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# **Small Cells for Broadband Internet Access in Low-Income Suburban Areas in Emerging Market Environments**

Master's Thesis submitted in partial fulfillment of the degree of Master of Science in Technology

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<p>Mobile broadband technologies are providing the best and most commonly used broadband connectivity in many emerging markets. In some regions such as Africa, mobile networks provide the only feasible ways for extending the socio-economic benefits of broadband Internet access to the masses. The use of small cell technologies, like femtocells provide an attractive solution for such areas as femtocells are most cost – effective option for coverage and capacity expansion. Furthermore, femtocells are operator managed access points which can be easily deployed and operated by the end user.</p> <p>It is well known that increased densification of cell sites is the most effective means for broadband mobile network capacity and coverage enhancements. However, cell densification through adding new macrocell sites by operators is usually a costly option. Therefore, this thesis will investigate methods to achieve mobile broadband capacity and coverage enhancements in low – income informal settlements or slum area, through more cost – effective cell densification using femtocells. Moreover this thesis will validate the performance gains of small cell concept for the case study through extensive simulations.</p> <p>The impacts of femtocell in the network, the performance gain from femtocell and gain provided by different deployment strategies have been studied. Simulation results highlight the potential benefits of using femtocells in the network for extended broadband connectivity. With the femto increment the network performance increases up to a great extent.</p>	
<p><b>Keywords:</b> <i>Small cell, Femtocell, Broadband, Heterogeneous Network (HetNet), WCDMA, HSPA, Home Base station.</i></p> <p><b>Language:</b> English</p>	

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*To my Parents*

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## ABBREVIATIONS

2D	Two Dimensional
2G	Second Generation
3D	Three Dimensional
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACK	Acknowledgement
ACS	Auto-Configuration Server
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
BFF	Broadband Forum
BoD	Bandwidth on Demand
BSC	Base Station Controller
BTS	Base Transceiver Station
CAPEX	Capital Expenditure
CDF	Cumulative Distribution Function
CN	Core Network
CPE	Consumer Premises Equipment
CRC	Cyclic Redundancy Check
CSG	Closed Subscriber Group
CSGID	CSG Identity
CSP	Communications Service Providers
DCH	Dedicated Channel
DL	Downlink
DMP	Dominant Path Model
DS - CDMA	Direct Sequence CDMA
E - DCH	Enhanced Dedicated Channel
EDGE	Enhanced Data rates for GSM Evolution
ESS	Enhanced System Selection
Ev - Do	Evolution Data Only
FAP	Femtocell Access Point
FAP - GW	Femtocell Access Point Gateway
FDD	Frequency Division Duplex
FUE	Femtocell UE
GDP	Gross Domestic Product
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications

GWT	Guided Wave Tracing
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
HLR	Home Location Register
HMS	Home NodeB Management System
HNB	Home Node B
HNB - GW	Home Node B Gateway
HNBAP	HNB Application Part
HS - DPCCH	High Speed Dedicated Physical Control Channel
HS - DSCH	High Speed Downlink Shared Channel
HS - PDSCH	High Speed Physical Shared Channel
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
ICT	Information and Communication Technology
IN	Indoor
IP	Internet Protocol
ISP	Internet Service Provider
LoS	Line-of-Sight
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
ME	Mobile Equipment
MNB	Macro Node B
MS	Mobile Station
MSC	Mobile Switching Center
MUE	Microcellular UE
NACK	Negative Acknowledgement
NGMN	Next Generation Mobile Networks
NLoS	Non Line-of-Sight
NSN	Nokia Siemens Networks
OPEX	Operational Expenditure
OTD	Observed Time Difference
PC	Power Control
PLMN	Public Land mobile network
PoP	Points of Presence
PSC	Primary Scrambling Code
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Pulse Shift Keying
RANAP	Radio Access Network Application Part



RAT	Radio Access Technology
RNC	Radio Network Controller
RRC	Radio Resource Control
RT	Rooftop
RUA	RANAP User Adaptation Part
SDO	Standards Development Organizations
SeGW	Security Gateway
SGSN	Serving GPRS Support Node
SIR	Signal to Interference Ratio
SON	Self - Organizing Network
TDD	Time Division Duplex
TTI	Transmission Time Interval
Tx Power	Transmit Power
UDP	Urban Dominant Path Model
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile telecommunication System
USIM	UMTS Subscriber Identity Module
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
WAP	Wi - Fi Access point
WCDMA	Wideband Code Division Multiple Access
WG	Work Group
WiMAX	Worldwide Interoperability for Microwave Access

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# 1. INTRODUCTION

Use and demand of mobile broadband are growing day by day. So far, the number of mobile broadband subscriptions reached close to 1 billion, and is predicted to reach 5 billion in 2017 [1]. Sooner or later, mobile broadband will be the most attractive solution for affordable broadband internet access.

To meet the future traffic demand with proper quality of service the 3rd Generation Partnership Project (3GPP) introduces broadband mobile internet access based on two Radio Access Technologies (RATs), namely: Wideband Code-Division Multiple Access (WCDMA) and High Speed Packet Access (HSPA). The popularity of these RATs is growing in terms of mobile broadband all over the world. Several interesting features like Home base stations, Self-Organizing Network (SON) and others have been introduced to provide higher data rate at the cell edge to increase the coverage area and thus to enhance the performance of the mobile network. Traditional approach where transmission power is increased to improve the cell edge data rate will also increase the interference in the network. On the other hand approach where the cell size is decreased will increase the number of macro base stations in the network and the deployment costs grow. An advanced idea to build a network by deploying different types of access nodes with different cell size can provide an optimal solution in terms of cost and quality of service.

Considering the Emerging markets, such as Africa, whereby the mobile networks provide the only feasible ways for extending the socio-economic benefits of broadband internet access to the masses [2]. Use of femtocell based network provides an attractive solution for such regions. Femtocells provide cheapest option for expanding the network and can be deployed by the end user.

In fact, already now the third generation (3G) mobile technologies are providing the best and most commonly used broadband connectivity in most emerging markets. Using WCDMA/HSPA, it has already been ramping up the use of internet via mobile handheld devices in most urban centers in Africa [3].

