UNIVERSITÉ DU QUÉBEC À MONTRÉAL

THE CO-EXISTENCE OF FEMTOCELL WITH WIFI (IN CASE OF UNLICENSED SPECTRUM SPLITTING & SHARING)

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LA COEXISTENCE DE FEMTOCELL AVEC LE WIFI (EN CAS DE FRACTIONNEMENT ET LE PARTAGE DU SPECTRE SANS LICENCE)

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ABREVIATIONS

2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
ANDSF	Access Network Discovery and Solution Function
AP	Access Point
BS	Base Station
CDMA	Code Devision Multiple Access
CDPD	Cellular Digital Packet Data
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSG	Closed Subscriber Group
DOFF	Data Offloading
DoS	Denial of Service
DSL	Digital Subscriber Line
EPS	Evolved Packet Core
ESP	Encapsulating Security Payload
EU	End User
EV-DO	Elovution Data Optimizer
FAP	Femtocell Access Point
FBS	Fametocell Base Station

FMC	Fixed Mobile Convergence
FMS	Femtocell device Management System
GSM	Global System for Mobile communication
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
IPsec	International Protocol Security
ITU	International Telecommunication Union
LTE	Long Term Evolution
MBS	Macrocell Base Station
NGMN	Next Generation Mobile Network
NP-hardness	Non-deterministically Polynomial-time hard
OFDMA	Orthogonal Frequency Division Multiple Access
OSS	Operational Support System
QoS	Quality of Service
RB	Resource Block
RF	Radio Frequency
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SDR	Software Defined Radio
SeGW	Security Gateway
SIM	Subscriber Identity Module
SINR	Signal to Interference plus Noise Ration

SSA	Secondary Spectrum Access
UE	User Equipment
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
WCDMA	Wide-band Code Devision Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area

RÉSUMÉ

Les femtocellules et le WiFi sont souvent présentés comme étant deux technologies concurrentes. Cependant, la réalité dit totalement l'inverse; ces technologies sont supposées jouer des rôles complémentaires dans le but d'accompagner la croissance fulgurante du trafic mobile. De plus, elles sont souvent implémentées dans un même et unique équipement d'accès. Les équipements mobiles pourront ainsi choisir l'utilisation de la technologie qui représente la meilleure option. Le déploiement des femtocellules dans les hotspots WiFi permettra aux opérateurs de donner aux usagers la possibilité d'utiliser les technologies 3G. Par conséquent, grâce à ces deux technologies, la qualité de l'expérience de la communication pendant la mobilité sera sans doute meilleure. Toutefois, cette coexistence présente de nouveaux défis en vue de l'amélioration de performances en termes des débits de transmission et de qualité de service des usagers. Ainsi, nous croyons qu'un partitionnement efficace des ressources spectrales accompagné d'un réglage minutieux des paramètres de transmission permettra de maximiser les performances des deux technologies.

Dans ce mémoire, nous nous intéressons à la coexistence des technologies femtocellule et WiFi: (i) Dans un premier lieu, nous proposons une technique de partage des bandes spectrales ouvertes entre le réseau WiFi et le réseau femtocellule. La technique proposée assure une qualité de service et une équité entre les transmissions concurrentes. En se basant sur plusieurs simulations, nous démontrons que la technique proposée assure un partage équitable du spectre. (ii) Dans un second lieu, nous proposons un Framework ayant pour objectif l'amélioration du débit total du réseau des femtocellules lorsque ces dernières utilisent simultanément des bandes de spectres ouvertes et d'autres sous licences. Le système étudié, comprenant le réseau WiFi et le réseau des femtocellules, a été modélisé analytiquement et ses performances ont été évaluées par plusieurs simulations. Ces dernières ont permis de quantifier l'effet de plusieurs paramètres de la technologie WiFi sur les performances du système étudié.

Mots-clés—Femtocellule, WiFi, allocation de spectre, qualité de service, équité, capacité, spectre sans licence, modèle de back-off.

ABSTRACT

Femtocells and WiFi are often presented as opposing technologies. The reality is that both have a vital role to play in supporting future mobile traffic growth. In many cases both technologies will eventually be employed in a single box with access via an intelligent mobile device that will automatically select the best option. Deploying Femtocells in WiFi hotspots would let access providers add 3G capacity for users who do not have WiFi on their device and improve their quality of experience during mobility. Partitioning of the spectrum resources and fine-tuning the performance in case of co-existence carry critical importance for maximizing the total capacity and quality of service (QoS) satisfaction of end users.

In this thesis, we have investigated two studies in case of co-existence of Femtocell and WiFi: (i) We propose fair and QoS-based unlicensed spectrum splitting strategy between WiFi and Femtocell networks. Numerical results show that spectrum splitting under total capacity maximization constraint allows for unfair spectrum allocation, while a more equitable spectrum splitting can be accomplished by taking into account the fairness and QoS constraints. (ii) We propose and develop a framework to increases the total sum of throughput for Femtocells while they simultaneously access both licensed and unlicensed bands. The channel access of both Femtocell and WiFi networks are analytically modeled and numerically verified. Moreover, the effects of WiFi channel access parameters on the performance of WiFi and Femtocell networks are investigated.
Keywords—Femtocell, WiFi, spectrum allocation, QoS, fairness, capacity, unlicensed spectrum, back-off model.

INTRODUCTION

Overview

A cellular network is a radio network distributed over land areas called cells, each served by at least one fixed-location transceiver known as a cell site or base station. When joined together, these cells provide radio coverage over a wide geographic area. This enables a large number of portable transceivers (mobile phones, pagers, etc.) to communicate with each other and with fixed transceivers and telephones anywhere in the network, via base stations, even if some of the transceivers move through more than one cell during transmission. The increasing demand for higher data rates, higher speed, and higher accuracy in wireless communication systems has led the researchers to invent new mobile communication standards such as WiMAX (Worldwide Interoperability for Microwave Access), HSDPA (High Speed Downlink Packet Access) / HSUPA (High Speed Uplink Packet Access), LTE (Long Term Evolution), EV-DO (Evolution-Data Optimized) and UMB (Ultra Mobile Broadband) (Ahson and Ilyas, 2011). Another competitor, known as the WiFi network, is designed to ensure high data rate services in a more distributed fashion. Despite the fact that WiFi networks are not able to offer high mobility and coverage similar to that supported by cellular systems, cellular systems need to offer services roughly comparable to those provided by WiFi networks inside home and office environments in order to present a real competition (Ahson and Ilyas, 2011). With the fast-advancing of mobile Internet, mobile data traffic has dramatically increased. The wireless capacity has grown about one million times over the last 50 years because of different factors such as: (i) better transmitter/receiver efficiency, (ii) larger spectrum, and (iii) larger number of cells (Glisi, 2006). This trend has produced tremendous pressures on the capacity and deployment strategies of mobile networks. Besides, the growth in term of capacity caused by transmitter/receiver efficiency and larger spectrum corresponds to 20 times and 25 times, respectively, compared to the original state; whereas, the capacity growth resulted from using a larger number of cells corresponds to 2000 times (Glisi, 2006). Furthermore, it has been predicted that the growth in capacity will continue to increase enormously by the year 2015 as the result of adopting small cell deployments strategy (Zhang and de la Roche, 2010). In order to enhance the capacity of wireless networks, numerous attempts follow the path of reducing cell sizes and transmit distances, reusing spectrum, and enhancing spectral efficiency (Nuaym, 2007). While it is increasingly difficult and expensive for Macro networks to provide cost-effective and flexible capacity expansion by cell splitting, the small cell deployment option is now becoming a very attractive solution, especially for providing better user experience in outdoor/indoor high-traffic areas (Chandrasekhar et al., 2008).

Femtocell is a small, short-range, low cost and low-power cellular base station for better indoor coverage. It is typically designed to serve under 10 users in indoor environments such as homes or a small offices. It is connected to the service providers' network via a broadband, such as Digital Subscriber Line (DSL) and supports 2 to 4 mobile phones in a residential setting, and 8 to 16 mobile phones in an enterprise setting (Katiyar et al., 2011). A Femtocell allows service providers to extend service coverage indoors, especially where access would otherwise be limited or unavailable. From a mobile operator perspective, the attractions of Femtocell include improvements to both coverage and capacity. End users (EUs), on the other hand, benefit from improved coverage and potentially better voice quality and battery life. The key advantages of Femtocells are:

- Better coverage, capacity, and Quality of Service (QoS).
- Self-organized networks.
- Improved Macrocell reliability.
- Cost benefits.
- Reduction of subscribers' turnover.

On the other hand, Femtocells come with their own challenges. The foremost challenge is the presence of an interference among neighboring Femtocells and also among the Femtocells and Macrocell because the allocated spectrum to the Femtocell is traditionally from the same licensed spectrum bands of the Macrocell.

Motivation

According to the extent research, most of the voice calls and data traffic are generated indoors (Chandrasekhar et al., 2008). The users of cellular systems experience difficulty in receiving quality service due to low quality signals from the Macrocell base stations. To solve the dead zone problem in the indoor environments, Femtocell technology has been taken into consideration. Femtocells offer a different reliable way to cope with the challenge of overgrowing users' requirements on mobile broadband. Because of Femtocells short range transmission-reception, they can easily reduce transmission power, extend phone battery life, and also achieve an increased signal-to-interference-plus-noise ratio (SINR), all of which consequently boost reception to higher capacity (Kim et al., 2009).

Beside Femtocell advantages, severe mutual interference amongst Femtocell and Macrocell users is the main challenge (Sang et al., 2009). In the last decade, many cellular service providers have been offloading data traffic from their licensed bands to unlicensed ones over prevalent WiFi access points. Hence, given the Femtocells' short-range coverage, they can be an ideal alternative platform for making the most of both licensed and unlicensed spectrum benefits. Specifically, licensed frequencies ought to be allocated to the tiers that can use them efficiently, and unlicensed bands ought to be used for higher levels of interoperability and capacity. Femtocell and WiFi play crucial roles in sustaining the continued growth in mobile traffic. As unlicensed bands provide excellent capacity and coverage (Fuxjger et al., 2010), deploying Femtocells in WiFi hotspots would let access providers to provide more capacity to users who do not have WiFi on their device. On the other hand, offloading traffic to unlicensed band would be a solution to mitigate the interference with Macrocell. Femtocells resemble WiFi access points in many aspects, namely the small size, the cheap price, and the low-power base stations. Femtocells, along with WiFi offloading, are expected to carry over 60% of all global data traffic by 2015 (Publisher, 2011).

In principle, Femtocells act as other base stations. However, even if their number and position are unknown to the operators, their self-organization characteristic allows them to scan the air interface and tune their parameters according to the dynamic behaviour of network, traffic and channel. Therefore, Femtocells can utilize existing mobility procedures (Sang et al., 2009). Althought, Femtocell mobility presents a number of unique challenges that require special consideration. Standard bodies such as 3rd Generation Partnership Project (3GPP) have devoted considerable attention to these mobility issues. For example, in the specifications (3GPP, 2011b) and (3GPP, 2012), EPS (Evolved Packet Core) has defined the support of connectivity over WiFi as part of the Non-3GPP access support. In EPS, ANDSF (Access Network Discovery and Selection Function) has defined mechanisms that enable devices to determine which access technology is preferable for certain IP traffic under specific conditions. In certain scenarios, such as severe interference which causes poor QoS and capacity, WiFi access will be preferable to certain 3GPP access technologies (3GPP, 2011a). With the spreading use and the increasing playing role of WiFi in 3GPP operator network deployments, improving the use of WiFi in EPS would be beneficial to operators and to user experience. In addition, different procedures like the Generic Access Network framework are being developed for vertical handovers between Femtocells and non-cellular access technologies such as WiFi (Ghosh et al., 2005).

Goals

Femtocells accessing unlicensed bands have to coexist with WiFi. To investigate the coexistence challenges, two different aspects are considered in this research:

- **Spectrum splitting**: partitioning of the spectrum resources carries critical importance for maximizing the total capacity and QoS satisfaction of EUs. For the Macro-Femtocell networks, spectrum sharing has been investigated in different aspect of capacity, throughput and etc (Xiaoli et al., 2011). Same as in Macro-Femtocell case, we would face a two-tiered network structure in case of Femtocell-WiFi network, where resource is allocated by using either shared or split spectrum methods.
- **Channel access** : modelling of back-off mechanisms for both Femtocell and WiFi networks, give them priority of using unlicensed band. Also a Femtocell adjustment of its impacts to the coexisting WiFi nodes by tuning its channel access parameters (Liu et al., 2011).

As the first step, we seek to investigate what metric of fairness should be perceived for splitting the unlicensed band, how these metrics are measured or evaluated, and how different level of fairness will affect the spectrum splitting. Then we want to define a QoS satisfaction parameter as it is an important part of spectrum allocation process (Erturk et al., 2010).
The traditional metrics of fairness for resource allocation are variance, coefficient of variation (CoV), min-max ratio, and normalized distance (Jain et al., 1984). Different fairness metrics

in the literature have been investigated, but Jain's fairness index is by far the most used fairness index in recent studies while considering QoS parameters in spectrum splitting. The objectives of splitting bandwidth is to maximize overall capacity, ensure fairness and guarantee QoS requirements (Erturk et al., 2010) in both tiers of WiFi and Femtocell networks. In other words, we plan to explain how the perceived level of fairness and QoS affect the total capacity of Femtocell and WiFi network, in specific contexts. Next step, we study analytical models of the co-existence of different networks to access same spectrum and investigate the proper model in case of Femtocells and WiFi to access the unlicensed spectrum over a fully-utilized unlicensed band. Moreover, we conduct an enquiry for modeling WiFi exponential backoff with Markov Chain to describe the service process of a single station and analyze the performance of the WiFi.

Since some recent research and proposed methods for a Femtocell to access both licensed and unlicensed bands are inadequate, our research project aims to develop and propose a framework to fine-tune the Femtocell performance while it co-exists with WiFi network and also it simultaneously accesses both licensed and unlicensed bands. To conclude, our objectives include:

- Fairness metrics and QoS satisfaction factor definition and investigation of their measurement methods;
- Investigation and improvement of unlicensed spectrum splitting methods;
- Investigation and improvement of WiFi backoff mechanism;
- Investigation of an accurate framework for Femtocell channel access;

Contribution

The prominent contributions of this research are as follows:

- After reviewing the existing spectrum splitting methods in case of other networks than Femtocell-WiFi, we have proposed an accurate fair and QoS-based unlicensed spectrum splitting strategy between WiFi and Femtocell networks to maximize the total capacity. To the best of our knowledge, this is the first work tackling the case of spectrum splitting

between Femtocell and WiFi.
(The associated publication is (Hajmohammad and Elbiaze, 2013).)

- To reach our last objective, Co-existence of Femtocell and WiFi carries critical importance for improving the total performance of network and meeting the promised quality of service (QoS) satisfaction of Femtocell EUs. We have proposed and developed a framework to increases the total sum of throughput for Femtocells while they simultaneously access both licensed and unlicensed bands. The channel access of both Femtocell and WiFi networks are analytically modeled and the effects of WiFi channel access parameters on the performance of WiFi and Femtocell networks are investigated.
(The associated publication is (Hajmohammad et al., 2014).)

