femtoUEs are allowed to access the spectrum sub-bands only in those time slots where the macroUEs are not accessing the same. This avoids simultaneous transmission in multi-tier network along the same

sub-band and hence avoids interference. Just like frequency orthogonalization, time orthogonalization can be classified into STO (Static Time Orthogonalization) and DTO (Dynamic Time Orthogonalization). In STO, the partitioning of the time resources between neighboring base stations is fixed and the femtoUEs accesses the spectrum only in its allotted time when the macroUE is silent. The partitioning pattern can either be decided by the macroBS, which is then communicated to the femtoBS or the femtoBS may observe the RF environment over a series of time-slots and then select the optimum slots for transmission [102]. STO interference mitigation technique has been adopted in the LTE-advanced standard in which it is used to create interference free tunnels, and is termed as almost blank sub-frame [103] in the standard. In DTO, the partitioning of the temporal resources is randomized, which is achieved through time-hopping [101]. The transmission period is divided into a number of time-slots (hopping slots), which is randomly picked up by each BS during each hopping period. Although, this approach is not collision free, it has been proven effective in terms of inference mitigation [68] especially in TH-CDMA (Time Hopped CDMA) systems. This work was further extended and collision models were developed for the critical analysis of its performance [104-105].

Figure 2.7: Time orthogonalization

2.3.2.3 Spatial Orthogonalization

Spatial orthogonalization technique exploits the spatial separation between an aggressor (interferer) and the victim (interference recipient). In this approach, antenna arrays with different weights are assigned to the antenna elements to selectively attenuate unwanted signals. In case of femto-macro network, the receiver attenuates the interfering signal and amplifies the desired signal through optimum estimation of the set of weights.

2.3.2.4 Polarization Orthogonalization

Even though the concept of polarization diversity is not new, it remained under-utilized for the past several years. Exploiting it for introducing orthogonalization and subsequent improvement of spectral efficiency and system capacity of multi-tier network seems to be the next logical step to undertake. Exploring polarimetric dimension is an intriguing research direction and may bring revolutionary subversion, fundamentally for wireless communication. The concept of cross-polarization allocation is already introduced in systems operating under line-of-sight (LOS) conditions as a means of isolating the interfering signal from the desired signal [106]. Specifically, a heuristic scheduling algorithm along with a terminal classification procedure is proposed in [107] for interference reduction. This concept is extended in [108], with a different scheduling algorithm for odd and even sectors. In [109] the scheme is further improved with the introduction of power shaping concept. The above concepts of combined scheduling of the intra-cell and inter-cell transmissions and cross-polarization allocation method have been integrated in [110] for minimizing the interference and hence improving the QoS. On the other hand, an alternate polarization allocation scheme for Local Multipoint Distribution Service (LMDS) operating under LOS conditions is presented in [111]. A similar scheme for systems operating under non line-of-sight (NLOS) operation is proposed in [112] which gives due importance to the channel allocation policy and thereby reduce co-channel interference (CCI). The potential benefits of dual-polarized antenna systems in wireless communication scenario is addressed in [113] whereas the measurements and modelling of polarized transmission in indoor NLOS environments is carried out in [114]. It agrees that a compact antenna system with lower inter-antenna correlation can be obtained with the help of perpendicularly polarized antennas. Taking into consideration, the aforementioned application of polarization in wireless systems, orthogonalization through cross polarized transmission may act as the key to interference mitigation in next generation multi-tier systems which demand extensive research.

In essence, the selection of an interference management scheme is significantly dependent on the inevitable trade-off between complexity and efficiency. In fact, static frequency reuse represent a cost-efficient, low complexity approach since it demands limited signaling overhead between the macrocell and the femtocell tiers. However, due to the heterogeneity of the interference scenario which is composed by base stations with different coverage areas and different cross-tier interference in the uplink and downlink, additional adaptive techniques need to be combined to effectively meet the users' QoS requirements. Also, in the downlink, femtoUEs may suffer from low SINRs because of the strong interference from the macroBS and vice-versa especially when the

separating distance from the BS is small. Devising techniques to control the downlink interference from the BSs can significantly improve the downlink capacity, where the user traffic is also comparatively higher. In short, the complexity in multi-tier interference management lies in handling the autonomous and uncoordinated spectrum allocations at the randomly positioned femtocells with minimal impact on the existing cellular network. It is in this context that the self-organizing capabilities of femtocells can play a key role in the operation of multi-tier networks which enables them to make decisions dynamically in the real-time environment.

2.3.3 Boosting Network Performance through Cognitive, Self-organization Capabilities

Figure 2.8: Self-Organizing femtocell network operation

Even though the operation of legacy macrocell network with a centralized controller has proved its efficiency, the same cannot be adopted for femtocell network whose deployment is totally ad-hoc and unplanned. This renders the classic network design, configuration and planning tools inadequate. As a result, spectrum allocation for the femtocell network is a tedious task since its installation and location information cannot be predicted well in advance. This calls for the femtocells to be autonomous and intelligent in case of its frequency selection process so that it can sense the environment, determine the interference footprint and then adaptively access the spectrum without causing any performance degrading impact on the primary macrocell network.

Understanding these complexities within the wireless spectrum balancing act is one of the key challenges faced during massive deployment of femtocells. It is in this context that the combination of femtocells with cognitive radio features [115] known as self-organizing femtocells acts as a promising approach towards next-generation cellular networks.

By leveraging self-organization capabilities, which involves approaches like power control, coverage planning, frequency reuse, neighboring entity awareness and mobility management, the user intervention in several network operations can be reduced, which in turn saves the capital expenditure (CAPEX) and OPEX incurred. In fact, autonomous operation can assure performance and operational profits, without a centralized control which further translates into reduced interference, increased capacity and better QoS in the network. A self-organizing network entity can focus on optimizing a single performance parameter or can adopt a hybrid approach with a smart trade-off between different attributes for a demand driven operation. This concept is at par with 3GPP technical specification, which outlines self-organization as the process which implants in a network entity, the capability to activate itself and resume operation with minimum human/operator intervention or none at all. Self-organization concepts have been first included in the Release 8 of LTE (E-UTRAN) standard and is mainly based on cross-layer methods and heuristics for interference management as demonstrated in Figure 2.8 [116]. It is expanding in scope with future releases and involves the following significant features:

2.3.3.1 Self-configuration

Automating repetitive process clearly offer savings in terms of time and effort. Self-configuration falls under this category. The necessity of this phase comes into picture during the occurrence of an event like addition or removal of new BSs. During addition, the newly introduced femtoBS is expected to configure its parameters by sensing the network environment whereas in the case of a femtoBS removal, the rest of the femtoBSs in the network is expected to reconfigure its parameters to optimize its performance [116]. In short, self-configuration helps in minimizing the human intervention in planning, configuration and integration of new femtoBSs in the existing cellular network. This results in a rapid and efficient network deployment with reduced CAPEX and OPEX in addition to a more integral inventory management system that is less susceptible to human error. For example, upon power-up, each femtoBS is expected to perform a basic configuration so as to make itself fully operational. Accordingly, each femtoBS sets the transport and radio parameters like pilot power, neighboring cell list etc. for data transmissions and acquires information on the current spectrum allocation. In this phase, neighboring femtoBSs discover and

identifies one another, and keep track of their operational information in the neighboring cell list. Based on this shared information, each femtoBS performs individual optimization [117-118].

2.3.3.2 Self-optimization

The objective of self-optimization is to prudently adapt the femtoBSs' operations in accordance with the changing network parameters in order to assure better QoS to the customers, while simultaneously optimizing the system performance. Typically, when in operation, the femtoBS collects measurement reports from its registered UEs. Based on these reports, the femtoBS auto-tunes its configuration parameters like transmit power, modulation, and coding schemes etc. and adapts to the best possible access modes [119]. Self-optimization operations such as adaptive power regulation, admission control and user mobility management are periodically performed during ordinary transmission so that the femtoBS dynamically adapts to the current network state and optimizes the usage of available system resources [117-118].

2.3.3.3 Self-healing

Self-healing functionalities in a self-organizing network are basically event driven which strive towards the recovery of the normal functioning state in the occurrence of an unexpected error or failure. It is this phase that reconfigures the network parameters in times of network emergencies. The femtoBSs are incorporated with diagnostic capabilities to detect failures and apply healing mechanisms, which resets the system to its normal operational state. Such automations help in minimizing the human intervention in the network operations, resulting in significant savings in the operational and maintenance costs. It also renders the network to be functional throughout without any room for glitches in its operation [120-121].

Extensive research is being carried out to make the femtocells autonomous in its decision making by embedding self-organizing capabilities into them. Both centralized and distributed approaches for this purpose are available in the literature. Centralized approaches function with the help of a centralized controller and comparatively achieve better resource utilization but at the cost of higher complexity and signaling overhead. An example for the centralized approach can be observed in [122] which carries out resource partitioning based on graph coloring technique. Unlike the classical graph coloring based approaches where the resources are equally distributed among the BSs, here more number of sub-bands are allocated to BSs subjected to less interference signature which in turn enhances the system competence. Distributed approaches on the other hand, though not efficient like the centralized approach avoids the necessity of a centralized controller, which proves to be beneficial from the implementation point of view. It makes use of several strategies

like proactive, reactive or hybrid dynamic power control mechanisms [123], adaptive clustering heuristic algorithms [124], flexible re-use partitioning [125], semi-dynamic inter-cell interference coordination [126] etc. which demand coordination and cooperation among the network entities to achieve the goals.

In fact, self-organizing femtocells with cognition capability can intelligently perceive the radio environment, effectively decode the macrocell operational spectrum and independently identify the transmission opportunities, i.e., the non-allocated component carriers [119]. The spectrum sensing results and the scheduling information obtained from the macroBS can be used by the femtoBS to detect and access the macrocell frequency resource blocks which are spatially located far away from the femtoBS and thereby avoid cross-tier interference [127]. Based on the same information, femtocells can perform well-targeted operations for enhancing the QoS [128] or optimizing the spectrum access [129]. For example, through cognitive spectrum sensing, the femtocells can determine the interfering sub-channels and hence control the transmission power or discontinue the transmission on these sub-channels to alleviate the cross-tier interference effects [130]. Nevertheless, the greatest challenge involves the decision making on efficient spectrum allocation among femtocells. As a matter of fact, sustaining a balanced and coordinated operation among the femtocells becomes highly challenging since co-channel interference intensifies rapidly with increase in density of femtocell deployment. Moreover, a cognitive approach would promote a network concept that allows for unconditional and unrestricted access to licensed and unlicensed spectrum, even though it has not been recognized by several network consortia or regulatory commissions.

Self-organizing femtocells also possess the capability to sense, identify and exploit the existing spectrum allocation information so as to avoid interference, rather than alleviating it. An opportunistic channel scheduling scheme that determines the operational channel and its optimal transmission power based on the information regarding uplink cognitive spectrum allocation is proposed in [131]. Similarly, dynamic cognitive-based spectrum allocation schemes have been proposed in [119, 130, 132] based on current bandwidth occupation and the corresponding path loss information. It is also to be noted that the performance of self-organizing femtocells is influenced by the transmission activity in both macrocell and femtocell tiers, which considerably depend on user distributions and base station deployments. On one hand, this has been exhaustively addressed through distributed carrier selection, in order to guarantee the target QoS for the cognitive UEs [115, 128, 131, 133, 134]. On the other hand, alternative opportunistic spectrum access techniques have been developed, such as the underlay time division duplexing (TDD) transmission technique which operates in the uplink spectrum of a frequency division duplexing (FDD) macrocell [135, 136].

Specifically, this strategy initiates the femtocells to carry out its own TDD transmissions while the macrocell simultaneously operates in these bands using FDD technique. Thereby, macrocell FDD gets rid of inter-tier interference while femtocell TDD offers innovative transmission opportunities by taking advantage of the asymmetry between the uplink and downlink transmissions of the macrocell spectrum. A self-initializing technique with preamble design for femtocells which makes use of the power control method is presented in [65, 137]. The challenge of scanning very large number of neighboring entities is solved in [138] in which the broadcast information from a femtoBS is utilized by other femtoBSs to improve the overall performance of the femtocell network. Additional flexibility is introduced into the femtocell network through the Dynamic Self-Organizing Network Planning and Management Module (DSNPM) developed in [139] which efficiently enable the femtocells to respond to the real-time network variations.

2.4 Summary

This chapter provides the background knowledge on the challenges faced by co-existing femto-macro architectures. It briefly describes significant concerns regarding the spectrum allocation strategies adopted and the subsequent effect on the interference signature of the network. Hence it precisely direct towards the research trails to be adopted to enhance the operational quality of multi-tier networks. The explicit focus will be on the need for effective interference management in harmonious co-existence of femto-macro cellular architectures.

In summary, the transmission characteristics of a multi-tier cellular architecture is significantly challenged by the allocation approach of available spectral resources, and the interference coupling between the existing tiers. Optimizing the usage of available network resources can definitely contribute towards energy saving with adequate spectral resources made available for transmission and the user-demands satisfied through efficient wireless operation. The self-organization capabilities of the femtoBS are further envisioned as major enablers for performing real-time interference mitigation and adaptive resource management in a decentralized fashion. In this respect, critical unanswered questions remain in femtocell access control, such as determining a valid tradeoff in the interests of network operator and user-deployed femtocells, and how such access mode and operational spectrum need to be selected based on factors such as user distribution, traffic priority class, interfering neighbors, power savings and backhaul constraints.

To sum up, managing the interference from different tiers (i.e., macrocell and femtocell) is challenged by the asymmetry between uplink and downlink transmissions, the absence of coordination between the two tiers and above all the scarcity of resources. Moreover, as the two tiers have different physical properties (e.g., transmit power levels, number of users that can be

supported, access modes), a differentiated approach for optimal resource distribution and mitigation of interference components is essential. This needs to be carefully formulated and embedded into the network topology in order to optimize the performance of radio communication systems.

Chapter 3

Optimizing Femtocell Usage through Energy Efficient, Interference Limited Femto-Relays

*Coming together is a beginning,
Keeping together is progress,
Working together is success.*

-Henry Ford

3.1 Introduction

Heterogeneous network (HetNet) proves to be one of the most efficient and prominent candidate for future wireless communication systems. This is due to its ability to achieve high spectral efficiency per unit area and better energy saving with lower transmission power. Within these heterogeneous architectures where end users are granted universal connectivity opportunities, femtocells emerge as key players in the enhancement of critical performance indicators such as capacity, coverage, QoS, etc. [140]. Much of the early attention on femtocells was concentrated on providing better indoor voice call services. However, with data services becoming a major source of revenue for mobile network operators, the focus is once again diverted towards utilizing femtocells for providing high quality data service in an interference-free network. The research in this direction finally pointed out that the deployment of interference-limited femtocells and its aggressive exploitation is economically feasible for improving network capacity and restricting the power consumption. It could also significantly contribute towards better energy efficiency and data-rate improvement in LTE-A cellular systems. As of now, there exists a large number of under-utilized femtocells which are capable of supporting users who would otherwise depend on the macrocell network. Judicious use of these free and under-utilized femtocells will help to reduce the bandwidth utilization of macrocell network, thereby providing improved QoS for other users and

reduce the costs for network operator. Deployment of these home base stations are also useful to the consumers since they possess the flexibility of being placed at any point that require coverage and capacity enhancement. However, the major limitation in this case is the smaller coverage area of the femtocells and the interference caused to the classical macrocell network due to its massive roll-out [58].

It is in this context, that the concept of Femto-relays is introduced in this chapter which rely on under-utilized femtoBSs to extend the BS coverage and thereby accommodate more number of users. This further helps in offloading the macrocell traffic and relieve the pressure on the limited macrocell backhaul. Initially the proposed method is analyzed from an interference limited coverage extension perspective with a two-hop scenario (Section 3.3) which is further developed into an energy-efficient self-organizing scheme that proves to be fully autonomous in terms of its operation (Section 3.4).

3.2 Femto-relay Concept

Figure 3.1: The femto-relay concept

As per the propagation properties of radio signal, the signal strength decays quickly with growing distance, which means that every femtoBS has its own radio transmission range. Relaying can be proved to be very effective if it succeeds in extending the coverage of femtoBS even beyond its radio transmission range. If a femtoBS wants to communicate with a UE which is not in its transmission range, the intermediate relay nodes can forward the data from the source node to the destination node. In this case, the cumulative path loss suffered on the femtoBS-relay and the relay-destination UE route is much smaller than that for direct transmission. Hence relaying ensures that

the SINR at the receiving end is better than through direct transmission. The greatest benefit of relaying is thus to extend the “communication range” of a BS in the wireless network. In this context, the concept of femto-relays is proposed.

The basic idea behind this femto-relay concept as evident from Figure 3.1 is to extend the coverage of a femtoBS through its registered femtoUEs to accommodate nearby macroUEs and thereby enable them to have a better quality connection with the network. In short, the femto-relay system essentially consists of three main entities: macroBS, femtoBS and the UEs. The macroBS and the femtoBS are assumed to be well synchronized to enable proper exchange of information which can further help in minimizing the interference due to mismatch of UL and DL frequency channel allocations. Due to delay sensitivity, the macroUE voice calls are served by the macroBS themselves whereas the data traffic is routed through the femto-relays which assures comparatively higher data-rate. However, in case of heavy traffic in the macrocell network, even voice calls can be routed through the femto-relays. The voice calls from the registered users of the femtoBS will be served by the femtoBS itself while the data service requests of all users within its vicinity can be routed through femto-relays for better efficiency.

3.2.1 Femto-relay System Model and Simulation Setup

The system assumes an OFDMA downlink cellular scenario with two tiers corresponding to macrocell network with M macroBSs and femtocell network with F femtoBSs. P_{fb} , P_{fu} , P_{mb} and P_{mu} represent the transmit powers of the femtoBS, femtoUE, macroBS and macroUE respectively, σ^2 represents the noise power, P_s^{rc} corresponds to the transmitted signal power from sender s to receiver rc , d denotes the random variable which represents the distance between the transmitting BS and the UE under consideration, n represents the path loss exponent and $|h_0|^2$ represents the channel attenuation that follows a general statistical distribution which includes all random effects like fading, shadowing etc. between any BS under consideration and the attached UE. The interference power at a receiver is assumed to be the sum of received power from all other BSs making use of the same sub-carrier as that of the home BS. The femtoBS communicates with the macroBS via wired backhaul, whereas the macroUE is capable of communicating with the BSs and other UEs via wireless transmission.

3.3 Coverage Extension through Interference Limited Femto-relay Network

The limited coverage of the femtoBS often inhibits it from serving more users with its high data-rate service. In addition to this, even though the density of femtoBSs in the network is increasing on a daily basis, majority of them remain under-utilized throughout the day due to their placement

in the indoor environment. However, the concept of femto-relays paves the way for under-utilized femtoBSs to optimize the network performance by playing a key role in offloading traffic from the macrocell network through the femto-relays. This may turn beneficial for them in terms of pricing or other data-services from the network operator.

In the following sections, we discuss how a dual-hop transmission from the femtoBS to the macroUE via the femtoUE offers better coverage probability, minimizes interference, and reduces dead-zone in a multi-tier cellular network.

3.3.1 Femto-relay Operation and Assumptions

This section explains the channel allocation model and the access policy in the current cellular overlay network along with the assumptions for the proposed method. The adopted system model involves a multi-tier OFDM transmission system with each macrocell having an omni-directional antenna deployed at the center. The proposed method assumes both femtoBS as well as the registered femtoUE to have the same transmit power. If we consider that the dual-hop route can only support the worst hop SIR, then an optimal SIR and hence capacity is achieved when the relay node is located midway between the femtoBS and the destination macroUE [141]. Hence in our analysis, we assume the registered femtoUE or the relay node to be located mid-way between the femtoBS and the destination macroUE.

3.3.1.1 Channel Allocation Model

In a two-tier cellular network, the lack of direct coordination between the macrocell and femtocell, and the completely distributed nature of femtocell makes channel allocation an extremely challenging task. Fixed allocation of channels between the macrocell and femtocell results in inefficient usage of the available spectrum. Also, sharing the same spectrum can end up in interference problems. In the proposed system, we leave all the frequency channels to the macrocell while at the same time allowing the femtocells to reuse some of them to communicate with their associated users. This can be achieved with future OFDMA based standards (WiMAX and LTE), which ensure an efficient channel usage with controlled interference.

Relay transmission mode has gained great importance recently, mainly due to increase in the range of transmission and reduction in transmission power. Studies indicate that the capacity of the macrocell network is significantly affected by the co-existing femtocell network due to the cross-tier interference generated by them which ultimately affects the QoS requirements of the macrocell network [12]. As a solution to this problem, it is advocated that the interference caused by the femtocell network to the macrocell can be reduced by employing the low power femto-relay mode

of transmission. Under this model, the femtoUE that acts as a relay node can transmit along the same channel by which it connects to the femtoBS, to connect to the macroUE as well.

3.3.1.2 Access Scheme

MacroBS can obviously cover a very large area while the low transmit power and path loss always restrict the femtoBS from serving the users only within a small coverage area. The proposed model assumes that each user is capable of sensing the pilot signal channels from the macroBS as well as from the femtoBS. In order to achieve this, the femtoBS has to adopt an *open access policy*, which allows any user to attach with it. This helps in avoiding the *loud neighbor effect* [142]. This will be of great use in highly crowded areas like malls, railway stations etc. where an idle femtoUE can serve as a relay to many nearby macroUEs. The femtoUEs that act as relays may also benefit from this at a later point of time, especially when it happens to be outside the femtocell's transmission range with a lesser signal quality. This makes it a '*give and take policy*' mutually beneficial to each other. The advantage is mainly exploited when a UE is in a dead zone area, unable to communicate with the macrocell network but can communicate to a nearby femtoBS through a registered UE already attached to it.

3.3.1.3 Femto-relay Operation with Dual-hop

The macroBS always maintains information about the femtoBSs and the registered femtoUEs within its coverage area. When the macroUE makes a high data rate request, it notifies the macroBS by sending the NCL (Neighboring Cell List) along with its request; which contains the information regarding the femtoBS and the attached femtoUEs in its neighborhood. Upon reception of this request, the macroBS will initiate handover of this request to a femtoBS chosen from the NCL, which in turn establishes connection with the macroUE through multiple hops (if it is located beyond its coverage area). This selection of femtoBS is based on the number of idle users attached to it, and having the largest value for the available UL data-rate to average UL data-rate usage ratio in the near past [143]. However, the macroBS do not initiate the handover if it finds that its backhaul is under-utilized and it has sufficient resources to serve the request. This decision is made by the macroBS based on its average backhaul utilization in the near past (BU_{past}) and a backhaul utilization threshold (BU_{min}). In other words, macroBS transfers the UE data request to femtoBS only if $BU_{past} > BU_{min}$. If not, it means that the macroBS has sufficient resources to serve the data demand. The femtoBS now connects with the UE through multiple hops, the first hop being to the registered femtoUE and the next hop from the femtoUE to the destination macroUE. It is expected that the femtoBS will reach the UE within two hops, since this femtoBS is part of its NCL. Once

the data demand is served, the connection is terminated. Whenever the associated user participating in this data transfer moves out of the femtoBS coverage area, the femtoBS tries to connect to the next UE registered with it (available from the NCL) to continue the transmission. In the worst case, if it does not have any more UEs registered with it to continue the data transfer; it should notify the same to the macroBS. The macroBS in turn initiates the handover to the next femtoBS in the NCL. Signaling and security aspects involved in the proposed implementation demands further research for a smooth transition without any bottlenecks. The process would be just the reverse when the UE requests a UL transmission. Extending the coverage of femtoBS through this method helps the macroBS to serve more voice call requests and femtoBS to serve more data requests. Utilizing femtoBS backhaul to serve the high data rate requests of the macroUEs will indirectly increase the macrocell backhaul bandwidth and thereby improve the spectrum efficiency [53].

3.3.2 Simulation and Performance Evaluation

Table 3.1: Simulation Parameters

PARAMETER	VALUE
Channel Bandwidth	10MHz
Carrier Frequency (f_c)	2.5GHz
Sub-carrier Spacing	15 KHz
Max Power of macroBS	46 dBm
Max Power of femtoBS	23 dBm
Max power of macroUE and femtoUE	23 dBm
Thermal Noise Density	-174 dBm/Hz
Log normal std. deviation (outdoor)	8 dB
Log normal std. deviation (indoor)	4dB
Shadowing std.	10 dB
P_{b_CPICH}	1/10
N_{UE}	7dB
$\frac{E_c}{N_0} _{femto}$	-16 dB

For simulation purpose, the central macrocell within a group of 19 macrocells is taken as the reference cell site for collecting performance results while the other 18 macrocells act as two rings of interferers to the central macrocell. In the simulations, the non-line of sight (NLOS) path loss variations are modelled as per Wireless World Initiative New Radio (WINNER) II model [19], the details of which are furnished in Chapter 2. In this femto-relay setup, the macroUEs follow a Poisson distribution with a density $\lambda_p = 1/(2500\pi^2)$ per m^2 within the macrocell network while the femtoBSs are uniformly distributed with their registered femtoUEs positioned at half the distance from the nearby macroUE but within the femtoBS coverage area. The simulation parameters used for evaluation is provided in Table 3.1.

3.3.2.1 Coverage Extension

The maximum femtoBS power levels required to deliver adequate coverage can be obtained from [144] as:

$$L_{max} = 10 \log_{10} \left(\frac{P_{fb}}{N_{UE}} \left(\frac{P_{fb_CPICH}}{\frac{E_c}{N_o}|_{femto}} - 1 \right) \right) (dB) \quad (3.1)$$

where L_{max} is the maximum acceptable path loss, required to deliver an adequate pilot channel signal quality $\left(\frac{E_c}{N_o}|_{femto}\right)$, N_{UE} is the UE received noise power and P_{fb_CPICH} is the proportion of femtoBS power (P_{fb}) allocated to the pilot channel. Figure 3.2 explains the need for gradual increase in femtoBS transmit power to deliver a specific pilot channel signal quality, with increase in coverage area.

Figure 3.2 Coverage radius dependency on femtoBS transmit power to deliver a specific pilot channel signal quality

With direct transmission, coverage level requisites for a typical house are achieved even at very low femtoBS transmit powers (5 dBm) in comparison to the transmit powers of Wi-Fi access point (+24 dBm) and phones (+24 dBm). However, it is evident from Figure 3.2 that by employing the dual-hop transmission, the femtoBS transmit power required to achieve the same coverage can be further reduced due to the advantages in terms of path loss reductions when compared to direct transmission. Moreover, extending the radio transmission range of the femtocells helps in accommodating more number of macroUEs and hence offloads the traffic on the macrocell network.

This indicates that transmit power savings are possible by integrating dual hop transmission to femtocell network as it covers larger area and serves more number of users with the same power.