## **1.1. *Motivation and Background***

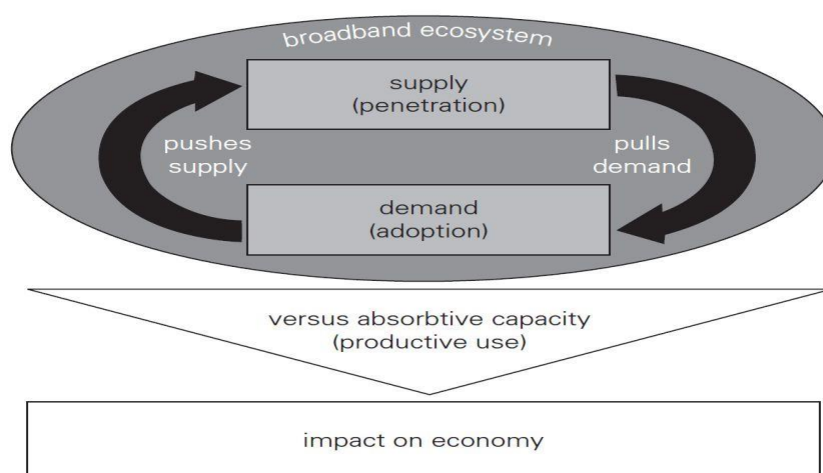
The current focus in many emerging markets is much specified on available affordable broadband [4]. But what is broadband? There is no such specific definition of broadband. Traditional definition focuses on bandwidth and speed. Recent ideas show that broadband cannot be defined with fixed speed or bandwidth as it should also consider the market environment and affordability. From both demand and supply perspective the entire ‘eco-system’ of internet data services should be considered in broadband policy [4]. Yet the demand perspective is not same everywhere, but the in supply perspective the context differs largely. That is, in developed countries availability of fixed line to households is almost complete, on the other hand, in emerging markets it is totally absent. So a more prosper definition for broadband has to be given in terms of capability and not through in the immediate market context, but also taking into account the ability of adapting to the future market with advanced technologies and updated prices [4]. Broadband connectivity has several enabling components like, international connectivity, national connectivity, local connectivity and end user connectivity. In this thesis, end user connectivity is more focused as this is the last mile of broadband connectivity and also the most challenging to implement for a large user base.

### **1.1.1. *Why Broadband?***

Beside Information and Communication Technology (ICT) broadband networks have great impact on the economic growth in both low and high income economics. This connectivity allows higher level of communication and data transfer. It allows access to a wide range of services like, voice, video, education, healthcare and others. So every individuals, firms, companies increase their knowledge and skills through communicating the larger sector of business and technologies via broadband connectivity. In rural areas where broadband has been introduced, the farmers, villagers gained better crop market prices, training and job opportunities. The worldwide accessible information on the internet is making broadband more attractive and beneficial for an economy.

If we consider broadband as ‘eco-system’ the components of the system are ‘Supply’ and ‘Demand’. Figure 1 shows ‘broadband eco-system’ where supply and demand are driven by

each other. When this available connectivity is used productively, it has great a positive impact on the economy. Supply term is the first condition of this eco-system. It has some specific elements also. When the supply is there, it pulls the demand and demand pushes the supply forward. The productive use then has an impressive impact on the economy. For example, a broadband access study in Canada is focusing on the importance of broadband for economic growth over the last few years. In 2005 a study shows that in China, more than 80% of all business respondents reported that if they did not have broadband connectivity, their business would be negatively affected access. 62% reported that broadband increased their productivity to some extent [5]. A study released in December 2010 by Analysis Mason found that each percentage of broadband penetration could increase India's Gross Domestic Product (GDP) by 0.11 percent by 2015 [Analysis Mason 2010].

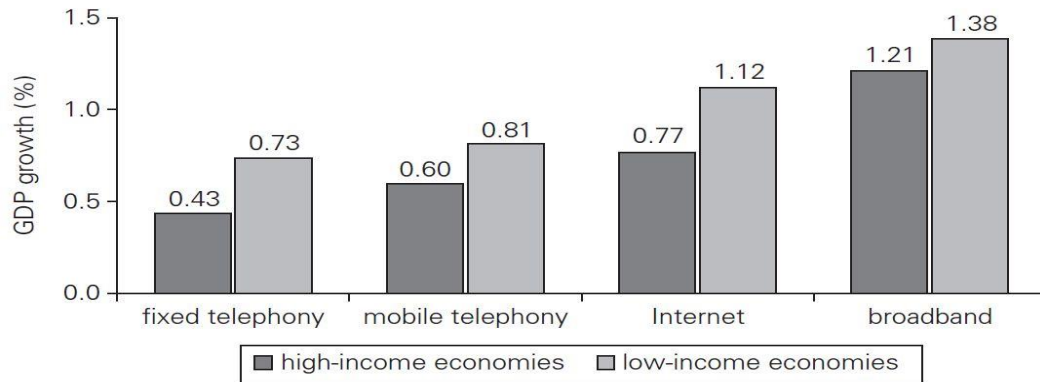


Source: World Bank.

*Figure 1: Broadband eco-system and its impact on economy [5]*

Effect of broadband in GDP growth is more significant for the low-income economy it has an enormous impact. Figure 2 shows the effects of various technologies on GDP growth in both high and low income economies.





Source: Adapted from Qiang and Rossotto 2009, 45.

Figure 2: *Effect of various Information and Communication Technologies on GDP Growth in high- and low-income economies, 2000–06 [5]*

Numerous studies have found the positive impact of broadband on economic growth, the estimate of its actual magnitude varies obviously. A 10% increase in broadband penetration has been found to increase economic growth from a low range of 0.24% to a high of 1.5% [5].

Broadband effect can drive productivity, employment growth, research and development, business, customer relationship, supply chain management, human capital, health and medical improvements. Study shows potential employment gains could result from effective broadband development. This is between 2.5 and 4.0 additional jobs for each broadband job [5]. In education, communication and banking system the broadband effect is so much that it can change the traditional system to worldwide compatible.

#### 1.1.2. **Broadband Access Options**

Usage of broadband is becoming more and more effective. As previously discussed its impact of social economy, importance can be attached as the use of broadband for entertainment and social purpose. Social networking with voice and data services attached with it provides reasons why everyone wants to be connected. But the affordability is different for developed and developing markets. Competition and regulation policy can drive the affordability for low income or developing markets.

Affordability of broadband partly depends on the access policy deployed by the operators and policy by the regulator as well. And this policy varies largely for developed and developing

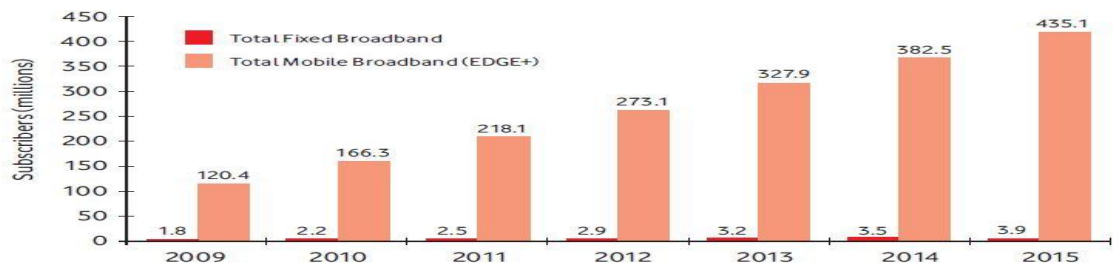
countries. Basic technologies for broadband connectivity are fiber Optic, satellite, microwave, copper wire. In developed countries, operators have installed a fiber line near to the user end and reached directly into the household or office. Due to non-existence or unavailability of fixed broadband connection this is not the case in developing countries. Now making the new infrastructure with wired line in developing countries will be too expensive to be beneficial from operator's point of view. That is why over the next few years wireless broadband is more popular and effective solution for developing countries. Figure 3 shows the comparison of wire line and wireless broadband subscriptions for different regions. The growth of broadband infrastructure partly depends on the broadband enabled devices as well. Every access nodes are improving mobility, portability and capabilities. That is why wireless broadband is already more prevalent than wired line broadband in many developed and developing countries, but to a much greater extent in developing countries, as wire line broadband is not a feasible option there. Figure 4 shows more recent and future prediction for emerging markets.