STRUCTURE OF THIS DISSERTATION

This master thesis is organized as follows. Chapter 1 provides a comprehensive definition of Femtocell, principal concepts and general explanation of several technical terms. Afterward, Chapter 2 explains background information and literature review of our research work. Chapter 3 discusses how to split unlicensed spectrum between Femtocell and WiFi fairly and based on QoS. The results of proposed model have shown at the end of chapter. Chapter 4 presents a framework in case of Femtocell-WiFi co-existence to fine-tune Femtocell performance. The results of proposed framework have been presented at the end of this chapter Finally, we present the conclusions of our work and suggest directions for future research in Chapter 5.

CHAPTER I

BACKGROUND

1.1 Wireless Wide Area Network

WWAN technologies enable users to establish wireless connections over remote public or private networks. These connections can be maintained over large geographic areas, such as cities or countries, through the use of multiple antenna sites or satellite systems maintained by wireless service providers. WWAN technologies are known as 2nd Generation (2G) systems (key 2G systems include Global System for Mobile Communications (GSM), Cellular Digital Packet Data (CDPD), and Code Division Multiple Access (CDMA)), 3rd Generation (3G) technologies follow a global standard and provide worldwide roaming capabilities. The International Telecommunication Union (ITU) is actively promoting the development of a global standard for 3G and 4th Generation (4G).

1.1.1 3GPP

3rd Generation Partnership Project (3GPP) is a collaboration between groups of telecommunications associations, known as the Organizational Partners. The initial scope of 3GPP is to make a globally applicable 3G mobile phone system specification based on evolved GSM specifications within the scope of the International Mobile Telecommunications-2000 project of the ITU (3GPP, 2011b).

1.1.2 Evolved Packet Core (EPC)

The EPC is the latest evolution of the packet-switched in the 3GPP core network architecture. The EPS also allows non-3GPP technologies to interconnect the EU and the EPC. Non-3GPP means that these accesses were not specified in the 3GPP. These technologies include WiMAX, CDMA2000, Wireless Local Area Networks (WLAN) or Fixed Networks (3GPP, 2011a).

1.1.3 Access network discovery and selection function (ANDSF)

It is an entity within an evolved packet core (EPC) of the system architecture evolution (SAE) for 3GPP compliant mobile networks. The purpose of the ANDSF is to assist EU to discover non-3GPP access networks, such as Wi-Fi or WIMAX (3GPP, 2012).

1.2 WiFi

WiFi stands for Wireless Fidelity and it is used to describe the underlying technology of WLAN based on the IEEE 802.11 standard. This technology enables users to establish wireless connections within a local area (for example, within a corporate or campus building, or in a public space, such as an airport) (Parata et al., 2007).

1.2.1 WiFi Alliances

The WiFi Alliance is a non profit industry organization with goal of driving adoption of IEEE 802.11 WLAN standards through its certification process. For example, under 802.11b, data is transferred at a maximum rate of 11 Mbps over a 2.4 GHz frequency band. Another standard is 802.11a, which specifies data transfer at a maximum rate of 54 Mbps over a 5 GHz frequency band. At the end, 802.11n was added to 802.11 which it operates in both the 2.4 GHz and 5 GHz bands at a maximum data transfer rate of 300 Mbit/s.

1.2.2 802.11 standard Architecture

802.11 is primarily a Physical (PHY) and Media Access Control (MAC) layer and these two layers correspond to Physical and Data Link layers in the OSI reference model. Its architecture consists of following blocks which they are common among all 802.11 protocols:

- Mobile Station (STA) and Access Point (AP)
- Basic Service Set (BSS)
- Extended Service Set (ESS)
- Distribution System (DS)
- DCF/PCF
- 802.11 Frame Types

1.3 Femtocell

Femtocell is a small cellular base station, typically designed for use in a home or small business. It connects to the service provider's network via broadband (such as DSL or cable). A Femtocell allows service providers to extend service coverage indoors, especially where access would otherwise be limited or unavailable. Although much attention is focused on WCDMA, the concept is applicable to all standards, including GSM, CDMA2000, TD-SCDMA, WiMAX and LTE solutions. For a mobile operator, the attractions of a Femtocell are improvements to both coverage and capacity, especially indoors. Consumers benefit from improved coverage and potentially better voice quality and battery life (Chowdhury and H., 2010). Depending on the carrier, they may also be offered more attractive tariffs discounted calls from home. Femtocells are an alternative way to deliver the benefits of Fixed Mobile Convergence (FMC). The distinction is that most FMC architectures require a new (dual-mode) handset which works with existing unlicensed spectrum home/enterprise wireless access points. While a Femtocell-based deployment will work with existing handsets, it requires installation of a new access point that uses licensed spectrum. Fig.1.1 is an example of Femtocell Base Station (FBS) device.

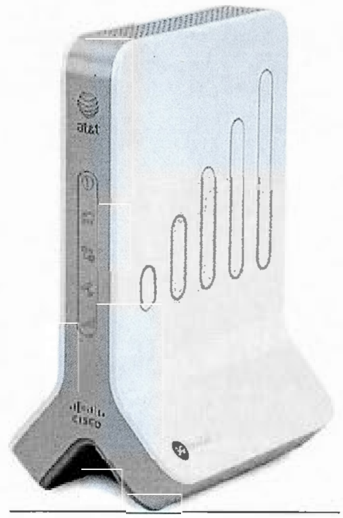


Figure 1.1: Cisco Femtocell Base Station Device(Rassweiler, 2013)

Besides of main challenge of interference with Macrocell, IP base backhaul may not be able to provide the acceptable QoS. For instance, Macrocell networks guarantee 15 ms for latency which should be met by the backhaul networks while they may not be equipped to provide the delay resiliency. Another important issue in Femtocell networks is the effect of various environmental factors, such as wall structure, distance between Femtocell and users, or required distance from Macrocell. For example, based on following equation, network capacity increases as d and α decrease, where d is the distance between transmitters, and α is the path loss exponent.

$$Path_{loss} = A * d^{-\alpha} \tag{1.1}$$

1.3.1 Femtocell Network Architecture

Femtocell networks have a flat architecture with a Base Station Router (BSR) (Fig. 1.2). BSR is a technology which combines all functions of a radio access network and a core network into a single network element. It also includes the concept of self-deployment and fully automatic base station. BSR has the three characteristics/components which a

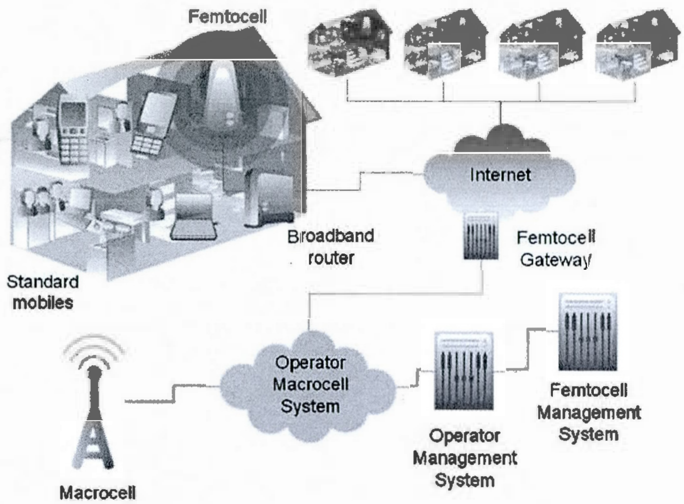


Figure 1.2: Basic Femtocell Architecture (Zhang and de la Roche, 2010)

cellular system needs to achieve ubiquity: scalability, providing a cost effective architecture that could support cellular mobility, and a mechanism to place provided architecture into an autonomic paradigm (Zhang and de la Roche, 2010). There are three network elements which are common to any Femtocell network architecture, including:

- Femtocell Access Point (FAP) is the primary node in a Femtocell network that resides in the user premises (home or office). The main function of the Femtocell is to act as a small base station. Typically, these devices provide cellular services in licensed spectrum within range of 10 to 12 meters. The Femtocell connects the mobile devices via its radio interface to the mobile service operators core network. It relays the mobile user data by establishing a secure IPsec encapsulating security payload (ESP) (Younchan and Peradilla, 2011) tunnel with the Security Gateway (SeGW) over an insecure backhaul link (broadband Internet connection). These devices can be deployed either as a residential model or an enterprise model by mobile network operators. In residential deployment model, the Femtocell device is intended to use for a closed group and supports typically 4 simultaneous voice calls per device. Whereas in enterprise model, it supports 4 to 32 devices simultaneously.

- Security Gateway (SeGW) is a network node that secures the Internet connection between Femtocell users and the mobile operator core network (see Fig.1.3). The SeGW acts as a border gateway of the operators core network. First, it mutually authenticates and registers the Femtocell devices to establish a secure tunnel, and then forwards all the signalling and the user data to the operators core network. Mutual authentication can be performed using certificates, Extensible Authentication Protocol Method for GSM Subscriber Identity Module (EAP-SIM) or Extensible Authentication Protocol Method for Universal Mobile Telecommunications System (UMTS) Authentication and Key Agreement (EAP-AKA) method. For mutual authentication, either security certificates or a Subscriber Identity Module (SIM) card is stored on Femtocell device. The interface between the SeGW and the operators core network is considered to be secured. It uses standard Internet security protocols such as IPSec and IKEv2 to authenticate and authorize Femtocells and to provide encryption support for all signalling and user traffics.

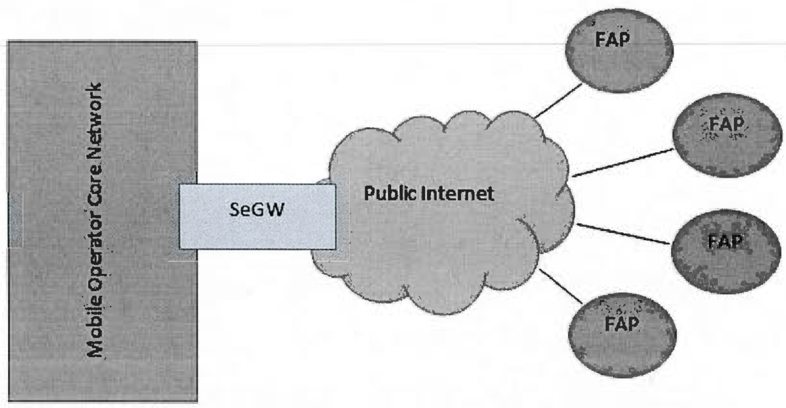


Figure 1.3: Femtocell network elements

- Operator Core Network: The Femtocell Device Management System (FMS) which is located in the operator core network plays a critical role in the provision, activation and operational management of Femtocells. To ensure low-cost deployment and easy setup for subscribers, the activation and provisioning of the Femtocell must be plug-and-play with no on-site assistance required from the mobile operator. Various standard bodies specify the use of the TR-069 family of standards as the base device management framework for Femtocells. The Automatic Network Planner adds Radio Frequency (RF) planning algorithms, RF configuration and a northbound interface to Operational Support Systems (OSS).

Other elements, which are common between all Femtocell network architectures, are entities that enable Femtocells' connectivity to the mobile operator core.

1.3.2 Access Methods in Femtocells

In Femtocell networks, EUs are classified in two categories: (1) subscribers who are defined as the rightful users of the Femtocell, and (2) non-subscribers who are the users not registered in the Femtocell. These EUs can access Femtocells through three different methods: closed access, open access, and hybrid access. The closed access mode is also called Closed Subscriber Group (CSG) in which the list of Femtocell subscribers is called the CSG list. Table 1.1 shows the access modes for two categories of EUs (Chowdhury and H., 2010)(Kim et al., 2009)

	Closed access	**Open access**	**Hybrid access**
Subscriber	Access	Access	Preferential access
Non-subscriber	No access	Access	Limited access

Table 1.1: Access Modes for Femtocell End Users

1.3.3 Self–Organization Concept in Femtocells

Standardization bodies and groups, such as 3GPP, Next Generation Mobile Networks (NGMN), and Femto Forum, have identified self- organization as the needed feature to deploy, maintain and sustain the future wireless networks. A self-organizing network is defined as a network that requires a minimal human involvement due to the processes of planning, configuration and optimization in a set of autonomous/automatic functionalities. Through these functionalities, Femtocells scan the air interface and tune their parameters (such as power and frequency) according to the dynamic behavior of the network, traffic and channel (Chowdhury and H., 2010). The first phase of self-organization for Femtocells is the plug and play, and the second phase is their awareness of the presence of neighboring cells, their power and spectrum allocation to enhance coverage and avoid interference. Different strategies such as network listening mode, message exchange, measurement report, and cognitive radio can be used to achieve this cognitive radio stage which makes Femtocells to learn about the structure and behavior of the network and the channel conditions (Zhang and de la Roche, 2010). There are three main functionalities in self-organizing network (shown in Fig. 1.4):

- Self-configuration: include functions that allocate frequency intelligently.
- Self-optimization: include optimizing attributes of transmission power, maintenance of neighbour cell list, coverage control and robust mobility management.
- Self-healing: includes features for automatic detection.

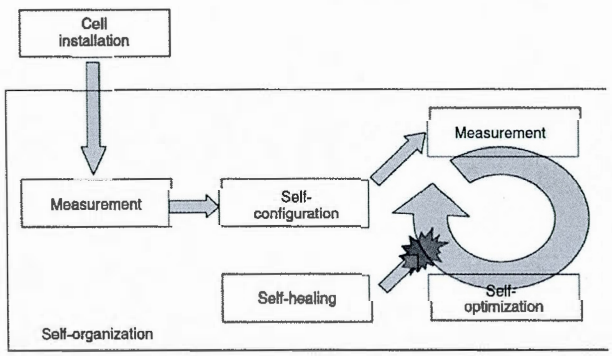


Figure 1.4: Life cycle of self-organizing cell (Zhang and de la Roche, 2010)

1.4 QoS (Quality of Services)

The level of network performance that is needed for network applications to function properly is QoS. The QoS helps to monitor the estimated bandwidth, identify network state variations (for instance congestion) and to prioritize a type of traffic over another. QoS over wireless requires solutions that involve: (i) Medium Access Control (MAC) which regulates the access of the wireless channel, (ii) Admission Control which regulates the access of flows, (iii) Routing which in case of multi-hop networks, the routing protocol determines a path tothe destination.

1.4.1 Femtocell QoS

Femtocells make it possible for high-quality voice, data and video sessions to flow efficiently, securely and reliability using the consumers' existing broad band connection. In the design of any system QoS is one of the important issues from both customers and providers point of view. Indeed, customers expect the service of best quality from the system providers and also network providers want to give best quality of service to the customers from the system. To manage and control the QoS over the Femtocell networks, admission control and interference mitigation are the most important issues in wireless part of the network beside of using the QoS techniques for Internet in part of broadband network (DSL). However, beside investigating techniques for controlling these two aspects, the QoS in broadband part of network should be considered. Hence, to provide higher levels of QoS, it is necessary to increase capacity in integrated networks by dynamic frequency allocation, interference management and provisioning QoS. Also Fuzzy Control Systems for admission control and interference mitigation are being deployed. In order to meet Fetocells' user satisfaction, following parameters of QoS should be considered:

- Delay: would be considered in voice traffic.

- Packet Loss: would considered in data traffic.

1.5 Overal Concepts

1.5.1 Signal to interference plus noise ratio (SINR)

In communication systems, the received signal is always weaker than the original transmitted signal due to different attenuation factors. One of these factors is the noise created by the circuit components at the receiver side. To measure the link quality, communication systems usually utilize the Signal to Noise Ratio (SNR). This ratio represents the power of transmitted signal over the generated noise. In cellular networks, the noise is insignificant compared to the interferences created by neighboring mobile users. As a result, cellular systems use a modified link quality indicator ratio known as SINR (Stalings, 2002).