3.3.2.2 Capacity Improvement

Taking into consideration the cross-tier interference in a femto-macro network, the SINR at the j^{th} femtoUE attached to femtoBS i , in the downlink is formulated as:

$$SINR = \frac{P_i^f |h_{oi}|^2 d^{-n}}{\sum_{j=1}^M P_{mb} I_j^f + \sum_{k=1, k \neq i}^F P_{fb} I_k^f + \sigma^2} \quad (3.2)$$

where I_j^f and I_k^f correspond to the channel attenuation along the transmission paths from interfering macroBSs j and femtoBSs k which includes shadowing, wall loss and path loss parameters. In fact, the first two terms in the denominator represent the cross-tier interference from the nearby macroBSs and co-tier interference from the nearby femtoBSs respectively. The *Shannon-Hartley* [145] bound is further used to calculate the maximum amount of error-free digital data that can be transmitted over the communication link with a specified bandwidth. In practice, adaptive modulation and coding schemes allow data-rate to scale with increasing SINR. However, the detailed performance of specific modulation and coding techniques are not taken into consideration in this work, since it mainly involves the comparison between direct transmission and relay-assisted transmission in femtocell networks.

When deriving the capacity with dual hop, each hop is assumed to have half of the total bandwidth. However, since the main focus is on the Capacity Gain factor, the bandwidth values are neglected. The capacity enhancement achieved from the femto-relay transmission is further analyzed with the help of *Capacity Gain (CG)* factor given by:

$$\frac{C_{dual_hop}}{C_{direct}} = \frac{0.5 \log_2(1 + SINR_{dual_hop})}{\log_2(1 + SINR_{direct})} \quad (3.3)$$

where C_{dual_hop} and C_{direct} are the capacities achieved by the user in dual hop and direct transmission mode respectively. Assuming that the dual-hop route supports the worst hop SINR and that an optimal SINR and hence optimal capacity is achieved when relaying femtoUE is located half way between the femtoBS and macroUE, we have:

$$SINR_{dual_hop} = 0.5^{-n} SINR_{direct} \quad (3.4)$$

As the path loss exponent in the urban microcells varies from 2.7 to 3.6, the path loss exponent value for our calculations is taken as 3.6; hence (3.4) gets reduced to

$$SINR_{dual_hop} = 12.13 \times SINR_{direct} \quad (3.5)$$

Hence from (3.3), (3.4) and (3.5); CG becomes:

$$CG = \frac{0.5 \log_2(1 + 12.13 \times SINR_{dual_hop})}{\log_2(1 + SINR_{direct})} \quad (3.6)$$

Figure 3.3: MacroUE capacity gain analysis for different femtoBS transmit power

Figure 3.3 shows the CG improvement with increase in number of femtoBSs in the network. It is evident from the figure that the capacity gain increases with decrease in femtoBS transmit power. This is because relaying provides the greatest benefit when the target UE has very low SINR. On the other hand when the UEs already have significantly high SINR, relaying performs worse than the conventional direct hop due to additional slot required for transmission. However CG reaches almost a stable state at about -30 dB, as at this point onwards the interference from macroBS becomes predominant when compared to that from femtoBSs in the downlink scenario. Also, asymptotic increase in capacity, coverage and energy reduction as a function of relay density, highlight that there is a law of diminishing returns as stated in [146]. Hence, in the case of femtocell environment, considering the maximum number of users that can be registered to a single femtoBS, the number of relay nodes present would likely be very few, which ensures greater multi hop gains. In addition to this, the coverage analysis proves that the femtoBSs are capable of offering the guaranteed service quality and data rate even with lower transmission power. In short, higher

capacity gains can be achieved by lowering the femtoBS transmit power and adopting relaying transmission, which results in better power efficiency and lower interference.

3.3.2.3 Interference Reduction

The transmit power level of femtoBS has a clear impact on the coverage that it can provide as well as the amount of interference that it generates in the network. Even though higher transmit power can offer extended coverage and better signal quality, it creates tremendous interference to the co-existing macrocell users. Therefore reduction in femtoBS transmit power plays a key role in controlling the interference that it generates in the network. It is in this context that the engagement of relaying in transmission is considered as a solution for minimizing the overall cross-tier interference since it demands lower transmit power.

Assume P_{fb} to be the total transmit power required for the direct transmission between femtoBS and macroUE, and d be the distance of the nearby macroUE from the femtoBS in operation. The interference at the macroUE due to this transmission by the femtoBS is given by:

$$P_{int} = P_{fb} |h_0|^2 (d)^{-n} \quad (3.7)$$

Here the assumption is that the femtoBS transmission interferes only those macroUEs which are present within a coverage radius D . Hence according to the Poisson point process, the $(d)^2$ variables have identical uniform distributions within $[0, D^2]$. The PDF of $(d)^n$ is given as:

$$f_{d^n}(x) = \frac{2}{nD^2} x^{2/n-1} \text{ for } 0 \leq x \leq D^n \quad (3.8)$$

If we consider the maximum DL transmit power of the femtoBS (P_{fb}^{Max}) as the maximum possible interference received at the macroUE, then the distribution of P_{fb}^{Max} is given as [147] :

$$F_{P_{fb}^{Max}}(x) = \exp \left(-\lambda_p \Pi D^2 \left(1 - F_{P_{int}}(x) \right) \right) \quad (3.9)$$

where $F_{P_{int}}(x)$ is the CDF of P_{int} and λ_p is the macroUE density. Introducing the distribution function $F_{(P_{int})^{-1}}(x)$, the CDF of $(P_{int})^{-1}$, we have the relation:

$$F_{(P_{int})^{-1}}(x^{-1}) + F_{P_{int}}(x) = 1 \quad (3.10)$$

Now the value for $D^2 \left(1 - F_{P_{int}}(x) \right)$ in equation (3.9) can be obtained by letting $D \rightarrow \infty$ as:

$$D^2 \left(1 - F_{P_{int}}(x) \right) = \left(\frac{P_{fb}}{x} \right)^{\frac{2}{n}} \Gamma \left(\frac{2}{n} + 1 \right) \exp \left(\frac{2\sigma^2}{\epsilon^2 n^2} \right) \quad (3.11)$$

where $\Gamma(x)$ represents the gamma function and $\epsilon = \frac{10}{\ln(10)}$.

Hence equation (3.9) gets further reduced to:

$$F_{P_{fb}^{Max}}(x) = \exp\left(-\lambda_p \Pi\left(\frac{P_{fb}}{x}\right)^{\frac{2}{n}} \Gamma\left(\frac{2}{n} + 1\right) \exp\left(\frac{2\sigma^2}{\epsilon^2 n^2}\right)\right) \quad (3.12)$$

While employing the femto-relay transmission, let P_r be transmit power opted by the femtoBS and the femtoUE (relay node) on alternate hops. Let P_{fb}^{max} and P_{fu}^{max} be mutually independent random variables (which are dependent on fast fading, shadowing and path loss) that represent the maximum interference caused by the femtoBS and the relaying femtoUE respectively at the nearby macroUE. Hence the maximum interference at the macroUE in the relaying mode is given by:

$$F_{P_r^{Max}}(x) = F_{P_{fb}^{max}}(x) \cdot F_{P_{fu}^{max}}(x) \quad (3.13)$$

$$F_{P_r^{Max}}(x) = \exp\left(-2\lambda_p \Pi\left(\frac{P_r}{x}\right)^{\frac{2}{n}} \Gamma\left(\frac{2}{n} + 1\right) \exp\left(\frac{2\sigma^2}{\epsilon^2 n^2}\right)\right) \quad (3.14)$$

Comparing $F_{P_{fb}^{Max}}(x)$ and $F_{P_r^{Max}}(x)$ we find that the interference caused by the direct transmission mode will be equal to that of relay mode only when $P_{fb} = P_r \cdot 2^{n/2}$. Thus the interference caused to the macroUEs in femto-relay transmission mode is found to be lower than that of direct transmission mode for $P_r < P_{fb} 2^{-n/2}$. For typical values of the path loss exponent in the indoor environment (1.4 -3.6), the interference reduction by the use of femto-relays is observed when $P_r < 0.616 P_{fb}$ to $P_r < 0.29 P_{fb}$ which is quite practical in the proposed scheme.

3.3.2.4 Deadzone Control

Dead zones are areas of non-uniform coverage in the macrocell network, which are formed due to the ad-hoc deployment of femtoBSs. In uplink, a macroUE located at the cell edge transmitting at maximum power causes unacceptable interference to nearby femtoBSs. Consequently, femtoBSs located at the cell edge experience significantly higher interference compared to cell-center region femtoBSs. In the downlink, at the cell edge where femtocells are most needed—macroUEs are disrupted by the DL transmissions of nearby femtoBSs, in addition to the higher path-loss experienced by them compared to cell-center region macroUEs. This interference to the macroUEs can be controlled to a large extent by the use of femto-relays as shown in Figure 3.1. Here the

macroUEs, which are unable to attach to the macroBS due to heavy interference from the femtoBS can depend on the nearby femtoBS for its connectivity.

Figure 3.4: Dependency of dead zone on macrocell RSSI and femtoBS transmit power

Figure 3.4 shows that the dead zone radius can be decreased by reducing the femtoBS transmit power and maintaining the same coverage through dual hops [144]. Also the dual hop transmission enables the macroUEs that are located in the dead zone regions to connect to the nearby femtoBS via a registered femtoUE. This proves to be beneficial in heavily crowded metropolitan areas where UEs are located behind buildings or at corners where macroBS coverage is restricted due to obstacles in the transmission path. Also this mode of transmission is found to be efficient in terms of system capacity as well as shared spectrum usage when the separation between the femtoBS and the interfering macroBS increases. When the femtoBS is located far away from the macroBS, such that the interference from the macroBS reduces significantly, bandwidth becomes the dominant factor for determining the received throughput instead of the SINR. Hence the relay transmission helps the macroUEs in achieving a better throughput even if they are at the macrocell edge that too with shared spectrum usage. In short, as the separation between the femtoBS and the co-existing macroBS increases, the interference from macroBS with shared spectrum usage to the femtocell reduces due to increased path loss, and hence the achieved capacity increases. However, this will not affect the macroUE throughput as it still remains connected to the femtoBS via the femtoUE.

Even though the basic concept of femto-relays explored in this section project significant advantages in terms of coverage extension, interference reduction, capacity enhancement and dead

zone elimination, the model discussed demands macroBS intervention in its operation and assumes that the distance from the relay node to the femtoBS and macroUE to be the same. However, these assumptions may not be always true in real-time situations. In addition, the task of selecting the most appropriate femto-relays from the immediate neighborhood is vested upon the macroUE which involves multiple signaling and can hence cost its battery power. Since the UEs with limited battery power cannot afford the detection of femto-relays, an innovative approach for the macroUEs to detect the nearby femto-relays must be devised. The simplest solution is to embed the self-organization capability into the femtoBSs, so that it announces its availability for relaying to the nearby network entities which also helps in achieving significant energy savings. In fact, femtocells can guarantee a 7: 1 operational energy efficiency advantage ratio in comparison to the densification of macrocell network to provide an equivalent indoor coverage [148]. However, mass deployment of femtocells can result in throughput degradation of the macrocell network which demands a tradeoff between energy efficiency and system throughput [149]. The concept of energy-efficient self-organizing femto-relays was developed in this context. The details are discussed in the next section.

3.4 Energy Efficient Self-Organizing Femto-relay Network

The drawbacks of the former femto-relay operation and the critical need for energy conservation while promising better QoS encourages the development of an energy efficient context-aware, coordinated multi-tier cooperation in femto-relay networks. The more precise, the details regarding changes in the network are exchanged between multiple tiers, the better will be the decisions made regarding the connectivity options in a femto-relay network. For the same reason, we analyze the possibility of exploiting self-organization features within a femto-relay network in order to boost the network capacity by assuring significant energy savings. Clearly, the improvements that it brings along, are essentially limited by the choice of an efficient network architecture devised with proper signaling capabilities. The contributions of this work address these challenges to make it capable of overcoming the glitches in communication between tiers.

The former case of femto-relay operation demands the macroBS intervention in its operation. In addition, it was the responsibility of the macroUE to individually check for cooperating femtoBS and notify the macroBS with its NCL. With limited resource, periodic updation of NCL information with the macroBS would result in rapid battery drain in the UEs. However, since the UEs are individually managed by the femtoBS and macroBS, introducing certain amount of cooperation and coordination between both the networks would enable a smooth transition from macro to femto network and vice-versa. Hence the concept of self-organization can be introduced in the femto-relay

network whose cognition capabilities will enable the energy efficient routing of macrocell traffic via femtoUEs, taking into consideration the channel parameters and other network environmental factors. These self-organizing femtocells are capable of acting as relay nodes, which assure connectivity to macroUEs in times of enormous data-traffic. The essential idea is that the femtoBSs should provide relay service via their femtoUE to the nearby macroUEs which expect a better QoS due to its proximity to the femtoBS. The relaying service offered by a UE at a given point of time can be beneficial for them in the future. This is because, when the same UE is connected to a macroBS and needs a high data rate service, it can rely on the femtocell network for a better QoS in exchange for what it had done in the past. This reward policy can further be initiated by the network operator as well in terms of pricing or any further data services.

3.4.1 Self-Organizing Femto-relay operation

The main motivation behind the proposed concept of self-organizing femto-relay is to enable the macroUEs to explore and exploit better data rate services available through pre-existing high efficient links in the immediate neighborhood. This should help them in attaining better energy efficiency by conserving the battery power and at the same time reducing the transmit power. This further helps in reducing the overall interference created in the network to the same tier as well as to the co-existing tier. It also aims at exploiting the idle-femtoBS and femtoUEs in the network to meet the ever increasing traffic demands and thereby enhances the aggregate system performance. The main difference between the proposed scheme and the earlier schemes available in the literature is the enabling of information exchange between the self-organizing femtoBSs to aid the macroUE in identifying the nearby femto-relay without compromising on its battery power.

This section explains in detail, the signaling flow involved in this architecture. It describes how a femtocell dynamically self-adjusts to the environment, broadcast the information regarding their availability to serve user-requests and finally establishes connection with the users through their attached femtoUEs to maintain and improve the network stability and performance. It basically involves the following procedures:

3.4.1.1 Creation of Femto_relay_table

The execution of this procedure is part of the self-organization process, which enables every femtocell to be aware of its immediate neighbors and their operational status. This further forms the basis for making future decisions to support subscribers, initiate handovers and improve the network capacity. Femtocell being a plug and play device, connects itself to the operator IP network via backhaul connection when switched on. The femtocell registers and authenticates itself with a

femtoBS ID provided by the operator network and initializes its radio parameters with the default configuration automatically. It also obtains the broadcast channel (BCH) information during start-up. The same BCH is used by every femtocell under a given macrocell coverage area to broadcast its messages. The femtoBS further needs to configure its own neighboring entity list by sensing the environment. It also enables the macroUEs to create the *femto_relay_table* by listening to the femtocell BCH. The process involves the following steps:

Step 1: Upon initialization and establishing connection with the network, each femtoBS broadcasts the message ACTIVE_MSG (femtoBS_ID, idle_femtoUEs) over the BCH to notify the nearby network entities regarding its presence (femtoBS_ID) along with the information on the number of idle femtoUEs attached to it (idle_femtoUEs). This message is transmitted at short intervals with double the regular signal strength (but not too large to introduce intolerable interference) through the air interface. Reception of this message by the macroUE helps in the creation of *femto_relay_table*.

Table 3.2: FRS Algorithm for routing the traffic through femto-relays

```

1: for all macroUE  $m$  do
2:   for all femtoBS  $f$  do
3:     if idle_fUE > 0
4:        $\text{SINR}_{\text{best}_f} = \min(\text{SINR}_{f\text{BS}_f\text{UE}}, \text{SINR}_{f\text{UE}_m\text{UE}})$ 
5:       if  $\text{SINR}_{\text{best}_f} > \text{SINR}_{m\text{BS}_m\text{UE}}$ 
6:         Store  $\text{SINR}_{\text{best}_f}$ 
7:       end if
8:     end if
9:   end for
10:  Prepare femto_relay_table in descending order of  $\text{SINR}_{\text{best}_f}$ 
11:  if femto_relay_table not equal to NULL
12:    route  $m^{\text{th}}$  macroUE traffic through femto_relay_table[0]
13:  else
14:    resume  $m^{\text{th}}$  macroUE traffic through macroBS
15:  end if
16: end for

```

Step 2: On receiving the ACTIVE_MSG, every other entity in the network (including other femtoBS and macroUEs) stores this information to generate a list of neighboring entities based on their signal strength which they update periodically. Periodic transmission of the ACTIVE_MSG also helps the macroUE to update the *femto_relay_table* by removing a switched off neighbor from its list, if it does not receive the message for a given period of time. The table essentially arranges the femtoBSs based on a femto-relay selection (FRS) algorithm and the number of idle femtoUEs attached to it. The FRS algorithm employs an opportunistic selection algorithm, which first

eliminates all the femtoBS without any idle femtoUEs and then arranges the list of femtoBS taking into consideration the end-to-end SINR of each femtoBS-femtoUE-macroUE link greater than a predetermined threshold. The algorithm is explained in detail in Table 3.2.

Unlike the earlier methods proposed in the literature, where the UEs always initiate a connection request with the femtoBS, here the broadcast messages from the femtoBS helps a macroUE to proceed with a high bandwidth connection establishment with the femtoBS. This approach is adopted due to the significant power consumption concern and helps to save the limited battery life of the UEs.

3.4.1.2 Initiation of MacroUE-femto-relay Connection

After preparing the *femto_relay_table*, a macroUE can always request for connection to the femtoBS via the femtoUE. For this, firstly, the macroUE notifies the macroBS regarding the availability of nearby femtoBSs with idle femtoUEs capable of serving its data requests. The macroUE initiates the RELAY_SERVICE_REQ along with the *femto_relay_table* to the macroBS so as to update the mobility management information which then initiates the handover to the first femtoBS within the list. The macroBS also keeps track of the amount of data transfer that takes place during this process, which may be rewarded to the relaying femtoUE either economically or in terms of similar free data-services when it is under the macrocell coverage. Figure 3.5 highlights the signaling involved in the connection establishment procedure.

3.4.1.3 Connection Handover from MacroBS to Femto-relay

The macroBS on receiving the RELAY_SERVICE_REQ and *femto_relay_table* from the macroUE, notifies the same to the MCN through the SGW. MCN connects to the first femtoBS in the list through the FGW, and enquires on its availability to participate in the relaying operation. The femtoBS makes the same query to that idle femtoUE which assures the best channel quality as per the *femto_relay_table*. Once the femtoBS receives a positive response from its subscriber, it notifies the macroBS with its positive acknowledgement through the RELAY_SERVICE_ACK message along with UE details through the MCN. At this point, it is also possible for an idle femtoUE attached to the femtoBS to deny the relay-service request due to various reasons like low battery. If every attached femtoUE denies the relay service request, then the femtoBS signals the negative acknowledgement to the MCN, which forces it to select the next femtoBS in the list. This process continues until the macroBS finds a cooperative idle femtoUE attached to a femtoBS ready for relay service. Now the SGW sends a proxy binding update (PBU) message to the MCN which carries the information of the selected femtoBS as well. In response to this, the MCN suspends the

routing information for the macroBS and initiates the connection of the bi-tunnel endpoint to FGW. This helps in redirecting the data destined to SGW to the FGW. In the meantime, SGW receives the proxy binding acknowledgement (PBA) suspension message from the MCN in response to which it collects the channel information from the macroBS and delivers to the MCN via PBU suspension message. Now the MCN initiates the handover to the selected femtoBS through the FGW by passing on the PBA relay message containing the channel information. FemtoBS sends the RELAY_SERVICE_INITIATE message to the femtoUE which uses the channel information to communicate with the macroUE. Initial channel that was occupied by the femtoUE is now released for the other femtoUEs which helps in efficient spectrum utilization.

Figure 3.5: Femto-relay establishment and termination signalling

3.4.1.4 Connection Handover from Femto-relay to Femto-relay

When the femtoUE acting as relay node has its own personal requests to serve or if the femtoUE is moving out of the femtoBS coverage area, it may no longer serve the macroUE. The same situation may also arise when the macroUE is moving out of the femto-relay coverage area (i.e. when the RSSI falls below a predetermined threshold). In all these cases, a handover request is initiated to other idle femtoUEs attached to the same femtoBS which also assures a better channel

quality than the macroBS-macroUE direct link. Thus the femtoBS restarts the querying process in which it enquires every other idle UE attached to it for its interest in relay service. As soon as it receives a positive acknowledgement from a femtoUE, it initiates the handover and pass on the details of the new relay node to the macroUE and FGW which updates the MCN. If it concludes, that none of the attached femtoUE is ready to participate in the relay service, it sends the relay-handover message to the macroUE through the femto-relay. In response, the macroUE sends the updated *femto_relay_table* to its serving femtoBS. The serving femtoBS routes this to the FGW which continues with the querying till it finds an idle femtoUE attached to a femtoBS to serve its request. The FGW finally hands over the request to the newly selected femtoBS while it updates the same information to the MCN for mobility management. The signalling proceeds in the same way as explained earlier. Considering the worst case scenario where none of the femtoUEs is ready to participate in the relay operation, femtoBS signals this information to the macroUE via femto-relay which causes the macroUE to initiate the macroUE-femto-relay connection termination request, explained further. Then macroUE migrates back to its serving macroBS and resumes the transmission directly in its initial channel which will be released by the femtoBS. The macroUE information stored in the MCN by the macroBS enables this smooth transition from the femto network to the macro network without any IPv6 registration.

3.4.1.5 Termination of MacroUE-Femto-relay Connection

The termination procedure involves the reverse signalling as that of the connection initiation except that a relay termination request is used instead of connection initiation. The termination of the macroUE-femto-relay connection can happen on completion of macroUE service. During this process, the macroUE sends the RELAY_TERMINATION_REQ to femtoBS via femtoUE. FemtoBS notifies the same to FGW which passes on the information to the core network. The core network informs the macroBS through the SGW and initiates the PBU relay termination. This clears the radio link connectivity of the macroUE with the femtoBS as well as the macroBS. The signaling procedures involved in self-organizing femto-relay termination is highlighted in Figure 3.5.

3.4.2 Simulation and Performance Evaluation

The efficiency of the self-organizing femto-relay network is evaluated through extensive simulation runs which analyzes different network scenarios to project its performance enhancement in comparison to the earlier methods available in literature.

In this setup, the macroUEs and femtoUEs follow a Poisson distribution with a density $1/(2500\pi^2)$ per m^2 within the macrocell network. The SINR threshold for correct decoding is assumed to be 10 dB. The simulation parameters are same as that provided in Table 3.1 and additional parameters used for the setup are provided in Table 3.3.

Table 3.3: Simulation Parameters

PARAMETER	VALUE
SINR threshold for correct decoding	10 dB
FemtoBS coverage radius	20 m
MacroBS coverage radius	600 m
Number of femtoUEs attached to each femtoBS	2-5

3.4.2.1 Capacity Improvement

The associated SINR of the m^{th} macroUE attached to macroBS i , in the downlink is formulated as:

$$SINR_{mBS-mUE} = \frac{P_i^m |h_0|^2 d^{-n}}{\sum_{j=1, j \neq i}^M P_{mb} I_j^m + \sum_{k=1}^F P_{fb} I_k^m + \sigma^2} \quad (3.15)$$

where I_j^m and I_k^m represent the channel attenuation between macroBS j - macroUE m and femtoBS k - macroUE m , respectively. The interference at macroUE m is due to the signal transmissions from neighboring macroBS j and femtoBS k . Similarly the SINR of the f^{th} femtoUE attached to femtoBS i , in the downlink is formulated as:

$$SINR_{fBS-fUE} = \frac{P_i^f |h_0|^2 d^{-n}}{\sum_{j=1}^M P_{mb} I_j^f + \sum_{k=1, k \neq i}^F P_{fb} I_k^f + \sigma^2} \quad (3.16)$$

where I_j^f and I_k^f represent the channel attenuation between macroBS j - femtoUE f and femtoBS k - femtoUE m respectively. The interference at femtoUE f is due to the signal transmissions from neighboring macroBS j and femtoBS k . However, in both the cases the interference from the neighboring network entities is assumed to be minimum. This is because the channel used for transmission is allotted by the MCN to the macroBS for its transmission and falls within the interference limited network planning parameters. This assures a better quality link (SINR_{best}) which is finally selected as per the algorithm given in Table 3.2 and is used in calculating the channel capacity by Shannon's Theorem.

In the first simulation scenario, we analyze the efficiency of the proposed FRS algorithm by evaluating the number of macroUEs that can be served in a two-tier network by means of femto-relays. It is evident from Figure 3.6 that the number of cooperating femto-relays increases

significantly with the increase in femtoBS density. This reflects the reduction in interference, conservation of power and increase in system capacity that is achievable by means of the proposed method.

Figure 3.6: MacroUEs served through FRS algorithm with increase in femtoBS density

Figure 3.7: MacroUE downlink capacity analysis with and without femto-relays

Figure 3.7 projects the capacity improvement for the macrocell users in a femto-relay activated system. We find that the use of femto-relays guarantee better throughput for the macroUEs due to the reduction in radio transmission range and the improvement in QoS. Unlike the expected scenario

where the increase in femtoBS density may result in network interference aggregation, the concept of relays in fact helps in minimizing the interference and hence improve the system capacity.

3.4.2.2 Energy Efficiency

The channel allocation to the users in turn aims at enhancing the overall network energy efficiency (EE), which is measured in terms of number of bits transmitted per joule of energy. Total Power consumption (P_{tot}) of a macroBS in transmission mode consists of two parts. First part corresponds to the static part (P_{stat}) also known as fixed site power, which includes the signal processing power, battery backup and site cooling. This is independent of data rate and exists whenever the macroBS is in transmission mode [150]. Static power of femtoBS is comparatively lower, since it does not require any cooling. The second part corresponds to the dynamic transmit power (P_{dym}) also known as the radiated power which depends on the data rate, QoS demanded by the customer and the channel environment. In this case too, femtoBS power consumption is comparatively lower due to advantageous path loss conditions. Thus the EE of the self-organizing femto-relay network with a single macrocell is given by [151]:

$$EE = \frac{C_{mb} + \sum_{k=1}^{FR} C_{fr_k}}{P_{tot_mb} + \sum_{k=1}^{FR} (P_{tot_fb} + P_{tot_fu})} \quad (3.17)$$

where FR is the total number of femto-relays, C_{mb} corresponds to the average throughput via macroBS with total power consumption P_{tot_mb} and C_{fr_k} corresponds to the average throughput via femto-relay k with power consumption $(P_{tot_fb} + P_{tot_fu})$. P_{stat} of the macroBS being significantly larger than that of femtoBS, expects more data traffic to be routed through femtoBS so as to increase the EE of the system as a whole. In short, switching the transmission of macroUEs to femtoBS via femto-relays assure a significant reduction in total power consumption.