Region	Wireless	Wireline
Sub-Saharan Africa	2.9	0.3
East Asia and Pacific	16.6	10.5
Eastern Europe and Central Asia	14.5	9.2
European Union and Western Europe	45.9	27.6
Latin America and the Caribbean	12.2	7.1
Middle East and North Africa	13.1	2.5
North America	34.0	24.5
South Asia	1.6	0.8
Global	13.6	8.1

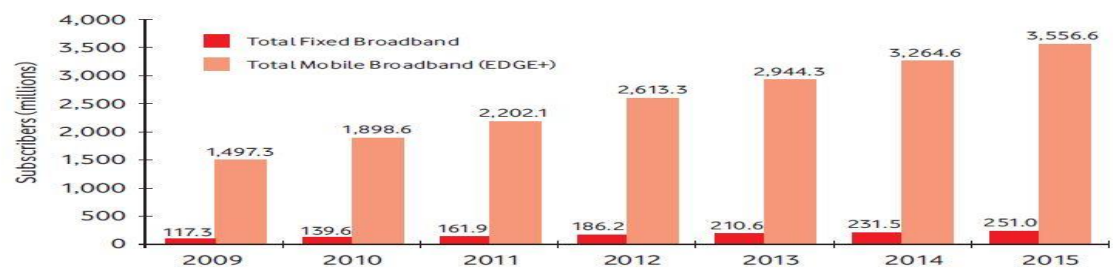
Source: World Bank analysis based on data from TeleGeography's GlobalComms database.

*Figure 3: Wireless and Wireline broadband subscription per 100 inhabitants by Region, June 2011 [5]*

### Sub-Sahara Africa



### Emerging Asia-Pacific



Source: Analysys Mason Fixed Broadband Worldwide Forecast 2009-2015; and Strategy Analytics, Cellular User Forecasts, 2010-2015.

Figure 4: Broadband subscription by access network in two regions [4]

However from a low-income area the expected revenue is not much higher. But still it is considered as a “Coverage Gap” as, it can refund the operational cost but not the initial installation cost [2]. In Africa, there are lots of areas which are not connected to internet service and no upgraded RATs are available there. But these regions can be considered as potential area for future business. That is why current WCDMA/HSPA network deployment in most major urban centers of Africa have led to a significant ramp-up in Internet access via mobile handheld devices. Like, Kenya’s regulator statistics estimated that 99% of users accessed the internet via mobile networks among total 36% of the internet penetration [6]. There are much more countries having more than 50% of potential population (Coverage Gap) out of broadband coverage (Zimbabwe, Eritrea) [2]. And most of the African countries have “coverage gap” more than 20%. Introducing mobile broadband with minimum expenditure in such regions is challenging for operators. A heterogeneous network can be an attractive solution for these regions to bring broadband internet to all. In other words, as the demand of affordable mobile broadband is growing it is driving the deployment of heterogeneous networks (HetNet) [7].

### 1.1.2.1. *Heterogeneous Network (HetNet)*

A network where different types of cells with different cell radius are employed together to provide coverage enabling handoff capabilities between them is known as a Heterogeneous Network (HetNet) [8]. The main purpose of HetNet is to cover the total network properly in a cost efficient manner. To maintain the capacity, quality of service in both indoor and outdoor, HetNet gives efficient solution. There could be two types of HetNet.

- a) **Multi- RAT:** This type of HetNet is deployed with multiple RATs. For example, when Communications Service Providers (CSPs) have an already covered area with WCDMA/HSPA in populated urban areas, they can deploy LTE in hotspots or rural areas to exploit digital dividend. Recent days, using Wi-Fi is very popular option from CSPs point of view in terms of cost, which allows reduction of traffic from 3G/4G networks and use comparatively inexpensive backhaul infrastructure.
- b) **Multi- Layer:** Using the same RAT total network can be deployed with different types of access nodes with different cell sizes. Outdoor deployment can be combined macro cells and pico cells. And indoor terminals can be served by small cells. This type of HetNet deployment is driven by the need for better indoor coverage, traffic demand, and cost and energy efficient consideration. In Chapter 2 detail discussion about small cells are available.

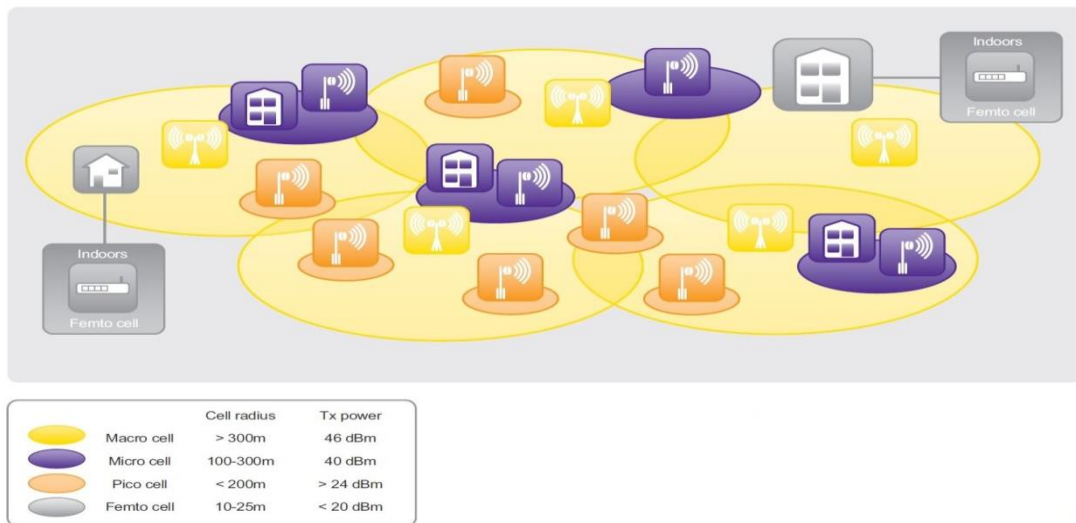


Figure 5: Typical deployment of multi- layer HetNet [9]

### 1.1.2.2. *Other considered network upgrade options*

An optimal network expansion roadmap depends on various parameters and assumptions. Such as, the legacy infrastructure in term of sites, availability or lack of new sites, health regulation issue in terms of maximum authorized emitted power, availability of spectrum, traffic demand, cost related aspects and others. According to these specifications, expansion procedure can be selected. Figure 6 gives a clear idea about some options for network upgrades. Three basic approaches can be pointed out. Existing macro expansion is the easiest way to deploy. Multicarrier and sectorization add more capacity to the existing macro site and expands the coverage to some extent. Outer small cell deployment and offload to indoor are most cost efficient and effective solutions for expansion of network with better capacity and quality of service. Table 1 shows a capacity gain comparison between different expansion techniques.