1.5.2 Backhaul

The Backhaul link is the portion of network that covers the links connecting the intermediate links between the core network and the small sub-networks.

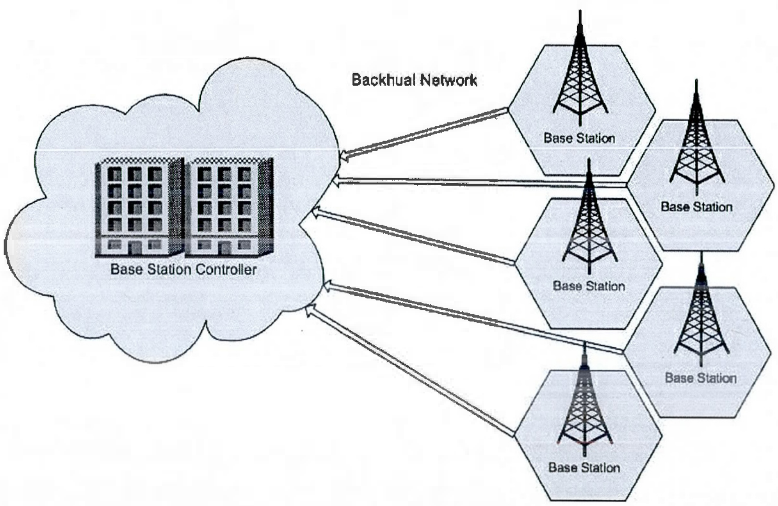


Figure 1.5: Backhual Network

1.5.3 Handover

The handover is the procedure responsible for transferring an ongoing communication from a frequency channel offered by a Base Station (BS) to another channel offered by another BS. Soft handover is a special case of handover where the transfer of ongoing communication from one BS to another is performed without interruption. Hence, the EU must be connected at least to two or more BSs at the same time.

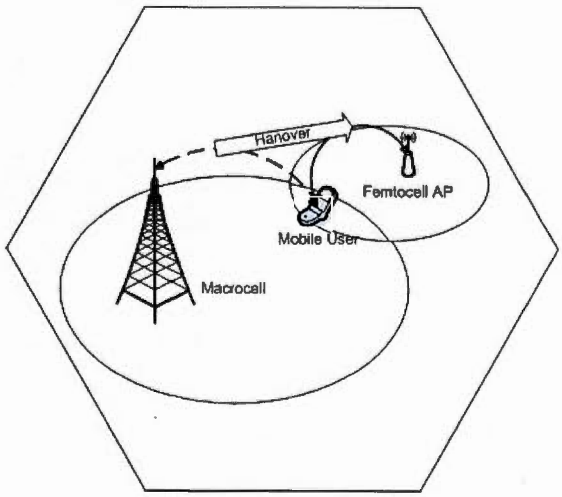


Figure 1.6: Hanover between Macrocell and Femtocell for a Mobile User

1.5.4 Cognitive radio (CR)

The key enabling technology of dynamic spectrum access is cognitive radio (CR) technology, which provides the ability of sharing wireless channels in an opportunistic way for the licensed users. A cognitive radio senses the environment (cognitive capability), analyses and learns sensed information (self-organized capability), and adapts to the environment (reconfigurable capability) (Akyildiz et al., 2008). In cognitive radio networks, depending on sensor readings and the spectrum decision algorithm, the secondary users are able to use the unused parts of spectrum in such a way that primary users' communications do not get disturbed (Urgaonkar and Neely, 2012). Cognitive communication is based on a vertical spectrum access rights paradigm. In this context, CR nodes are secondary spectrum users authorized to access frequency channels only on a no- or limited-interference manner with respect to the licensed users of the band. This secondary spectrum access (SSA) status makes CRNs particularly vulnerable to attacks aiming to deny the CR nodes from spectrum access, Denial of Service (DoS) attacks. CR encloses both adaptive radio technology (which enable the automatic monitoring and calibration of system behavior) and Software Defined Radio (SDR) technology (wherein intelligent software replace the conventional hardware components) (Attar et al., 2012).

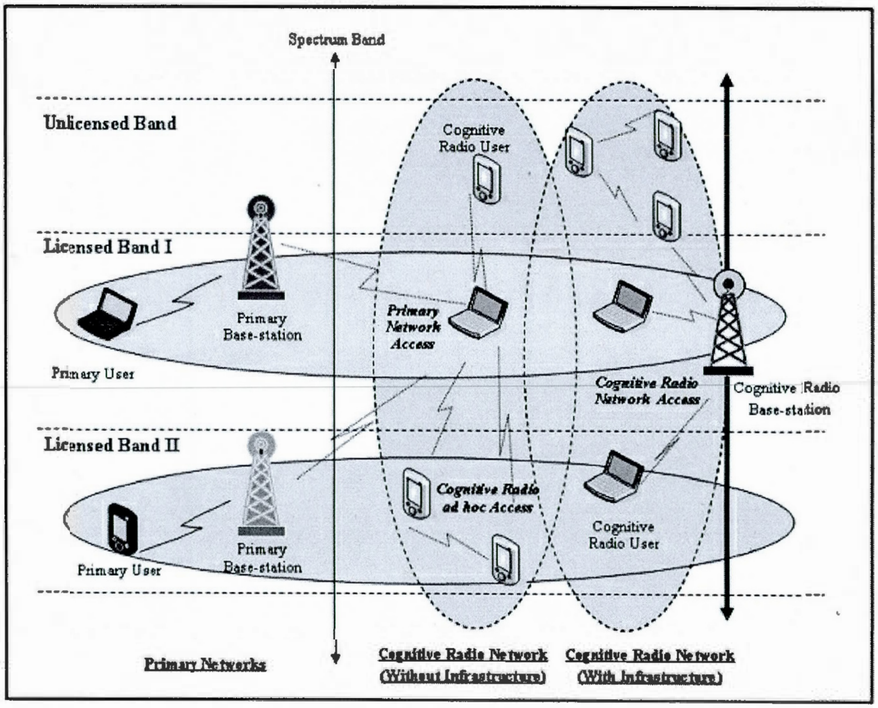


Figure 1.7: Cognitive radio network architecture (Akyildiz et al., 2008)

CHAPTER II

REVIEW OF THE LITERATURE

Femtocell not only provides coverage at the customer premises, but also radiates toward neighboring houses as well as outdoors, introducing interference. Considering that Femtocells are deployed within the coverage area of existing Macrocells, they can cause strong degradation of the Macrocells' performance. Furthermore, the deployment of new Femtocells could also disturb the normal functioning of already existing Femtocells. Therefore, in order to reduce the appearance of dead zones within the Macrocells and successfully deploy a Femtocell network, interference avoidance, randomization, or cancellation techniques must be applied. In the following, considering that Femtocell and Macrocell networks define two separate layers (the Femtocell and Macrocell layers), interference can be classified as follows:

- Cross-layer: This refers to situations in which the interference caused by FAP and MBS belonging to different network layers.
- Co-layer: In this case the interference caused by neighboring FAP which belong to the same network layer.

To overcome the effects of interference, cancellation techniques have been proposed but often disregarded due to errors in the cancellation process. The use of sectorial antennas at the FAP has also been suggested in (Chandrasekhar and Andrews, 2009) as a means of reducing interference by decreasing the number of interferers. Similarly, a dynamic selection of predefined antenna patterns has been used in (Claussen and Pivit, 2009) to reduce the power leakage outdoors. However, hardware-based approaches usually imply an increase in FAP cost. Therefore, to achieve promised goals of Femtocell, researchers mainly focus on mitigating interferences through strategies based on interference avoidance that also represent efficient alternatives (power and sub-channel management). Moreover power control algorithms and radio resource management are tools which often used in cellular systems to mitigate interference. These techniques are also necessary in FAPs for the same reasons plus the added problem of cross-layer interference. For example, in closed access Femtocells, users located far from the FAP and being asked to raise their power level might produce high levels of interference to neighboring Femtocells or even to the Macrocell. Load management algorithm, efficient resource allocation algorithms, FBSs cooperation and enhanced feedback reporting solutions, advanced sensing solutions, frequency reuse and power control schemes are the research basis for interference mitigation.

2.1 Power Control Scheme

Power optimization technique is one important component of radio resource management, since the deployment of Femtocells may cause serious cross-tier interference and consume large amounts of energy. Femtocell networks are about to be extensively deployed with the aim of providing substantial improvements to cellular coverage and capacity. However, their deployment is nontrivial because of the extra interference that the Femtocell nodes cause to the Macrocell nodes with which they share the same portion of the spectrum.

In (Wei et al., 2012), authors present an energy-efficient power control solution for interference-limited two-tier Femtocell networks in the analytical setting of a game theoretic framework, where both circuit and transmission powers have been considered. They investigate a non-cooperative power control game for two-tier spectrum sharing Femtocell networks, and then based on obtained SINR, they propose an algorithm that reduces transmission powers of the strongest Femtocell interferers. They show that the equilibrium always exists and is unique. The equilibrium discourages strongly interfering Femtocells to use large transmit powers. According to their results, the proposed scheme can improve energy efficiency of Femtocell networks and mitigate cross-tier interference significantly. In (Douros et al., 2012), they show a non-cooperative power control approach for interference mitigation in a two-tier Femtocell network where the first tier is a conventional cellular network and the second tier is a set of (short-range) Femtocells. They prove the existence and uniqueness of a Nash Equilibrium for the resulting game and propose a distributed power control algorithm that, based on the best response dynamics method, converges to this unique set of transmission powers.

Based on results from stochastic geometry, (Bendlin et al., 2011) propose a power control algorithm situated at the Macro base stations. Each Macro base station independently computes the transmit power level for all Femto base stations in the corresponding cell. The computations are solely based on measurements readily available at each Macro base station and no further communication between any set of base stations is required other than the broadcasting of the results to the Femto base stations in a quasi-static fashion. The algorithm addresses the limitations present in a practical system such as delays in the backhaul and scalability with the number of femto base stations. The paper concludes by demonstrating the benefits of the algorithm through system level simulations.

2.2 Resource Allocation

Considering the problem of channel allocation and power control to different users within a Femtocell play crucial role, as improvement of the coverage and capacity in a cellular system by Femtocell have been promised. Knowing the channels available, the channel states and the rate requirements of different users the FBS, allocates the channels to different users to satisfy their requirements. Also, the Femtocell should use minimal power so as to cause least interference to its neighboring Femtocells and outside users. In (Lee, 2011), the authors propose a new scheme to balance the traffic load among FBSs while ensuring at the same time the requested QoS by moving user equipments (UEs). In order to achieve that, the authors consider several factors such as UE's prediction, QoS satisfaction and load balancing between neighboring FBSs to make the best possible handover decisions. More precisely, the authors calculate the weight of each UE connected to an overloaded FBS using three different parameters: the remaining time index (measuring how long the UE is going to remain under the coverage area of its current serving FBS), mobile station satisfaction index (responsible of choosing the appropriate FBS for each UE), and FBS load balance indexes (selecting the future/target FBS with the best system balance).

In (Sankar and Sharma, 2012), they propose efficient and low complexity subchannel allocation and power control algorithms for uplink and downlink users within a FC in a multi

FC sparse scenario (suburban/rural environment) where interference between the FCs are neglected. Their model includes sub channel power constraints, considers QoS to voice and data traffic and provides fair, efficient, low complexity algorithms. Their proposed algorithms not only improve the QoS of MSs within the FC and the Macro Cell (MC) but also cause less interference to the outside MSs by minimizing the transmit power of FC users.

Authors, in (Kang and Dung, 2011), propose a load control strategy with virtual coverage adjustments for downlink transmission. The coverage area of both serving macrocell and target cell can virtually change by tuning the handover thresholds. In other words, by reducing the handover's threshold values, the virtual coverage area of current/serving macrocell becomes smaller while, alternatively, the virtual coverage area of neighboring cells, macrocells and Femtocells, becomes larger. Therefore, the transfer of Macrocell UEs to adjacent cells becomes more frequent and quicker, while the transfer of adjacent-cells' UEs to the current/serving cell becomes less frequent and slower. As a result, the addition of Femtocells to the two-tier network helps macrocells to avoid being overloaded through lessening the traffic load handled by MBSs.

2.3 Self-Organization Algorithms

To practically solve and overcome interference challenge, sophisticated self-organized techniques can be employed which successfully deploy and manage Femtocell networks over the existing Macrocell networks. The nodes of self-organizing networks should be self-configuring in order to be able to integrate themselves into networks efficiently. By automating these procedures based on QoS parameters, nodes will be more responsive to the changing conditions of the environment and enhancing their performance due to the minimization of delay between consecutive optimization tasks (Zhang and de la Roche, 2010).

In (Bennis and Niyato, 2010), authors aim to propose an algorithm for mitigating the interference between Femtocells and the Macrocell network. In doing so, the authors have looked into different self-organization strategies like time-hopped CDMA physical layer for Wide-Band Code Division Multiple Access (WCDMA) and sub-channel allocation for Orthogonal Frequency Division Multiple Access (OFDMA) networks. Focusing on OFDMA, they propose a Q-Learning based algorithm for sub-channel allocation to mitigate the interference. They differentiate their study from other similar studies using Q-Learning algorithms by assuming that there is no communications or coordination among Femtocells. They also compare their approach with random and static sub-channel allocation strategies. In their system model, a reinforcement-learning protocol has been proposed for mitigating the imposed interference based on which Femtocells select their carrier channels and change their transmission power when they receive a self-organization message from Macrocell base station. This message will be prepared in Macrocell base station based on the periodic reports of measured parameters by macro-users, such as the Received Signal Strength Indicator (RSSI).

In (Bennis et al., 2011), the authors provide an overview of the BeFEMTO project followed by an implementation of interferences mitigation techniques such as Radio Resource Management (RRM) and power control algorithm. Their proposed radio resource management algorithm starts by determining the appropriate transmission parameters (number of Resource Blocks (RBs), modulation/coding schemes and the transmission power) for each Femtocell UE. Then, the algorithm starts to allocate more available RBs to each served UE. In addition, in order to reduce the generated interference on each RB, the authors suggest to increase the number of allocated RBs for each UE while decreasing their power level. According to the authors, their proposed RRM performs better than the conventional RRM (that limits the number of assigned RBs for each UE) in term of decreasing the outage probability of UEs.

In (Stocchi et al., 2011), the authors propose a novel algorithm that focuses on mitigating co-layer interference at downlink transmission. Their proposed algorithm offers self-configuration and self-optimization capabilities. It combines three different schemes: flexible spectrum usage, power control and initial spectrum selection. It aims to ensure a high cells throughput and improved performance for UEs with poor condition. First, they propose to split the total system bandwidth into orthogonal portions with identical number of RBs. Therefore, each portion is assigned to a single FBS which has the transmission priority. However, a FBS is only allowed to use other FBSs' prioritized portions of bandwidth when all of its priority portion's RBs are already used. The usefulness of prioritizing portion of bandwidth to FBSs becomes clear when a new FBS is switched-on for the first time. They show that in case of high traffic load, their power control scheme is utilized in order to avoid each FBS to generate high interferences to the others due to the fact of utilizing all the frequency spectrum's RBs.

2.4 Cognitive Radio Solution

Some researchers got inspired by the cognitive radio technology which enables a station to recognize and adapt to the communication environment to reach the optimum network performance. They focus to improve the sensing capabilities of FBS antenna by integrating Cognitive Radio features in Femtocell deployment.