With cell-coverage being a primary concern in wireless communication systems, increasing the base-station density is considered as the primary solution to guarantee effective coverage. However, with the same transmission power, femtocells and macrocells can result in different cell-coverage providing different data rate to individual users and hence resulting in varying energy efficiency. Therefore, analyzing mere energy efficiency per site is not enough for comparing networks that involve base stations providing different cell coverage. It is in this context that we use area energy efficiency (AEE) to assess the energy efficiency of the network relative to the coverage area that it provides. AEE for a base-station is defined as the energy efficiency that it offers per unit area of its coverage. Hence AEE of the self-organizing femto-relay network with a single macrocell and FR femto-relays is given by:

$$AEE = \frac{EE_{mb} + \sum_{k=1}^{FR} EE_{fr_k}}{A_{mb} + \sum_{k=1}^{FR} A_{fr_k}} \quad (3.18)$$

Where A_{mb} and A_{fr_k} correspond to the coverage area of the macroBS and femto-relay system respectively.

Figure 3.8: Energy efficiency comparison of the network with and without relaying

Figure 3.9: Area Energy efficiency comparison of the network with and without relaying

The energy efficiency and area energy efficiency achieved through femto-relays is clear from Figure 3.8 and Figure 3.9 respectively. It explains that for a given static power of femtoBS and macroBS, relaying assures better data rate while at the same time decreases the overall energy utilization, and hence improves the EE and AEE. This is due to the fact that femto-relays can extend

the coverage of the femtocell with lower transmit power which enables them to deliver more information bits with lower energy consumption due to significantly reduced path loss. However, the increase in femtoBS density way beyond the macroUE density saturates the achievable EE and does not contribute much towards the system performance. The reason being that the excessive interference generated in the system is not compensated by the effective and efficient usage of the increased base-station density.

3.5 Summary

Network congestion caused by the exponential increase in user traffic is a major concern for many operators around the world. Operators cannot address the problems by resorting to the traditional cell splitting approaches because unequal demands on data bandwidth require a more granular treatment in providing the needed data capacity in a cost-effective manner. However, optimizing the utilization of the existing cellular architecture can solve the problem to a great extent. It is in this context, this chapter proposed a novel multihop based femtocell network design known as femto-relays, which is capable of extending the femtocell coverage beyond its radio transmission range. The advantages of femto-relays are very compelling since they blend easily into the existing network, using the under-utilized femtocell backhaul and network architectures to offload the macrocell traffic and thereby offer them better quality of service. Operators can leverage existing infrastructure to seamlessly offload macrocell data through femto-relays, which in turn rewards the femtocell users in terms of pricing options or other data services. The solution also proves to be best suited for coverage extension and dead zone reductions. As interference mitigation forms an integral part of the femto-relay concept, it can be one of the best strategic options for operators to guarantee better system performance as well.

The femto-relay concept was further extended to a self-organizing network solution where its operation was automated with minimum intervention from the macroBS which assured comparatively lower signaling overheads. In addition, it also helped in improving the energy efficiency of the network along with capacity benefits. The significant benefits and the major contribution of this method towards harmonious co-existence of femto-macro network was validated through extensive simulation studies.

Chapter 4

Interference Limited Frequency Reuse through Reverse Frequency Allocation

Without deviation from the norm, progress is not possible.

-Frank Zappa.

4.1 Introduction

The evolving future wireless communication systems are envisioned to overcome the fundamental challenges of existing cellular networks to offer its customers, the best possible services which include higher throughput, better coverage, efficient interference management and intelligent frequency reuse, all at relatively flat revenues per bit. The key challenge among them is still the efficient resource allocation, which demands aggressive frequency reuse mainly due to its high price and scarcity. As a result, a variety of resource allocation methods have already been explored and pushed towards their limits. At the same time, the commercial success of cellular networks has paved way to enhance the system capacity by increasing the spatial reuse through femtocells. This further complicated the resource allocation challenge through cross-tier interference in the network which ironically degraded the system performance.

At this standpoint, the most sought after interference avoidance technique that presents pragmatic solution to mitigate interference is via orthogonalization of wireless resources across those subset of users in multi-tiers that are severely affected by it. The interference management methodologies proposed are also expected to smoothly integrate into the current multi-tier cellular architecture, without causing any additional signaling overheads but at the same time capable enough to optimize the resource utilization. It is in this context, that this chapter investigates an innovative scheme of network-aware spectrum management for cross-tier interference avoidance between macrocells and femtocells in FDD networks known as the Reverse Frequency Allocation (RFA).

Here, the main focus is on solving the spectrum sharing challenge for which, a low-complexity strategy that allows a quick construction of orthogonal frequency patterns with emphasis on improved spectral efficiency and increased downlink system capacity is proposed. The primary idea behind the proposed scheme is to incorporate complementary spectrum allocation between overlapping macrocell and femtocells. It tries to address the interference problem by restricting the macroBS and femtoBS from simultaneously transmitting on the same frequency at a given location in a given direction, say UL or DL. One of the significant benefits of this method is that, by opportunistically reusing the degrees of freedom in different regions of macrocell coverage, the femtocells intensify the frequency reuse, which in turns translates into better system spectral efficiency. A similar approach in TDD using reversed-pair frame is proposed in [135] which requires proper time synchronization between the femtocell and macrocell network since the operation is restricted in time domain. Also it demands processing at the receiving end based on channel quality estimations for interference mitigation. On the contrary, the proposed scheme is implemented in frequency domain, which avoids the processing complexity and timing synchronization for femto-macro transmissions. Furthermore, [152, 153] suggests the reuse of macrocell uplink spectrum by the TDD femtocells, whereas FDD femtocells in the RFA method reuse the entire macrocell spectrum and not the uplink segment alone. Hence, to the best of our knowledge, the proposed RFA scheme seems to be the first of its kind available for FDD networks, which reuse the entire macrocell spectrum and thereby enhance the long term downlink system capacity.

The system performance in this work is mainly evaluated from downlink perspective, since traffic asymmetry through downlink dominance projected by many data surveys [154] makes boosting of downlink capacity as the priority of the hour.

4.2 RFA Strategy and Planning

In times when network operators were facing the challenge of efficient balancing of traffic-load among different tiers in a multi-tier cellular network, SFR (also known as Soft Frequency Allocation-SFA) emerged as an efficacious solution due to its effectiveness in inter-cell interference coordination without compromising on spectral efficiency [155]. Moreover the inter-cell interference problem in the OFDMA multi-cellular systems is even more serious than that in the CDMA systems, hence SFR once again becomes an important option for the next generation OFDMA broadband cellular mobile systems. However, even with SFR, achieving a unity frequency reuse factor (FRF) was almost impossible. As a result, by modifying and incorporating all the benefits of SFR, the RFA strategy is developed to raise the FRF in multi-tier cellular network even

beyond the unity scale. This hybrid method of frequency reuse is in fact a broader extension of the recommendation given in [156]. The basic idea is to partition the entire available spectrum into sub-bands, which are allotted to spatially separated macrocell regions. In addition, their direction of transmission is reversed and assigned to femtocells. The spectrum access by the femtocells are planned such that they are positioned at an acceptable separation from those regions of the macrocell which operates on co-channel frequency reuse. The steps in RFA are as follows:

4.2.1 Spatial Partitioning and Spectrum Allocation for a Single Macrocell

As in the case of SFA, the macrocell is partitioned into two non-overlapping regions namely cell-center (inner region) and cell-edge (outer region). The boundary separating the inner region and outer region can be a design parameter. A hard-division with 63% of the macrocell coverage area belonging to cell-center and the rest to cell-edge region can be adopted as in [157]. Else, a more dynamic decision on whether a macroUE belongs to the inner or outer region can be made on the basis of reported SINR of the reference signal during the initial configuration of the periodic status update [158]. If the reported SINR is well above the pre-determined SINR threshold (say T_{RFA}), then the macroBS considers the macroUE to be located within the inner region. If not, i.e., the reported SINR of the macroUE is below the pre-determined SINR threshold, then the macroBS concludes it to be in the outer region. This partitioning may vary depending on the specific multipath and fading profiles which has not been considered in our studies for fair comparison. Now, the available frequency spectrum (S) of the macrocell is allocated to the inner region (S_1) and outer region (S_2) macroUEs such that $S = S_1 \cup S_2$. The partition S_1 contains the UL and DL frequency carriers for the inner region macro-users whereas the partition S_2 contains the corresponding carriers for the outer region macro-users. The macrocell spectrum partitioning and allocation is not random and is done as a part of the network planning by the network operator.

4.2.2 Femtocell Location Identification and Spectrum Access in a Single Cell

Being a plug and play device, a femtocell is expected to autonomously integrate into the network by intelligently choosing its own operating spectrum. Hence femtocells also classify themselves into inner region or outer region femtocell based on the reported SINR of the reference signal at the macroBS during the initial configuration of the femtoBS. On the basis of the SINR of the reference signal of the femtoBS received at the macroBS (received signal strength indication (RSSI) value) during the process of pilot sensing, a macroBS determines whether the femtoBS and the attached UEs are located in the cell-center region or the cell-edge region and the information is notified to the femtoBS. However, in the worst cases where the channel conditions are deteriorated due to

excessive fading and shadowing, the registered physical address associated with the broadband IP address or the GPS location information obtained during its installation can be used as an additional precautionary measure to assist in location selection. During switching on, the femtoBS locks itself to the GPS signal to ensure that it is located within an area where it is legal to operate at its specific frequency sub-band. This information can be communicated to the network controller over the internet backhaul and the femtocell-gateway to make accurate decisions on zone selection and hence sub-band allocation.

Figure 4.1: Reverse Frequency Allocation

Table 4.1: Spectrum arrangement in RFA Method

	Inner Region	Outer Region
Macrocell Frequency	Downlink: S_{1a} (green arrow pointing down) Uplink: S_{1b} (pink arrow pointing up) S_1	Downlink: S_{2a} (orange arrow pointing down) Uplink: S_{2b} (yellow arrow pointing up) S_2
Femtocell Frequency	Downlink: S'_{2a} (yellow arrow pointing down) Uplink: S_{2a} (orange arrow pointing up) S'_2	Downlink: S'_{1a} (pink arrow pointing down) Uplink: S_{1a} (green arrow pointing up) S'_1

The random deployment of the femtocells demand spectral resources which are orthogonal to the macrocell spectrum to be allocated in its area of operation to minimize the cross-tier interference. Hence the frequency spectrum of the cell-center region macroUEs (S_1) is used by the femtoUEs in the cell-edge region and that of the cell-edge region macroUEs (S_2) is used by the cell-center region femtoUEs. However, the FDD technology allocates UL and DL frequency carriers in pair for each user. It is in this context that the Reverse Frequency Allocation (RFA) between femtoUEs and

macroUEs is proposed as a potential solution for interference mitigation. In this method, the term “*Reverse Frequency*” highlights the fact that the UL carriers of the macroUEs are allocated as DL carriers to the femtoBS and the DL carriers of the macroBS are allocated as UL carriers to the femtoUEs. It is this complementary frequency allocation in UL and DL between femto-macro networks that makes this scheme different from the classical soft fractional frequency reuse method. This “*Reversed Mode*” of frequency allocation neither requires a dedicated spectrum for the femtocells, nor does it operate on the macrocell spectrum. However it enhances the spectral efficiency when compared to that of other fractional frequency reuse schemes. This is because, femtocells reuse the entire macrocell spectrum but with UL and DL frequency carriers interchanged/reversed to ensure minimal interference.

Figure 4.2: Reverse Frequency Allocation Algorithm flowchart for a single cell

Figure 4.1 explains how the complementary spectrum is allocated in two-tier femto-macro network with spatial separation. Here the spectrum partitions S'_1 and S'_2 of femtocell corresponds to the reversed UL and DL frequency pairs of spectrum partitions S_1 and S_2 of macrocell respectively. The frequency carriers in S_1 used for UL transmissions in the macrocell is used as the DL frequency carriers in S'_1 for the femtocell and the frequency carriers in S_2 used for DL transmissions in the

macrocell is used as the UL frequency carriers in S'_1 for the femtocell. Same is the case for S_2 and S'_2 also. This is explained in Table 4.1.

The flow-chart in Figure 4.2 demonstrates the reverse frequency allocation carried out in a two-tier femto-macro network consisting of femtocells operating within the macrocell coverage area. It highlights how the UEs are categorized into cell-center and cell edge region UEs in the case of femtocell as well as macrocell. Finally, it explains how orthogonal sub-carriers are allocated to femtoUEs and macroUEs located within the cell-center region or cell-edge region. However, this allocation is valid for the case of a single macrocell. Details of RFA in multi-cell scenario is discussed in the next section.

4.2.3 RFA in Multi-cell Scenario

Figure 4.3: Reverse Frequency Allocation for 3 cell cluster

Figure 4.3 explains the approximate layout of the proposed femto-macro network with reverse frequency allocation for a 3-cell cluster which can be scaled to any number of cells in the network. Unlike in figure 4.3, in reality, the boundaries of every single region is neither rigid nor of uniform geographical size or shape due to fading. It merely highlights the need for a spatial separation for

resource allocation and can be perceived as the average coverage footprints of the multiple antenna elements over a period of time. Here, the total available macrocell spectrum is divided into seven orthogonal sub-bands A, B, C, D, E, F and G as a part of network planning, with major portion of carriers allocated to sub-band A, for the macroUEs in the cell-center region. The rest of the available orthogonal sub-bands B, C, D, E, F, and G are allocated to macroUEs in each of the 6 cell-edge zones (E1-E6). This distribution of carriers among specific geographical region for macroUEs along the cell-edge is performed dynamically based on user density and their average channel states. This distribution decision is dependent on the system performance and the QoS requirements of the specific region users. Hence it permits the scheduling algorithm at the BS to operate beyond tight limits and perform resource allocation as per the system requirements.

In order to avoid any uplink performance degradation, the radio transmission in the cell-center region is carried out by a centrally located macroBS with omni-directional antenna that holds the main processing modules like the channel cards. For the cell-edge region, we resort to the distributed antenna system (DAS) [159]. The DAS in our proposed architecture constitutes the central macroBS and 6 directional distributed antenna elements (DAE) connected through high-speed back bone network via dedicated wires, fiber optics, or an exclusive RF link, in star connection topology within the cell. With proper configuration and planned positioning of DAEs; DAS has the potential for outperforming centralized antenna system. For this reason, the location decision of DAE is important. Hence the directional DAEs are 120 degree directional antenna, each located at the vertex of the cell, facing towards the central macroBS as shown in Figure 4.3 [160]. The mainspring behind deploying distributed antenna system is to avoid the location optimality problem, which can be annoying in case of real cellular systems. The other reason being the inter-cell interference mitigation through reduced transmit power as DAS offers lesser amount of strong interference sources in comparison to the classical centrally located omnidirectional antenna system. In our work, the connection between the macroBS and the DAEs is through optical fiber, so that the assumption of near-perfect reception of data at the DAE from the macroBS becomes realistic. The DAS deployment proves to be a potential inter-cell interference countermeasure that boosts the system capacity. At the same time, it assures power efficiency and better coverage mainly due to the absence of overlapping frequency bands [159]. All these benefits make DAS suitable for the proposed architecture even though the complexity and CAPEX that it brings along cannot be neglected.

Let us consider the resource allocation for femtoUEs. Since the macroUEs in the cell-center region are allocated with sub-band A, the femtoUEs in the cell-edge region are allocated with the reversed sub-band i.e. A'. Since the macrocell radio transmission range for sub-band A is restricted

to the cell-center region, the femtoUEs making use of A' in the cell-edge region are free from interference. Also, the smaller transmission range of femtoBS in the cell-edge region assures that the macroUEs operating on the same sub-band in the cell-center region are free from interference. The same sub-bands of the cell-edge region macroUEs are allocated in reverse mode to femtoUEs in each of the 6 cell-center sectors (C1-C6) assuring proper spatial separation from the macroUEs utilizing these sub-bands. The assignment of carriers to the sub-bands used by femtoUEs in the cell-center sectors are not strict and is not restricted by the rigid boundaries represented in Figure 4.3. This increases the trunking efficiency of the scheduling operation performed in the cell-center region. This is again dependent on the channel parameters and the QoS requirements of the femtocell users.

The operational sub-band determination (and hence the sub-zone) by the femtoBS (and hence that of its attached femtoUEs) is carried out during its switching on by sensing the neighboring macroBS signals. It then eliminates those with higher signal strength and chooses the one with least signal strength in the macrocell sub-area. The detailed operational algorithm is explained later in this section. In short, FRF of 1 is applied to the cell-center region and FRF of 6 is applied to the cell-edge region of the macrocell network whereas an FRF of 1 is applied to the cell-edge region and that of 6 is applied to the cell-center region of the femtocell network. Here the intra-cell interference is mitigated since the cell-center macroUEs do not share the same spectrum with cell-edge macroUEs and inter-cell interference is controlled due to the sectoring technique employed in spectrum allocation. The use of distributed antenna system (DAS) with efficient power control further supports this mode of spectrum allocation within the macrocell coverage area where it prevents the radio transmission in one sector from interfering with the other. Also the inter-tier interference is controlled since the UEs in both tiers make use of different spectrum in a given zone that too in reversed mode.

The benefits of RFA method can be enumerated as follows. Firstly, cross-tier interference is minimized to a great extent since simultaneous transmission by femtocells and macrocells along a given frequency carrier do not take place in a given region (inner or outer) at a given time. This offers better capacity to the femtoUEs during femtocell transmission since they operate independent of the macrocell interference. Secondly, unlike the dynamic spectrum allocation schemes, the proposed method do not depend on any continuous signal exchange (other than for the RSSI reporting) between the femtoBS and the macroBS. This is because, once the decision on UE location is made, the resource allocation can be carried out independently by the femtoBS and the macroBS. Also the geographical separation in the sub-band allocation permits interference-free co-channel operation. Thirdly, since the femtocell is not interfered by the downlink transmissions from

the macroBS, the femtoBS coverage area is not restricted and does not require any additional power control mechanisms even if it is located close to the macroBS. This is because, reversing the direction of transmission frequency replaces the macroBS interferers with the macroUE interferers whose interference effect is comparatively negligible.

4.2.4 Operational Algorithm for Femtocell Spectrum Access with RFA

An operational algorithm for RFA is proposed for OFDMA cellular network with two tiers - macrocell network and femtocell network which is precisely explained in Table 4.2. The macrocell network is assumed to comprise of 3-cell clusters within which femtocells are distributed as independent spatial Poisson Point Process (PPP). The algorithm is applied to this overlapping tiers and can be further extended to any number of cells. Let F_o and F_i represent the number of femtocell users in the outer and inner region respectively whereas M_o and M_i represent the number of macrocell users in the outer and inner region respectively.

Table 4.2: RFA operational algorithm for femtocell spectrum access

```

1: for all femtoBS  $j \in (F_o \cup F_i)$  do
2:    $S_j \leftarrow S$  {Initialization}
3: end for
4: for all femtoBS  $j \in (F_o \cup F_i)$  do
5:    $R \leftarrow$  Set of RSSI values for all sub-bands allocated to the macrocell
6:    $R_f^* \leftarrow$  Highest RSSI value at the femtoBS  $j$ 
7:   if ( $R_f^* = R_A$ ) then {femtoBS  $j$  is located in the cell-center region}
8:      $S_j^* \leftarrow$  Set of six sub-bands with comparatively higher RSSI value
9:      $S_j \leftarrow (S_j - S_j^*)'$  {frequency sub-bands allocated for femtoBS  $j$ }
10:  else {femtoBS  $j$  is located in the cell-edge region}
11:     $S_j^* \leftarrow$  Set of all sub-bands except A
12:     $S_j \leftarrow (S_j - S_j^*)'$  {frequency sub-band allocated for femtoBS  $j$ }
13:  end if
14: end for

```

In the case of multi-cell clusters, firstly the set of usable frequency sub-bands S_j for the femtoBS j is initialized to the entire available macroBS spectrum S , where $S = S_{Mi} \cup S_{Mo}$, similar to the methodology in [125]. Here S_{Mi} is the frequency spectrum available to the inner region macroUEs and S_{Mo} is the frequency spectrum available to the outer region macroUEs. As the femtoBS j is switched on, it senses the radio signals received from the neighboring macroBS with the help of the femtoUE and estimates the received signal strength indicator (RSSI) value R_f for each received frequency sub-band. Let R denote the set of RSSI value for all available frequency sub-bands in the macrocell and R_f^* denote the highest RSSI value. If RSSI value of sub-band A is found to be the

highest, it means that femtoBS j is located in the cell-center region i.e. within any of the 6 sectors C1-C6 as in Figure 4.3. In this case, femtoBS j forms S_j^* , a set of six sub-bands among the pack of 7 sub-bands, whose signal strength received at femtoBS j is comparatively higher. The set S_j^* is now excluded from S_j , which leaves behind the 7th sub-band to be allocated to femtoBS j in the reversed mode. If the RSSI value of sub-band A is not the highest, then it means that femtoBS j is located in the cell-edge region within any of the 6 zones represented by E1-E6. In this case femtoBS forms S_j^* which comprises of the set of all sub-bands except A. Excluding S_j^* from S_j results in sub-band A to be allocated to femtoBS j in the reversed mode (A'). In worst case scenarios where the channel conditions do not permit the sectorized resource allocation with rigid boundaries, selection of a sub-band (and hence the UL-DL sub-carriers) by the femtoBS from which it receives the least interference ultimately serves the purpose.

4.3 System Model and Analysis

Multi-tier systems experiencing unpredictable channel conditions and erratic traffic load will have random priorities to satisfy, which can be formulated by different metrics. For example, networks expecting heavy traffic load should enhance their spectral efficiency while those that serve high-data rate requests should attain interference free operation. Prioritizing better efficiency for one metric may cause performance degradation of other metrics. Hence designers fix a hierarchy for the priorities based on system requirements, then fix optimal thresholds for multiple metrics. This section analyzes and evaluates such thresholds that play an important role in satisfying the customer QoS.

An OFDMA downlink cellular scenario with two tiers corresponding to macrocell network and femtocell network is considered as the system model. The location of the macroUEs and femtoUEs are modeled as independent spatial PPP of density λ . A standard power loss propagation model is used in our analysis which accounts for the mobile nodes that are permissible in a homogeneous PPP [161]. Now, let P_{fb} , P_{fu} , P_{mb} and P_{mu} represent the transmit powers of the femtoBS, femtoUE, macroBS and macroUE respectively, S_{Mi} , S_{Fi} and S_{Mo} , S_{Fo} represent the bandwidth allotted to the macroUEs and femtoUEs in the inner region and outer region respectively, σ^2 represents the noise power, P_s^{rc} corresponds to the transmitted signal power from sender s to receiver rc , r denotes the random variable which represents the distance between the interfering BS and the UE under consideration, n represents the path loss exponent and $|h_0|^2$ takes care of the shadowing effects, wall loss and small scale fading between any BS under consideration and the attached UE. The interference power at a receiver is assumed to be the sum of received power from

all other base stations in the network making use of the same sub-carrier as that of the home base station and is assumed to follow a general statistical distribution that includes all random effects like fading, shadowing etc.

4.3.1 Sub-carrier Allocation

Using Monte-Carlo simulations, it is shown in [162] that, the average network throughput is maximized when the sub-carrier allocation between the cell-center and cell-edge users is proportional to the square of the ratio of the inner region radius (αR where $\alpha \in (0, 1)$) to the macrocell radius (R) which is in turn dependent on the SINR threshold T_{RFA} . Hence, the ratio of the sub-carrier allocation (k) between the cell-center and cell-edge region of a macrocell network with frequency reuse 3 can be expressed as a factor of the area occupied and is given by:

$$k = \frac{\alpha^2}{1-\alpha^2} \quad (4.1)$$

However, in case of the Poisson distribution, this is not applicable since the likelihood of a dominant interferer is comparatively more and the allocation is based on SINR distribution. The number of sub-bands allocated is chosen as a value proportional to the complementary cumulative distribution function (CCDF) of SINR evaluated at the pre-determined RFA threshold T_{RFA} [165]. For e.g. $S_{Fo} = \lfloor (1 - F_o(T))S \rfloor$ and $S_{Fi} = \lfloor (1 - F_i(T))S \rfloor$ where $F_o(T)$ and $F_i(T)$ represents the coverage probability of the outer region and inner-region femto-users with T being the minimum received SINR threshold to be in coverage area. The allocation of sub-carriers is always planned and initiated by the network operator. Hence the threshold T_{RFA} can be set to an optimal value by the operator for an efficient partitioning of macrocell area and hence carry out a fair allocation of sub-carriers in the inner region and outer region. However, PPP model is considered to be nearly accurate as the uniform distribution case, with PPP serving the lower bound and uniform distribution serving the upper bound on the actual coverage probability [163]. Thus, the total number of available sub-carriers for macrocell users are subdivided into $S_{Mi} = \left\lceil S \left(\frac{k}{1+k} \right) \right\rceil$ ($\sim A$ band allocation) and $S_{Mo} = \lfloor S - S_{Mi} \rfloor$ and allotted among the macroUEs in the inner and outer region respectively. S_{Mo} is further partitioned (B, C, D, E, F, G) and allotted to macroUEs in 6 zones within the cell-edge region as shown in Figure 4.3. Now, as per RFA, the frequency spectrum available for resource allocation is doubled with macrocell operating on the conventional frequency bands and femtocell operating on the reversed frequency bands. Hence, sub-carrier allocation is reversed for femtoUEs with $S_{Fo} = S_{Mi}(\sim A')$ and $S_{Fi} = S_{Mo}$ made available to femtoUEs in the cell-edge and cell-center region respectively. S_{Fi} is further divided (B', C', D', E', F', G') and allotted to femtoUEs in 6 sectors

within the cell-center region as per the operational algorithm explained in Table 4.2. From these equations, it can be concluded that one of the main advantages of using the RFA scheme is the ability to achieve comparably higher spectral efficiency within each cell as well as within each tier.

4.3.2 Power Allocation

Higher transmit power is needed to reach the cell-edge region macroUEs when compared to cell-center region macroUEs if it is in case of conventional cellular architecture. However, such networks results in inter-cell interference. As a potential solution to this problem, in RFA scheme the overall transmit power is reduced and inter-cell interference is controlled through the use of DAS which possesses the additional merit of better and efficient coverage along with extended battery life [164]. Thus, efficient interference-limited transmission in the cell-edge region can be assured through DAS [160]. Assuming the total transmitting power (P_t) to be evenly distributed among all the sub-carriers (or PRBs) within the cell-center and cell-edge region of the macrocell, with P being the power per PRB (the power consumption per PRB is assumed to be equal for the sake of fair comparison) we have:

$$PS \left(\frac{k}{1+k} \right) + \sum_{i=1}^6 P_i = P_t \quad (4.2)$$

Here $\sum_{i=1}^6 P_i = P S \left(\frac{1}{1+k} \right)$ where P_i corresponds to the transmit power from the DAE i . Thus it is evident that the factor k , which is indirectly dependent on the SINR threshold T_{RFA} , has a critical influence on the system performance. At the same time, we have $S_{Fo} = \lfloor (1 - F_o(T))S \rfloor$ and $S_{Fi} = \lfloor (1 - F_i(T))S \rfloor$. This explains that with increase in T_{RFA} , the cell-center region radius decreases which results in more PRBs or sub-bands to be allocated to the cell-edge region UEs which in turn increases their average throughput. The reverse happens for decrease in T_{RFA} value, resulting in an improved throughput for the cell-center region UEs. In short, the implementation of DAS helps in maintaining an optimal value for UE performance. At the same time, variation in service distribution in each cell can be ensured by adjusting the SINR threshold value T_{RFA} . Hence it is always the choice of the system designer to choose a value for T_{RFA} based on the requirements of the macrocell and femtocell users to be served. Selecting an appropriate value for T_{RFA} and hence the corresponding k , based on the system preferences can enhance the overall performance by having a strict control over the interference and thereby improving the average user throughput.