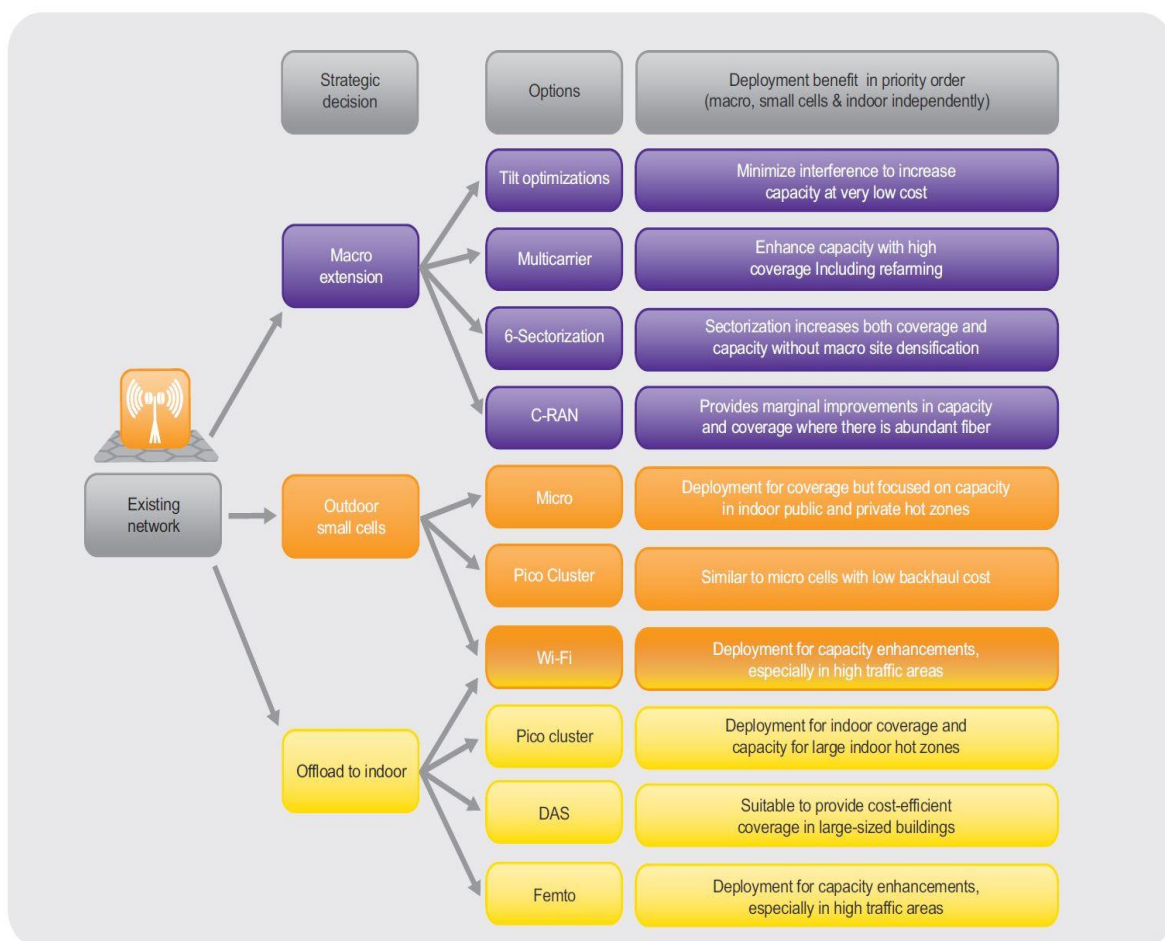


Figure 6: Different options of network upgrade [7]

<b>Techniques</b>	<b>Capacity Gain</b>
Frequency Division	5
Modulation techniques	5
Access to wider range of frequency spectrum	25
Frequency reuse through more cell sites	1600

*Table 1: Network enhancement techniques vs capacity gain [10]*

We can conclude that, frequency reuse through more cells (densification) gives the highest gain compared to other expansion techniques.

### **1.2. Problem Statement**

It is well known that increased densification of cell sites is the most effective means for broadband mobile network capacity and coverage enhancements. However, cell densification is usually costly and increases probability of interference in the network. For low – income areas, the cell densification through operator – deployed macro (and/ or small cell) site is a particularly big challenge from the operators’ cost point of view. Operators cannot expect much revenue from these low – income areas, so they are reluctant to commit excessive investments in those regions. Therefore, this thesis will investigate methods to achieve mobile broadband capacity and coverage enhancements in low – income areas through more cost – effective cell densification.

### **1.3. Objective of the Thesis**

The idea of frequency reuse with small cells or deployment of HetNet gives an attractive solution in terms of capacity, coverage and cost. A network with different types of cells can be deployed to cover the area with lowest expenditure. In this thesis, we will discuss how HetNet can be used for solving the stated problem. The objectives of this thesis are:

- Investigate the feasibility of Small cells as solution for future emerging markets.

- Select a realistic service area that exemplifies a low-income densely populated suburban area for use as a case study in Small cells deployment study.
- Validate the performance gains of Small cell concept for the case study through extensive simulations.

#### 1.4. *Outline of the Thesis*

Chapter 2 gives a total picture of the idea of Small cells along with some basic discussion of air interface used in 3G network (WCDMA/HSPA). For better understanding of the network architecture of 3G femtocell based networks, this chapter also has some discussion of that particular network architecture. Chapter 3 describes the proposed implementation techniques in terms of some basic implementation parameters.

In Chapter 4, the model and methodology for the simulation is described with selected experimental area details, description of the tools and parameter assumptions for the simulation. Chapter 5 describes the detailed result of the experiment and comparison gain between different deployment strategies. Chapter 6 concludes the thesis with mentioning the future research options related to this study.

## 2. SMALL CELL CONCEPT

### 2.1. *Background*

“Small cell” is an umbrella term for low-powered radio access nodes that have a range of 10 meters to several hundred meters and operate in licensed and unlicensed spectrum, whereas typical mobile macrocell might have a range of up to several tens of kilometers. The so called umbrella term covers femtocells, picocells, microcells and metrocells [10]. Small cells provide improved cellular coverage, capacity for homes and enterprises as well as metropolitan and rural public spaces.