Authors in (Gyr et al., 2010) propose a Femtocell-based Cognitive Radio architecture that enables an opportunistic access to the broadband wireless systems. They combine the infrastructure-based overlay Cognitive network model the existing Femtocell networks to deliver additional efficient dynamic spectrum access and management to Femtocell. The UEs are divided into two classes of mobile users; primary users (Macrocell UEs) and secondary users (Femtocell UEs). The key advantage of using cognitive FBSs is to discover and detect spectrum opportunities more efficiently and allocates them to the secondary UEs.

In (Urgaonkar and Neely, 2012), authors consider two models for opportunistic cooperation between secondary (Femtocell) users and primary (Macrocell) users in Cognitive-Femtocell networks. They call first model as the Cooperative Relay Model where a secondary user cannot transmit its own data concurrently with a primary user. In the second model, called the Interference Model, a secondary user is allowed to transmit its data concurrently with a primary user. In both models, Femtocells must make intelligent cooperation decisions which are different during idle and busy periods of Macrocells. Authors design a novel greedy and online control algorithm based on constrained Markov decision to overcomes the challenges of decision making.

In (Attar et al., 2011), the authors argue of the advantages of incorporating Cognitive Radio capabilities into FBSs and the abilities of cognitive FBSs, such as improved sensing capability, knowledge of the radio scene to cleverly allocate resources and reduce severe co-layer interference. Also they discuss the important role of radio scene analysis and argue the expected benefits of integrating cognitive BSs to LTE network. Then they formulate the co-layer interference problem into either a coalition formation game or a game with correlated equilibrium due to the distributed nature of Femtocell networks. The main idea of their work prove the importance and the capability of incorporating a cognitive radio technology to the existing Femtocell-based cellular network to reduce severe interferences.

2.5 Traffic Offloading Schemes

Many cellular user equipments (UEs) today are able to access both the unlicensed band (via WiFi) and the cellular licensed band. However, in most regions of the world, they are not allowed to access both bands simultaneously for data communications as users can only choose either WiFi or cellular. This issue draws researches attention to investigate the studies which allow Femtocell UEs to enjoy both bands at the same time.

In (Vivier et al., 2010), authors argue about technical and non-technical issues which show Femtocell envisaged benefits are not easily achievable. Based on Femtocell-based netwoRk Enhancement by intErference management and coorDination of infOrmation for seaMless connectivity (FREEDOM), they investigate the planned activities which target at providing a new vision of a Femto-based network and giving solutions to major concerns about a massive deployment of FAPs. They show that the combination of the new paradigms employed in the project constitute a realistic and technologically viable set of solutions to enable the achievement of the targeted high density in FAPs deployment. Also FREEDOM project will address key technical and industrial concerns about the foreseen mid-term massive deployment of Femtocells. It adopts a new approach based on cooperative/coordination paradigms which is enabled by the quality-limited ISP backhaul link.

In (Liu et al., 2011), based on a few papers which apply cognitive technology to Femtocells, authors study FBSs use cognitive technology to access the radio resources where they are not utilized by the Macrocell and also they are not secondary users in the licensed or unlicensed bands. They propose a framework for a Femtocell to access both licensed and unlicensed bands and uses both spectrums but not as a secondary user. Authors, as result, show the performance improvement of Femtocell by using unlicensed band. They continue their work in (Liu et al., 2012) and extend their framework with strategies for Femtocells to balance their traffic in licensed and unlicensed bands. They formulate the optimal Femtocell traffic balancing scheme over the licensed and unlicensed bands, in order to maximize the sum utility (satisfaction) of Femto and WiFi users while controlling the interference leaked from Femtocell to Macrocell. This is achieved by Femtocell power control in the licensed band and channel usage control in the unlicensed band. Their problem formulation allows the traffic balancing scheme not only to improve the utilities of Femto and WiFi users, but also to improve Macro user utility by reducing Femto-Macro interference.

In (Gao et al., 2013), authors investigate the network-initiated mobile data offloading through third-party WiFi or FAPs, and focus on the economic interactions between network operators and APs. They use a market-based data offloading solution, where network operators share the data offloading benefits with APs through market mechanisms. Then, they present a multi-leader multi-follower Data Offloading game (DOFF), where BSs (leaders) propose market prices, and accordingly APs (followers) determine the traffic volumes they are willing to offload. Their analytical result indicate that the price participation (of BSs) will drive market prices down, compared to those under the Market Balance (MB) outcome, and the price competition (among BSs) will drive market prices up, compared to those under the Monopoly Outcome (MO).

To control offloading and achieving the required balance of users and traffic served by each network tier, authors in (El Sawy et al., 2013) develop a model to quantify offloading of users to the Femto network tier in a Nakagamim fading environment. Three offloading techniques have been investigated: (i) offloading via power control, (ii) offloading via biasing, and (iii)offloading via increasing the relative intensity of FAPs. Also the natural offloading due to the favorable channel conditions to the FAPs has been quantified. Their numerical result show that to achieve higher user offloading to the Femto network tier, FAPs should be deployed at places where there are favorable channel conditions to the FAPs. They show that offloading via increasing the intensity of the FAPs should be planned carefully to decrease the percentage of idle FAPs. Moreover, they observe that power control has the least impact on offloading. Hence, offloading via biasing should be avoided as much as possible in order to avoid increasing the outage probability.

In (Zhixue et al., 2013), authors investigate the dynamic OFDMA subchannel assignment problem while jointly considering power assignment and association control to provide max-min fairness. First they study a Non-interfering Model (NINT model), which disallows interfering Femtocells in the solution. Then a more general Interfering Model (INT model) is considered where the challenge is transformed into the partition coloring problem. They show the NP-hardness of the problems and design centralized approximation algorithms with provable bounds and distributed solutions. They did extensive simulations in realistic settings to prove that solutions under the NINT model can achieve two times the minimum throughput, and under the INT model the minimum throughput can be up to three times the baseline algorithms, compared to previous works.

In (Elsherif et al., 2013), authors work on how to offload traffic or enhance per-user throughout via dynamic switching and/or aggregating LTE and WiFi air interfaces. They consider joint radio resource management of both licensed and unlicensed bands. Besides, they investigate inter-cell interference management under different situations. Then, they formulate an optimization problem as a linear programming problem with the objective of maximizing the sum of the total throughput in both licensed and unlicensed bands while satisfying QoS requirements of UEs. Their simulation results clearly results show the advantage of joint resource allocation over both licensed and unlicensed bands when compared to conventional Femtocells and WiFi hotspots.

An overview on all the studied articles in the literature, shows that Femtocell-based architectures have the potential to position the cellular service providers to compete head-on with the WiFi market. But current use of hard partitioning approaches for resource allocation, and lack of guidelines for configuring the Femtocells, makes it difficult to obtain significant performance gains over traditional cellular networks. Based on our research, we came to conclusion of traffic offloading and transmission in both licensed and unlicensed, would maximize the sum throughputs of Femtocell network over both bands while maintaining the promised QoS of Femtocell EUs.

CHAPTER III

UNLICENSED SPECTRUM SPLITTING BETWEEN FEMTOCELL AND WIFI

In this chapter, we analytically model the performance of coexisting Femtocells and incumbent devices such as WiFi and Bluetooth in the unlicensed spectrum over a fully-utilized unlicensed band, respectively to the analytical measurement of total capacity of both networks.

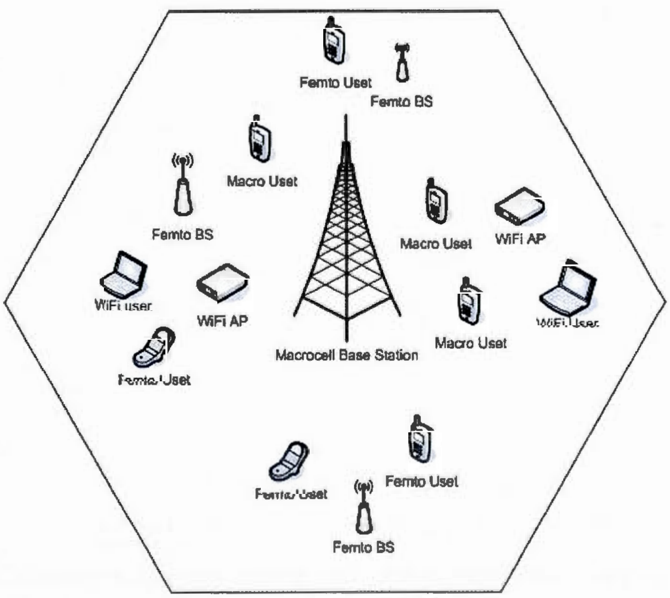


Figure 3.1: Macrocell-Femtocell-WiFi Network

Due to its widespread utilization, WiFi network is selected as the incumbent system for investigating the coexistence problem (Fig. 3.1). In this study, Femtocells access unlicensed bands considering that they are not secondary users and they are equal compared with WiFi.

We consider a co-existence of Femtocell and WiFi scenario, where N Femtocells and M WiFi's are attempting to use the same allocated bandwidth (B). The aim is to split the total bandwidth (B) among these networks by determining ρ as bandwidth partitioning value while (i) maximizing total capacity and (ii) ensuring fairness and (iii) QoS metrics.

3.1 Spectrum Splitting Between Femtocell and WiFi

As shown in Fig. 3.2, the portion of accessed bandwidth for Femtocells (B_F) is $(1-\rho)B$ and the portion of accessed bandwidth for WiFi (B_W) is ρB.

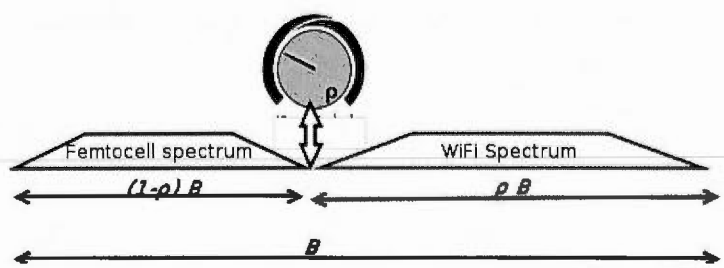


Figure 3.2: Spectrum Splitting in a Femtocell-WiFi Network

Using the notation defined in Table 3.1, we consider a scenario where in which T networks (Femtocells and WiFi's) co-exist. Lets assume that T denotes the number of co-existing networks (in our case, Femtocells and WiFi's), N denotes the number of base stations in each network and K denotes the number of users per base station. The spectrum splitting problem consists of maximizing $C_{Total}(\rho)$ which is defined as:

$$C_{Total}(\rho) = \sum_{k=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{K} C_{k,i,j}(\rho). \tag{3.1}$$

As we assumed Femtocells co-exist only with WiFi's, at the first step, the goal is to

Parameters	Description
ρ	If B is total bandwidth, ρ is the portion of the accessed bandwidth for WiFi and 1-ρ is the portion for Femtocell network
Γ_1	SNR of Femtocells $\frac{P_F N}{N_0}$
Γ_2	SNR of WiFi $\frac{P_F N}{N_0}$
N_F	Number of Femtocells in each network
$N_{u,i}$	Number of users in each Femtocells
M_W	Number of WiFi in each network
$M_{u,i}$	Number of users in each WiFi
$C_{i,j}$	Capacity of j^{th} user in i^{th} network
$B_{i,j}$	Allocated bandwidth to j^{th} user in i^{th} network

Table 3.1: Description of Parameters

maximize the total capacity of network to evaluate the value of ρ:

$$\begin{aligned} C_{Total}(\rho) &= C_F(\rho) + C_w(\rho) \\ C_F(\rho) &= \sum_{i=1}^{N}\sum_{j=1}^{K} C_{i,j}(\rho) \\ C_W(\rho) &= \sum_{i=1}^{M}\sum_{j=1}^{K} C_{i,j}(\rho). \end{aligned} \tag{3.2}$$

While the allocated bandwidth would be:

$$\begin{aligned} B &= (1-\rho)B_F + \rho B_W \\ B_F &= (1-\rho)B \Longrightarrow B_F = \sum_{i=1}^{N}\sum_{j=1}^{K} B_{i,j} \\ B_W &= \rho B \Longrightarrow B_W = \sum_{i=1}^{N}\sum_{j=1}^{K} B_{i,j} \end{aligned} \tag{3.3}$$

where $C_F(\rho)$ and $C_W(\rho)$ denote the capacity of Femtocell and WiFi networks respectively. Without loss of generality, the following assumptions are considered in our analytical model:

- The number of the users for each base station is fixed.
- Inter-Femtocell/Inter-WiFi interference is inconsiderable so, $\forall(i,j), I_{i,j} = 0$.

- Received power of Femtocells and WiFi is constant so $\forall(i,j), P_{i,j} = \mathbf{P}$.
- Bandwidth for each Femtocell/WiFi is distributed in a round robin strategy.
- Signal to interference plus noise ratio (SINR) of each user in a Femtocell/WiFi, where N_0 is the spectral density of noise, would be:

$$SINR_{i,j} = \frac{P_{i,j}}{I_{i,j} + B_{i,j}N_0}. \tag{3.4}$$

3.2 Splitting Unlicensed Spectrum without Fairness

In this section, based on our extracted equations, we proposed the spectrum splitting scheme without considering fairness factors.

3.2.1 Femtocell and WiFi Capacity

Considering the parameters in Table 3.1 and the above mentioned assumptions, if the bandwidth of each Femtocell is $B^F_{i,j} = \frac{B_F}{N}$ then the Femtocell network capacity $C_F(\rho)$ can be expressed as follows:

$$C_F(\rho) = \sum_{i=1}^{N}\sum_{j=1}^{K} \frac{B_F}{N} log_2(1 + \frac{P_{i,j}}{I_{i,j} + \frac{B_F}{N}} N_0) = \sum_{i=1}^{N}\sum_{j=1}^{K} \frac{(1-\rho)B}{N} log_2(1 + \frac{P_{i,j}}{I_{i,j} + \frac{(1-\rho)BN_0}{N}}). \tag{3.5}$$

Considering our analytical assumptions ($\forall(i,j), I_{i,j} = 0$ and $\forall(i,j), P_{i,j} = \mathbf{P}$), then:

$$C_F(\rho) = \frac{(1-\rho)B}{N} log_2(1 + \frac{\mathbf{P}}{\frac{(1-\rho)BN_0}{N}}). \tag{3.6}$$

Finally, equation (3.6) could be expressed as follows:

$$C_F(\rho) = \frac{B_F}{N} log_2\left(1 + \frac{\mathbf{P}_F}{\frac{B_F N_0}{N}}\right). \tag{3.7}$$

Similarly, the total capacity of WiFi network can be derived as:

$$C_W(\rho) = \frac{B_W}{M} log_2\left(1 + \frac{\mathbf{P}_W}{\frac{B_W N_0}{M}}\right), \tag{3.8}$$

where $B_{i,j}^W = \frac{B_W}{N}$.