4.3.3 Throughput

The associated SINR of the l^{th} femtocell user attached to femtoBS i , in the downlink is formulated as:

$$SINR_{DL_Fi} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{Fi} P_{fb} I_j^l + \sum_{k=1}^{Mo} P_{mu} I_k^l + \sigma^2} \quad (4.3)$$

$$SINR_{DL_Fo} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{Fo} P_{fb} I_j^l + \sum_{k=1}^{Mi} P_{mu} I_k^l + \sigma^2} \quad (4.4)$$

where $SINR_{DL_Fi}$ is the SINR of the inner region femtocell, $SINR_{DL_Fo}$ is the SINR of the outer region femtocell, $I_j^l (= |h_0|^2 r^{-n})$ and $I_k^l (= |h_0|^2 r^{-n})$ represent the attenuation on the channel connecting l^{th} femtocell user with j^{th} femtoBS and k^{th} macroUE respectively which is assumed to be zero if the sub-carrier used for transmission is not the same as that used by the serving femtoBS. In short, the interference at femtoUE l is due to the signal transmission from femtoBSs (j) and macroUEs (k) which are using the same frequency band as that of femtoUE l . The attenuation term is expected to take care of the wall penetration losses as well. As evident from equations (4.3) and (4.4), unlike the conventional system, the femtoUEs in the inner region is subject to interference from those femtoBSs located within the same sector in the inner region and is never subject to interference by transmissions from femtoBSs located in the outer region. DL transmissions of femtoUEs in the inner region is subject to interference from the UL transmissions of outer region macroUE which use the same sub-band. Similarly, DL transmissions of femtoUEs in the outer region is subject to interference from UL transmissions of the inner region macroUEs. The SINR at the femtoBS i with attached femtoUE l , in the uplink is formulated as:

$$SINR_{UL_Fi} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq l}^{Fi} P_{fu} I_j^l + \sum_{k=1}^{Mo} P_{mb} I_k^l + \sigma^2} \quad (4.5)$$

$$SINR_{UL_Fo} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq l}^{Fo} P_{fu} I_j^l + \sum_{k=1}^{Mi} P_{mb} I_k^l + \sigma^2} \quad (4.6)$$

where $SINR_{UL_Fi}$ is the SINR of the inner region femtocell, $SINR_{UL_Fo}$ is the SINR of the outer region femtocell, $I_j^l (= |h_0|^2 r^{-n})$ and $I_k^l (= |h_0|^2 r^{-n})$ represent the attenuation on the channel connecting i^{th} femtoBS with j^{th} femtoUE and k^{th} macroBS respectively. The interference at femtoBS i is due to the signal transmission from femtoUEs (j) and macroBSs (k) which are using the same frequency band as that of femtoBS i which on the other hand is taken as zero. The attenuation term is assumed to take care of the wall penetration losses as well. Here also, UL transmissions of femtoBSs in the inner region are subject to interference by the DL transmission from the macroBS-DAEs in the outer region which use the same sub-band and UL transmissions of femtoBSs in the outer region are interfered by the DL transmission from the central macroBS to its subscribers in

the inner region. Every single node in our analysis is assumed to have good throughput for the sake of fair comparison.

The maximum capacity of error-free digital data that can be offered to the end-users over the communication link is further calculated using the Shannon-Hartley theorem.

4.3.4 Outage Probability

Outage probability (P_{ot}) is defined as the probability that a user's instantaneous SINR falls below a threshold, conditioned on the locations of the user and the interferers. In short it is the probability that the user moves out of the coverage area of the base station. Here T is the SINR threshold for the user to be in coverage. Thus, the outage probability in downlink for the cell-center and cell-edge femtoUEs respectively is given by:

$$P_{ot_DL_Fi} = \mathbb{P}(\text{SINR}_{DL_Fi} < T) = 1 - \mathbb{P}(\text{SINR}_{DL_Fi} > T) \quad (4.7)$$

$$P_{ot_DL_Fo} = \mathbb{P}(\text{SINR}_{DL_Fo} < T) = 1 - \mathbb{P}(\text{SINR}_{DL_Fo} > T) \quad (4.8)$$

where $\mathbb{P}(\text{SINR}_{DL_Fi} > T)$ and $\mathbb{P}(\text{SINR}_{DL_Fo} > T)$ represents the coverage probability of the inner region and outer region femtoUEs respectively. Coverage probability is equivalently the CCDF of the SINR for a particular reuse strategy which will be represented as $F(T)$. The general expression for the coverage probability of a typical MUE as a function of the SINR threshold (T), for given BS density (λ), path loss exponent (n) and the number of available frequency sub-carriers (Δ) is [155]:

$$P_c(T, \lambda, n, \Delta) = \pi\lambda \int_0^\infty e^{-\pi\lambda v \left(1 + \frac{1}{\Delta}\rho(T, n)\right) - \mu T \frac{\sigma^2}{P} v^{n/2}} dv, \quad (4.9)$$

$$\text{where } \rho(T, n) = T^{2/n} \int_{T^{-2/n}}^\infty \frac{1}{1+u^{n/2}} du$$

In case of RFA scheme, cell-edge users are classified as the ones whose SINR value is less than the threshold T_{RFA} and cell-center users represent the group which has SINR value well above T_{RFA} . Consider a femtoUE j with $\text{SINR} < T_{RFA}$ allocated a sub-carrier $\delta \in (1, \Delta)$ with uniform probability $1/\Delta$ experiencing new fading power $\hat{h}$. Then, equations (4.7) and (4.8) get modified to a conditional probability given by:

$$P_{ot_DL_Fi} = \mathbb{P}(\text{SINR}_{DL_Fi} < T) = 1 - \mathbb{P}(\text{SINR}_{DL_Fi} > T / \text{RSSI} > T_{RFA}) = 1 - F_i(T) \quad (4.10)$$

$$P_{ot_DL_Fo} = \mathbb{P}(\text{SINR}_{DL_Fo} < T) = 1 - \mathbb{P}(\text{SINR}_{DL_Fo} > T / \text{RSSI} < T_{RFA}) = 1 - F_o(T) \quad (4.11)$$

$F_i(T)$ and $F_o(T)$ represent the coverage probability of the inner and outer region femtoUE, respectively. From equations (4.4) and (4.11), the CCDF of the cell-edge user $F_o(T)$ conditioned on its previous SINR is given by the conditional probability:

$$F_o(T) = \mathbb{P} \left(\frac{P_i^l \hat{h}_0 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} l_j^l + \sum_{k=1}^{M_i} P_{mu} l_k^l + \sigma^2} > T \mid \frac{P_{mb} |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} l_j^l + \sum_{k=1}^{M_i} P_{mu} l_k^l + \sigma^2} < T_{RFA} \right) \quad (4.12)$$

Applying Bayes' Rule we have:

$$F_o(T) = \frac{\mathbb{P} \left(\frac{P_i^l \hat{h}_0 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} l_j^l + \sum_{k=1}^{M_i} P_{mu} l_k^l + \sigma^2} > T, \frac{P_{mb} |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} l_j^l + \sum_{k=1}^{M_i} P_{mu} l_k^l + \sigma^2} < T_{RFA} \right)}{\mathbb{P} \left(\frac{P_{mb} |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} l_j^l + \sum_{k=1}^{M_i} P_{mu} l_k^l + \sigma^2} < T_{RFA} \right)} \quad (4.13)$$

FemtoBS (P_{fb}) and macroUE (P_{mu}) transmit powers are comparable. Hence they can be generalized to a common term say P for ease of evaluation. Assuming that z represents the set of all interferers from the cell-center region femtoBSs and cell-edge region macroUEs, equation (4.13) can be simplified as:

$$F_o(T) = \frac{\mathbb{P} \left(\frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} > T, \frac{P_{mb} |h_0|^2 r^{-n}}{P I + \sigma^2} < T_{RFA} \right)}{\mathbb{P} \left(\frac{P_{mb} |h_0|^2 r^{-n}}{P I + \sigma^2} < T_{RFA} \right)} \text{ where } I = \sum_z |h_0|^2 r_z^{-n} \quad (4.14)$$

Since $\hat{h}_0$ and $|h_0|^2$ are i.i.d exponentially distributed with mean μ , the numerator of equation (4.14) can be simplified as:

$$\begin{aligned} & \mathbb{P} \left(\frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} > T, \frac{P_{mb} |h_0|^2 r^{-n}}{P I + \sigma^2} < T_{RFA} \right) \\ &= \mathbb{E} \left[e^{\left(-\mu \frac{T}{P} r^n (P \hat{I} + \sigma^2) \right)} - e^{\left(-\mu \frac{T}{P} r^n (P \hat{I} + \sigma^2) \right)} e^{\left(-\mu \frac{T_{RFA}}{P_{mb}} r^n (P I + \sigma^2) \right)} \right] \\ &= P_c(T, \lambda, n, \Delta) - \mathbb{E} \left[e^{\left(-\mu \frac{T}{P} r^n (P \hat{I} + \sigma^2) \right)} e^{\left(-\mu \frac{T_{RFA}}{P_{mb}} r^n (P I + \sigma^2) \right)} \right] \end{aligned} \quad (4.15)$$

Hence from equations (4.9), (4.14) and (4.15), we get:

$$F_o(T) = \frac{P_c(T, \lambda, n, \Delta) - \mathbb{E} \left[e^{\left(-\mu \frac{T}{P} r^n (P \hat{I} + \sigma^2) \right)} e^{\left(-\mu \frac{T_{RFA}}{P_{mb}} r^n (P I + \sigma^2) \right)} \right]}{1 - P_c(T_{RFA}, \lambda, n, 1)} \quad (4.16)$$

From [165] equation (4.16) simplifies to:

$$F_o(T) = \frac{P_c(T, \lambda, n, \Delta) - \pi \lambda \int_0^\infty e^{-\pi \lambda v (1 + 2\varepsilon(T, T_{RFA}, n, \Delta)) - \mu \sigma^2 \left(\frac{T}{P} + \frac{T_{RFA}}{P_{mb}}\right) v^{n/2}} dv}{1 - P_c(T_{RFA}, \lambda, n, 1)} \quad (4.17)$$

where $\varepsilon(T, T_{RFA}, n, \Delta) = \int_1^\infty \left[1 - \frac{1}{1 + T_{RFA} x^{-n}} \left(1 - \frac{1}{\Delta} \left(1 - \frac{1}{1 + T x^{-n}}\right)\right)\right] x dx$, and $P_c(T, \lambda, n, \Delta)$ is obtained from equation (4.9).

Substituting equation (4.17) in equation (4.11) gives the outage probability of the cell-edge region femtoUEs. Here, we observe that the results do not have a simple closed form expression but they can be evaluated using several numerical techniques. This is applicable for the forthcoming analysis as well. From equations (4.3) and (4.7), the CCDF of the cell-center users $F_i(T)$ conditioned on its previous SINR is given by:

$$F_i(T) = \mathbb{P} \left(\frac{P_i^l \hat{h}_0 r^{-n}}{\sum_{j=1, j \neq i}^{F_i} P_{fb} \hat{h}_j^l + \sum_{k=1}^{M_o} P_{mu} \hat{h}_k^l + \sigma^2} > T \mid \frac{P_{mb} |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_i} P_{fb} \hat{h}_j^l + \sum_{k=1}^{M_o} P_{mu} \hat{h}_k^l + \sigma^2} > T_{RFA} \right) \quad (4.18)$$

which can be simplified as:

$$F_i(T) = \frac{\mathbb{P} \left(\frac{P \hat{h}_0 r^{-n}}{P \hat{h}_0 + \sigma^2} > T, \frac{P |h_0|^2 r^{-n}}{P |h_0|^2 + \sigma^2} > T_{RFA} \right)}{\mathbb{P} \left(\frac{P |h_0|^2 r^{-n}}{P |h_0|^2 + \sigma^2} > T_{RFA} \right)} \quad (4.19)$$

Now the coverage probability in the cell-center region depends on the factor $\frac{\Delta-1}{\Delta}$, since one of the sub-bands from Δ is already allotted for the femtoUEs in the cell-edge region. Hence on applying Bayes' rule, equation (4.19) becomes:

$$F_i(T) = \frac{\mathbb{P} \left(\frac{P \hat{h}_0 r^{-n}}{P \hat{h}_0 + \sigma^2} > \max\{T, T_{RFA}\} \right)}{\mathbb{P} \left(\frac{P |h_0|^2 r^{-n}}{P |h_0|^2 + \sigma^2} > T_{RFA} \right)} = \frac{P_c \left(\frac{\Delta-1}{\Delta} \max\{T, T_{RFA}\}, \lambda, n, 1 \right)}{P_c \left(\frac{\Delta-1}{\Delta} T_{RFA}, \lambda, n, 1 \right)} \quad (4.20)$$

Substituting equation (4.20) in equation (4.10) gives the outage probability of the cell-center region femtoUEs.

4.3.5 Average Cell-Edge User Rate

The average data rate of a cell-edge femtoUE in the downlink is directly related to the downlink SINR derived in equation (4.4) as well as the system's resource allocation algorithm. The ergodic rate of a typical user is given by:

$$R = \mathbb{E}[\ln(1 + \text{SINR})] \quad (4.21)$$

which is averaged over the spatial PPP and the fading distributions. In the case of Reverse Frequency Allocation, from equations (4.4) and (4.21), the average edge user rate for a cell-edge femtoUE is given by:

$$\Gamma(T_{RFA}, \lambda, n) = \int_{r>0} e^{-\pi\lambda r^2} \mathbb{E} \left[\ln \left(1 + \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{Fo} P_{fb} l_j^l + \sum_{k=1}^{Mi} P_{mu} l_k^l + \sigma^2} \right) \right] 2\pi\lambda r dr \quad (4.22)$$

This can be further simplified by taking a positive random variable $\tau = \ln(1 + \text{SINR})$ for which $\mathbb{E}[\tau] = P(\tau > t)dt$. On conditioning the edge user's SINR based on previous value, which is guaranteed to be below T_{RFA} as in equation (4.12), we have:

$$\Gamma(T_{RFA}, \lambda, n) = \int_{r>0} e^{-\pi\lambda r^2} \int_{t>0} \mathbb{P} \left[\ln \left(1 + \frac{P_i^l \hat{h}_0 r^{-n}}{\sum_{j=1, j \neq i}^{Fo} P_{fb} l_j^l + \sum_{k=1}^{Mi} P_{mu} l_k^l + \sigma^2} \right) > t \mid \frac{P_{mb} |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{Fo} P_{fb} l_j^l + \sum_{k=1}^{Mi} P_{mu} l_k^l + \sigma^2} < T_{RFA} \right] 2\pi\lambda dt dr \quad (4.23)$$

Similar to equation (4.14), the generalized power is taken as P and z represents the set of all interferers from the cell-center region femtoBSs and cell-edge region macroUEs. Thus equation (4.23) can be simplified as:

$$\Gamma(T_{RFA}, \lambda, n) = \int_{r>0} e^{-\pi\lambda r^2} \int_{t>0} \mathbb{P} \left[\ln \left(1 + \frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} \right) > t \mid \frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right] 2\pi\lambda dt dr$$

where $I = \sum_z |h_0|^2 r_z^{-n}$ (4.24)

On applying Bayes' rule:

$$\begin{aligned} & \mathbb{P} \left[\ln \left(1 + \frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} \right) > t \mid \frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right] \\ &= \frac{\mathbb{P} \left[\ln \left(1 + \frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} \right) > t, \frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right]}{\mathbb{P} \left(\frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right)} \\ &= \frac{\mathbb{P} \left[\left(1 + \frac{P \hat{h}_0 r^{-n}}{P \hat{I} + \sigma^2} \right) > e^t, \frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right]}{\mathbb{P} \left(\frac{P_{mb} |h_0|^2 r^{-n}}{P \hat{I} + \sigma^2} < T_{RFA} \right)} \end{aligned}$$

The denominator of the above expression gets simplified to $1 - P_c(T_{RFA}, n, 1)$ whereas the numerator gets simplified as:

$$\begin{aligned}
& \mathbb{E} \left[e^{\left(-\mu \frac{e^t-1}{P} r^n (P\hat{I} + \sigma^2) \right)} \right] - \mathbb{E} \left[e^{\left(-\mu \frac{e^t-1}{P} r^n (P\hat{I} + \sigma^2) \right)} e^{\left(-\mu \frac{T_{RFA}}{P_{mb}} r^n (P\hat{I} + \sigma^2) \right)} \right] \\
&= \mathbb{E} \left[e^{\left(-\mu \frac{e^t-1}{P} r^n (P\hat{I} + \sigma^2) \right)} \right] - \mathbb{E} \left[e^{\left(-\mu r^n \sigma^2 \left(\frac{e^t-1}{P} + \frac{T_{RFA}}{P_{mb}} \right) \right)} e^{\left(-\mu r^n \left((e^t-1)\hat{I} + \frac{P}{P_{mb}} T_{RFA} \right) \right)} \right] \quad (4.25)
\end{aligned}$$

Therefore, substituting the numerator and denominator into equation (4.24) results in:

$$\begin{aligned}
\Gamma(T_{RFA}, \lambda, n) &= \int_{r>0} 2\pi\lambda \int_{t>0} e^{-\pi\lambda r^2} \frac{\mathbb{E} \left[e^{\left(-\mu \frac{e^t-1}{P} r^n (P\hat{I} + \sigma^2) \right)} \right]}{1 - P_c(T_{RFA}, n, 1)} dt r dr - \\
&\quad \int_{r>0} 2\pi\lambda \int_{t>0} e^{-\pi\lambda r^2} \frac{\mathbb{E} \left[e^{\left(-\mu r^n \sigma^2 \left(\frac{e^t-1}{P} + \frac{T_{RFA}}{P_{mb}} \right) \right)} e^{\left(-\mu r^n \left((e^t-1)\hat{I} + \frac{P}{P_{mb}} T_{RFA} \right) \right)} \right]}{1 - P_c(T_{RFA}, n, 1)} dt r dr \quad (4.26)
\end{aligned}$$

$$= \int_{t>0} \frac{P_c(e^t-1, \lambda, n, \Delta) - \xi(e^t-1, T_{RFA}, n, \Delta)}{1 - P_c(T_{RFA}, n, 1)} dt \quad (4.27)$$

where $\xi(e^t-1, T_{RFA}, n, \Delta) = \int_1^\infty \left[1 - \frac{1}{1 + T_{RFA} x^{-n}} \left(1 - \frac{1}{\Delta} \left(1 - \frac{1}{1 + (e^t-1)x^{-n}} \right) \right) \right] x dx$, and $P_c(e^t-1, \lambda, n, \Delta)$ is obtained from equation (4.9).

4.3.6 Average System Sum Rate in Downlink

The maximum achievable downlink capacity for an FUE j on a sub-carrier s is given by:

$$C_{j \in Fi}^S = \Delta B \log_2(1 + \gamma \text{SINR}_{DL_Fi}) \quad (4.28)$$

$$C_{j \in Fo}^S = \Delta B \log_2(1 + \gamma \text{SINR}_{DL_Fo}) \quad (4.29)$$

where ΔB corresponds to the sub-carrier spacing and γ is a constant defined by $-1.5 / \ln(5 \times \text{BER})$ where BER represents the target bit error rate (e.g., 10^{-6}) [157].

Similarly, the maximum achievable downlink capacity for an MUE k on a sub-carrier s is given by:

$$C_{k \in Mi}^S = \Delta B \log_2(1 + \gamma \text{SINR}_{DL_Mi}) \text{ and } C_{k \in Mo}^S = \Delta B \log_2(1 + \gamma \text{SINR}_{DL_Mo}).$$

where

$$SINR_{DL_Mi} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_o} P_{fb} I_j^l + \sum_{k=1}^{M_i} P_{mu} I_k^l + \sigma^2} \quad (4.30)$$

$$SINR_{DL_Mo} = \frac{P_i^l |h_0|^2 r^{-n}}{\sum_{j=1, j \neq i}^{F_i} P_{fb} I_j^l + \sum_{k=1}^{M_o} P_{mu} I_k^l + \sigma^2} \quad (4.31)$$

where $SINR_{DL_Mi}$ is the signal to interference plus noise ratio of the l^{th} macroUE in the inner region macrocell, $SINR_{DL_Mo}$ is the signal to interference plus noise ratio of the l^{th} macroUE in the outer region macrocell, I_k^l is the interference caused at the macroUE l due to the signal transmission from the macroUE k and I_j^l is the interference caused at the macroUE l due to the signal transmission from femtoBS j . The average system sum rate C_{avg} is given by:

$$C_{avg} = \frac{\sum_{j \in F_i} \sum_{s \in S} \chi_{j \in F_i}^s C_{j \in F_i}^s}{F_i} + \frac{\sum_{j \in F_o} \sum_{s \in S} \chi_{j \in F_o}^s C_{j \in F_o}^s}{F_o} + \frac{\sum_{k \in M_i} \sum_{s \in S} \chi_{k \in M_i}^s C_{k \in M_i}^s}{M_i} + \frac{\sum_{k \in M_o} \sum_{s \in S} \chi_{k \in M_o}^s C_{k \in M_o}^s}{M_o} \quad (4.32)$$

where in general $\chi^s = 1$ when a sub-carrier s is allocated to a UE, otherwise it is set to 0.

4.3.7 Spectral Efficiency

The spectral efficiency is defined as the average bits per second successfully received by a UE per unit sub-carrier. The spectral efficiency on sub-carrier s for transmission to macroUE is given as:

$$SE_{k \in M_i}^s = \log_2(1 + \gamma SINR_{DL_Mi}) \quad (\text{for cell-center region}) \quad (4.33)$$

$$SE_{k \in M_o}^s = \log_2(1 + \gamma SINR_{DL_Mo}) \quad (\text{for cell-edge region}) \quad (4.34)$$

Similarly the spectral efficiency on sub-carrier s for transmission to femtoUE is given as:

$$SE_{j \in F_i}^s = \log_2(1 + \gamma SINR_{DL_Fi}) \quad (\text{for cell-center region}) \quad (4.35)$$

$$SE_{j \in F_o}^s = \log_2(1 + \gamma SINR_{DL_Fo}) \quad (\text{for cell-edge region}) \quad (4.36)$$

Thus, the average network spectral efficiency is given by [166]:

$$SE_{avg} = \frac{\sum_{j \in F_i} \sum_{s \in S} \chi_{j \in F_i}^s SE_{j \in F_i}^s}{S_{Fi}} + \frac{\sum_{j \in F_o} \sum_{s \in S} \chi_{j \in F_o}^s SE_{j \in F_o}^s}{S_{Fo}} + \frac{\sum_{k \in M_i} \sum_{s \in S} \chi_{k \in M_i}^s SE_{k \in M_i}^s}{S_{Mi}} + \frac{\sum_{k \in M_o} \sum_{s \in S} \chi_{k \in M_o}^s SE_{k \in M_o}^s}{S_{Mo}} \quad (4.37)$$

4.4 Simulation and Performance Evaluation

This section provides the RFA system design guidelines used for performance analysis verified through Monte-Carlo simulations. The simulation model takes into consideration the advantages of the framework developed in [163] which introduces a certain amount of randomness in the model. Hence, the macroUEs and femtoUEs are modeled as independent spatial PPP of density $\lambda = \frac{1}{1800\pi}$ base stations per m^2 , where the UEs in a bounded area is a Poisson distributed random variable which are uniformly distributed within that area. A channel bandwidth of 10 MHz, carrier frequency of 2.5 GHz and a sub-carrier spacing of 15 KHz is used for the simulation. The maximum transmit power of the macroBS is assumed to be 46 dBm whereas that femtoBS and UEs is 23 dBm. The log normal std. deviation in the indoor and outdoor environment is taken as 4 dB and 8 dB respectively. The simulation environment assumes hexagonally-shaped macrocell (with a centrally positioned omni-directional antenna and 120 degree directional antenna positioned at the 6 vertices facing the central macroBS) to be located within a group of 7 macrocells, and each femtocell is attached to a single femtoUE. The simulation studies assume a macrocell of coverage radius 600m. For simulation purpose, the approximate boundary between the inner region and outer region are determined (around 425 m), the partitioning of which is based on the received SINR values being larger than or less than the threshold T_{RFA} (3 dB). The “macroBS-femtoBS” separation in the plots correspond to the normalized mean of the distance between macroBS and the random femtoBS chosen over a series of simulation runs. We assume a ‘snapshot model’ where all the simulation parameters remain constant over a simulation run.

To examine the effectiveness of reverse frequency allocation (RFA) in multi-tier networks, it is compared with the conventional sectoring method (CM - where femtocells are randomly distributed within the macrocell environment with both femtocell and macrocell sharing the same spectrum) and the soft fractional-frequency allocation (SFA) method. Figure 4.4 projects a comparison of the femtocell downlink capacity analysis for these different methods as well as with different inner region radius for RFA and SF method. It also highlights that, contrary to CM and SFA methods, the downlink capacity of femtocells for RFA does not deteriorate with increasing distance from the central macroBS and maintains a stable high value throughout the macrocell coverage area due to effective interference mitigation. Simulation results clearly project the better performance for the RFA scheme when compared to other methods. Also, eliminating the downlink interference to femtocells from the macroBS in RFA seems to improve the throughput drastically even at a distance very close to the macroBS.

Figure 4.4: Femtocell DL capacity comparison of different methods

Figure 4.5 explains the impact of RFA method on uplink capacity. It shows that RFA is capable of providing a steady higher throughput in the uplink than the conventional method. However, while comparing with SFA, interference to the femtoUEs from the downlink transmissions of the macroBS seems to have a minor impact on the uplink throughput especially in the cell-center region. But this is compensated in the cell-edge region with a comparatively higher throughput. Partitioning the macrocell coverage area into cell-center and cell-edge region and the deployment of DAS seems to effectively contribute to a comparatively better performance for RFA in the uplink as well. However, designers should weigh the benefit of better downlink performance for RFA scheme in contrast to the minor performance degradation that it may cause in the uplink capacity.