***Femtocell:*** Also known as ‘home base station’, is a cellular network access point using residential DSL, cable broadband connections, optical fibers or wireless last-mile technologies to connect standard mobile devices to a mobile operator’s network [11]. In other word, it is a low power, short range, self-optimizing base station. Initially, use of femtocell was described for residential home, but later it expanded to enhance the capacity for rural, metropolitan areas. Very easy to deploy and can be managed by both operator and users.

***Picocell:*** This type of small cell is typical low power base station, used in an enterprise or public indoor areas. Sometimes the term picocell implies outdoor small cell as well [10]. Proper network planning is required to deploy such small cells. Newer picocells are also having the self- optimizing feature like femtocells.

***Microcell:*** To enhance the coverage for both outdoor and indoor where macro coverage is insufficient, microcells are used which are generally short ranged outdoor base stations [10]. Sometimes it can be installed indoor also if the area is out of scope of picocells.

***Metrocell:*** A new term to describe the small cell technologies designed for high capacity metropolitan areas. Metrocells are typically installed on building walls or street furniture [10].



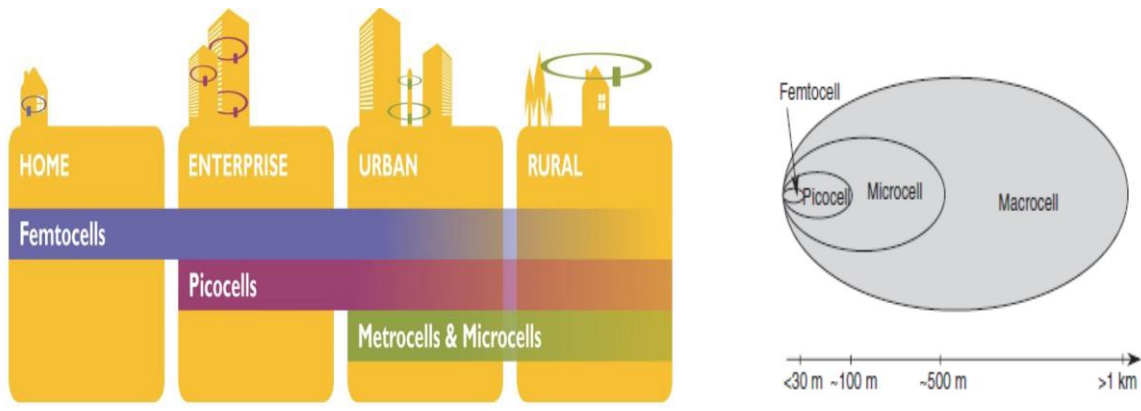


Figure 7: A continuum of applications of small cell technology and cell range comparison [10]

Three main purposes can be concluded for using small cells: coverage expansion, capacity expansion and power saving with minimum expenditure. Several distinct applications for small cell can be concluded as: residential, enterprise, metro areas, public spaces and rural applications.

## 2.2. Focus on Femtocell

The concept of ‘home base station’ was first studied by Bell Labs of Alcatel-Lucent in 1999 [11]. In 2002, Motorola announced first 3G-based home base station product. In February ‘2007 number of companies demonstrated femtocells at the GSM World Congress (Barcelona). Over the last few years the term femtocell has evolved considerably. Now, femtocell technology has evolved to deliver longer range and higher capacity designs while retaining the early benefits of scalability, cost- effectiveness, self-configuration and self-management. That is why, Figure 7 shows femtocell covering the entire scenario. A femtocell access point (FAP) looks like a Wi-Fi Access point (WAP), but it also contains large part of Radio Network Controller (RNC) functions. However, WAP implements Wi-Fi technologies like IEEE 802.11b, 802.11g and 802.11n. On the other hand a FAP implements technologies like UMTS/HSPA/LTE. To a mobile station (MS), FAP appears indistinguishable from traditional base stations as they have all usual overhead channels and are capable of in-band handoffs. Femtocells are now primarily viewed as a cost-effective means of offloading data traffic from the macrocell network. By the start of 2011, an estimated 2.3 million femtocells were already deployed globally, and is expected to reach 50 million by 2014 [12].

Depending on access method, femtocell can be three types. All of them have some advantages and drawbacks.

***Public/Open access Femtocells:*** In enterprise and public spaces this type of femtocell is used. Any user from the host network can connect to these femtocells for better quality of services. Sometime, residential femtocells are also public access. An outdoor user might get stronger signal from the femtocell than from a distant macrocell. With public access femtocell those outdoor users also can connect to the residential femtocell. This is beneficial for the outdoor users but not for the owner of the femtocell as sometime the unwanted user uses the full capacity and prevents access from the owner.

***Private/Closed access Femtocells:*** Residential femtocells are generally designed with a closed access model [10]. With this method, only a list or registered users can access the femtocell and the list is defined by the owner of a femtocell. This avoids potential abuse by uninvited or unknown users in the area. But this type of approach increases the interference in the network [11]. If passing outdoor user gets low signal from the macrocell, will increase their power and produce interference with the neighbor femtocell.

***Hybrid class Femtocells:*** It is clear that public access is suitable for non-home scenario. But the study [13] shows that home users would prefer the closed access method as they are paying for the femtocell and the backhaul connection. But it might create a small number of situations that can affect the service of non-femto user, so a more sophisticated method can be used for residential femtocells. This sophisticated method gives priority to the listed users, but still allows open access to anyone for the remaining capacity. It can be considered as a hybrid method with combining the benefit of both the access methods.

### ***2.3. Standardization of Femtocell Technologies***

For any new technology, industry standardization is a very important factor from both the market acceptance and economy of scale perspective. From service aspects, femtocell can meet the solutions for a macrocell - based network, ensuring good indoor signal quality and low number of simultaneous users per cell. With minimum expenditure femtocell deployment will lead to uptake of true 3G service. So standardizing of the key features of femtocells were very necessary, most notably the mobile operators [14]. Besides, femtocell has its own set of

problems like radio interference mitigation, regulatory aspects, location detection. So, technical solutions for these problems should be addressed for real deployment of femtocell.

3GPP started femtocell feasibility study in March 2007. However, in 2008 when Femto Forum (now known as Small Cell Forum) started discussing femto architecture, there were 15 different variations [15]. It was necessary to come to a single architecture to make the product successful. In May 2008 members of Femto Forum came to a single architecture. 3GPP release 8 described the feasibility of femtocell and basic network architecture. Femtocell network architecture according to 3GPP standards is discussed detail in section 2.5.1.