3.2.2 Total Capacity of Femtocell/WiFi Netwrok

Taking into account (3.2), and using (3.7) and (3.8), the total capacity of the system would be express as follows:

$$C_{Total}(\rho) = \frac{B_F}{N} log_2\left(1 + \frac{\mathbf{P}_F}{\frac{B_F N_0}{N}}\right) + \frac{B_W}{M} log_2\left(1 + \frac{\mathbf{P}_W}{\frac{B_W N_0}{M}}\right). \tag{3.9}$$

If we consider $\Gamma_1 = \frac{P_F N}{N_0}$ and $\Gamma_2 = \frac{P_W M}{N_0}$, then:

$$C_{Total}(\rho) = \frac{B_F}{N} log_2\left(1 + \frac{\Gamma_1}{B_F}\right) + \frac{B_W}{M} log_2\left(1 + \frac{\Gamma_2}{B_W}\right). \tag{3.10}$$

Therefore, the objective function to be investigated is a re-interpretation of the total capacity expressed by (3.10) and would be:

$$C_{Total}(\rho) = N(1-\rho)B log_2\left(1 + \frac{\Gamma_1}{(1-\rho)}\right) + M\rho B log_2\left(1 + \frac{\Gamma_2}{\rho}\right), \tag{3.11}$$

where spectrum splitting ρ value which maximizes the $C_{Total}(\rho)$ in (3.11) can be expressed as follows:

$$\rho = arg \max_{0 \leqslant \xi \leqslant 1} C_{Total}(\xi). \tag{3.12}$$

On the other hand, the objective function in (3.12) can be viewed as a convex combination of (3.7) and (3.8).

Numerical results in Figures 3.3, 3.4, 3.5 show that the capacity would be maximized at

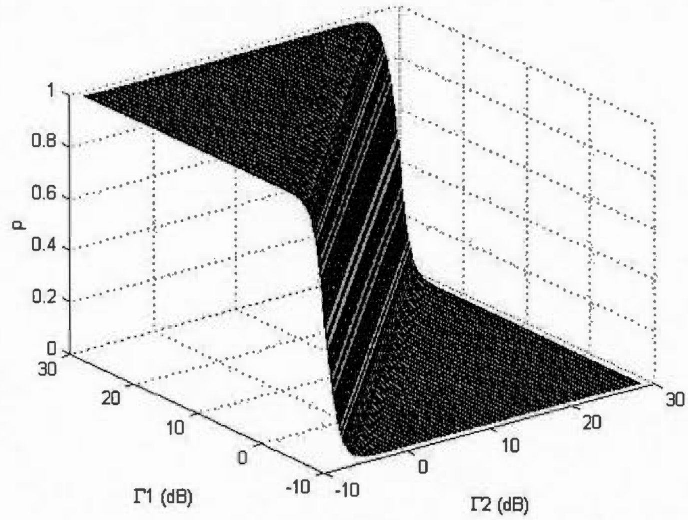


Figure 3.3: ρ values for various Γ1, Γ2 without fairness or QoS metric for maximizing the capacity (where N_F=10 and M_W = 10).

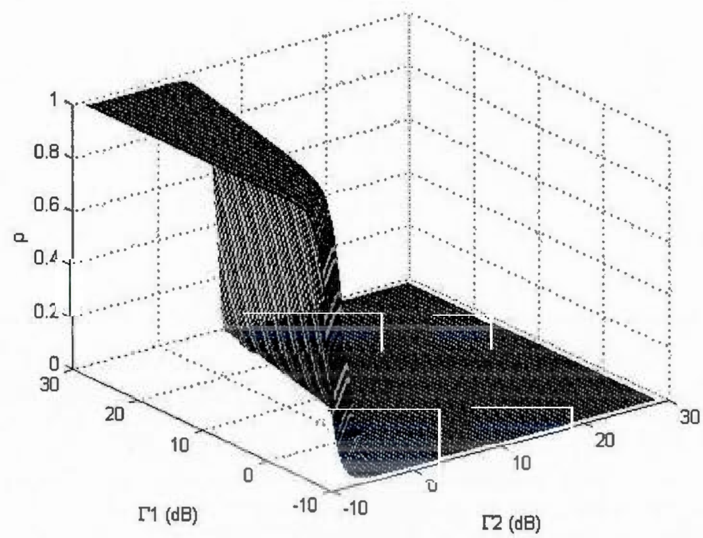


Figure 3.4: ρ values for various Γ1, Γ2 without fairness or QoS metric for maximizing the capacity (where N_F=50 and M_W = 10).

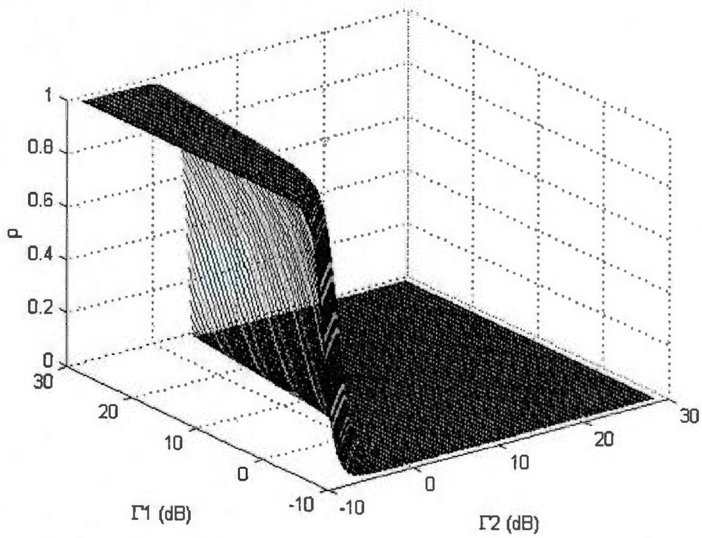


Figure 3.5: ρ values for various $\Gamma 1$, $\Gamma 2$ without fairness or QoS metric for maximizing the capacity (where N_F=100 and $M_W = 10$).

intense points corresponding to $\rho \in [0, 1]$, without a fairness or QoS parameter. These Figures precisely indicate that the above partitioning is unfair and it causes a greedy allocation to one of the considered networks. Also it shows that most of the time, the total capacity is maximized when ρ=0 where the bandwidth is totally assigned to the Femtocell network. Besides, we calculate ρ for different values of $\Gamma 1$ and $\Gamma 2$, and for $N_F = 10$, $N_F = 50$, $N_F = 100$ where the M_W is always equal to 10 and number of users in Femtocell is fixed to 6 and in WiFi is fixed to 4. However, while the number of Femtocell networks are small and $\Gamma 2 \leq \Gamma 1$, the allocating of bandwidth to WiFi network would be more and also could get to better capacity. The maximization of capacity without considering fairness and QoS parameter in objective function (3.12) would lead to very unfair bandwidth splitting.

3.3 Splitting Unlicensed Spectrum with Fairness

As it was shown in Section 3.2, maximizing the total capacity and also bandwidth splitting without fairness and QoS metrics would lead to unfair resource allocation. Fairness is an important performance criteria in all resource allocation schemes (Jain et al., 1984) and it has been investigated in different aspects. Jain's fairness index (JFI) has been used a lot in the fairness criterion literature for resource allocation. The desired properties of Jain's fairness index (JFI) are as follow (Jain et al., 1984):

- Population size independence (be applicable to any number of users).
- Scale and metric independence (be independent of scale).
- Boundedness (be bounded between 0 and 1).
- Continuity (be continuous not non-discrete).

Jain's fairness index is:

$$f(x) = \frac{(\sum_{i=1}^{N} x_i)^2}{N \cdot \sum_{i=1}^{N} x_i^2} \tag{3.13}$$

where N denotes the total number of users and x_i denotes the received allocation for the i^{th} user. Based on the Jain's index, the fair index while considering total capacity would be as following:

$$f_{JFI}(C) = \frac{1}{N_{Total}} \left(\frac{(\sum_{i=1}^{N} \sum_{k=1}^{K} C_{i,k})^2}{\sum_{i=1}^{N} \sum_{k=1}^{K} C_{i,k}^2} + \frac{(\sum_{i=1}^{M} \sum_{k=1}^{K} C_{i,k})^2}{\sum_{i=1}^{M} \sum_{k=1}^{K} C_{i,k}^2} \right) \tag{3.14}$$

$$N_{Total} = \sum_{i=1}^{N} N_{u,i} + \sum_{i=1}^{M} M_{u,i}, \tag{3.15}$$

Where $N_{u,i}$ = Number of users in i^{th} Femtocell and $M_{u,i}$ = Number of users in i^{th} WiFi. Equation (3.14) would not support the boundedness property of Jain's fair index as the number of users has not been considered. It means, since the number of users change, the upper bound of JFI varies and it will not be bounded to 1. Weighting (3.14) by summation of number of networks (Femtocells and WiFi's) could be another way to provide the upper bound for fairness index.

$$f_{TFI}(C) = \frac{1}{N+M} \left(\sum_{i=1}^{N} \frac{(\sum_{k=1}^{K} C_{i,k})^2}{N_{u,i} \sum_{k=1}^{K} C_{i,k}^2} + \sum_{i=1}^{M} \frac{(\sum_{k=1}^{K} C_{i,k})^2}{M_{u,i} \sum_{k=1}^{K} C_{i,k}^2} \right). \tag{3.16}$$

Although (3.16) bounded the upper bound to 1, the lower bound no longer would be bounded to $1/N_{Total}$ (Table 3.2). Also as total number of users have not been considered,

Fairness Indices	Lower bound	Upper Bound
$f_{JFI}(C)$	$1/N_{Total}$	could not be expressed without C
f_{TFI}	$1/N_{Total}$	1
f_{WJFI}	$\frac{\sum_{i=1}^{T}\sum_{j=1}^{M} N_{u,i,j}}{\sum_{i=1}^{T} N_{u,i}}$	1
f_{QTFI}	$1/N_{Total}$	1

Table 3.2: Bounds for Fairness Indices (Erturk et al., 2010)

for example even if Femtocells have twice number of users compared to WiFi, (3.16) provides equal weights for each network. Regarding (Erturk et al., 2010), the Jain's fairness index for different networks would be:

$$f_{TFI}(C) = \frac{1}{N_{Total}}\left(\frac{(\sum_{i=1}^{N}\sum_{k=1}^{K} N_{u,i}C_{i,k})^2}{\sum_{i=1}^{N}\sum_{k=1}^{K} N_{u,i}^2 C_{i,k}^2} + \frac{(\sum_{i=1}^{M}\sum_{k=1}^{K} M_{u,i}C_{i,k})^2}{\sum_{i=1}^{M}\sum_{k=1}^{K} M_{u,i}^2 C_{i,k}^2}\right). \tag{3.17}$$

If γ be considered as fairness metric ($1/N_{Total} \leq \gamma \leq 1$), the $\widetilde{\rho}$ could be given as:

$$\widetilde{\rho} = f_{TFI}^{-1}(\gamma), \tag{3.18}$$

where f_{TFI}^{-1} signifies the inverse function of f_{TFI} in (3.17).
The total capacity of networks for the fixed set of γ (while $f_{TFI}(\rho) \geq \gamma$) would be written as follows:

$$\rho = arg \max_{1/N_{Total} \leqslant \gamma \leqslant 1} C_{Total}(\gamma). \tag{3.19}$$

Figures 3.6, 3.7 and 3.8 show the value of ρ for different $\Gamma1$ and $\Gamma2$ which it has maximized the total capacity in (3.19), for different number of Femtocells (N = 10, 50, 100, $N_{u,f}$= 6) and total number of 700 users. As the value of ρ has been bounded to fixed set of γ, Fig. 3.6 indicates that the capacity would not be maximized for the $\rho = 0$ while $\Gamma2 \leq \Gamma1$ and also it would be the same in case of $\rho = 1$ while $\Gamma1 \leq \Gamma2$. Also it can be seen from Fig. 3.8 that increasing number of Femtocells decreases the ρ values which maximize the total capacity.

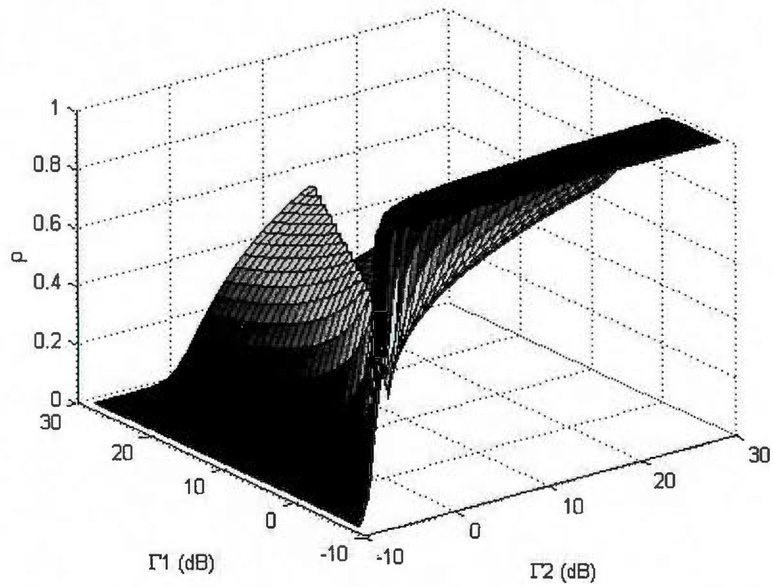


Figure 3.6: ρ values for various $\Gamma 1$, $\Gamma 2$ while N_{Total} = 700 and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ without QoS metric for maximizing the capacity (where N_F=10 and M_W = 10).

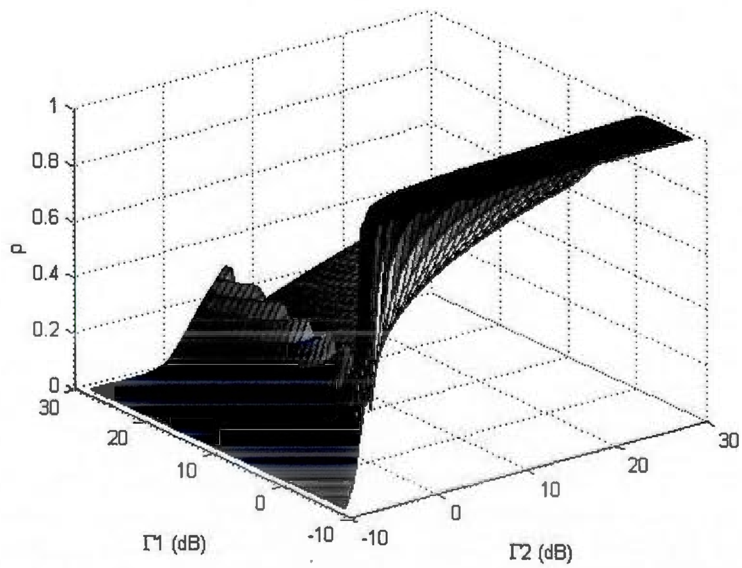


Figure 3.7: ρ values for various $\Gamma 1$, $\Gamma 2$ while N_{Total} = 700 and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ without QoS metric for maximizing the capacity (where N_F=50 and M_W = 10).