Figure 4.6 projects the variation of the femto-macro system downlink capacity with increase in number of femtoBS in the macrocell. For this simulation, the number of macroUEs is kept constant at 50 whereas the number of femtoUEs is steadily increased. It is evident from the figure that the DL system capacity of the RFA scheme outperforms all others even with very high increase in femtoBS density. In downlink, femtoUEs in the inner region is affected by the uplink transmissions of the macroUEs in the outer region and the femtoUEs in the outer region is affected by the uplink transmissions of the macroUEs in the inner region. However, the minimal path loss incurred between the femtoBS and femtoUE, ensures that the interference from the macroUEs does not overpower the signal transmission from the femtoBS. This ensures that the throughput degradation is far less in the reverse frequency allocation scheme when compared to that of the conventional scheme. In the conventional scheme, the major source of interference is the macroBS whose higher

transmission power is capable of overpowering the femtoBS transmissions. Thus, the results confirm that the femtocell throughput is not dependent on the macroBS interference when RFA is incorporated, since the spectrum allocation help both networks to operate independently.

Figure 4.5: Femtocell UL capacity comparison of different methods

Figure 4.7 compares the overall downlink system throughput for different schemes obtained numerically and via simulation as a function of macroBS-femtoBS separation. The accuracy of analytical evaluation is evident from the close match of curves with the simulation results. Unlike Figure 4.4 which projects the downlink capacity of the femtocell network alone, Figure 4.7 shows the combined throughput of the entire system (macrocell+femtocell) with increasing distance between the macroBS and the femtoBS. This provides clarity on the performance of the cell-center and cell-edge users based on the separation between femtoBS and macroBS. Even though the femtocell downlink throughput maintains a steady high value throughout the macrocell coverage area in case of RFA as explained in Figure 4.4, the deterioration of macrocell downlink throughput with increasing distance from the macroBS, causes the overall system throughput to reflect a contiguous fall as well. However, Figure 4.7 shows that the system throughput with RFA scheme outperforms all other schemes in the downlink especially in the cell-edge region (mainly when the macroBS-femtoBS separation exceeds 425m) due to the incorporation of DAS architecture. The improvement in system throughput with RFA scheme when compared to the soft fractional frequency reuse scheme is clearly evident in the downlink in both the cell-center region as well as in the cell-edge region. At the same time, it is far above that is achievable through the conventional method too.

Figure 4.6: DL system (femto+macro) capacity comparison for varying femtoBS-density

Figure 4.7: DL system (femto+macro) capacity comparison with varying distance of femtoBS from the macroBS

Figure 4.8 demonstrates the outage probability comparison for the femtoUEs as its location is varied from the cell-center region towards the cell-edge for different schemes. From the analytical results, it is evident that the outage probability is boosted multiplicatively, with increase in strength of downlink interference. This is reflected in the simulation results which prove that the outage probability of the RFA scheme is comparatively lower than that in other schemes since the interference from the macroBS is replaced by lower strength macroUEs. Even in cell-edge region

too, though the femtoUEs face interference from the inner region macroUEs; the increased radio transmission distance between them helps in decreasing the outage probability. Meanwhile, for the conventional scheme and the soft fractional frequency allocation scheme, the interference from the macroBS is very high in the cell-center region, which may result in the formation of coverage holes and hence increase the probability of outage. To sum up, the RFA scheme proves to be better than the other two schemes in increasing the coverage probability of the femtoUEs.

Figure 4. 8: Outage probability of femtoUEs with $T = -10\text{dB}$

Figure 4.9: Average system sum-rate (femtoUE+macroUE) comparison in the downlink

Figure 4.9 highlights the improvement in average system sum rate with RFA method in comparison to the SFA method and the conventional method. This finally helps to conclude that the downlink capacity can be improved to a great extent with the use of RFA scheme in comparison to the conventional method and slightly better than soft fractional frequency reuse method. This ultimately helps in serving more data traffic in the downlink.

4.5 Summary

Even though, opportunistic capacity-driven deployment of femtocells is recognized as a key solution to overcome the capacity-crunch issues especially in the downlink, the interference challenges that it brings along is not negligible. In this era, where almost all possible techniques for interference mitigation has been investigated, intelligent spectrum allocation combined with an aggressive frequency reuse can be a key solution towards enhancing system performance by alleviating cross tier interference. In this context, this chapter carries out an in-depth analysis of reverse frequency allocation scheme, which involves the virtual partitioning of the macrocell service area into different geographical regions served by multiple antenna elements followed by the complementary allocation of macrocell spectrum to femtocell users. This efficient spectrum management helps in eliminating the downlink interference to the femtocell from the macroBS. As a result, it enhances the cell-edge user's performance by controlling interference with superior spectral efficiency since it supports full frequency reuse within each cell. When compared to the soft fractional frequency allocation and conventional sectorized scheme of spectrum sharing, simulation results provide a clear evidence of higher throughput especially in the downlink where network traffic is high. In addition to it, the incorporation of transmit power control between the cell-edge and cell-center region through DAS proves to enhance the system performance in accordance with the requirements of the network operator.

To sum up, the adoption of this hybrid scheme based on resource partitioning with RFA and DAS assures an overall increase in DL system capacity by eliminating cross-tier interference in femto-macro network. Additionally, this work motivates a natural extension of addressing the cellular uplink performance with RFA architecture. While many of the system takeaways would be expected, the inclusion of distributed antenna system along with reverse frequency allocation to curb the interference levels would be expected to have a profound impact on the performance.

Chapter 5

Interference Limited Frequency Reuse through Orthogonal Polarized Transmission

When you have exhausted all possibilities, remember this - you haven't.

-Thomas Edison

5.1 Introduction

The traditional resource management techniques employed in multi-tier cellular networks have almost reached the zenith where nearly unity frequency reuse and above is used in each cell. In this scenario, the major challenge is to determine the possibility of re-using the same frequency channels for different users without degrading each other's performance. Since, orthogonalization of spectral resources is considered as the key to address this challenge, extensive research has been carried out in time domain orthogonalization, frequency domain orthogonalization and spatial domain orthogonalization to enable seamless communication in multi-tier networks. This orthogonalization mechanism was indeed effective in enhancing the spectral efficiency of the system by intelligent reuse of spectral resources. However, the proliferation and relentless penetration of new generation mobile devices have raised customers' expectation for ubiquitous data services leading to a stunning increase in mobile data traffic during recent years. This finally leaves the communication researchers with the nightmare of spectrum inefficiency mainly due to the inadequate frequency reuse mechanisms devoid of interference. It is in this technical standpoint that the need for exploiting polarization dimension becomes critical in order to achieve more degrees of freedom in wireless transmission.

Classical wireless communication systems have relied on one channel per frequency, although it is well understood that two polarization states of plane wave allow two distinct information channels. Techniques such as 'polarization diversity' already take advantage of this. Even though the concept of orthogonalization in polarization domain is not new, it was never aggressively

explored for wireless communication industry and hence exploring it for improving the spectral efficiency and system capacity seems to be the next logical step to undertake.

In this chapter, we investigate an OFDM multiplexing transmission system named Cross Polarized Wireless Access (CPWA) that employs orthogonally polarized antennas for transmission in femto-macro systems as demonstrated in Figure 5.1. As already known, most of the frequency reuse schemes available in the literature reduce spatial reuse by using sub-channels used in one cell that are not utilized in the neighboring cell. On the contrary, CPWA permits universal frequency reuse where all cells have the potential to access all available resources but with different polarization across tiers, which licences the same frequency carrier to be reused by both networks simultaneously. Thus in co-existing femto-macro network, it provides an acceptable trade-off and overall enhanced system performance. Also due to the independence of the polarization states, the incorporation of polarization division multiple access (PDMA) and polarization modulation (PM), is expected to further improve the spectrum efficiency as well [167]. Apart from this, the orthogonal sense of rotation doubles the OFDM system capacity devoid of cross-tier interference between the femto-macro networks. Even though similar frequency reuse strategy is employed in satellite transmission systems, this is the first ever proposed system for a femto-macro system to the best of our knowledge.

Figure 5.1: Cross Polarized Wireless Access in femto-macro network

5.2 Choice of Polarization for Improved QoS

In order to ensure orthogonalization and enable frequency reuse, we make use of orthogonality in signal polarimetric dimension that can be employed in transmission schemes. Figure 5.2 explains the different polarization states using a Poincare-spherical surface. It establishes one-to-one

mapping between the polarization states and each point on the Poincare-spherical surface resulting in infinite polarization states intuitively. Here the north-pole signifies the left-hand circular polarization, south-pole signifies the right-hand circular polarization, equator of the sphere represents linear polarization, surface of the northern hemi-sphere denotes the left-hand elliptical polarization and the surface of the southern hemi-sphere denotes the right-hand elliptical polarization [167].

Figure 5.2: Polarization representation in Poincare-sphere form

Table 5.1: Comparison between linear polarization and circular polarization [168]

LINEAR POLARIZATION	CIRCULAR POLARIZATION
Random antenna orientation results in out of phase issues.	Transmission takes place in all direction and hence random antenna orientation does not lead to misalignment.
Adversely impacted by obstructions in the transmission path.	Effective in establishing and maintaining links even in the presence of obstructions.
Inclement weather conditions can cause signal degradation.	Advanced signal propagation characteristic makes it resistant to signal degradation due to changing weather conditions.
Technical and implementation challenges are more in case of mobile networks.	Technical and implementation challenges can be solved.
Signal degradation occurs if reflection does not take place along the same plane as that of transmission.	Least sensitive to reflection since transmission takes place along all directions due to which signal strength is just transferred to another plane.
Wall penetration of linear polarized signal is difficult resulting in signal strength reduction.	Circular polarized signals have higher probability of wall penetration and hence deliver a stable and successful link.
High frequency systems using linear polarization requires a clear line-of-sight path between the source and destination	High frequency systems making use of circular polarization can easily propagate through non-line of

	sight paths between the source and destination, without weakening the signal strength.
More susceptible to multi-path due to increased possibility of reflection.	Lower likelihood of signal cancellation, since the transmission takes place in all directions.
Skew adjustment needed, based on geographical location.	Skew adjustment is not mandatory.
Sensitive to Faraday's rotation caused by earth's magnetic field.	Rotation of EM vectors has no effect since the transmit and receive antenna eliminates the negative effect of rotation.

Based on the insights on these different types of polarization, it is quite intriguing to investigate on the type of polarization that should be adopted for the CPWA scheme. The main debate occurs in choosing between –linear (vertical and horizontal) and circular (right-hand and left-hand) polarization for the CPWA scheme. Definitely linear polarization has an edge over circular polarization in terms of expense and ease of implementation in case of fixed networks due to which it is considered as the *de facto* polarization standard in most of the network implementations. However, these advantages do not stand valid in mobile ad-hoc environment where the user equipment is not stationary. On the other hand, the complex signal propagation transmission requirements and traditionally higher expenses had always limited the use of circular polarized antennas for satellite transmission. However, the recent breakthrough in antenna design and innovative scientific advancement has made this superior technology affordable for common applications as well. The analysis of polarization effects in high data-rate indoor wireless communication scenarios in [169] claims that appropriate use of circular polarization could lead to significantly reduced channel delay spread, and hence improved error performance even with minor attenuation. In addition to this [170] shows that the variation of RMS delay spread as a mobile moves over several wavelengths is greatly reduced when circular polarized antennas are used. Extensive simulations and analysis carried out in [171, 172] proves that the use of circular polarization is advantageous in reducing reflections from the wall even when it has a multi-layered structure. The experimental studies show that multipath delayed waves due to wall reflection could effectively be suppressed by employing circular polarization than linear polarization. It is also observed that the reflection coefficients of the ceiling for circular polarization were much smaller than those for linear polarization at small angles of incidence. The computer simulations based on measured impulse responses for indoor multipath propagation further demonstrated that the use of circular polarization is effective in reducing the bit error rate due to multipath propagation in high-speed transmission channels as well. Above all, the significant advantage of circular polarization is that even after multiple reflections, refractions and delay, its sense of rotation can never be altered

by any naturally existing substance even though there can be a minor shift in angular orientation. This assures that orthogonality is always maintained while using cross-polarized circular transmission in wireless networks.

Table 5.1 evidently points out the additional reasons behind choosing circular polarized transmission over linear polarized transmission in wireless-cellular network [168, 173]. Hence, it is obvious from the comparison that there is a reason behind the choice made. It is always about ensuring the highest reliability of reception due to which circular polarization is preferred over linear polarization in femto-macro wireless network.

5.3 CPWA Frequency Allocation Strategy

The spectrum allocation employed in the CPWA strategy is intelligently designed in order to facilitate flexibility, scalability and higher efficiency. Ideally, frequency reuse through cross polarized transmission doubles the system capacity. However in practice, this is hard to achieve due to propagation impairments, antenna imperfections and cross-polarization interference. Hence frequency allocation along the femto-macro tiers needs meticulous planning along with spatial separation in order to prevent performance degradation.

Figure 5.3: CPWA frequency allocation in femto-macro network

Sectorization technique is widely used in cellular mobile radio systems for mitigating co-channel interference as well as for increasing the system capacity. Sectorization coupled with 60 degree directional antennas with 3dB beamwidth combined with orthogonal polarized transmission aids efficient frequency reuse in two-tier femto macro networks. To facilitate this, firstly, the macrocell service area is divided into hexagonal cells which are further partitioned into 6 triangular sectors

S1-S6. Each sector is equipped with its own directional antenna. The entire available frequency spectrum of the macrocell is divided into 6 sub-bands namely A, B, C, D, E and F, which is allocated to the 6 sectors in such a way that no two adjacent sectors make use of the same frequency sub-band. On the other hand, distribution of femtocells within the macrocell network must be carried out harmoniously so that it does not affect the normal functioning of the legacy macrocell network but should aid in maximizing the performance of the network as a whole. The spectrum allocation for the randomly distributed femtocells within the macrocell is carried out as in Figure 5.3. However deployment of femtocells in pre-existing macrocell network results in several problems that need to be addressed to guarantee the QoS requirements of the customers. The main issue among them is the intelligent allocation of frequency spectrum to the femtocells considering the effect of co-channel interference on the legacy macrocell network. Since frequency resources are limited, it is important to come up with methods that enable frequency reuse without causing interference. Traditionally, there exist frequency allocation mechanisms, which allocate frequency resources according to FRFs in multi-cell environment. The most commonly used among them is the shared frequency allocation mechanism, in which frequency spectrum is shared with adjacent, or co-existing cells i.e., universal frequency reuse or FRF of 1. The other is the orthogonal frequency allocation mechanism, which allocates frequency according to the predetermined frequency patterns among multi-cells with the FRF of 1 or more. Even though the former may seem to be more efficient since all the frequency resources may be utilized in each of the cells, it can suffer from performance degradation due to co-channel interference, which is very well taken care of in the later scheme. However, combining both these schemes i.e. shared spectrum and orthogonal allocation in a smart way can bring about a significant improvement in the system performance without affecting the users' QoS. Thus, co-channel interference being the limiting factor in the performance of femto-macro network, cross-polarized transmission is employed as a means of reducing this interference, improve SINR and hence increase the system capacity. In addition to this, circular cross-polarization is chosen as the best mode for transmission in wireless network as explained Section 5.2. Hence the transmission along all the sub-bands in the macrocell network is enabled through circular polarized signals say left hand circular polarization (LHCP). The spectrum allocated to the randomly distributed femtocells, will make use of a polarization orthogonal to that of the macrocell network i.e. right hand circular polarization (RHCP) as explained in Figure 5.3. As explained before, reflections, refractions and random fluctuations in case of circular polarization may cause a change in angular orientation by a few degrees but do not alter the sense of rotation. This is because, rather than for any metamaterial, no naturally existing substance has negative permeability or permittivity and is hence incapable of reversing the handedness of a polarized transmission [174]. Thus the sense

of rotation being orthogonal to each other ensures isolation and limits interference between the tiers. In short, co-existing femtocell and macrocell users make use of orthogonal/alternate polarization so as to maximize the isolation between their transmissions and hence increase the communication quality.

Figure 5.4 explains the different orthogonal polarization states (LHCP and RHCP) of a given frequency (F_k) on a Poincare [167]. Two points on the surface of the Poincare-sphere are orthogonally polarized if the line joining them passes through the center of the sphere and is cross polarized if they are symmetrically placed with respect to the equator of the sphere. This property makes it possible for the same frequency (F_k) to be allocated to femtocell users and macrocell users simultaneously with orthogonal/cross polarization. Furthermore, since both the desired signal strength and SINR vary in a random fashion, a more meaningful system performance evaluation can be carried out by the measurement of SINR in the two-tier network, which we make use of in the next section.

Figure 5.4: Circular polarization representation in Poincare-sphere form

5.4 System Model and Analysis

As demonstrated in Figure 5.3 the system under consideration includes a two-tier femto-macro network making use of orthogonal polarization in their respective domains to exploit smart frequency-reuse and thereby increase system capacity. Polarization diversity can be used as a tool to exploit frequency diversity by assuring minimal co-channel interference by virtue of its property known as Cross Polarization Discrimination (XPD). XPD is defined as the ratio between the

temporal-average power in the emitted co-polar signal and the value of temporal-average power that has leaked into the cross-polar signal [175]. XPD represents the polarization state of a wireless signal. In a transmission channel, maximum signal strength between nodes occurs when both transmitter and receiver use identical polarization. However, due to XPD, when a given antenna receives a co-channel signal sent from a cross-polarized antenna, the effective signal strength is reduced by several dBs. The larger the XPD between polarized transmissions, the larger will be the isolation. With two distinct polarization modes of a dual-polarized wireless channel being *co-polar* (represented by $\parallel$) and *cross-polar* (represented by $\perp$), the XPD of a co-polar signal whose power is $P^{\parallel}$ is given by:

$$XPD_{\parallel} = \frac{P^{\parallel}}{P(\parallel \rightarrow \perp)} \quad (5.1)$$

and that of a cross-polar signal is given by :

$$XPD_{\perp} = \frac{P^{\perp}}{P(\perp \rightarrow \parallel)} \quad (5.2)$$

Extensive measurements prove that the XPD value varies over distance [176] as well as time [177]. Hence, the value of XPD can be calculated as $XPD = XPD_0 d^{-\beta}$ where XPD_0 is the XPD value at a unit distance $d = 1m$ and β is the decay factor ($0 \leq \beta \leq 1$). In short, unlike MIMO systems which require at least half wavelength in antenna spacing at terminal devices, there is no spacing requirement for placing the orthogonally dual-polarized antenna (ODPA), i.e., the schemes leveraging degrees of freedom provided by polarization are space and cost-efficient. To add on, the depolarization effect is found to be significantly low for carrier frequencies below 11GHz which proves to be an advantage to the LTE technology having a frequency band from 2-8GHz. Hence the assumption of a constant XPD value is also reasonable. Above all, the effect of multi-path delay spread is assumed to be minimal due to the use of highly directional sector and terminal antennas in our scheme. Furthermore, polarization signal processing is an additional method besides time, frequency, and space based methods, which show that the use of polarization is a promising framework for wireless communication.

For the analysis, an OFDMA downlink cellular scenario with two tiers is taken into consideration - macrocell network being cross-polar and femtocell network being co-polar respectively. The macro-users are uniformly distributed whereas the femto-users are modeled as independent spatial Poisson Point Process (PPP). In this model, no mobility condition is assumed. Every user is static and is assumed to be served by its own femtoBS. Let n represent the path loss exponent, P_{fb} , P_{fu} , P_{mb} and P_{mu} represent the transmit powers of the femtoBS, femto-user, macroBS and macro-user

respectively. Now a series of theoretical results are furnished to establish the performance improvement with the adoption of CPWA scheme.

Theorem 1: In a narrowband Rayleigh-faded channel, for a two tier femto-macro network, the downlink SINR at a femtoUE located at a distance d from the femtoBS in the presence F co-polar interferers and M cross-polar interferers with a cross-polar discrimination coefficient XPD is given by:

$$SINR_{DL} = \frac{P |h_0|^2 d^{-n} (XPD - 1)}{\sum_{j=1, j \neq i}^F P_{fb}^{\parallel} (XPD - 1) + \sum_{k=1}^M P_{mb}^{\perp} + \sigma^2}$$

where σ^2 represents the noise power.

Proof: The average received power at the femtoUE in the downlink is given by:

$$P_{avg} = P_{fb} I = P_{fb} d^{-n} |h_0|^2 \quad (5.3)$$

where d is the distance between the femtoBS and the femto-user, I represents the interference and $|h_0|^2$ is the Rayleigh distributed random variable which represent the small scale fading between any BS under consideration and the attached UE. The set of interfering BSs are assumed to use the same co-polar sub-carrier within the same tier but with orthogonal polarization in different tier. While making use of cross polarized signals for transmission in femto-macro network, let P_s^{rc} represent the average power received at receiver rc when transmitted from sender s which is represented in terms of the XPD value based on the signal polarization as [112]:

$$\text{For cross-polarized reception: } \frac{1}{XPD} P_s^{rc} \quad (5.4)$$

$$\text{For co-polarized reception: } \frac{XPD-1}{XPD} P_s^{rc} \quad (5.5)$$

Let P be the instantaneous received power at a distance d . The signal to interference ratio of the femtocell in the downlink is represented by:

$$SINR_{DL} = \frac{P(d)}{P_{int_DL} + \sigma^2} \quad (5.6)$$

where P_{int_DL} represents the total downlink interference. This interference is assumed to be from all the femtoBSs (j) and macroBSs (k) in the network which are using the same frequency carrier as that of femtoBS i . On substituting equations (5.4) and (5.5), equation (5.6) becomes:

$$SINR_{DL} = \frac{P |h_0|^2 d^{-n(XPD-1)}}{\sum_{j=1, j \neq l}^F P_{fb}^{\parallel}(XPD-1) + \sum_{k=1}^M P_{mb}^{\perp} + \sigma^2} \quad (5.7)$$

where $P_{fb}^{\parallel} (= P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n})$ is the interference at femto-user l due to the signal transmission from the femtoBS j and $P_{mb}^{\perp} (= P_{mb} |h_0|^2 (d_{mb}^{fu})^{-n})$ is the interference at femto-user l due to the signal transmission from macroBS k . The Shannon- Hartley theorem is further used to calculate the achievable throughput. Theorem 1 highlights that cross-polarized transmission can be utilized as an effective measure to improve the downlink system capacity of the femto-macro network if one tier makes use of a polarization orthogonal to that of the other tier which in turn depends on the cross-polarization discrimination maintained between the two tiers.

In the ideal case, exploiting the polarimetric dimension for cross polarized transmission ensures perfect orthogonality. However this is not the case in reality, since an imperfect antenna cross-polar isolation (XPI) and depolarization mechanism that take place during electromagnetic wave propagation, cause the signal sent on a given polarization to leak into other. These effects can combine to result in what is known as polarization mismatch losses. The polarization mismatch loss for linear polarization is given by $\Gamma = \cos^2(\theta)$ where θ is the angle between the polarization vectors. However, in case of circular polarization, if ρ_t and ρ_r represent the circular polarization ratio of the transmitting and receiving antenna respectively and r_t and r_r represent the axial ratio (r = ratio of major axis to minor axis or $20\log[E_{max}/E_{min}]$ dB) of the transmitting and receiving antenna respectively, then the mismatch loss for any angular alignment θ between major axes of the transmitting and receiving antenna can be calculated as [178]:

$$\Gamma \text{ (dB)} = 10 \log \left[\frac{1 + \rho_t^2 \rho_r^2 + 2 \rho_t \rho_r \cos 2\theta}{(1 + \rho_t^2)(1 + \rho_r^2)} \right] \quad (5.8)$$

Where

$$\rho_t = (r_t + 1)(r_t - 1) \text{ and } \rho_r = (r_r + 1)(r_r - 1)$$

Also the cross polarization discrimination is related to the axial ratio (r) as:

$$XPD = 20 \log \frac{r+1}{r-1} \text{ dB} \quad (5.9)$$

Assuming the axial ratio of the transmitting and receiving antenna to be the same i.e. $r_t = r_r = r$, for a given value of XPD, its value can be determined. From this, the polarization mismatch losses during transmission can be calculated, which helps in evaluating the actual system capacity.

Theorem 2: In a narrowband Rayleigh-faded channel, for a two tier femto-macro network making use of cross-polarized transmission, the coverage probability (P_c) in the femtocell downlink is given by:

$$\exp\left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)}\right) \times \prod_{j=1, j \neq i}^F \left\{ 1 - \frac{TA}{\left(\frac{P}{P_{fb}^{\parallel}}\right)\left(\frac{d}{d_{fb}^{fu}}\right)^{-n} + T} \right\} \times \prod_{k=1}^M \left\{ 1 - \frac{TA}{(XPD-1)\left(\frac{P}{P_{mb}^{\perp}}\right)\left(\frac{d}{d_{mb}^{fu}}\right)^{-n} + T} \right\} \quad (5.10)$$

Proof: In a two-tier network which makes use of cross-polarized transmission, it is essential to determine the probability of successful transmission. Coverage probability analysis can project a clear picture in this respect. A node is said to be in coverage or the transmission from a femtoBS to a femto-user is considered successful if and only if the SINR is above a threshold say T . This threshold value definitely depends on the receiver's characteristics like sensitivity, modulation, coding scheme etc. Let the traffic at the interfering femtoBSs and macroBSs be modeled by a sequence of independent indicators with for all $i, A_i \in \{0,1\}$ such that $\mathbb{P}\{A_i = 1\} = A$ and $\mathbb{P}\{A_i = 0\} = 1 - A$. Thus the coverage probability in the downlink is expressed as :

$$P_c \triangleq \mathbb{P}(SINR_{DL} > T)$$

$$= \mathbb{E}_{P_{int_DL}} [\mathbb{P}(SINR_{DL} > T) | P_{int_DL}] \quad (5.11)$$

$$= \mathbb{E} \left[\exp \left(\frac{-T}{P d^{-n}(XPD-1)} \left(\sum_{j=1, j \neq i}^F P_{fb}^{\parallel} A_j (XPD-1) + \sum_{k=1}^M P_{mb}^{\perp} A_k + \sigma^2 \right) \right) \right] \quad (5.12)$$

$$= \exp \left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)} \right) \times \mathbb{E} \left[\prod_{j=1, j \neq i}^F \exp \left(\frac{-TP_{fb}^{\parallel} A_j}{P d^{-n}} \right) \right] \times \mathbb{E} \left[\prod_{k=1}^M \exp \left(\frac{-TP_{mb}^{\perp} A_k}{P d^{-n}(XPD-1)} \right) \right] \quad (5.13)$$

The expectation in the middle term of equation (5.13) can be expressed as:

$$\begin{aligned} \mathbb{E} \left[\exp \left(\frac{-TP_{fb}^{\parallel} A_j}{P d^{-n}} \right) \right] &= \mathbb{P}(A_j = 1) \times \int_0^{\infty} \exp \left(-\frac{TP_{fb}}{P d^{-n}} \right) f_{p_{fb}^{\parallel}}(p_{fb}) dp_{fb} + \mathbb{P}(A_j = 0) \times 1 \\ &= 1 - \frac{TA}{\left(\frac{P}{P_{fb}^{\parallel}}\right)\left(\frac{d}{d_{fb}^{fu}}\right)^{-n} + T} \end{aligned} \quad (5.14)$$

The expectation in the last term of equation (5.13) can be expressed as:

$$\begin{aligned}
\mathbb{E} \left[\exp \left(\frac{-TP_{mb}^{\perp} \Lambda_k}{P d^{-n}(XPD-1)} \right) \right] &= \mathbb{P}(\Lambda_k = 1) \times \int_0^{\infty} \exp \left(-\frac{TP_{mb}}{P d^{-n}(XPD-1)} \right) f_{p_{mb}^{\perp}}(p_{mb}) dp_{mb} + \\
&\quad \mathbb{P}(\Lambda_k = 0) \times 1 \\
&= 1 - \frac{TA}{(XPD-1) \left(\frac{P}{P_{mb}^{\perp}} \right) \left(\frac{d}{d_{mb}^{fu}} \right)^{-n} + T} \tag{5.15}
\end{aligned}$$

Substituting equations (5.14) and (5.15) in equation (5.13), yields the coverage probability of femtocell in the downlink as given in equation (5.10). Coverage probability analysis definitely provides interesting insights into the expected system performance. The first term on right hand side of the equation (5.13) is relevant only in systems where the throughput is limited by the background noise in comparison to the interference from neighboring nodes. However, in dense multi-cell, multi-tier networks where the background noise is negligible when compared to the interference, the transmission is limited by the interference and polarization terms (i.e. the second and third terms in the expression). This in turn depends on the polarization characteristics of the interferers, traffic distribution and network topology.