Standards Development Organizations (SDOs) that are shaping standard for femto technology are: 3rd Generation Partnership Project (3GPP), 3rd Generation Partnership Project 2 (3GPP2), and Broadband Forum (BFF) with industry alliances: Small Cell Forum and Next Generation Mobile Networks (NGMN).

In 1999, along with the partnership among SDOs around the world 3GPP (<http://www.3gpp.org>) was created to assemble the worldwide 3G (3<sup>rd</sup> Generation) WCDMA standardizations. It created Universal Mobile Telecommunication System (UMTS) evolved from Global System for Mobile communication (GSM). For 3G and beyond, it defined HSPA to enhance both Downlink (DL) and Uplink (UL) capacity. WCDMA and HSPA are discussed more detail in section 2.4. 3GPP actually standardized UMTS based 3G femto technology. It discussed about *architecture and terminology, radio and minimum performance aspects, circuit and packet services, security aspects, Quality of Service (QoS), management, handover* and so on. In 3GPP specific terminologies are used for the femtocell. Table 2 shows terminology definitions for 3G femtocell.

In 1999, 3GPP2 (<http://www.3gpp2.org>) was created to facilitate the standardization of Code-Division Multiple Access (CDMA) based radio technology for cellular communication as a partnership among SDOs from the United States, Korea and Japan [16]. In the following years, 3GPP2 added SDO membership from China and market representation partnership with organizations like Small Cell Forum. 3GPP2 standardized femto technology based on cdma2000 air interface. It defined some new terminology and objectives to make femto technology available for cdma2000.

<b>3GPP terminology</b>	<b>Generic terminology</b>	<b>Definition</b>
HNB (Home NodeB)	Femtocell	The consumer premises equipment (CPE) device that functions as the small-scale nodeB by interfacing to the handset over the standard air interface (Uu) and connecting to the mobile network over the Iuh interface.
HNB-GW (Home NodeB Gateway)	FAP-GW	The network element that directly terminates the Iuh interface with the HNB and the existing IuCS and IuPS interface with the CN. It effectively aggregates a large number of HNBs and presents it as a single IuCS/PS interface to the CN.
HMS (Home NodeB Management System)	ACS (Auto-Configuration Server)	The network element that terminates TR-069 with the HNB to handle the remote management of a large number of HNBs.

*Table 2: 3G femtocell terminologies*

It stated FAP as a CPE that includes cdma2000 radio elements with base stations for cdma2000 1x and/or access network for cmda2000 EV-DO services. It is possible to define new enhancements to the cmda2000 1x and EV-DO air interface specifications to permit future mobile devices to operate even more efficiently with femtocells. 3GPP2 defined enhancement to 1x air interface to optimize and simplify the use of Enhanced System Selection (ESS). Like 3GPP, 3GPP2 also discussed about *architecture and terminology, radio and minimum performance aspects, circuit and packet services, security aspects, Quality of Service (QoS), management, handover* and others.

Until 2008, BFF was called as DSL Forum. It is a SDO which created specifications mainly for DSL related technologies to meet the needs for fixed broadband technologies. Along with

the other Working Groups (WG) the Broadband Home WG is particularly responsible for CPE specification.

Small Cell Forum, formerly known as the Femto Forum, supports the wide-scale adoption of small cells [<http://www.smallcellforum.org>]. It is not-for-profit, international membership organization that allows membership for providers of small cell technology and for operators with spectrum licenses for providing mobile services. With 137 members, Small Cell Forum is working on to promote the rapid creation of appropriate open standards and interoperability for small cells. From the beginning of small cells idea, this forum is working with it. Though it is not a standard setting body, but works with standards organization and regulators worldwide to provide an aggregated view of the small cell market.

## **2.4. *Radio Access technologies (RATs)***

WCDMA (Wideband Code Division Multiple Access) is the most commonly adopted radio interface in 3G UMTS (Universal Mobile telecommunication System) networks. UMTS and WCDMA are widely described in 3GPP specifications. To enhance the performance of WCDMA, 3GPP introduced HSPA (High Speed Packet Access) on their later releases. In this thesis deployment of 3G femtocell is focused, so as radio interface WCDMA/HSPA was used. This section gives a total review about WCDMA and HSPA for better understanding to the reader.

### **2.4.1. *UMTS Radio access network architecture***

#### **2.4.1.1. *Network Elements***

UMTS system architecture has the similar architecture that has been used in the second generation system. UMTS system consist of a number of logical network elements that each has a defined functionality [17]. Functionally the network elements are grouped into Radio Access Network (RAN/UTRAN) that handles radio-related functionalities, Core Network (CN) that is responsible for switching and routing calls and data connections to external networks, User Equipment (UE) that interfaces with the user. To make the new technology deployment easier and cost effective, the CN part is adopted from the second generation GSM system. But from specification and standardization point of view, UE and UTRAN are different from second generation architecture.

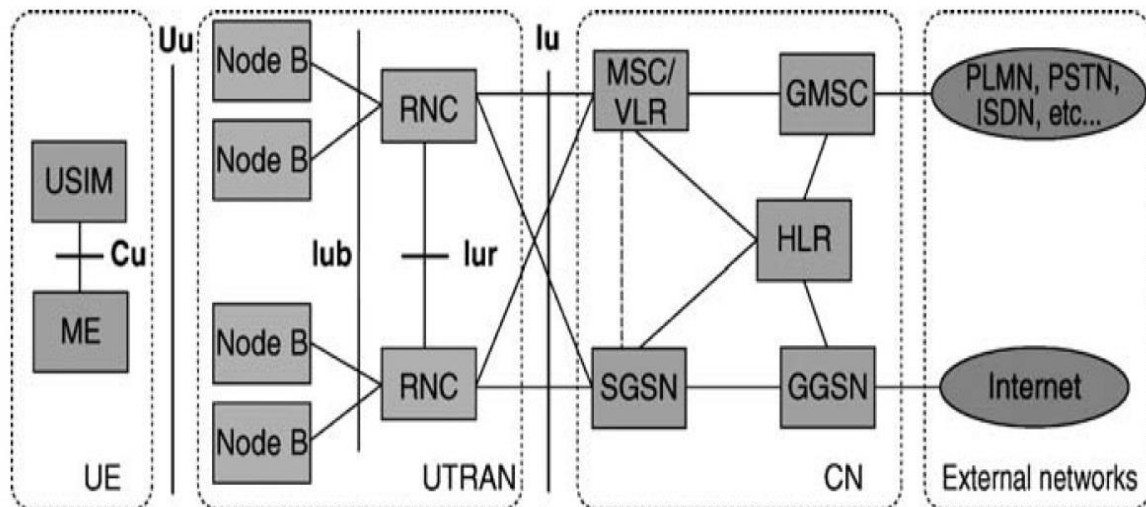


Figure 8: Network elements in WCDMA based PLMN [17]

#### 2.4.1.1.1. UE

UE is the user terminal. UE connects to the base station (known as NodeB) via Uu interface.