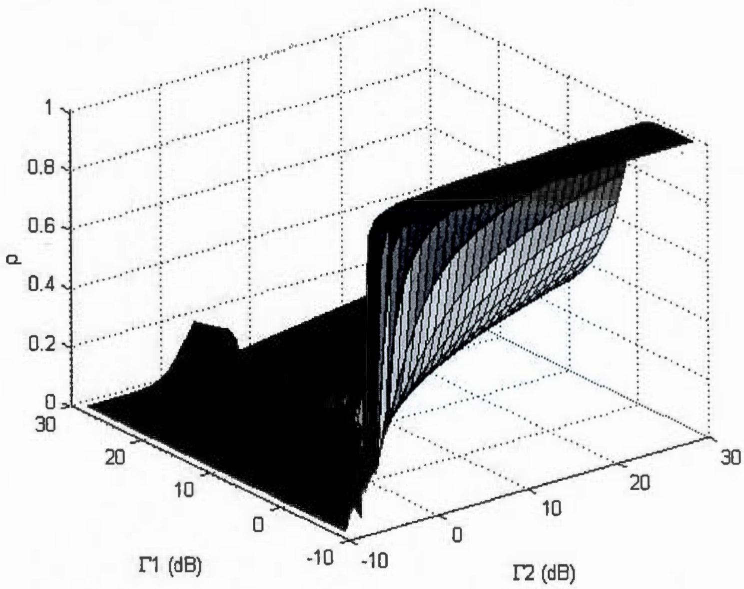


Figure 3.8: ρ values for various $\Gamma1$, $\Gamma2$ while $N_{Total} = 700$ and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ without QoS metric for maximizing the capacity (where N_F=100 and $M_W = 10$).

3.4 Splitting Unlicensed Spectrum with Fairness and QoS metric

Since different networks come with their own requirements for the QoS, the QoS measurement of each network should be considered in the discussed fair index in Section 3.3. Thus, we assume the β_i as QoS metric where $\beta_i(i = 1, ..., T)$ is the ratio of the sum capacity in the first network (WiFi) to the sum capacity in the other network (Femtocell). In other words, QoS parameter (β_i) indicates the relative resource allocation for each network:

$$\beta_i = \frac{\frac{1}{M}\sum_{i=1}^{M}\sum_{k=1}^{K} C_{i,k}}{\frac{1}{N}\sum_{i=1}^{N}\sum_{k=1}^{K} C_{i,k}}. \tag{3.20}$$

By adding QoS parameter (3.20) to (3.17), it would be modified as follows:

$$f_{QTFI}(C) = \frac{1}{N_{Total}}\left(\frac{(\sum_{i=1}^{N}\sum_{k=1}^{K}\beta_i N_{u,i} C_{i,k})^2}{\sum_{i=1}^{N}\sum_{k=1}^{K}\beta_i^2 N_{u,i}^2 C_{i,k}^2} + \frac{(\sum_{i=1}^{M}\sum_{k=1}^{K}\beta_i M_{u,i} C_{i,k})^2}{\sum_{i=1}^{M}\sum_{k=1}^{K}\beta_i^2 M_{u,i}^2 C_{i,k}^2}\right). \tag{3.21}$$

Moreover, (3.21) is the modified model of (3.14) and it satisfies the boundedness property within $[1/N_{Total}, 1]$ while supporting QoS requirements for each network (Table 3.2). By using the capacity formulas of Femtocell (3.7) and WiFi (3.8), (3.21) would be re-writen as follows:

$$f_{QTFI}(\rho) = \frac{(\beta_1 MC_W(\rho) + \beta_1 NC_f(\rho))^2}{N_{Total}[\beta_1^2 MC_W^2(\rho) + \beta_2 NC_F^2(\rho)]}, \tag{3.22}$$

where $\widetilde{\rho} = f_{QTFI}^{-1}(\gamma)$ and $\rho = arg \max_{1/N_{Total} \leqslant \gamma \leqslant 1} C_{Total}(\gamma)$.

The results of different values of β_i (QoS-orientation) for different scenarios where N_F= 10, 50, M_W = 20 and total number of 400 users, have been shown in Fig. 3.9 and Fig. 3.10. Setting the value of β_i= 0.8 (Figures 3.9(b) and 3.10(b)) means that Femtocell network experiences 80 percent of the average rate of WiFi network. Hence, decreasing the value of β_i would also decrease the value of ρ, which leads to achieving higher total capacity maximization. Results in Fig. 3.11 show the maximized total capacity of Femtocell for various $\Gamma 1$ and $\Gamma 2$ without fairness index, where the allocated bandwidth (B) has been considered as 100MHz, N_F= 10, M_W= 10, 30 and N_{Total}= 400. The final results in Fig. 3.12 indicates that as unlicensed spectrum could allocate more bandwidth to Femtocell, the maximized total capacity of Femtocell would be extremely achieved compared to the case of splitting bandwidth between Macrocell and Femtocell.

3.5 Conclusion

This chapter presents a spectrum allocation method for bandwidth splitting between Femtocell and unlicensed band network devices. Our scheme is shown to improve the total capacity of Femtocells while underlaying with other networks in unlicensed band and also the total capacity of whole system while considering fairness criteria and QoS orientations. In next chapter, we will propose a framework for licensed and unlicensed coexistence under a single radio access technology, in an effort to improve Femtocell performance and reduce interference in Macro-Femto networks and increase the throughput of cellular and non-cellular users.

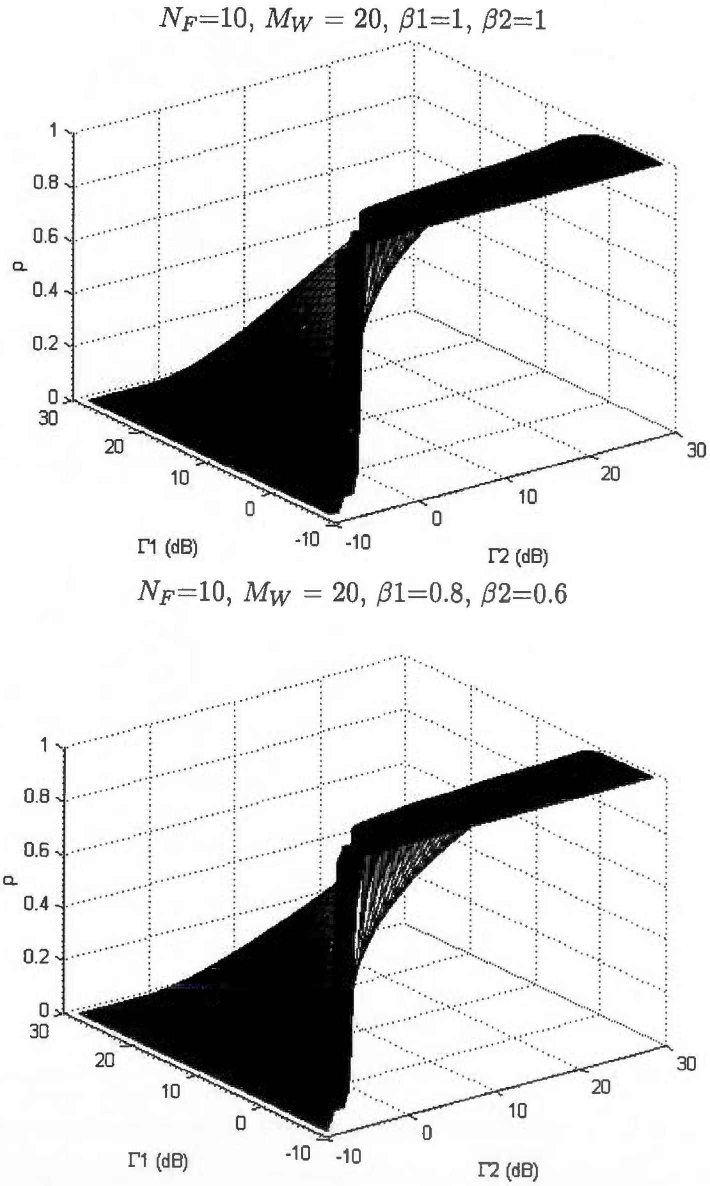
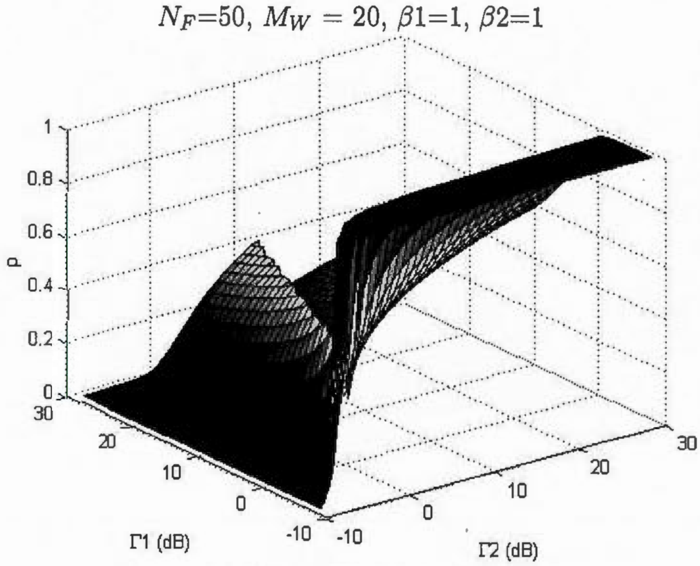


Figure 3.9: ρ values for various $\Gamma1$, $\Gamma2$ while N_{Total} = 400 and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ with QoS metric ($\beta1$ and $\beta2$) for maximizing the capacity.



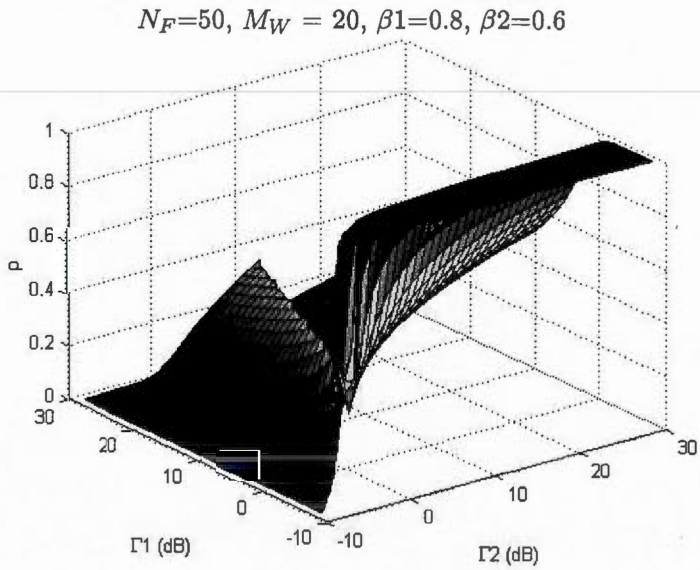
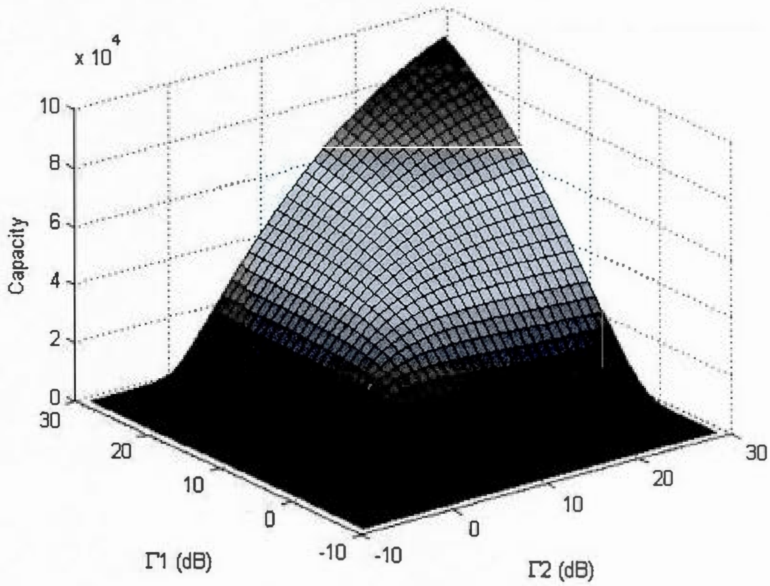
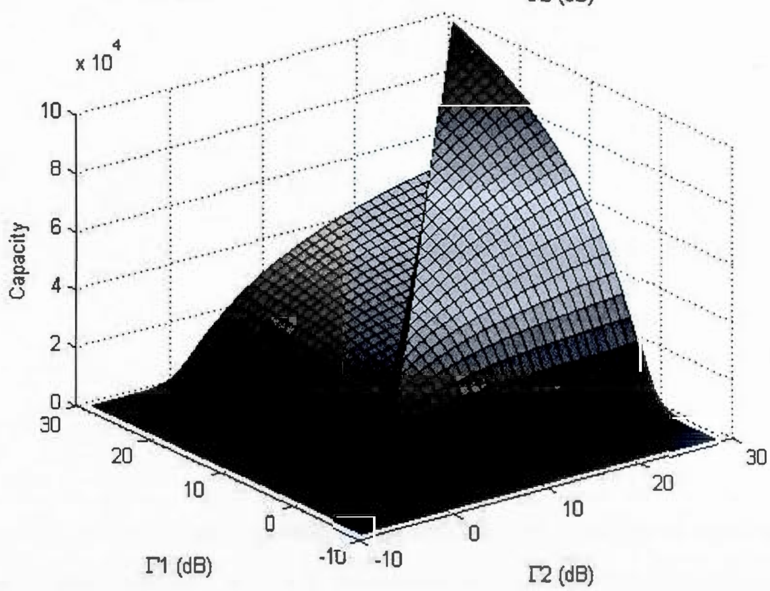


Figure 3.10: ρ values for various $\Gamma 1$, $\Gamma 2$ while $N_{Total} = 400$ and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ with QoS metric ($\beta 1$ and $\beta 2$) for maximizing the capacity.



N_F=30, $M_W = 10$



N_F=30, $M_W = 30$

Figure 3.11: Femtocell total capacity for various Γ1, Γ2 while $N_{Total} = 400$ and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ without QoS.

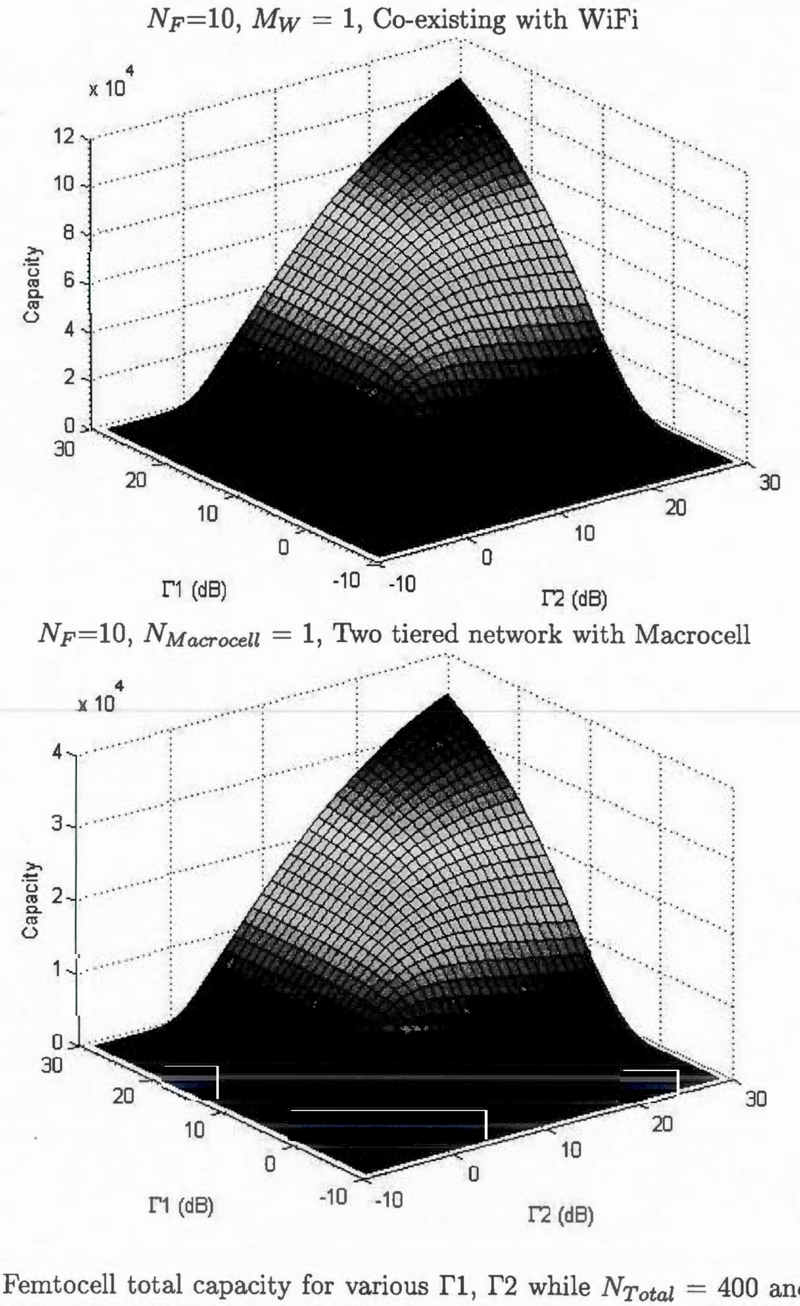


Figure 3.12: Femtocell total capacity for various Γ1, Γ2 while N_{Total} = 400 and fairness of $f_{(QTFI)}(\rho) \geq 0.9$ without QoS metric .