Theorem 3: In a narrowband Rayleigh-faded channel for a two tier femto-macro network making use of cross-polarized transmission, the interference free femtocell exclusive region (IFFER) is a circular region whose coverage area depends on the XPD value and path-loss exponent.

Figure 5.5: Interference free femtocell exclusive region (IFFER) in cross-polarized femto-macro network

Proof: The derivation of IFFER would play a key role in the placement of femtoBS in an indoor environment. This interference free coverage region is usually dependent on parameters like transmit power of the femtoBS and macroBS, distance of the femto-user from the macroBS and femtoBS, path loss exponent etc. The IFFER is defined as the area within a contour where the received power levels from the femtoBS and macroBS are the same [33]. Figure 5.5 explains the variation in IFFER with increasing distance from the macroBS.

Consider a simple scenario where the femto-user is located at the coordinates (x, y) . Let the received signal strength from the cross-polarized macroBS located at (x_1, y_1) be $P_{mb}^\perp$ and that received from the co-polarized femtoBS located at (x_2, y_2) be $P_{fb}^\parallel$. Considering the signal to interference ratio to be 0 dB [66] at the border of the IFFER, it can be written as $P_{mb}^\perp = P_{fb}^\parallel$

$$\text{i.e. } P_{mb} |h_0|^2 (d_{mb}^{fu})^{-n} = P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n} \quad (5.16)$$

Substituting equation (5.5) to equation (5.16), results in:

$$\frac{P_{mb}}{XPD (d_{mb}^{fu})^n} = \frac{(XPD-1)P_{fb}}{XPD (d_{fb}^{fu})^n} \quad (5.17)$$

Taking $n=2$, and substituting the distance from the macroBS and femtoBS to the femto-user we get:

$$\frac{P_{mb}}{(x-x_1)^2 + (y-y_1)^2} = \frac{(XPD-1)P_{fb}}{(x-x_2)^2 + (y-y_2)^2} \quad (5.18)$$

which can be rearranged and re-written as :

$$x^2 + y^2 + \frac{B_1}{A}x + \frac{B_2}{A}y + \frac{C}{A} = 0$$

where $A = P_{mb} - P_{fb}(XPD - 1)$, $B_1 = 2P_{fb}(XPD - 1)x_1 - 2P_{mb}x_2$, $B_2 = 2P_{fb}(XPD - 1)y_1 - 2P_{mb}y_2$, $C = P_{mb}(x_2^2 + y_2^2) - P_{fb}(XPD - 1)(x_1^2 + y_1^2)$. However, this denotes the equation of a circle centered at $\left(\frac{-B_1}{2A}, \frac{-B_2}{2A}\right)$ with radius $\sqrt{\frac{B_1^2}{4A^2} + \frac{B_2^2}{4A^2} - \frac{C}{A}}$. Hence IFFER will have an area given by $\pi \left(\frac{B_1^2}{4A^2} + \frac{B_2^2}{4A^2} - \frac{C}{A}\right)$. Thus, it becomes evident that, apart from the location and transmit power of the macroBS and femtoBS, IFFER is dependent on the XPD value too, in a cross-polarized transmission network. Higher the XPD between femto-macro transmissions, larger will be the IFFER. For n to be any arbitrary path loss exponent other than 2, the $(2/n)$ -th root needs to be applied to both sides in (5.16) which becomes exactly similar to the scenario where $n=2$ with an entirely different value for the transmit powers [66].

5.4 Simulation and Performance Evaluation

Simulation involves an OFDMA cellular scenario with two tiers - macrocell network and femtocell network respectively having a Rayleigh faded channel. The location of the macro-users and the femto-users are modeled as independent spatial Poisson Point Process (PPP). The femtocell network is assumed to have co-polar transmissions in comparison to the cross-polar transmissions of the macrocell network.

Table 5.2: Simulation Parameters

PARAMETER	VALUE
Channel Bandwidth	10MHz
Carrier Frequency (f_c)	2.5GHz
Sub-carrier Spacing	15 KHz
Max Power of macroBS	46 dBm
Max Power of femtoBS	23 dBm
Max power of macroUE and femtoUE	23 dBm
Thermal Noise Density	-174 dBm/Hz
Log normal std. deviation (outdoor)	8 dB
Log normal std. deviation (indoor)	4dB
Shadowing std.	10 dB
Angle between polarization vectors	90 degree

The simulation environment assumes circularly shaped femtoBSs with 2-3 femtoUEs attached to it and uniformly distributed within the hexagonally-shaped macrocell located centrally within a group of 7 macrocells. The macrocell coverage area is assumed to have a radius of 600m with inner region radius extending up to 400m from the macroBS and the outer region radius from 400m to 600m. For the purpose of analytical tractability, channel correlation is not taken into account since it does not affect the scaling behavior in link level performance. The parameters used for the simulation are given in Table 5.2.

Figure 5.6 analyses the femtocell downlink throughput for different values of XPD. It is observed that with increase in cross-polarization discrimination between the femtocell and macrocell transmission, the interference between the two tiers reduces. This causes an improvement in SINR value finally resulting in an increased throughput for the femtocell network. The conventional method, in which the polarization diversity is not exploited, seems to offer the lowest throughput for the femtocell network in comparison to CPWA scheme with increasing XPD value. However, it is noticed that the throughput variation is quite distinctly visible up to a distance of about 300m, whereas after 300m from the macroBS, it becomes substantially constant. This is mainly because of the linear decay of XPD value with increase in transmission range.

Figure 5.6: Femtocell downlink capacity analysis for varying XPD

Figure 5.7: Femtocell downlink capacity analysis for varying theta value

From Figure 5.7, it is clear that the phase difference between the excitation signals can cause changes in axial ratio, and hence affect the throughput of the system. The more the separation between the excitation signals from 90 degrees on either side, the more is the axial ratio variation and hence the throughput deterioration. It is validated from the simulation results that the maximum system throughput is always obtained when the major axes of the antennas of the femtocell and macrocell network are orthogonally aligned at an angle of 90 degree with each other. Even minor misalignments from 90 degree can cause the signal energy from one network to leak into the other,

thereby affecting the orthogonality of the system and hence resulting in interference. Hence special attention should be given in the antenna feed alignment of both the networks so as to ensure better system performance.

Potential throughput improvement with the use of cross-polarized transmission (CPWA with XPD=10 dB) in femto-macro network is analyzed by comparing it with the conventional method (CM) of random distribution of femtocells within the macrocell environment, the soft frequency reuse allocation (SFA) and the reverse frequency allocation (RFA) method. Figure 5.8 projects a comparison of the femtocell capacity analysis for different methods. Extensive simulation results project that the capacity achievable with CPWA scheme is well above that of all other methods due to higher transmission rate and lower inter-tier interference. It is clear from the results that the diversity of polarization drastically increases the throughput due to the clear advantage in terms of interference mitigation.

Figure 5.8: Femto-macro system downlink capacity comparison for different methods

Figure 5.9 compares the Primary Protection Ratio (PPR) for the macrocell users for varying XPD values to the conventional method. Primary protection ratio is nothing but an indicator of the impact of the proposed scheme on the legacy macrocell network. It is given by $PPR = \frac{C_{macro+femto}}{C_{macro_only}}$ where $C_{macro+femto}$ is the capacity of the macroUEs in the presence of interference from the femtoUEs and C_{macro_only} is the capacity of the macroUEs without any interference [208, 209]. It is evident from the figure that the legacy macrocell network has the least

impact with CPWA. Better PPR is observed with increase in XPD value throughout the macrocell coverage area in case of CPWA when compared with that of conventional method. This ensures that the incorporation of CPWA scheme can only result in the betterment of the system performance as a whole with minimal impact on the macrocell network.

Figure 5.9: Primary Protection Ratio Comparison

Figure 5.10 demonstrates the coverage probability analysis for the femtocells with and without the use of cross-polarization. In the conventional approach, the coverage probability is low in the cell-center region which increases with distance from the macroBS mainly due to the reduced interference experienced by the femtocell towards the cell-edge. However, it is observed that the coverage probability is comparatively higher in cross-polarized transmission mode mainly because of the spectral isolation achieved between the femtocell and macrocell networks. The coverage probability of the femtocells remains at a high stable value independent of the distance from the macroBS in case of cross-polarized network.

It is evident from Figure 5.11 that the IFFER expands in area with distance from the macroBS. This signifies that in a cross-polarized two-tier network, the IFFER is dependent not only on the transmit powers of the base stations and the path loss exponent but also on the XPD value. With larger XPD, higher is the isolation between the femtocell and macrocell networks and hence the larger is the IFFER. This increase in IFFER seems to be linear in case of polarization-free femto macro network, but exponential when it comes to a two-tier network where isolation is ensured by means of cross-polarization. Hence cross-polarized transmission plays a key role in increasing the coverage area of femtocells and reducing the probability of outage due to sharing of frequency

spectrum with the macrocell. Further, the operating environment and hence the corresponding value of n also proves to be a vital decision parameter, since increase in n for femtocell network decreases the IFFER whereas increase in n for macrocell network increases IFFER. Hence it becomes the choice of the network operator to have a trade-off between the throughput and coverage probability by manipulating the transmit power and the IFFER. However, the application of cross-polarization improves the system performance over these constraints and thereby guarantee the required QoS.

Figure 5.10: Coverage probability of femtoUEs in macrocell coverage area

Figure 5.11: Interference free femtocell exclusive region in macrocell coverage area

5.5. Implementation/Design Challenges and Solutions

In addition to the benefits of adopting cross-polarized transmission in two-tier mobile communication network, there arise a number of challenges, which needs to be properly addressed to prevent system performance degradation. This section discusses the major challenges involved and the potential solutions to further emphasize the attractiveness of the proposed scheme.

5.5.1 Improper Transmitter-Receiver Antenna Alignment

Figure 5.12: Antenna alignment in case of circular polarization and linear polarization

The main challenge of using orthogonally polarized transmission system for interference mitigation in wireless communication is the improper alignment of the receiver antenna with respect to the transmitter antenna. It is most important that the sense of polarization of antennas at both ends of the transmission medium are the same, the absence of which may result in polarization pattern distortion or depolarization effects. Depolarization will cause the energy from one polarization sense to be coupled into other, thereby causing interference. This is quite likely to happen in case of current cellular communication system where the user equipments are mobile and may be held in any random position while attending voice calls, browsing data etc. Polarization filtering helps in mitigating depolarization effects, interference suppression and signal separation to a great extent. However, the choice of circular polarization over linear polarization ensures that the random positioning of the mobile terminal does not affect the polarization pattern at the base station or vice versa and hence reduces the probability of cross polarization coupling. This is demonstrated in Figure 5.12. The benefit of circular polarized transmission/reception is reflected in its ability to

efficiently mitigate multipath fading caused by reflections from walls, ceiling and floors in the indoor environment which helps in delay spread reduction [179] and it maintains a stronger signal strength with better fading reduction capabilities [180]. In addition, due to the insensitivity to transmitter and receiver antenna polarization alignment, circular polarization maintains the dc output voltage irrespective of the rotation angle of the receiving antenna for rectenna applications, leading to low polarization loss [181]. Further, antennas with polarization filtering helps in mitigating depolarization effects, interference suppression and signal separation. An example is the new IWxCPA antenna which produces a 'drop-out free' transmitter and receiver combination that is never out of phase. The inherent technology, along with the antenna's directional attributes, guarantee the best possible RF signal link [182]. A detailed analysis of circular polarization diversity in indoor wireless environment is carried out in [183] where the correlation coefficient value is found to be lower than that of conventional linear polarization systems.

5.5.2 Need for Polarization Reconfigurability during Handover (HO)

Another drawback of using cross polarized transmission in femto-macro network is the need for polarization reconfigurability to prevent call drops when handover takes place from one network to another network. The polarization switching should be initiated as and when the handover takes place so that the user equipment/receiver antenna is properly aligned with respect to the transmitter antenna of the network with LHCP in macrocell network and RHCP in femtocell network.

Figure 5.13 explains the signaling and call flow in case of handover from macrocell network to femtocell network. Macrocell to femtocell handover is the most challenging issue for a large scale two-tier femto macro network. As demonstrated in Figure 5.13, it is the serving macroBS (MBS) that coordinates this handover based on measurement reports received. When a user (UE) in the macrocell network which carries out transmission with LHCP detects a femtoBS (FBS) signal, it notifies the same to the macroBS with its measurement reports. The macroBS provides the optimized and authorized neighboring femtoBS list and initiates the handover procedure by sending a request to the serving radio network controller (RNC) and the same request is passed on to the target femtoBS via the core network and the femto-gateway. The femtoBS checks the user's authorization, performs the call admission control/radio resource control (CAC/RRC) and responds to the handover request based on which a new link is established between the femto gateway and the femtoBS. Now the user, detaches itself from the macroBS, synchronizes with the femtoBS and changes its polarization from LHCP to RHCP before any further transmission takes place. The previously established radio links with the RNC are deleted by the macroBS as well. The reverse happens when a handover is initiated from femtocell to macrocell network i.e. the polarization

switches from LHCP to RHCP. However, in mobile communication systems, this polarization reconfigurability property required for handover, calls for the need of switchable circular polarization antenna design that can intelligently adjust its polarization based on the network to which it is connected i.e. LHCP in macrocell network and RHCP in femtocell network.

Figure 5.13: Signaling and call flow for handover from macrocell network to femtocell network

Earlier, in case of using alternating polarization in multi-cell environment, the assumption was that the operator has to visit subscriber sites in order to reorient the antenna of the subscriber so as to align it in terms of the polarization of the transmitter antenna. However this seems to be quite impractical in the current cellular network as the number of mobile subscribers is growing immensely on a daily basis. Hence the handovers from one network to another definitely calls for an instantaneous polarization switchable antenna circuit, which does not cause any delay and hence avoid call-drops. Due to their low-cost, low profile, light weight and ease of fabrication, micro-strip patch antennas prove to be the most promising and suitable candidate for achieving reconfigurability in mobile communication user equipments. A very large number of solutions making use of micro-strip patch antennas are available in the literature for achieving polarization reconfigurability [174-186]. The use of a reconfigurable feeding line in order to switch the polarization of patch antenna

between LHCP and RHCP is proposed in [184] whereas the design of an aperture coupled micro-strip antenna that ensures polarization reconfigurability is discussed in [185].

Polarization reconfigurability can be further coupled with frequency reconfigurability to achieve even better performance in FDD systems [186]. Here the proposed antenna design consists of a rectangular patch with a U-slot and truncating corners. A switch turns the U-slot on/off providing frequency reconfigurability while polarization reconfigurability is achieved through three switches that turn on/off the truncated corners. A patch antenna with switchable circular polarization using a branched feed circuit can also be deployed in the user equipment for smooth switching between LHCP and RHCP [187]. The simulation results guarantee an XPD greater than 30 dB with this antenna. However, if the LHCP signals suffer interference from RHCP signals or vice-versa, cross-polarization interference cancellers (XPIC) can be used which can reduce the BER from about 10^{-2} to about 10^{-5} . This technique makes it possible to transmit using both polarizations with same frequency at the same time without much interference. Also, reconfigurable patch antennas consisting of a square patch with two cross-shaped diagonal slots can be used for obtaining specific polarimetric dimensions like linear polarization, right hand circular polarization and left hand circular polarization [188]. It is the use of two pair of switches in the design which helps in achieving reconfigurability in both frequency and polarization domains.

5.5.3 Mitigating Depolarization Effects

When orthogonally polarized signals are used for frequency reuse purposes in femto-macro network, high levels of polarization purity is expected from both the incident field and the receiving antenna. Ideally, the cross-polar transmissions (e.g. from a RHCP Tx antenna to an LHCP Rx antenna) should be equal to zero and the XPD degradation of the antenna is not allowed. Also it is considered that the orthogonality can be easily maintained when the transmitting and receiving antennas are aligned along the main lobe or beam maximum of each other. This is actually not the case owing to three reasons: the finite cross-polar isolation (XPI) of antennas, the array tilting and the electromagnetic channel depolarization effects. As a result, in reality the transmission medium often distorts the orthogonality of the cross-polarized waves. Hence even though the antennas are designed to capture a given polarization, they seem to be sensitive and capture the orthogonal polarization. Ideal polarization isolation requires the incident field and the receiving antenna to have the same axial ratio and orthogonal polarization tilt angle orientations. If proper design attention is not paid to polarization purity, the cross-polar isolation undergoes significant degradation. Even though this channel depolarization may be pointed out as an immediate concern, analysis and modelling results of radio wave depolarization in urban environment seems to be positive for

wireless communication [189]. Moreover, the efficiency of polarization diversity significantly depends on the higher XPD maintained between the antennas in use. XPD, typically the order of 10-20 dB can be sustained between operating co-polar and cross-polar channels capable of assuring isolation between them [190]. Further, the investigation on practical limitations of using cross polarized antennas in wireless communication concludes that it is possible to preserve the polarization characteristics in NLOS transmissions and that high capacities are achievable with orthogonally oriented antennas [191]. In addition, typical indoor environments further seem to have very small cross-polar correlation values [192].

A dual-polarized antenna with high isolation (31dB) and lower cross-coupling serves the purpose of orthogonal polarized transmission in wireless communication [193]. Upon quantitatively and statistically analysing the propagation characteristics like received signal to noise ratio and delay spread through outfield measurements in cellular environment, circular polarization proves to be efficient in establishing and maintaining stable communication links [181]. Various cross-polarization interference cancellation techniques are also available which assures that the orthogonality is maintained at the receiving end too. The design in [194] makes use of a Poincare sphere for the analysis of orthogonalizing two polarization ellipses by a differential phase shifter and a differential attenuator. It also derives the condition of minimum differential attenuation for removing a given amount of non-orthogonality and thereby extracting orthogonally polarized signals at the receiving end with minimal interference. The design of a new cross-polarization interference canceler that assures polarization recovery in cellular radio environment is proposed in [195] which takes care of the phase variations that a polarized signal undergoes during transmission. It is capable of operating even in the presence of unknown and possible time-varying random phase fluctuations caused due to imperfect recovery at the receiver side. The technique of Adaptive Polarization Division Multiplexing (APDM) can assure cross-polarization isolation with minimal interference between user stations while maintaining high spectrum utilization efficiency through the use of dual polarization [196].

5.5. Summary

This chapter explored the use of cross-polarized transmission as a means of efficient frequency reuse with effective interference mitigation in two tier femto-macro network. The frequency reuse benefits reaped from orthogonal polarized transmission not only increases the spectral efficiency but contribute towards better network performance in terms of capacity and coverage as well. A theoretical framework exploiting the polarization and frequency diversity to improve the system capacity through frequency reuse has been demonstrated. The practical challenges involved in the

design and implementation has been analyzed on a point to point basis and feasible solutions are proposed. It has been validated with mathematical analysis and simulation results and shown that the system performance can be improved by increasing the XPD value and maintaining the orthogonality of the cross polarized signals at 90 degree antenna feed separation. The message is clear: the proposed interference avoidance strategies do not compromise on the spectral efficiency of the system but enhance it with intelligent orthogonalization techniques. To conclude, even with minor imperfect calibrations, the use of cross-polarization in femto-macro network seems to remarkably increase the system capacity and allow efficient frequency reuse in comparison to that in the conventional frequency reuse method.

Chapter 6

CPCFA for Performance Enhancement in Self-organized Femtocell Network

He that does good to another does good also to himself.

- Lucius A. Seneca

6.1 Introduction

The static spectrum allocation adopted in RFA though simple and straightforward in operation and helps in improving the cell edge user's performance, fails to adapt to the real-time traffic dynamics and user distribution. This is because, the pre-assigned static frequency reuse does not adjust based on traffic distribution, interference condition or QoS requirements of the unplanned femtocell users. As a result of this unpredictable, non-uniform traffic in cellular networks, static allocation of spectrum with spatial separation may result in high blocking probability in some cells while it may result in excessive unused channels in other. On the other hand, in a cross-polarized wireless access network served by a single omni-directional macrocell base station, the performance of the cell-edge users is essentially limited by the achievable SINR as evident from Figure 5.6. This is due to the augmented interference coupling experienced with degradation of XPD towards the cell-edge. All these concerns translate into inefficient resource utilization which needs to be properly addressed so as to enhance the system capacity and hence the performance. Even though numerous algorithms on non-uniform channel allocation and channel borrowing have been proposed, these may not be adequate in real-time scenarios. This demands the necessity for femtocell networks that are capable of adapting to the erratic real-time conditions and effectively solve the challenges faced. Moreover, with the proliferation of various multi-media devices, the future wireless access networks are expected to be autonomous in terms of operation. They are anticipated to exhibit a significant degree of self-organization and self-optimization characteristics,

which involves combining advances in communication technology, smart topology design, and spectrum reframing.

As an effective step towards addressing these challenges, self-organizing femtocells with ‘easy plug and play property’ have been recently gaining significant attention. Currently, 3GPP LTE-Advanced and IEEE 802.16m are standardizing the Self-Organizing Network (SON) concept for IMT-Advanced femtocell networks as well [137], [197-199]. In multi-tier femto-macro networks, this self-organization is considered not only as a network harmonization tool but also as an individual optimization technique. Hence it aids in offering better throughput and QoS to the femtoUEs while at the same time contributes to the holistic performance enhancement of the system through system scalability and enhanced spectrum efficiency. System scalability mainly arises from decentralization of self-organizing functionalities which involves categorizing the BSs into different zones which negotiate for resources on the basis of different performance metrics. However, promoting direct negotiation and coordination among femtoBSs and macroBSs still remain a challenging issue due to the complexity of signaling and inter-tier communication overheads. Nevertheless, exploiting the self-organization capability of the femtoBSs in accordance with the varying macrocell system dynamics, enables scalability and solves this problem to a great extent. Apart from scalable network expansion, self organization boosts the spectral efficiency of the system by promoting resource sharing through mutual coordination and contention resolution. In case of multi-tier networks sharing the same frequency spectrum, self-organization encourages the base stations to compete for larger bandwidth allocations in an uncoordinated fashion. Here, cooperation among femtoBSs counteracts the decrease in available spectral resources by performing orthogonal or smartly reused spectrum allocations within each zone.

In this chapter, we investigate the application of cross-polarized complementary frequency allocation (CPCFA) algorithm as a cooperative approach towards harmonious co-existence in self-organized femtocell networks. Here the introduction of self-organization feature enable the femtocells to adapt themselves to the rapidly changing user distribution, data traffic dynamics and interference scenarios. Also, the simultaneous incorporation of reverse frequency allocation with dynamic spectrum access enhances the system spectral efficiency. In addition, reducing the radio transmission range of the polarized antenna helps in minimizing the impact of XPD degradation with distance which is accomplished by assigning the coverage of macrocell area to different antenna elements. Even though several methods of self-organization [76, 138, 139, 200] which alleviate the macro-femto interference are available in literature, self-organizing femtocells that promote orthogonal resource allocation with selfish dynamic spectrum access has not drawn much attention and forms the main focus of this work.

6.2 Cross Polarized Complementary Frequency Allocation Strategy

With billions already spent, network operators always search for effective methods to squeeze the maximum out of the existing multi-tier networks. In these networks, when one of the tier is unplanned and uncoordinated, the key challenge of allocating scarce spectral resource to the users should be addressed effectively [201]. As we know, both higher cross-tier interference (with shared spectrum usage) and limited spectrum availability (with dedicated spectrum usage) are capacity-limiting factors. Hence, CPCFA strategy is designed by incorporating the merits of the aforementioned methods as discussed in Chapter 4 and Chapter 5, where frequency diversity along with polarization diversity is exploited to improve the system performance. Since, macrocell network operates with meticulous planning, frequency reuse with static frequency allocation has already proven to be efficient enough to satisfy user requirements. However, the unpredicted ad-hoc deployment of femtocells necessitate dynamic frequency reuse patterns based on macrocell user spatial distribution and their operational spectrum. In this standpoint, we consider a macrocell network with an operator-planned static frequency allocation having a FRF of 1. Within this macrocell, self-organizing femtocells are embedded which are capable of dynamic spectrum access by exploiting the CPCFA strategy. Here, the self-organizing femtoBS is embedded with the capability of sensing the user operations in its vicinity, which enables it to take real-time decisions regarding its operational spectrum. They are aware of the nearby user actions and future intentions enabled via inter-cell communication through femtocell gateways, or femtoBS assisted sensing. Thus, it collects operational information from the nearby base stations based on which it configures its own operational frequency with the aim of minimizing the interference that it causes to the users in its vicinity. Then comes the self-optimization, where the femtocell management system (FMS) ensures that the QoS demands of every subscriber is satisfied through optimal sub-carrier allocation and cross-polarized orthogonal transmission. It also ensures to maximize the spectrum access of femtocell during heavy user traffic within each zone of the macrocell. In addition, it also takes care of the self-healing part, where it switches its operational frequency or initiates a handover when it experiences intolerable co-tier interference. In essence, even with scarcity in the available radio spectrum, it is the self-organizing femtocells that operates on reverse frequency strategy that enables the two tier network to achieve better spectral efficiency. Also the femtocell nodes carry out transmission via RHCP signals which is orthogonal to that of LHCP transmission used by macrocell nodes. This supports independent operation across tiers by exploiting polarization diversity with orthogonal senses of rotation.