UE consists of two parts;

- Mobile Equipment (ME)
- UMTS Subscriber Identity Module (USIM) is smart card that holds the subscriber identity.

#### 2.4.1.1.2. UTRAN

UTRAN is also consists of two distinct elements;

- NodeB (Base Station), it handles and manages the traffic between Uu and Iub interfaces. It also participates in radio resource management.
- Radio Network Controller (RNC) controls radio resources of NodeB's in its operational area. It is the service access point for all services that UTRAN provides the CN. RNC terminates RRC (Radio Resource Control) protocol that defines the message and procedures between the mobile and UTRAN. RNC logically corresponds to the GSM BSC.

#### **2.4.1.1.3. CN**

UMTS CN, have the same elements of GSM CN like, Home Location Register (HLR), Mobile Services Switching Center/ Visitor Location Register (MSC/VLR), Gateway MSC (GMSC), Serving General Packet Radio Service (GPRS) Support Node (SGSN), Gateway GPRS Support Node (GGSN).

#### **2.4.1.2. Interfaces**

UMTS standards defined interfaces between the logical network elements as open interfaces. When the interface is 'open' the equipment at the endpoints can be from two different manufacturers.

- *Cu interface*: The interface between USIM and ME.
- *Uu interface*: WCDMA radio interface. Through this interface UE accesses to the fixed part of the system.
- *Iu interface*: It connects the UTRAN with CN.
- *Iur interface*: Interfaces to connect one RNC to another.
- *Iub interface*: The interface between NodeB and RNC.

#### **2.4.2. WCDMA**

WCDMA is based on Code Division Multiple Access (CDMA) technique where users share the same frequency and time plane. In CDMA, instead of time or frequency, user entities are identified from each other by using codes. WCDMA is a wideband Direct-Sequence Code Division Multiple Access (DS-CDMA) [17]. The chip rate of 3.84Mcps leads to a carrier bandwidth of approximately 5Mhz. WCDMA supports highly variable user data rates; in other words, the concept of obtaining bandwidth on Demand (BoD) is well supported. It supports two basic modes of operation: Frequency Division Duplex (FDD) and Time Division Duplex (TDD). And also, WCDMA is designed to be deployed in conjunction with GSM, so handovers between GSM and WCDMA are supported.

Multiple access method	DS-CDMA
Duplexing method	FDD/TDD
Base station synchronization	Asynchronous operation
Chip rate	3.84Mcps
Frame length	10ms
Service multiplexing	Multiple services with different quality requirements multiplexed on one connection
Multirate concept	Variable spreading factor and multicode
Detection	Coherent using pilot symbols or common pilot
Multiuser detection, smart antennas	Supported by the standard, optional in the implementation

Table 3: Main WCDMA parameters

Usage of codes in WCDMA is two-folds: Spreading (Channelization codes are used to spread the information signal) and scrambling codes are used on top of spreading codes to identify different sources from each other. In Uplink transmission path, Spreading codes are used to separate data and control of a user and scrambling codes are used for separate different users.



Figure 9: Uplink transmission path

In Downlink transmission path users in a cell are separated by orthogonal spreading codes (channelization code), and cells are separated by scrambling codes.



Figure 10: Downlink transmission path



#### 2.4.2.1. *Spreading and Despreading*

In WCDMA the information signal is spread over the whole frequency band. Spreading is done using orthogonal codes. This makes the transmission secure and robust against interference as well. The codes remain orthogonal if the synchronization is perfect. Multipath fading will reduce the orthogonality. Spreading provides processing gain.

Figure 11 shows basic operations of spreading and despreading. The example is taken from [17]. User data is assumed to be a BPSK-modulated bit sequence of rate  $R$ , the user data bits assuming the values of  $\pm 1$ . Multiplication of each user data bit with a sequence of 8 code bits is the spreading operation. So, in this case we can say used spreading factor is 8. And the resulting signal (Spread signal = Data  $\times$  Code) is a wideband signal which is transmitted across wireless channel.

In despreading operation, the spread user data is multiplied bit duration by bit duration with the very same 8 code chips as was used during the spreading of these bits. And the original signal is regained, as shown in the Figure 11.

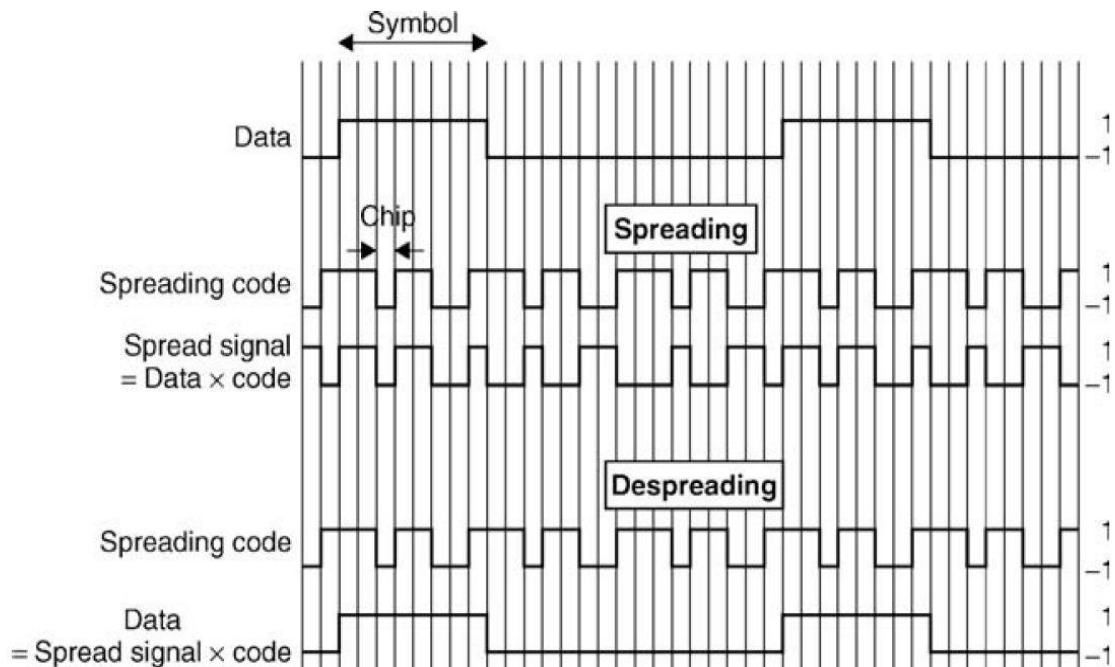


Figure 11: Spreading and despreading operation in DS-CDMA [17]

#### 2.4.2.2. *Multipath Radio Channels and Rake Reception*

Due to natural obstacles like buildings, hills, and so on multiple reflections, diffractions the attenuation of the signal energy occurs. This multipath propagation leads to reception of signals with different magnitude and time-of-arrival in the receiver. These different signals are known as multipath components, and create multipath fading. Each multipath component contains original information and all components can be added coherently (if the magnitude and time-of-arrival is known) to get the original signal.