CHAPTER IV

THE CO-EXISTENCE OF FEMTOCELL WITH WIFI

In this chapter, we analytically model the co-existence of Femtocells and incumbent devices such as WiFi to access the unlicensed spectrum over a fully-utilized unlicensed band. Due to its widespread utilization, WiFi network is selected as the incumbent system for investigating the co-existence problem. Femtocell's self-organization function allows it to scan

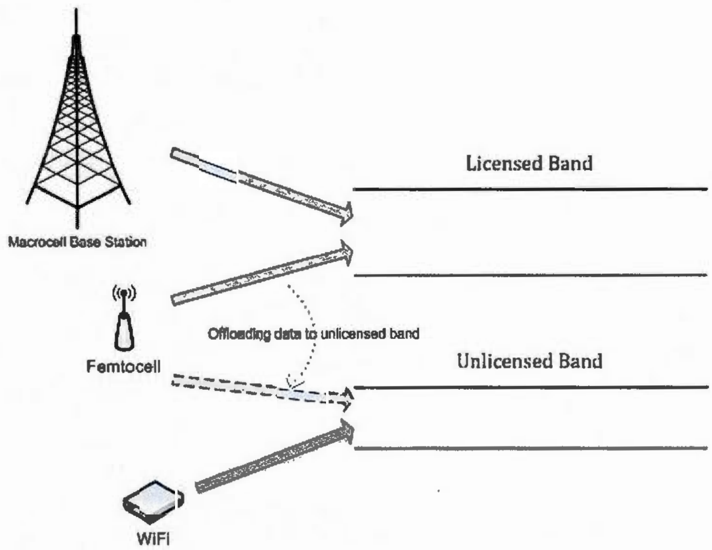


Figure 4.1: Macrocell-Femtocell-WiFi Network

the air interface and tune its parameters according to the dynamic behaviour of the network, traffic and channel. The FBS tries to access the channel only at preassigned periodic times. Upon the arrival of an access opportunity, the FBS starts sensing the unlicensed band. If the spectrum is idle for a predefined time, the FBS would access the channel and may use it for a fixed period.

The first step in this study is to model a back-off mechanism for WiFi network to obtain the probability of channel being in idle state (not being occupied by WiFi). It is the probability that the time of an FBS channel access attempt is within a WiFi idle period. As Femtocell and WiFi devices have the same priority to access the unlicensed bands, it can adjust its channel usage and the impact on WiFi users by tuning its channel access parameters and therefore achieving a friendly coexistence with WiFi users. Therefore, in section 4.2, an FBS channel access model has been proposed and developed. The following assumptions are considered in our analytical model:

- The number of WiFi nodes is greater than one.
- All nodes (WiFi and Femto) have infinitely backlogged data to transmit.
- WiFi transmissions have no channel errors .
- A WiFi transmission fails when it collides with either WiFi or Femto transmissions.
- All WiFi stations transmit at the same data rate defined by the 802.11 standard.

4.1 WiFi Backoff Model

The core contribution of this chapter is the analytical evaluation of the saturation throughput, under the assumption of ideal channel conditions. In the analysis, we assume a fixed number of stations which always have packets for transmission. In other words, we consider a saturation condition which means the transmission queue of each station is always nonempty. Then, by studying the events that can happen within a generic time slot, we calculate the throughput of RTS/CTS access methods.

Our proposed WiFi backoff mechanism is associated with the exponential backoff mechanism of the 802.11 MAC protocol. The contention window (CW) takes an initial value of CW_{min}, and every unsuccessful attempt to transmit a frame increments CW (as $CW_i = 2CW_{i-1}$) until it reaches the value of CW_{max}. In our model we consider no retransmission limit and hence, CW can be reset to CW_{min} just after every successful transmission. The value of the backoff counter is uniformly chosen in the range [0, W_{i-1}], where $W_i= 2^iW$ with W = CW_{min}. With reference to details of backoff mechanism of IEEE 802.11 (Tickoo and Sikdar,

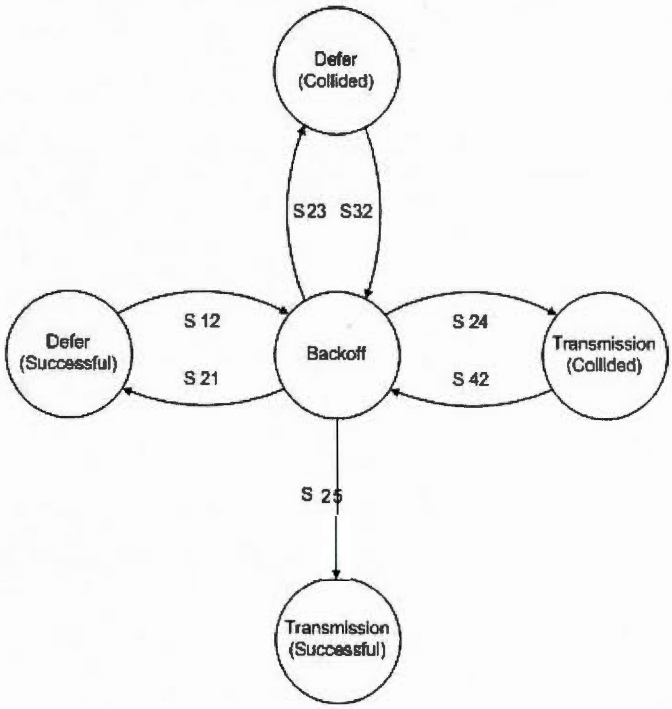


Figure 4.2: WiFi transition states

2003). With reference to (Tickoo and Sikdar, 2004a)(Tickoo and Sikdar, 2004b), the average backoff window would be:

$$\bar{W} = \frac{W[1 - P - P(2P)^n]}{2 - 4P} \tag{4.1}$$

where $n = log_2(CW_{max}/CW_{min})$.

To find the value of P, it is sufficient to note that the probability that a transmitted packet encounters a collision is equal to the probability that, in a time slot, at least one of the $N - 1$ remaining stations transmit. At steady state, we consider τ as the probability of each remaining station to transmit a packet and P as the probability that transmitted packet collides. P can then be calculated by equation 4.2, where the N shows the number of WiFi base stations.

$$P = 1 - (1 - \tau)^{N-1} \tag{4.2}$$

The fraction of idle channel time in a WiFi network can be obtained by analyzing the WiFi exponential backoff process, as done in Zhu and Niu (2005)Bianchi (2000). By modeling WiFi exponential backoff with Markov Chain, we provide accurate probabilities for a WiFi network being in five transition states: (i) Defer (Successful) when it senses a successful transmission of other stations, (ii) Backoff when it stays in a back-off stage owing to the channel being idle, (iii) Defer (Collided) when it senses a collision occurred due to the simultaneous transmission of more than two stations, (iv) Transmission (Successful) when it is transmitting successfully, and (v) Transmission (Collided) when it transmits but collides due to the characteristics of Markov process (as shown in Fig.4.2). According to the characteristics of Markov process, the spent time in each state is exponentially distributed. Therefore, we assume that both successful and collided transmissions have exponential distributions while WiFi occupies the channel. Moreover, as time slot for backoff is considered constant (20 μsec), the possible error because of exponential distribution is negligible.
If we consider $\tau_0 = \frac{1}{W}$ as the probability that a station transmits in a time slot (successful transmission) , then:

- P_{ds} is the probability that the station senses a successful transmission which occurred in a time slot.

$$P_{ds} = (1 - \tau_0)(N - 1)\tau(1 - \tau)^{N-2} \tag{4.3}$$

- P_{dc} is the probability that the station senses a collided transmission which occurred in a time slot (means at least two stations transmit at the same time slot).

$$P_{dc} = (1 - \tau_0)(1 - (1 - \tau)^{N-1}) - (N - 1)(1 - \tau)^{N-2} \tag{4.4}$$

- P_{idle} is the probability that station is in back-off state for a time slot.

$$P_{idle} = (1 - \tau_0)(1 - \tau)^{N-1} \tag{4.5}$$

- P_{tc} is the probability that the station transmits but collides.

$$P_{tc} = \tau_0(1 - (1 - \tau)^{N-1}) \tag{4.6}$$

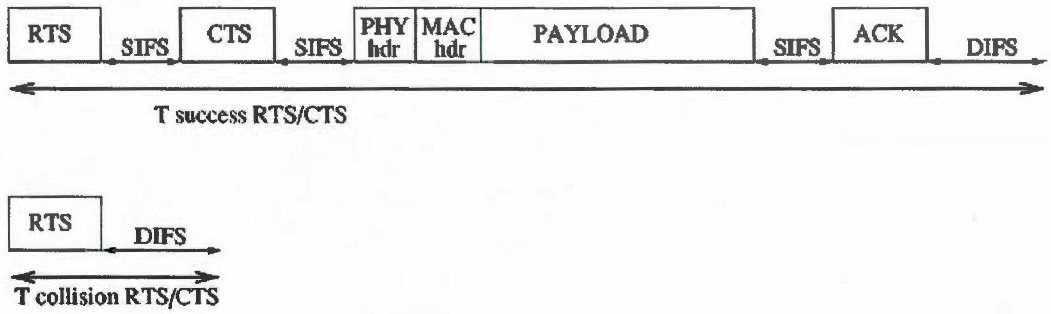


Figure 4.3: T_{trans} and $T_{collision}$ for RTS/CTS mechanisms

- P_{ts} is the probability that the station transmits successfully in a time slot

$$P_{ts} = \tau_0(1-\tau)^{N-1} \tag{4.7}$$

Let us now consider a system in which each packet is transmitted by means of the RTS/CTS access mechanism. In such a case, collision can occur only at RTS frames (see Fig. 4.3).

Therefore,

$$\begin{aligned} T_{trans} =& RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta \\ &+ ACK + DIFS + \delta \\ T_{collision} =& RTS + DIFS \end{aligned} \tag{4.8}$$

where δ is the propagation delay, $H = PHY_{hdr} + MAC_{hdr}$ is the packet header, and $E[P]$ is the average length of packet. The analytical model presented above is convenient to determine the maximum achievable saturation throughput, S as:

$$S = \frac{E[p]}{T_{trans} - T_{collision} + \frac{\frac{T_{idle}(1-P_{ts})}{P_{ts}+T_{collision}}}{P_{idle}}} \tag{4.9}$$

where $E[P]$ is the payload information transmitted in a time slot.

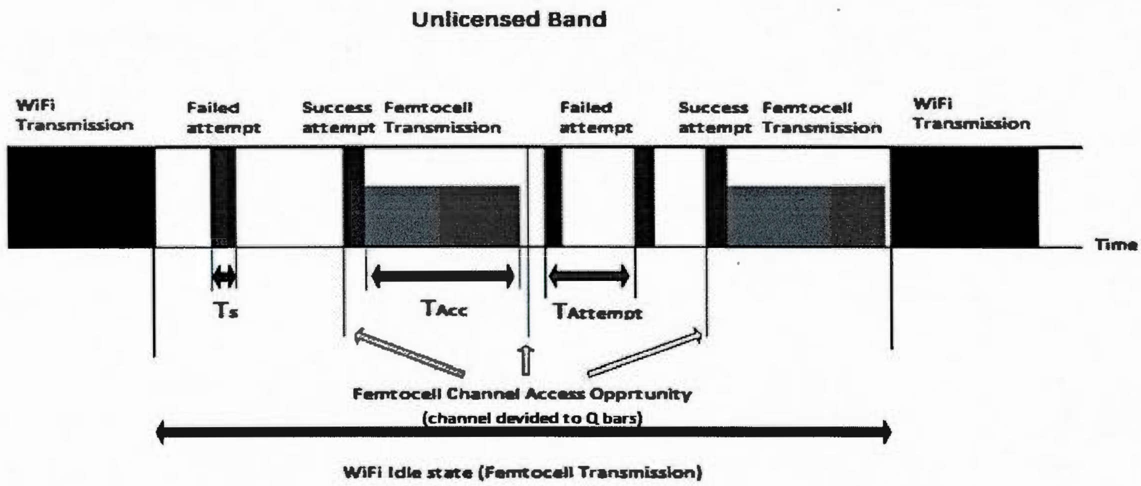


Figure 4.4: Femtocell Channel Access Model

4.2 Femtocell Access Model

In this co-existing model, FBS finds the channel in two states of transition: idle and non-idle. FBS senses the channel for a duration T_s to access the channel. If FBS finds the channel idle, it will attempt to occupy the channel for the fixed duration of T_{Acc} (Fig. 4.4). In addition, after FBS uses the channel for T_{Acc}, it is not allowed to access it consecutively. It should wait at least $T_{attempt}$ in between other unlicensed band users' attempts before it tries for a next channel access opportunity. Three key parameters governing the proposed channel access mechanism are ordered as follows:

- T_s: Channel Sensing Duration
- $T_{attempt}$: Channel Access Opportunity
- T_{Acc}: Transmission Duration

The sensing and transmission duration have been considered constant for FBS in our framework.