Figure 6.1 demonstrates the crucial idea behind orthogonal spectrum allocation in CPCFA strategy where a macrocell coverage area is initially partitioned into two non-overlapping regions namely the cell-center (inner region) and cell-edge (outer region). The total available macrocell spectrum is then partitioned and allocated to these two regions. Furthermore, the direction of transmission of these macrocell sub-bands are reversed and assigned to the femtocells located within these alternate regions. Depending on whether the user belongs to the femtocell network or the macrocell network, the polarization mode for transmission is further chosen between LHCP for macrocell and RHCP for femtocell. This spectrum partitioning and the reverse allocation for a single cell is demonstrated in Table 6.1.

Figure 6.1: CPCFA strategy for a single cell

Table 6.1: CPCFA for a single cell

	Inner Region	Outer Region
Macrocell (LHCP)	<div> S_1 S_{1a} (DL) S_{1b} (UL) </div>	<div> S_2 S_{2a} (DL) S_{2b} (UL) </div>
Femtoce (RHCP)	<div> S'_2 S_{2a} (DL) S_{2b} (UL) </div>	<div> S'_1 S_{1a} (DL) S_{1b} (UL) </div>

However, the spectrum allocation using CPCFA strategy in a multi-cell scenario needs to be wisely formulated in order to facilitate flexibility, scalability and higher efficiency. It should ensure that both macrocell and femtocell are benefited in terms of better capacity and lower interference. For this purpose, the femtocells must be capable of self-configuring its resource utilization and optimize its usage in accordance with the system parameters at run-time [21]. There is a series of steps involved to satisfy this criteria. The following procedures explain the operation of CPCFA strategy in a 3-cell cluster, which can be further scaled to any number of cells in the network.

6.2.1 Location Cognizance and Spectrum Allocation for MacroUEs

The macrocell spectrum allocation is assumed to be static and is methodically planned by the network operator. The spatial partitioning of spectrum is carried out along the same procedure as explained in Section 4.2.4, the demonstration of which is given in Figure 4.3. However, the radius of the cell-center region is a significant design parameter in CPCFA, which is dependent on the user density, QoS requirement of the customers, spectrum resource availability etc. To aid this decision making, as established in [157], the cell-center region radius is assumed to be 0.65 times the macrocell radius so that the average network capacity is maximized for uniformly distributed UEs. Thus macroBS identifies the macroUEs located within 65% of its radius as inner region macroUEs and those outside as outer region macroUEs. Even though the radius of the cell-center and cell-edge region is dependent on specific multipath and fading profiles; due to the incorporation of polarized transmission, the partitioning is carried out independent of the RSSI value unlike that in Chapter 4.

The macrocell spectrum partitioning is implemented as in Figure 4.3. The total available bandwidth (S) of the macrocell is divided into OFDMA time-frequency units and allocated to the inner region (S_1) and outer region (S_2) macroUEs such that $S = S_1 \cup S_2$. S_1 contains the UL and DL frequency carriers for the inner region macro-users whereas the partition S_2 contains the UL and DL frequency carriers for the outer region macro-users. Here (S_1) contains a major portion of the total available carriers, which is allocated to the cell-center region or the inner region (C1-C6) macroUEs by the network operator and is named as sub-band A. The cell-edge (outer) region spectrum (S_2) is further sub-divided into six sub-bands B, C, D, E, F, G and allocated to cell-edge region (E1-E6) macroUEs as in Figure 4.3. In short, frequency reuse factor (FRF) of 1 is applied to the cell-center region and FRF of 6 is applied to the cell-edge region resulting in the entire macrocell to embrace an FRF of 1. Thus, the macrocell employs static spectrum allocation meticulously planned by the network operator, which also assures the absence of intra-cell interference due to the adoption of OFDMA technology. Here the boundaries of every single zone is neither rigid nor of uniform geographical size or shape as projected in the figure, due to changes in channel environment. It

merely highlights the need for a spatial separation in resource allocation so as to enable reverse frequency reuse without interfering with either tier significantly. It also highlights that the cell-center region macroUEs do not reuse the spectrum of the cell-edge region macroUEs, as a result of which the entire macrocell system is free from inter-cell interference. Similar to the case of RFA discussed in Chapter 4, the use of distributed antenna system (DAS) supports this mode of sectorized spectrum allocation along with spatial frequency reuse within the macroBS coverage area [159].

6.2.3 Location Cognizance and Spectrum selection by FemtoUEs (Self-Configuration)

Femtocells are plug and play devices, which are installed by the customers without any prior planning. Unlike the macrocells, they can be turned on and off at any time making their deployment completely random. Hence the position and location of the femtocells within the macrocell may vary continuously. As a result, femtoBS requires to sense the environment and be aware of its own location as well as its neighbors in the macrocell coverage area. However, the radio transmission range between the femtoBS and the femtoUE is comparatively small, which lets us assume that the femtoUE lies within the same zone as that of the femtoBS. Hence similar to the macroUEs, femtoBSs along with its registered femtoUEs are also categorized based on their location.

Though the macrocell depends on static spectrum allocation with unity FRF, the massive ad-hoc deployment of femtocells demand more spectral resources, which encourages the adoption of dynamic spectrum access. As a result, the operation of femtocells is expected to be self-organizing with an autonomous spectrum selection process which varies with the macrocell system dynamics. The self-organization mechanism includes self-configuration and self-optimization phases. Self-configuration is the phase soon after the femtoBS is switched on, in which the femtoBS within each sector configures its own operational frequency based on the immediate input that it receives from the neighboring macrocell environment. It selects the sub-carrier from the least interfering sub-band for its operation along which it transmits in the reverse mode with a polarization orthogonal to that of the macrocell transmission.

The sectorization process and the corresponding frequency band selection by the femtoBSs is summarized in Stage 1 of the operational algorithm furnished in Table 6.2. In the self-configuration phase, each femtoBS selects its operational frequency among the N available sub-bands. Let F_o and F_i represent the number of femtocell users in the outer and inner region respectively and M_o and M_i represent the number of macrocell users in the outer and inner region respectively. Firstly, similar to the methodology in [125], the set of usable frequency sub-bands S_f for the femtoBS j is

initialized to the set of all frequency sub-bands within S made available to the macroBS, where $S = S_{Mi} \cup S_{Mo}$. Here S_{Mi} is the frequency spectrum available to the inner region macroUEs and S_{Mo} is the frequency spectrum available to the outer region macroUEs. Several wireless communication standards have highlighted the capability of wireless nodes in sensing and measuring the instantaneous signal strength (RSSI) for all sub-carriers [202-204]. Hence, as the femtoBS is switched on, it senses the radio signals received from the neighboring macroBS and estimates the RSSI value for each received frequency sub-band which is dependent on the network interference signature. By analyzing the strength of the received signals, it determines the dominant macrocell sub-band operational within its area. Based on this information, the femtoBS determines whether it is located in the cell-edge region or cell-center region of the macrocell. Further it chooses the macrocell sub-band from which it experiences the least interference, reverses its direction of transmission and uses it for its operation. Stage 1 of the operational algorithm in Table 6.2 explains this process in detail.

Table 6.2: Stage 1 of Operational Algorithm for CPCFA in a multi-cell environment

```

1: Stage 1
2:  $\forall$  RHCP femtoBS  $j \in (F_o \cup F_i)$  do
3:    $S_f \leftarrow S$  {Initialization}
4:    $N_i, N_o \leftarrow N$  (Total no: of sub-bands = 7)
5:    $R_x \leftarrow$  RSSI values for sub-band  $x$ 
6:    $R_f^* \leftarrow$  Highest RSSI value for a sub-band at femtoBS  $j$ 
7:   if ( $R_f^* = R_A$ ) then {femtoBS  $j$  is located in the cell-center region}
8:      $S_f^* \leftarrow$  Set of (N-1) sub-bands with comparatively higher RSSI value
9:      $S_{fi} \leftarrow (S_f - S_f^*)'$  {frequency sub-band allocated for femtoBS  $j$ }
10:  else {femtoBS  $j$  is located in the cell-edge region}
11:     $S_f^* \leftarrow$  Set of all sub-bands except A
12:     $S_{fo} \leftarrow (S_f - S_f^*)'$  {frequency sub-band allocated for femtoBS  $j$ }
13:  end if
14: end for

```

With reference to the static spectrum allocation adopted for the macrocell, Figure 4.3 projects the best possible sub-bands for femtocell operation in each zone during the first iteration of the algorithm owing to minimal interference. Since the macrocell radio transmission range for sub-band A is restricted to the cell-center region, the femtoUEs will make use of sub-band A' in the cell-edge region owing to least interference experienced. Here A' corresponds to the reversed UL and the DL carriers of sub-band A; which is used by femtoUEs in the cell-edge regions (E1-E6). Similar is the case for other sub-bands as well i.e. B', C', D', E', F' and G' are used by the femtoUEs in the cell-center regions (C1-C6). Selection of frequency sub-band by the femtoBS is based on the assumption

that the separating distance between the base stations on either tier is significantly large so that the interference is within tolerable limits. In addition to this, the smaller transmission range of femtoBS in the cell-edge region assures that the macroUEs operating on the same sub-band in the cell-center region and those in the neighboring macrocells are free from interference.

To sum up, the intra-cell interference is mitigated since the cell-center UEs do not share the same spectrum with cell-edge UEs and inter-cell interference is controlled due to the spatially separated frequency allocation with orthogonalized polarization. Also the inter-tier interference is controlled since the UEs in both tiers make use of different spectrum in a given zone that too in reversed mode.

6.2.4 Self-optimization by FemtoBS

A key issue addressed by the self-optimization phase is the dynamic selection of additional frequency spectrum, taking into consideration the effect of co-channel and co-tier interference in a heavy traffic environment. Since the frequency resources are limited, it is important to enable the flexibility of using the entire available spectrum in every region so as to satisfy the user's bandwidth requirements. In the current scenario, even though frequency reuse is enabled with proper geographic separation, the possibilities of inadequate spectrum cannot be neglected completely, owing to the increasing user traffic. As a result, proportional fairness measures are applied by the FMS to optimize the network performance by ensuring fair allocation of sub-carriers in every sector based on the user density and the corresponding QoS requirements. The resource allocation and QoS information recovered by the femtoBS from the FMS through the femto-gateway enables it to adopt a throughput constrained opportunistic scheduling [205]. During every periodic cycle of status update from the femtoBSs, FMS determine the sectors, which are lacking in bandwidth to satisfy their required QoS. On finding such sectors, immediate actions are taken by the FMS to inform and initiate the femtoBS to aggressively access additional sub-carriers from spatially separated, interference-limited neighboring sub-bands. This process always adheres to the condition that the resulting aggregated cross-tier interference and co-tier interference is constrained and maintained within acceptable limits owing to the fact that signal strength always degrades with distance.

Stage 2a and 2b of the operational algorithm in Table 6.3 and Table 6.4 respectively explain how the additional sub-bands and hence sub-carriers are accessed one after the other by the femtoBS in the inner region and outer region. In accordance with the varying user distribution, each femtoBS autonomously determines the sub-band with minimum interference and accesses the sub-carrier within these sub-band owing to the user bandwidth requirements. For this purpose, after accessing a new sub-band, the femtoBS monitors for a time interval τ_l , whether the SINR at the femtoBS due

to operation along the chosen sub-carrier falls below a pre-determined threshold T . If the SINR falls below the threshold, the self-optimization feature adopts the first countermeasure of decrementing the femtoBS transmit power by a value δ . This triggers a similar reaction from the interfering femtoBS as well, which will limit the overall interference and hence improve the SINR. If the received SINR is still below the threshold T , the femtoBS waits for a time interval τ_2 and determines whether the UE attached to the interfering femtoBS is within its own coverage area. If within its radio transmission range, the femtoBS initiates a handover for this UE and accepts it as its own registered user. If the UE is out of its coverage area, the femtoBS chooses the next sub-carrier within the selected sub-band for its operation and repeats these steps until the received SINR climbs above the threshold T enabling it to transmit with the guaranteed QoS. The introduction of timeouts τ_1 and τ_2 help in avoiding unnecessary handovers due to channel fluctuations or presence of fast-moving UEs within the femtoBS coverage area. This dynamic access of spectrum satisfies the lower capacity bound of every attached user, before additional sub-carriers are allocated to users with better channel quality to achieve maximum gain. When the same scheduling strategy is applied at the macroBS, the problem of lower throughput for the cell-edge region users can be solved to an extent by imposing higher value for their lower bounds, which is accomplished before serving cell-center region users. In short, the algorithm enables selfish optimization of resources by each femtoBS within each sector and assures bandwidth efficiency with the guarantee that the process does not exacerbate the interference in the network.

Table 6.3: Stage 2a of Operational Algorithm for CPCFA in a multi-cell environment

1:	Stage 2a	{no-more free sub-carriers in current inner region sub-band}
2:	while ($S_{fi} = NULL, N_i \text{ not equal } 0$) do	
3:	$N_i \leftarrow N_i - 1;$	
4:	$S_{fi} \leftarrow (S - S'_{fi})$	
5:	$S_f^* \leftarrow$ Set of $(N_i - 1)$ sub-bands with comparatively higher RSSI value	
6:	$S_{fi} \leftarrow (S_{fi} - S_f^*)'$ {frequency sub- band allocated for femtoBS j }	
7:	if ($SINR_{UL_Fi} < T$ at femtoBS j on occupied sub-carrier within S_{fi} for $t > \tau_1$) then	
8:	Decrease transmit power of femtoUE attached to femtoBS j by δ	
9:	end if	
10:	if ($SINR_{UL_Fi} < T$ at femtoBS j on occupied sub-carrier within S_{fi} for $t > \tau_2$) then	
11:	if (interfering femtoUE within coverage radius of femtoBS j) then	
12:	Initiate handover of the interfering femtoUE to femtoBS j	
13:	else	
14:	Occupy the next sub-carrier within S_{fi}	
15:	Goto Stage 2a	
16:	end if	
17:	end if	
18:	end while	

In addition to this, the self-optimization feature should also optimize the transmission characteristics of femtocells for which a combination of co-channel reuse with orthogonal allocation is introduced. While additional sub-bands and sub-carriers are accessed by the femtoBSs in cases of bandwidth scarcity as demonstrated in stage 2a and 2b of the operational algorithm, there may arise chances of interference between the macrocell and femtocell users. The use of cross-polarized transmission is considered as a means of eliminating these chances of cross-tier interference and thereby prevent the degradation of SINR. For this purpose, circular cross-polarization is chosen as the best mode of transmission in wireless network as explained before. Since the transmission along all the sub-bands in the macrocell network is enabled through left hand circular polarization (LHCP), the spectrum allocated to the randomly distributed femtocells, will make use of a polarization orthogonal to that of the macrocell network i.e. right hand circular polarization (RHCP) as explained in Figure 6.1. The sense of rotation being orthogonal to each other ensures isolation and cannot be altered even with random fluctuations or phase changes. In short, co-existing femtocell and macrocell users make use of orthogonal/alternate polarization so as to maximize the isolation between their transmissions and hence increase the communication quality.

Table 6.4: Stage 2b of Operational Algorithm for CPCFA in a multi-cell environment

1: Stage 2b	{no more free sub-carriers in current outer region sub-band}
2:	while ($S_{fo} = NULL, N_o$ not equal 0) do
3:	$N_o \leftarrow N_o - 1;$
4:	$S_{fo} \leftarrow (S - S'_{fi})$
5:	$S_f^* \leftarrow$ Set of ($N_o - 1$) sub-bands with comparatively higher RSSI value
6:	$S_{fo} \leftarrow (S_{fo} - S_f^*)'$ {frequency sub-band allocated for femtoBS j }
7:	if ($SINR_{ULFo} < T$ at femtoBS j on occupied sub-carrier within S_{fo} for $t > \tau_1$) then
8:	Decrease transmit power of femtoUE attached to femtoBS j by δ
9:	end if
10:	if ($SINR_{ULFo} < T$ at femtoBS j on occupied sub-carrier within S_{fo} for $t > \tau_2$) then
11:	if (interfering femtoUE within coverage radius of femtoBS j) then
12:	Initiate handover of the interfering femtoUE to femtoBS j
13:	else
14:	Occupy the next sub-carrier within S_{fo}
15:	Goto Stage 2b
16:	end if
17:	end if
18:	end while

6.2.5 Self-healing by Femtocells

In case of any sudden variation in the network configuration, the self-healing phase tries to address the challenge to bring the system to a stable state without compromising on the offered

services to the customer. It enables the automatic detection and resolution of failures and reconfigures the current settings to facilitate the smooth functioning of two-tier network with minimal impact on each other. When the failure is resolved, it should get back to its normal settings. Timers introduced in sub-carrier selection process enable self-healing by which they eliminate the sub-carrier that results in interference and selects the one that assures better SINR and hence throughput. The self-healing phase also takes care of the polarization changes during the handover procedures when a UE switches from a macrocell network to a femtocell network and vice-versa.

6.3 System Model and Analysis

An OFDMA downlink cellular scenario with two tiers corresponding to macrocell network and femtocell network respectively are considered as the system model. The basic radio resource unit that can be allocated in OFDMA transmission is a physical resource block (PRB). Intra-cell interference reduction is guaranteed by scheduling at most one UE per PRB in each cell. The network is composed of 7 macrocells with macroUEs uniformly distributed and femtoUEs randomly deployed. The sub-carriers from the designated frequency sub-bands as in Figure 4.3 are allocated to the macroUEs which trigger the femtoBSs to select their own operational frequencies owing to minimal interference [157]. Now, let P_{fb} , P_{fu} , P_{mb} and P_{mu} represent the transmit powers of the femtoBS, femtoUE, macroBS and macroUE respectively; S_{Mi} , S_{Fi} and S_{Mo} , S_{Fo} represent the bandwidth allotted to the macroUEs and femtoUEs in the inner region and outer region respectively; σ^2 represents the noise power spectral density, P_s^{rc} corresponds to the transmitted signal power from sender s to receiver rc , d denotes the random variable which represents the distance between the interfering BS and the UE under consideration, n represents the path loss exponent and $|h_0|^2$ represents the small scale fading gain between any BS under consideration and the attached UE. Because the bandwidth and time duration of PRB are restricted [206], it is assumed that all sub-carriers within a PRB, experience the same log-normal shadowing and frequency-flat Rayleigh fading [9]. Also the shadowing and fading coefficients are assumed to remain constant within each PRB [207], but may vary from one PRB to the next. Hence the interference power at a receiver is assumed to be the sum of received power from all other base stations making use of the same sub-carrier as that of the home base station. In addition, it is assumed to follow a general statistical distribution that includes all random effects like fading, shadowing etc.

6.3.1 Throughput

With RFA, the associated DL SINR at a femtoUE in the inner region and outer region of the macrocell is obtained from equations (4.3) and (4.4) respectively.

Further employment of polarimetric dimension to ensure orthogonal allocation of spectrum across tiers, assures significant capacity improvement by means of efficient interference control. In this case, the set of interfering BSs are assumed to use the same co-polar sub-carrier within the same tier but with orthogonal polarization in different tier. It is for this reason that femtocell network adopts RHCP for its transmission whereas the macrocell network employs the orthogonal LHCP for its transmission. Thus for the case of femto-macro network, femtocells are assumed to have co-polar transmissions whereas macrocells resort to cross-polar transmission with respect to the femto-user under consideration. Hence applying the polarimetric orthogonality in equations (5.4) and (5.5) to equations (4.3) and (4.4) yields DL SINR as:

$$SINR_{DL-Fi} = \frac{P_i^l |h_0|^2 d^{-n(XPD-1)}}{\sum_{j=1, j \neq i}^{Fi} P_{fb}^{\parallel} (XPD-1) + \sum_{k=1}^{Mo} P_{mu}^{\perp} + \sigma^2} \quad (6.1)$$

$$SINR_{DL-Fo} = \frac{P_i^l |h_0|^2 d^{-n(XPD-1)}}{\sum_{j=1, j \neq i}^{Fo} P_{fb}^{\parallel} (XPD-1) + \sum_{k=1}^{Mi} P_{mu}^{\perp} + \sigma^2} \quad (6.2)$$

where $P_{fb}^{\parallel} (= P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n})$ is the interference at femtoUE l due to the DL signal transmission from femtoBS j and $P_{mu}^{\perp} (= P_{mu} |h_0|^2 (d_{mu}^{fu})^{-n})$ is the interference at femtoUE l due to the UL signal transmission from macroUE k . The Shannon-Hartley bound is further used to calculate the maximum amount of error-free digital data that can be transmitted over the communication link with a specified bandwidth. Equations (6.1) and (6.2) highlight the fact that cross-polarized transmission can be utilized as an effective measure to improve the downlink system capacity of the femto-macro network that employs the CPCFA scheme. This is possible if one tier makes use of a polarization orthogonal to that of the other tier which in turn depends on the cross-polarization discrimination maintained between the two tiers. In addition to this, adoption of CPCFA proves to be a promising practical solution to minimize the chances of interference to the macrocell network as well which can be demonstrated in terms of Primary Protection Ratio (PPR) given by [208]:

$$PPR = \frac{C_{macro+femto}}{C_{macro_only}} \quad (6.3)$$

where $C_{macro+femto}$ is the capacity of the macroUEs in the presence of interference from the femtoUEs and C_{macro_only} is the capacity of the macroUEs without any interference [208, 209]. CPCFA seems to offer significantly higher value for PPR throughout the macrocell coverage area due to the effective interference control accomplished.

6.3.2 Coverage Probability

Coverage probability definitely decreases with increase in interference from the nearby radio transmissions which include femtocells, overlaid macrocell, and neighboring macrocells. Coverage probability analysis of the CPCFA scheme can project a clear picture on the probability of successful transmission. Unlike the case as in Chapter 5, in CPCFA the partitioning of the macrocell into inner region and outer region followed by the incorporation of RFA, eliminates the dominant DL interference from the macroBS and replaces it with the UL interference from the macroUE. This results in a significant increase in coverage probability for the femtoUEs throughout the macrocell coverage area. A node is said to be in coverage or the transmission from a femtoBS to a femtoUE is considered successful if and only if the SINR is above a threshold say T . This threshold value definitely depends on the channel conditions and receiver's characteristics like sensitivity, modulation, coding scheme etc. Let the traffic at the interfering femtoBSs and macroBSs be modeled by a sequence of independent indicators - $\forall i, A_i \in \{0,1\}$ such that $\mathbb{P}\{A_i = 1\} = \Lambda$ and $\mathbb{P}\{A_i = 0\} = 1 - \Lambda$. Thus the coverage probability for the femtocell downlink in the inner region ($P_{c,i}$) is expressed as :

$$P_{c,i} \triangleq \mathbb{P} (\text{SINR}_{DL_Fi} > T)$$

$$= \mathbb{E}_{P_{int_DL}} [\mathbb{P} (\text{SINR}_{DL_Fi} > T) | P_{int_DL}] \quad (6.4)$$

$$= \mathbb{E} \left[\exp \left(\frac{-T}{P d^{-n(XPD-1)}} \left(\sum_{j=1, j \neq i}^{Fi} P_{fb}^{\parallel} A_j (XPD - 1) + \sum_{k=1}^{Mo} P_{mu}^{\perp} A_k + \sigma^2 \right) \right) \right] \quad (6.5)$$

$$= \exp \left(\frac{-T \sigma^2}{P d^{-n(XPD-1)}} \right) \times \mathbb{E} \left[\prod_{j=1, j \neq i}^{Fi} \exp \left(\frac{-T P_{fb}^{\parallel} A_j}{P d^{-n}} \right) \right] \times \mathbb{E} \left[\prod_{k=1}^{Mo} \exp \left(\frac{-T P_{mu}^{\perp} A_k}{P d^{-n(XPD-1)}} \right) \right] \quad (6.6)$$

The expectation in the middle term of equation (6.6) can be expressed as:

$$\mathbb{E} \left[\exp \left(\frac{-T P_{fb}^{\parallel} A_j}{P d^{-n}} \right) \right] = \mathbb{P}(A_j = 1) \times \int_0^{\infty} \exp \left(-\frac{T P_{fb}^{\parallel}}{P d^{-n}} \right) f_{p_{fb}^{\parallel}}(p_{fb}) dp_{fb} + \mathbb{P}(A_j = 0) \times 1$$

$$= 1 - \frac{T \Lambda}{\left(\frac{P}{P_{fb}^{\parallel}} \right) \left(\frac{d}{d_{fb}^u} \right)^{-n} + T} \quad (6.7)$$

The expectation in the last term of equation (6.6) can be expressed as:

$$\begin{aligned}
\mathbb{E} \left[\exp \left(\frac{-TP_{mu}^\perp A_k}{P d^{-n}(XPD-1)} \right) \right] &= \mathbb{P}(A_k = 1) \times \int_0^\infty \exp \left(-\frac{TP_{mu}}{P d^{-n}(XPD-1)} \right) f_{p_{mu}^\perp}(p_{mu}) dp_{mu} + \\
&\quad \mathbb{P}(A_k = 0) \times 1 \\
&= 1 - \frac{T\Lambda}{(XPD-1) \left(\frac{P}{P_{mu}^\perp} \right) \left(\frac{d}{d_{mu}^{fu}} \right)^{-n} + T} \quad (6.8)
\end{aligned}$$

Substituting equations (6.7) and (6.8) in equation (6.6), yields coverage probability of inner region femtocell in the downlink as :

$$P_{c_i} = \exp \left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)} \right) \times \prod_{j=1, j \neq i}^{Fi} \left\{ 1 - \frac{T\Lambda}{\left(\frac{P}{P_{fb}^\parallel} \right) \left(\frac{d}{d_{fb}^{fu}} \right)^{-n} + T} \right\} \times \prod_{k=1}^{Mo} \left\{ 1 - \frac{T\Lambda}{(XPD-1) \left(\frac{P}{P_{mu}^\perp} \right) \left(\frac{d}{d_{mu}^{fu}} \right)^{-n} + T} \right\} \quad (6.9)$$

Similarly, the coverage probability for the outer region femtocell in the downlink (P_{c_o}) is expressed as:

$$P_{c_o} = \exp \left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)} \right) \times \prod_{j=1, j \neq i}^{Fo} \left\{ 1 - \frac{T\Lambda}{\left(\frac{P}{P_{fb}^\parallel} \right) \left(\frac{d}{d_{fb}^{fu}} \right)^{-n} + T} \right\} \times \prod_{k=1}^{Mi} \left\{ 1 - \frac{T\Lambda}{(XPD-1) \left(\frac{P}{P_{mu}^\perp} \right) \left(\frac{d}{d_{mu}^{fu}} \right)^{-n} + T} \right\} \quad (6.10)$$

6.3.3 Maximum Permissible Active Femtocell Density

When the femto-macro network shares the radio spectrum, and co-channel reuse is permissible within the system, there is always a maximum active femtocell density beyond which every single addition in the femtoBS density increases the interference to the macrocell network. When the femtoUE reuses the frequency sub-band of the macroBS in the downlink, the received SINR depends on its distance from the serving femtoBS and the interfering macroUE. The interference statistics measured by a femtoUE is a representative of that experienced by all other femtoUEs [40]. From equations (6.1) and (6.2), the interference experienced at a femtoUE l in the inner region and outer region respectively due to the downlink transmissions along the same frequency sub-band used by nearby femtoBS j is given by:

For inner region: $I_{fb}^{fu} = \sum_{j=1, j \neq i}^{Fi} P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n}$

For outer region: $I_{fb}^{fu} = \sum_{j=1, j \neq i}^{Fo} P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n}$

With λ representing the spatial density of the femtoUEs, the moment generating function of I_{fb}^{fu} is given by [210]:

$$\mathbb{E} \left[\exp(-s I_{fb}^{fu}) \right] = \exp \left(-2\pi\lambda \int_0^\infty \frac{u}{1 + \frac{u^n}{s P_{fb}}} du \right) = \exp \left(-\lambda (s P_{fb})^{\frac{2}{n}} K \right) \quad (6.11)$$

where $K = \frac{2\pi^2}{n \sin(\frac{2\pi}{n})}$

Here, the femtoUE is positioned at the coverage boundary of its serving femtoBS at shortest distance from the interfering macroUE in order to guarantee its outage due to cross tier interference.