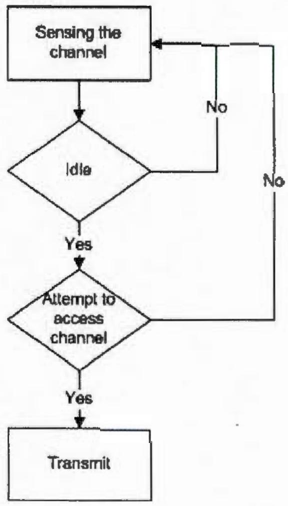


Figure 4.5: Femtocell channel access

The idle state is divided to Q idle time slots ($Q = 1, 2, \ldots$) with the probability of P_{idle}^{Q} (1-P_{idle}) and duration of QT_{idle}. In order to satisfy the condition of successful FBS channel access, the attempt must occur within a period where all WiFi nodes are idle. Therefore, to guarantee this condition, we define G as the fraction of time that channel is idle out of all WiFi channel times.

$$G = \frac{P_{idle}T_{idle}}{(P_{ds} + P_{ts})T_{trans} + (P_{dc} + P_{tc})T_{collision} + P_{idle}T_{idle}} \tag{4.10}$$

Therefore, G is just the probability that an FBS attempt happens within a WiFi idle channel period. The length of the period and the relative location of the attempt time in the WiFi idle channel period are random and these factors cannot be disregarded. For example, if $QT_{idle} \geq T_s$ and the attempt time happens in the first $\frac{QT_{idle}-T_s}{QT_{idle}}$ portion of the WiFi idle channel period, the FBS will find that the channel is idle during the following T_s channel sensing time and the attempt will be successful. The conditional probability of successful channel occupancy by the FBS is $\frac{QT_{idle}-T_s}{QT_{idle}}$, if we consider the start time of the FBS access attempt to be within T_{idle} period with $Q(Q \geq \lceil \frac{T_s}{T_{idle}} \rceil)$ time slots (see Fig. 4.4).

Consequently, we can say that if an FBS attempts to access the channel within a WiFi idle channel period, the conditional probability that it successfully obtains the channel is:

$$P_{SuccAcc} = G.P'_{SuccAcc}$$
$$P'_{SuccAcc} = \sum_{L=L_0}^{\infty} P_{idle}^{Q}(1 - P_{idle})\frac{QT_{idle} - T_s}{QT_{idle}} \tag{4.11}$$

where $L_0 = \lceil \frac{T_s}{T_{idle}} \rceil$.

4.3 Network Performance Evaluation

The states of WiFi and Femtocell networks are coupled with each other through the $P_{SuccAcc}$, the probability that an FBS successfully gets the channel in a channel access attempt. The whole network analysis is comprised of the following parts:

- Deriving $P_{SuccAcc}$ by modeling the exponential backoff mechanism of WiFi nodes with a Markov chain.
- Deriving a Femtocell performance by measuring S_{Femto} which is the fraction of channel time occupied by the Femtocell.
- Deriving WiFi network throughput in terms of S_{Femto} and WiFi parameters.

4.3.1 Femtocell Performance Evaluation

The states of WiFi and Femtocell networks are tightly linked together with a key parameter $P_{SuccAcc}$, the probability that the FBS successfully obtains the channel in a channel access attempt. The FBS attempts to access the channel by sensing the carrier. If the channel successfully gets occupied considering the above conditions, the FBS transmits for a fixed duration T_{Acc}. If the attempt is not successful, it will attempt again after a random time of $T_{Attempt}$. The $T_{Attempt}$ will be considered randomly to give the FBS more access opportunity

Parameters	Values
RTS	160 bits
CTS	112 bits
δ	1
SIFS	10 μsec
DIFS	30 μsec
Mean packet length	512,1024 bytes
time slot	20 μsec

Table 4.1: Values of Analytical Model Parameters

while the channel is in idle state. The success probability for each attempt is $P_{SuccAcc}$ and $1/P_{SuccAcc}$ attempts are required in average for the FBS to successfully senses it for the fixed time of T_s to get the channel and obtain it for a fixed duration of T_{Acc}. Therefore, the fraction of channel time occupied by the Femtocell showing the performance of Femtocell is:

$$S_{Femto} = \frac{T_{Acc}}{(\frac{1}{P_{SuccAcc}})T_{Attempt} + T_{Acc} + T_s} \tag{4.12}$$

4.3.2 WiFi Performance

Our earlier given assumptions by the equations (4.9) and (4.10) show that WiFi network has the same fractions of idle, collision, and successful transmission time to calculate the throughput. Also, WiFi throughput is attained by the fraction of time in successful transmission instead of collision or idle. In this case, WiFi would have access to the channel for $(1 - S_{Femto})$ period. The S_{WiFi} as the WiFi (WiFi/Femtocell coexistence) throughput in saturation condition is:

$$S_{WiFi} = (1 - S_{Femto}) \times \frac{P_{idle}T_{idle}E[P]}{(P_{ds} + P_{ts})T_{trans} + (P_{dc} + P_{tc})T_{collision} + P_{idle}T_{idle}} \tag{4.13}$$

Where $E[P]$ is the expected number of bits in the payload of a WiFi packet.

4.4 Analytical Model Evaluation and Results

In this section, we verify our analysis for the co-existence of WiFi/Femtocell in unlicensed bands. In our analytical model, we have just considered the performance of Femtocell in unlicensed bands and do not investigate its cellular performance in licensed bands. The system parameters for the analytical model are summarized in Table 4.1.

We study the impact of λ and τ on WiFi and Femtocell performances where τ designates the probability of our network being busy by WiFi stations and λ is a key factor of FBS channel access opportunity ($T_{Attempt} = 1/\ \lambda$). As predicted by equation 4.12, Femtocell performance S_{Femto} is an increasing function of $T_{Attempt}$ and consequently a decreasing function of λ (as T_{Acc} and T_s have constant value). Equation 4.13 suggests that WiFi performance degrades as Femtocell performance improves. It is an obvious consequence of the channel contention between WiFi and Femtocell. Following results indicate that different λ values lead to the same WiFi throughput and Femtocell channel usages. This demonstrates that λ is the main Femtocell parameter that impacts WiFi and Femtocell performance. In our model, we assume that WiFi network consists of 9 WiFi stations co-existing with one Femtocell. The WiFi RTS/CTS is enabled and all transmitters can sense each other.

Figure 4.7 shows the performance of WiFi and Femtocell for different values of τ and λ. Figure 4.6 shows the importance of factor λ when both WiFi and Femtocell have equal chances of using the channel. Results in Figures 4.6, 4.7 and 4.8 indicate that our model gives priority to Femtocell while keeping the effect of this co-existence at a low level. Figures 4.9, 4.10, 4.11 illustrate that even by increasing the number of WiFi stations, the performance of Femtocell is kept at an acceptable rate.

4.5 Conclusion

This chapter proposes a framework for co-existence of Femtocell and WiFi to access the unlicensed band under a single radio access technology. In this method, we try to improve Femtocell performance while provisioning its interference with WiFi users. Analytical results of our scheme show that by tuning and giving priority, the throughput of small cells and utilization of unlicensed spectrum have been improved.

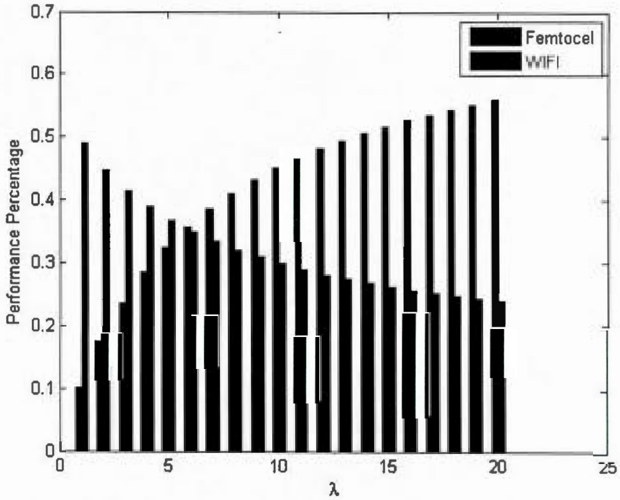


Figure 4.6: WiFi & Femtocell performance for various τ and λ while number of WiFi and Femtocell stations are fixed (where $\tau = 0.3$ & $N = 9$).

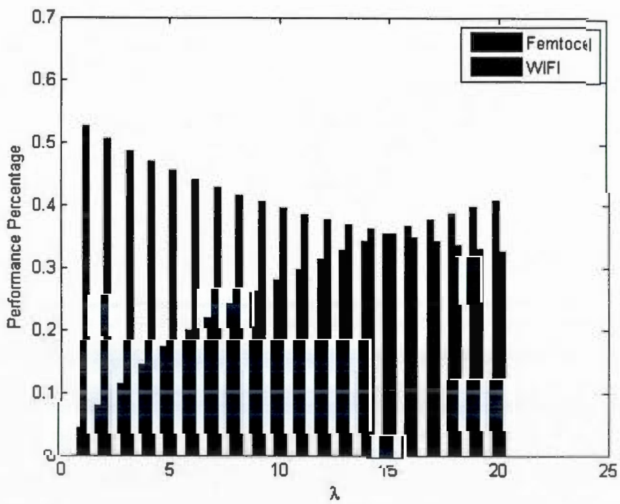


Figure 4.7: WiFi & Femtocell performance for various τ and λ while number of WiFi and Femtocell stations are fixed (where $\tau = 0.5$ & $N = 9$).

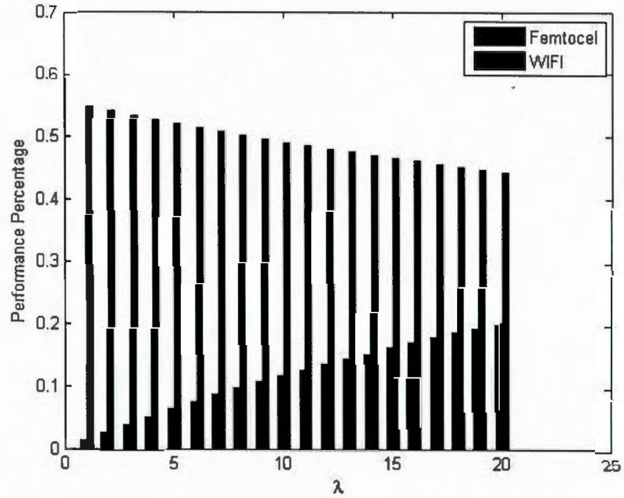


Figure 4.8: WiFi & Femtocell performance for various τ and λ while number of WiFi and Femtocell stations are fixed (where $\tau = 0.7$ & $N = 9$).

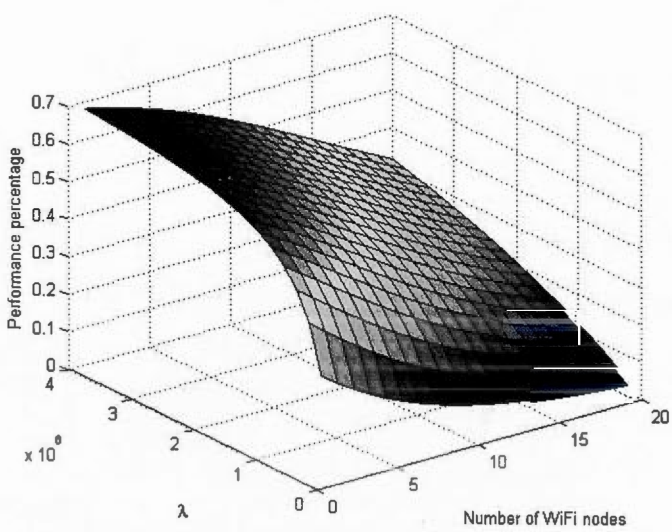


Figure 4.9: Femtocell performance for various τ, λ and number of WiFi stations (where $\tau = 0.3$).

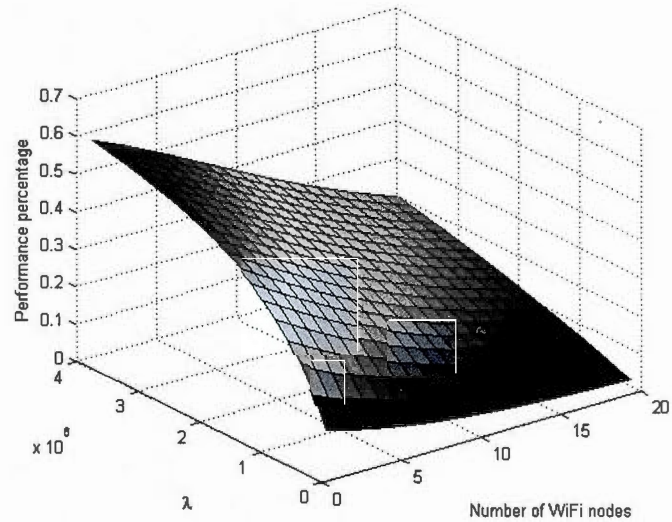


Figure 4.10: Femtocell performance for various τ, λ and number of WiFi stations (where τ = 0.5).

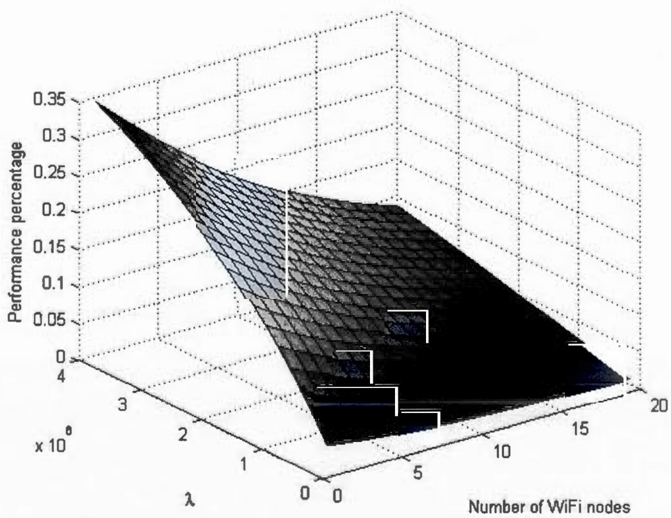


Figure 4.11: Femtocell performance for various τ, λ and number of WiFi stations (where τ = 0.7).

CHAPTER V

CONCLUSION & PERSPECTIVE

To conclude the thesis, the main contributions of this research are:

1- Fairness metrics and QoS satisfaction factor definition and investigation of their measurement methods

This thesis has provided a Fairness metrics and QoS satisfaction factor and investigation of their measurement methods.

2- Investigation and improvement of unlicensed spectrum splitting methods

We have reviewed the existing models of spectrum splitting and based on our achieved fairness and QoS metrics, we proposed a spectrum splitting method. In this thesis, our proposed method has been analyzed and improved upon. In the results, it is shown that proposed scheme improved the total capacity of Femtocells while underlaying with other networks in unlicensed band and also the total capacity of whole system while considering fairness criteria and QoS orientations.

3- Investigation and improvement of WiFi backoff mechanism

In this research, we have conducted extensive studies for investigating the WiFi backoff mechanism. First, unlike other similar studies, we have specifically focused on recent modelling WiFi exponential backoff with Markov Chain. Then, we modeled a scheme which Femtocell can access unlicensed band through calculating the probability of channel not being used by WiFi.

4- Investigation of accurate frame work for Femtocell channel access

We proposed a framework for co-existence of Femtocell and WiFi to access the unlicensed band under a single radio access technology. In this method, we try to improve Femtocell performance while provisioning its interference with WiFi users. Analytical results of our scheme show that by tuning and giving priority, the throughput of small cells and utilization of unlicensed spectrum have been improved.

Considering the current work limitations and the different aspects of Femtocell and WiFi co-existence, we propose three main research directions for future work: (i) The bandwidth limitations should be considered, as the broadband backhaul may not always support such rates, which it could cause limiting the throughput. (ii) Unlicensed spectrum usage by Femtocells, reduces the overall interference to the Macrocell network and potentially improve the overall cell performance. This challenge of offloading has to be balanced against the greater control of handover and interference within a cellular network. (iii) Development of our proposed framework for the Femtocells to assign traffic into both licensed and unlicensed bands to improve and assure Femtocell QoS for end users.

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