We have from the previous section,

$$\begin{aligned} P_{c,i} &\triangleq \mathbb{P} (SINR_{DL_Fi} > T) = \mathbb{P} \left(\frac{P_i^l |h|^2 d^{-n} (XPD-1)}{\sum_{j=1}^{Fi} P_{fb} |h|^2 (d_{fb}^{fu})^{-n} (XPD-1) + \sum_{k=1}^{Mo} P_{mu} |h|^2 (d_{mu}^{fu})^{-n} + \sigma^2} > T \right) \\ &= \mathbb{E} \left[\exp \left(\frac{-T}{P d^{-n} (XPD-1)} \left(\sigma^2 + \sum_{k=1}^{Mo} P_{mu} (d_{mu}^{fu})^{-n} \Lambda_k + \sum_{j=1, j \neq i}^{Fi} P_{fb} (d_{fb}^{fu})^{-n} \Lambda_j (XPD-1) \right) \right) \right] \end{aligned} \quad (6.12)$$

From equations (6.8) and (6.11), equation (6.12) becomes:

$$\exp \left(\frac{-T \sigma^2}{P d^{-n} (XPD-1)} \right) \times \prod_{k=1}^{Mo} \left\{ 1 - \frac{T \Lambda}{(XPD-1) \left(\frac{P}{P_{mu}} \right) \left(\frac{d}{d_{mu}^{fu}} \right)^{-n} + T} \right\} \times \left\{ \exp \left(-\lambda_i T^{\frac{2}{n}} K \Lambda (XPD-1) d^2 \right) \right\} \quad (6.13)$$

where λ_i is the maximum permissible femtoBS density in the inner region which is given by:

$$\lambda_i = \frac{-\ln \left[P_{c,i} \left(\prod_{k=1}^{Mo} \left\{ 1 - \frac{T\Lambda}{(XPD-1) \left(\frac{P}{P_{mu}} \right) \left(\frac{d}{d_{mu}} \right)^{-n} + T} \right\} \right)^{-1} \right] + \left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)} \right)}{\left(\frac{2}{T^n K \Lambda (XPD-1) d^2} \right)} \quad (6.14)$$

Similarly, the maximum permissible femtoBS density in the outer region is given by:

$$\lambda_o = \frac{-\ln \left[P_{c,o} \left(\prod_{k=1}^{Mi} \left\{ 1 - \frac{T\Lambda}{(XPD-1) \left(\frac{P}{P_{mu}} \right) \left(\frac{d}{d_{mu}} \right)^{-n} + T} \right\} \right)^{-1} \right] + \left(\frac{-T\sigma^2}{P d^{-n}(XPD-1)} \right)}{\left(\frac{2}{T^n K \Lambda (XPD-1) d^2} \right)} \quad (6.15)$$

6.3.4 Average System Sum Rate in Downlink

The maximum achievable downlink capacity for a femtoUE j on a sub-carrier s is:

$$C_{j \in Fi}^s = \Delta B \log_2(1 + \gamma SINR_{DL_Fi}) \quad (6.16)$$

$$C_{j \in Fo}^s = \Delta B \log_2(1 + \gamma SINR_{DL_Fo}) \quad (6.17)$$

Similarly, the maximum achievable downlink capacity for a macroUE k on a sub-carrier s is given by:

$$C_{k \in Mi}^s = \Delta B \log_2(1 + \gamma SINR_{DL_Mi}) \quad (6.18)$$

$$C_{k \in Mo}^s = \Delta B \log_2(1 + \gamma SINR_{DL_Mo}) \quad (6.19)$$

where

$$SINR_{DL_Mi} = \frac{P_i^l |h_0|^2 d^{-n}(XPD-1)}{\sum_{j=1, j \neq i}^{Fo} P_{fu}^\perp + \sum_{k=1}^{Mi} P_{mb}^\parallel (XPD-1) + \sigma^2} \quad (6.20)$$

$$SINR_{DL_Mo} = \frac{P_i^l |h_0|^2 d^{-n}(XPD-1)}{\sum_{j=1, j \neq i}^{Fi} P_{fu}^\perp + \sum_{k=1}^{Mo} P_{mb}^\parallel (XPD-1) + \sigma^2} \quad (6.21)$$

Here $SINR_{DL_Mi}$ is the signal to interference plus noise ratio of the inner region macrocell and $SINR_{DL_Mo}$ is the signal to interference plus noise ratio of the outer region macrocell. The average system sum rate is further calculated using equation (4.32).

6.3.5 Interference Free Femtocell Exclusive Region (IFFER)

The derivation of an interference free femtocell exclusive region (IFFER) in case of CPCFA demonstrate interesting insights. It clearly highlights how the IFFER is influenced by the replacement of interference from macroBS with macroUEs. As defined earlier [66] IFFER is defined as the area within a contour where the received power levels from the femtoBS and macroBS are the same. However in CPCFA case, the main source of interference in the femtocell downlink is from macroUEs rather than the macroBS. To be specific, the interference is from the UL transmissions of the outer region macroUEs for the inner region femtocell downlink and from the UL transmissions of the inner region macroUEs for the outer region femtocell downlink. The knowledge about IFFER enables the femtoBS to access any sub-carrier used by macroUEs or femtoUEs which are located outside the IFFER. This in fact grants every femtoBS with the right to access all the sub-carriers within the available macrocell spectrum except for the ones that are operational within the IFFER.

Consider a simple scenario where the femto-user is located at the coordinates (x, y) . Let the received signal strength from the cross-polarized macroUE located at (x_1, y_1) be $P_{mu}^\perp$ and that received from the co-polarized femtoBS located at (x_2, y_2) be $P_{fb}^\parallel$. Considering the signal to interference ratio to be 0 dB at the border of the IFFER, it can be written as $P_{mu}^\perp = P_{fb}^\parallel$.

$$\text{i.e. } P_{mu} |h_0|^2 (d_{mu}^{fu})^{-n} = P_{fb} |h_0|^2 (d_{fb}^{fu})^{-n} \quad (6.22)$$

Applying (5.4) and (5.5) to (6.22), results in:

$$\frac{P_{mu}}{XPD (d_{mu}^{fu})^n} = \frac{(XPD-1)P_{fb}}{XPD (d_{fb}^{fu})^n} \quad (6.23)$$

Taking $n=2$, and substituting the distance from the macroBS and femtoBS to the femto-user we get:

$$\frac{P_{mu}}{(x-x_1)^2 + (y-y_1)^2} = \frac{(XPD-1)P_{fb}}{(x-x_2)^2 + (y-y_2)^2} \quad (6.24)$$

which can be rearranged and re-written as :

$$x^2 + y^2 + \frac{B_1}{A}x + \frac{B_2}{A}y + \frac{C}{A} = 0$$

where $A = P_{mu} - P_{fb}(XPD - 1)$, $B_1 = 2P_{fb}(XPD - 1)x_1 - 2P_{mu}x_2$, $B_2 = 2P_{fb}(XPD - 1)y_1 - 2P_{mu}y_2$, $C = P_{mu}(x_2^2 + y_2^2) - P_{fb}(XPD - 1)(x_1^2 + y_1^2)$. However, this represents the equation of

a circle centered at $\left(\frac{-B_1}{2A}, \frac{-B_2}{2A}\right)$ with radius $\sqrt{\frac{B_1^2}{4A^2} + \frac{B_2^2}{4A^2} - \frac{C}{A}}$. Hence IFFER will have an area given by $\pi \left(\frac{B_1^2}{4A^2} + \frac{B_2^2}{4A^2} - \frac{C}{A}\right)$. Thus, it becomes evident that, apart from the location and transmit power of femtoBS, IFFER is dependent on the transmit power of the interfering macroUE and the XPD value in a CPCFA network. Higher the XPD between femto-macro transmissions, larger will be the IFFER.

6.4 Simulation and Performance Evaluation

In this section CPCFA performance is analyzed through extensive simulation studies. Simulation involves an OFDMA cellular scenario with two tiers - macrocell network and femtocell network respectively. The macroUEs are uniformly distributed in the network whereas the femtoUEs are randomly placed. The simulation environment assumes the hexagonally-shaped macrocell to be located centrally within a group of 7 macrocells and the central macrocell is assumed to have an omni-directional antenna serving 105 macroUEs with 50 in the cell-center region and 55 in the cell-edge region. Femtocells distribution is varying within this macrocell with a density $\lambda = 1/(2500\pi^2)$ femtoBS per m^2 with each one having single femtoUE attached to it. The simulation studies assume a macrocell of radius 600 m. The macrocell radius in the plots also correspond to the mean of the separation between macroBS and the random femtoBS chosen over a series of simulation runs. The non-line of sight (NLOS) path loss variations are tracked according to the channel environment modeled as per Wireless World Initiative New radio (WINNER) II model [19], and the transmissions are affected by shadowing and a wall loss attenuation of 12dB. In addition to the simulation parameters given in Table 5.2, the timeouts τ_1 and τ_2 are taken as 0.3s and 0.2 s respectively [211]. For the polarized transmissions, an XPD value of 10 dB is assumed.

Throughput improvement with the CPCFA scheme is analyzed by comparing it with the conventional sectorized frequency allocation method (CSFA), the optimal static fractional frequency allocation method (OSFFA) [166], the reverse frequency allocation (RFA) method and the cross-polarized wireless access (CPWA) method as a function of macrocell radius.

Figure 6.2 portrays the average downlink capacity comparison of femto-macro system for five different methods as the number of femtoBS varies within the macrocell with 105 macroUEs. The throughput enhancement with CPCFA strategy is clearly evident from the figure when compared with that in other schemes. This is due to reduced co-tier and cross-tier interference, especially for the femtocell users for which the interference from macroBS is completely eliminated. Even though frequency and polarization diversity achieved through RFA and CPWA offer better throughput than

OSFFA and CSFA, CPCFA guarantees a better system performance by exploiting both of them in a combined fashion. Further, in comparison to the CPWA, OSFFA and CSFA methods, the increase in usable sub-carriers in the cell-edge and cell-center region for CPCFA strategy, plays a significant role in enhancing the system performance.

Figure 6.2: Average downlink capacity comparison of femto-macro system

Figure 6.3 shows the primary protection ratio comparison for the different methods. It is evident from the figure that the legacy macrocell network has the least impact with the incorporation of CPCFA framework. Higher value of PPR is maintained well throughout the macrocell coverage area in case of CPCFA when compared with that of CPWA, RFA, OSFFA and CSFA. Unlike the monotonic trend observed for the CSFA and CPWA, a slight variation in PPR trend is observed for other methods towards the boundary of the cell-center region. This is due to increase in interference because of the higher density of femtoBSs near the cell boundary and decrease in macroBS signal strength. However, this is compensated by the incorporation of RFA and deployment of DAS in the cell-edge region which causes the PPR to attain a comparatively higher value by assuring better signal strength and lower interference. This ensures that the incorporation of CPCFA scheme can only result in the betterment of the system performance as a whole with minimal impact on the macrocell network.

Figure 6.4 compares the coverage probability of different methods. It is clear from the plot that CPCFA scheme offers the highest coverage probability for the femtoUEs throughout the network. The frequency diversity minimizes the interference and polarization diversity maximizes the co-

channel frequency reuse, and hence assures better coverage in CPCFA case. The probability of coverage for CPWA and RFA schemes are also comparable to that of CPCFA. Nevertheless, CPCFA, CPWA and RFA assures better coverage probability for the femtocells in the cell-center region due to the elimination of significant interference from the macroBS and their advantages in terms of frequency diversity and polarization diversity respectively. CSFA and OSFFA has lower coverage probability in the cell-center region and increases towards the cell edge region. This is because, coverage probability increases as the interference from the macroBS reduces with increase in separation between the femtoUE and the macroBS.

Figure 6.3: Primary Protection Ratio comparison for different methods

Figure 6.5 compares the IFFER expansion for different methods along with increase in XPD value. It is evident from the simulation results that with larger XPD, higher is the isolation between the femto-macro network, lower is the cross-tier interference and hence larger is the IFFER. This signifies that in a CPCFA network, the IFFER is dependent not only on the transmit powers of the base stations and the path loss exponent but also on the XPD value. This increase in IFFER seems to be almost linear in case of femto macro network with just reverse frequency allocation, but exponential when it comes to a two-tier network where isolation is ensured by means of polarization and frequency diversity through CPCFA scheme. Hence CPCFA plays a key role in increasing the coverage area of femtocells and reduces the probability of outage due to sharing of frequency spectrum with the macrocell. Further, the choice of n also proves to be fatal, since increase in n for femtocell network decreases the IFFER whereas increase in n for macrocell network increases IFFER. Hence it becomes the choice of the network operator to have a trade-of between the

throughput and coverage probability by manipulating the transmit power and the IFFER. However, the application of cross-polarization together with reverse frequency allocation improves the system performance over these constraints and thereby offer better QoS.

Figure 6.4: FemtoUE coverage probability comparison for different methods

Figure 6.5: Interference Free Femtocell Exclusive Region analysis for different methods

Table 6.5 demonstrate the improvement in average system sum rate with CPCFA method in comparison with other methods. We find a steady increase in average system sum rate as we move

from the CSFA method towards CPCFA method. Further, for different configuration of femto-macro user distribution too, CPCFA method steadily guarantees the highest throughput even when we observe slight fluctuations in other schemes. This finally helps to conclude that the CPCFA framework can bring in significant improvement in the downlink system performance and hence serve more data traffic in the downlink.

Table 6.5: Average system sum rate comparison for different femtoUE-macroUE distribution

Average System Sum Rate Comparison (bps)						
User	FUE	MUE	FUE	MUE	FUE	MUE
Occupancy	200	100	200	50	200	200
CPCFA	1.293×10^7		2.519×10^7		4.688×10^6	
CPWA	4.464×10^6		9.542×10^6		1.060×10^6	
RFA	3.413×10^6		6.152×10^6		9.067×10^5	
OSFFA	2.070×10^6		3.492×10^6		1.115×10^6	
CSFA	7.882×10^5		9.503×10^5		3.578×10^5	

6.5 Summary

In this chapter, we have presented a thorough downlink analysis of femto-macro network employing decentralized cross-polarized complementary frequency allocation strategy. Here self-organizing OFDM femtocells make use of their cognitive capabilities to select their operational frequency based on their location and owing to minimal interference from the macrocell. A theoretical framework exploiting the polarization and frequency diversity to improve the system capacity through frequency reuse has been demonstrated. It has been validated with mathematical analysis and extensive simulation that the system performance can be improved by increasing the XPD value and maintaining the orthogonality of cross polarized signals at 90 degree antenna feed separation. Results indicate that the performance of the two-tier system, which was degraded by the cross-tier interference issues was enhanced by eliminating the dominant downlink interference from the macroBS to the femtoBS through CPCFA scheme. It also enriched the cell-edge user's performance and at the same time guaranteed superior spectral efficiency mainly due to the transmission via orthogonal polarization. In addition, the incorporation of self-organization features in the CPCFA algorithm enabled dynamic spectrum access for the femtoUEs, which substantially enhanced the system performance.

Chapter 7

Conclusions and Future Directions

An idealist believes that the short run doesn't count. A cynic believes the long run doesn't matter.

A realist believes that what is done or left undone in the short run determines the long run.

- Sidney J. Harris

This chapter summarizes the key contributions of this dissertation and give pointers to the future avenues of research open for exploration.

7.1 Conclusions

The recent upsurge in the use of smart communication devices and the prompt diversification in wireless services has resulted in an alarming growth in data traffic in mobile communication systems especially in the downlink. The conventional paradigm of meeting cellular system demands by installing more macrocell base stations is not practical in the current scenario mainly due to economical unfeasibility and resource constraints. In contrast, the deployment of supplementary hotspot infrastructures like femtoBSs have the potential in ameliorating the wireless capacity by exploiting path-loss gains achieved due to the relative proximity with their users. The CAPEX and OPEX of this undelay architecture being economically viable, the network operators can recoup their investments at a tremendously fast pace, at the same time offer better QoS to the customers.

This dissertation explored the key challenges confronting the co-existing femto-macro cellular networks, investigated the possibilities of optimizing the performance of existing femtocell network without incorporating magnanimous changes in the current network architecture and proposed solutions to enhance the femtocell-macrocell system performance in a mutually beneficial manner. Giving priority to the harmonious co-existence of femtocells within the macrocell environment, spectrum allocation with effective interference management was investigated and solutions to address these challenges were proposed. The most significant among them includes- the concept of femto-relays as an energy efficient means to extend the coverage of femtocells to serve more users with minimal network overhead, the idea of reverse frequency allocation to improve the spectral

efficiency of the system by authorising the femtocells to reuse the macrocell spectrum by reversing the direction of transmission and the thought of exploiting polarization dimension to enable frequency reuse with limited interference. Our main thesis is that, optimizing femtocell usage coupled with intelligent spectrum management can augment the QoS offered by the wireless networks without encumbering the operations of the legacy macrocell network.

Extensive research in the past has already proved that the best solution for enhancing performance is to maximize the utilization of the existing architecture rather than burdening the network with the installation of new ones. The dissertation facilitates the incorporation of the same concept by means of femto-relays, which enables the utilization of idle femtocells to offload the macrocell traffic, accommodate more users through coverage extension, eradicate dead-zone regions and assure better coverage. Further, the seamless operation of femto-relays challenged by the lack of coordination between the macrocell and femtocell network was addressed through self-organization properties which assisted the macroUEs in selecting the most efficient femto-relay without compromising on their power constraints.

Relaying aided transmission offer significant energy savings along with coverage extension mainly due to the path-loss savings encountered due to reduced transmission distance. This necessitated the splitting of transmission into dual-hops, which was challenged by the scarcity of available spectral resources. Hence, the absence of an efficient spectrum allocation strategy would render the femto-relay concept self-defeating due to the spectrum unavailability for dedicated usage and the cross-tier interference generated due to shared usage. The concept of reverse frequency allocation was explored in this context, which facilitated the incorporation of a frequency reuse factor higher than unity in every macrocell. The macrocell spectrum reuse by the femtocells by reversing the direction of transmission along with spatial separation proved to limit the overall interference in the network, which resulted in better SINR and hence system throughput. Eliminating the heavy downlink interference from the macrocell base station assured better coverage to the femtocell base stations which led to superior QoS to the customers as well.

In addition to frequency diversity, polarization diversity was also exploited as a means for isolating the network operation across tiers through cross-polarized transmission which enabled spectrum reuse with limited interference. Even though, orthogonal polarized transmission is not a novel concept in terms of frequency reuse, this dissertation explored it from the cellular communication perspective and proved the possibility of reaping significant capacity gains due to effective interference alleviation. It also highlighted the extension of interference free femtocell exclusive region achievable with orthogonal polarized transmission and the corresponding improvement in coverage probability for the femtocells.

Even though network resource optimization and interference management guarantee enhanced cellular system performance, the lack of cooperation and coordination acted as a bottleneck for the harmonious co-existence of multi-tier networks. This was addressed by the incorporation of self-organizing characteristics into the femtocell network which offered them the intelligence for autonomous operation within the legacy cellular networks. It gave them the competency to select the operational spectrum by sensing the real-time network variations and adopting the complementary frequency allocation strategy within a cross-polarized network which exploited frequency and polarization diversity simultaneously.

To summarize, this dissertation developed advanced co-existence techniques for femtocell aided cellular architectures with focus on interference-limited spectrum access by both tiers. It optimized the effective contribution of femtocells towards holistic network performance augmentation and prevented mutual collision between their operational spectrum enabled via reverse frequency reuse, cell sectorization, cross-polarized transmission and periodic inter-cell communication with limited signaling overhead.

7.2 Future Directions

Femtocell industry is young but at the same time, it has taken significant steps towards maturity. Recent market forecasts indicate femtocells to be the ‘next big thing’ in cellular communication system mainly due to its potential in meeting the explosive consumer demand for higher data rates and capacity in wireless cellular networks. Currently, the femtocell deployment is carried out by the network operators. Hence, real challenges are not visible in practice due to the very small deployment numbers and comparatively better deployment planning carried out by the operators. The future work mainly aims in addressing the challenges faced during a more realistic scenario where mass deployment of femtocells is carried out in densely populated regions by the subscribers themselves without any planning. Concentrated effort on resolving these glitches will assist operators in launching femtocells at the right time to maximally benefit their businesses and in creating femtocell offers that will be attractive to their customers. The question now is how quickly this fledgling technology can overcome major challenges, both technical and commercial, in their way to increasing its credibility and making femtocell- the technology of choice for in-home wireless use.

Building on this framework, we continue to extend our study and apply the findings in the evolving multi-tier femto-macro network architectures. Retro-fitting and analysing our results into the existing cellular network can also provide inputs to design future cellular network architectures with better performance. Correspondingly, the findings, proposals and results presented in this work

open up several possible avenues for future research. Some of those research directions are briefly discussed below:

7.2.1 Advanced Decision Algorithms on Optimal Femto-relay Selection and Adaptive Femtocell Access

Coverage extension and energy saving assured through femto-relays translates into better system capacity. However, the choice of the optimal femto-relay is crucial since the benefits of relaying is reflected more in cases where destination UE has lower SINR. If the direct transmission assures significantly high SINR, then the use of relaying will be self-defeating. In addition, the benefits due to relaying depends on the radial position of the relay UE in the femtocell coverage area and the adopted access policy. Relaying projects more profits in closed access femtocell networks, where the access to unregistered UEs are restricted. Authorizing femto-relay operation with open access networks may result in undesirable handovers, power consumption and signaling overheads since the same benefits may be earned with direct access. Introducing adaptive femtocell access is a potential solution which not only avoids the unwanted bottlenecks of the open access but also help in sharing of resources which is restricted by the closed access mode. Hence, in addition to the selection of femto-relays based on number of idle attached users and channel quality better than the direct hop, potential design parameters must be taken into consideration which includes the optimal positioning of the femto-relay, access mode of the femtoBS, battery constraints of the relaying UE, user distribution in the femtocell neighbourhood whose interference signature may be dependent on relaying etc. Advanced decision algorithms must be developed in permitting adaptive femtocell access for better QoS and for determining the optimal femto-relay that can guarantee maximum capacity with minimal interference.

7.2.2 Harmonization of Network Architectures for Minimizing Signaling Overhead and Overcoming Backhaul Constraints

A potential challenge that needs immediate attention for massive femtocell deployment is the need for a standard architecture that enables seamless integration of femtocells into the cellular core network. The booming femtocell industry has fostered a system that promotes many proprietary, integration solutions. At least 15 different femtocell architectures have been identified, spanning all air interfaces including CDMA, GSM, WCDMA, and WiMAX [144]. Such extensive diversity may result in market fragmentation, which also possess the capability to jeopardize scalability, complicate interoperability, and ultimately increase roll-out costs.

While the expansion of high capacity wired ethernet networks strives hard to cope with the femtocell's fast integration into the cellular architecture, synchronization of network architectures is essential. This should also enable wireless inter-operability between femto-macro networks through wireless backhaul so as to promote efficient inter-cell communication without depending on the macrocell backhaul bandwidth. Nevertheless, femtocells being located indoors, may be deficient of LOS communication throughout their operation which demands effective backhaul connectivity in cases where link connectivity is not guaranteed. Thus the evolving standardization should support adaptive backhaul connectivity, wired or wireless based on the user necessities and prevailing network conditions. This will also assist the self-organizing femtocell network to incorporate certain amount of planning in their operation especially in spectrum access with support from the serving macroBS. This conjoined approach will not only diminish the interference signature left behind in the network by co-existing wireless networks, but will also aid in promoting effective information exchange between nodes, which helps them to adapt to the rapidly fluctuating wireless network characteristics and support far-reaching femtocell applications.

7.2.3 Practical Solutions for Decentralized Resource Management through Femtocell Clusters

In open-access operation, the network overhead arising from handoffs from the macroBS to femtoBS will seriously challenge practical deployments of large number of femtocells. One method of minimizing frequent handoff events is that femtoBSs dynamically adapt their coverage radius also called "cell breathing" depending on their channel conditions, operational status and the number of users served. FemtoBSs with no users attached can switch to its minimum transmission power and hence the least possible coverage area so as to control the interference signature in the network.

Algorithms to group femtocells into clusters and initiating handovers between clusters must be figured out. This not only reduces the number of handoffs in densely deployed femtocell networks but also plays a significant role in conserving femtoBS power and reducing the traffic in the backbone network. It can even cover a floor area with support for soft handover. The clustering algorithm is also expected to group the femtocells into different frequency reuse clusters and UEs of different femtocells in the same cluster can use the same sub-channels which is like incorporating a "frequency reuse within a frequency reuse phenomenon". Clustering femtoBS with similar soft frequency reuse patterns can assure better system performance as well. Proper cluster head selection algorithm must also be incorporated, so that the periodic cluster head election ensures even

distribution of extra work load and power utilization. This also calls for improving the femtocell receiver sensitivity through antenna diversity, interference cancellation and enhanced signal processing in synchronization, channel estimation and equalization.

Even though the concept of Femtocell Cluster-Based Resource Allocation (FCRA) is not novel [212, 213], the problem of determining the optimal femtocell cluster radius, the selection of its members as a function of the available excess backhaul bandwidth, the time-varying channel strength and cellular user mobility (governing dwell times), and the algorithm of creating the clusters is an open avenue for further research.

Co-existing femto-macro cellular architectures is currently in the process of overcoming the numerous technical and commercial barriers to its launch that too within a short span of time. This is in fact possible due to the various technical contributions made towards promoting their co-existence in a mutually beneficial manner. In the years to come, the sharing of best practices learned from the existing technology and the contribution from the innovative solutions proposed would definitely assist in overcoming the unexpected challenges and enable the scale of femtocell deployments to reach their full potential.

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