RAKE receiver is designed to counter the effects of multipath fading. If the time difference between multipath components is larger than the chip rate time, the receiver can separate those multipath components and combine. It uses several fingers to catch individual multipath component. Then component signals from different fingers are combined coherently for the sum signal that is used in the decoding.

#### 2.4.2.3. *Scrambling*

Scrambling codes are used on top of spreading, and used to separate users in uplink and cells in downlink. It does not change the signal bandwidth. In downlink scrambling codes are allocated in network planning phase.

	<b>Spreading Code</b>	<b>Scrambling Code</b>
Usage	UL: Separation of control and data from the same user DL: Separation of connections within a cell	UL: Separation of users DL: Separation of cells
Length	UL: 4-256 chips DL: 4-512 chips Code length defines symbol rate	UL: 38400 chips = 10ms = frame length DL: 38400 chips = 10ms = frame length
Bandwidth	Increases transmission bandwidth	No impact to transmission bandwidth

Table 4: Spreading and scrambling summary

#### 2.4.2.4. *Power Control*

Power control (PC) is one of the key features included in WCDMA. The purpose of PC is to ensure that each user receives and transmits just enough energy to prevent blocking of distant user (near-far-effect) and exceeding reasonable interference level. PC helps to maintain the link quality in UL and DL also minimizes the effects of fast and shadow fading. Besides, accurate PC is very important in WCDMA as no time-frequency separation of users (all use the same bandwidth) and inaccurate PC can lift up the interference level in the network.

In WCDMA, Open loop power control is used to provide initial power control setting of the mobile station at the beginning of the connection. As in WCDMA FDD system, there is large frequency separation between uplink and downlink, so the fast fading is essentially uncorrelated [17]. So, after establishment of connection open loop power control is not accurate anymore. Then fast closed loop power control steps in. In the uplink, according to closed loop power control base station performs frequent estimation of received Signal-to-interference Ratio (SIR) and compares with the target SIR. If measured SIR is higher than target SIR, base station commands the mobile station to lower its power. If the measured SIR is lower, base station commands the mobile station to higher its power. This measure-command-react cycle is executed at a rate of 1500 times per second [17]. That's why it is called fast power control. In downlink, same closed loop power control is used. As it's a one-to-many scenario, so there is no near-far problem, but the cell edge users are expected to get additional power as they suffer from other-cell interference. And also weak signals due to Rayleigh fading are desired to be enhanced by additional power.

Another control loop is connected to closed loop power control, is outer loop power control. Outer loop power control is typically implemented by having the base station tag each uplink user data frame with a frame readability indicator, such as a Cyclic Redundancy Check (CRC) [17]. According to this control method, RNC commands the base station to lower or higher the target SIR based on frame indicator.

Uplink power control increases the number connections that can be served with the required QoS. It reduces both the interference and the total amount of radiated power in the network.

Whereas, downlink power control minimizes the transmission power of the NodeB and compensates for channel fading which maximizes the downlink capacity.

#### 2.4.2.5. **WCDMA Handover**

There are four main categories of handovers in WCDMA.

- *Inter-system Handover*: Handover to another system, e.g. UMTS to GSM.
- *Intra-system Handover*: Handover in same system, e.g. UMTS to UMTS.

Intra-system Handover can be two different types:

- *Intra-frequency Handover*: A handover procedure within the same system and same frequency.
- *Inter-frequency Handover*: A handover procedure within the same system but different frequency.

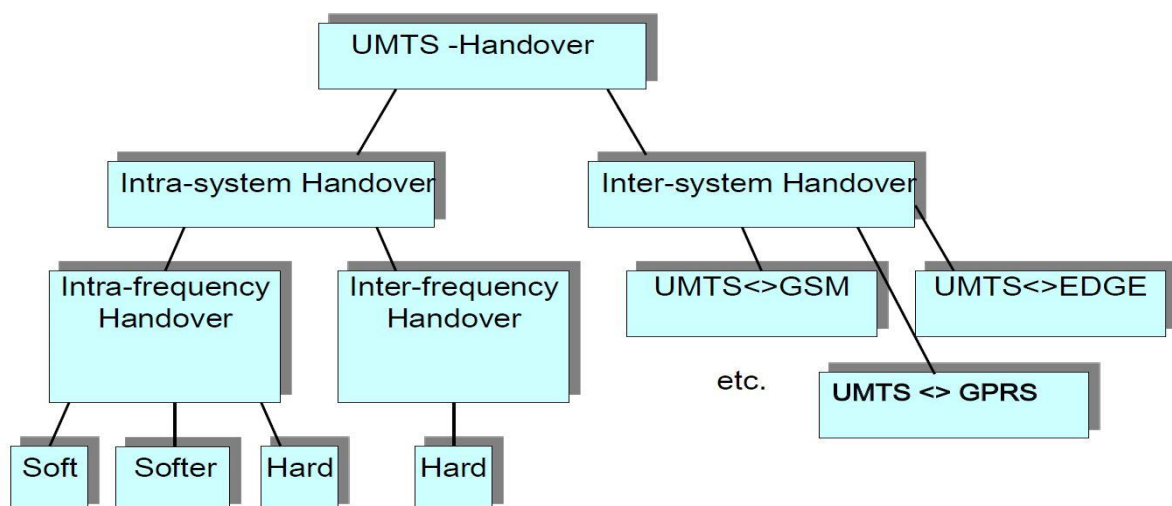


Figure 12: Handover types in WCDMA

Intra-frequency handover can be three types:

- *Soft*: MS is simultaneously controlled by two or more cells belonging to different BTS of the same RNC or to different RNC.
- *Softer*: MS is controlled by at least two cells under one BTS

- *Hard*: Before establishing new radio link, all the old radio links are released. It causes shoort disconnection is transmission, but a lossless procedure.

For Soft and Softer handover, MS always keeps at least one radio link to UTRAN. Handover can be either UE or network initiated.

### 2.4.3. *HSPA*

High Speed Downlink Packet Access (HSDPA) was introduced by 3GPP in release 5 in March 2002. High Speed Uplink Packet Access (HSUPA) was part of release 6 in December 2004. HSDPA and HSUPA are together called HSPA.

HSPA was originally conceived to achieve higher capacities and coverage for non-real time traffic with high transmission rate requirement. With some new features (discussed on section 2.4.3.1) those requirements were achieved as HSPA pushes the data rate up to 1-2Mbps in practice and even beyond 3Mbps in good conditions. Besides, HSPA also reduces the latency to below 100 ms, the end user experienced performance is similar to the fixed line DSL connections.

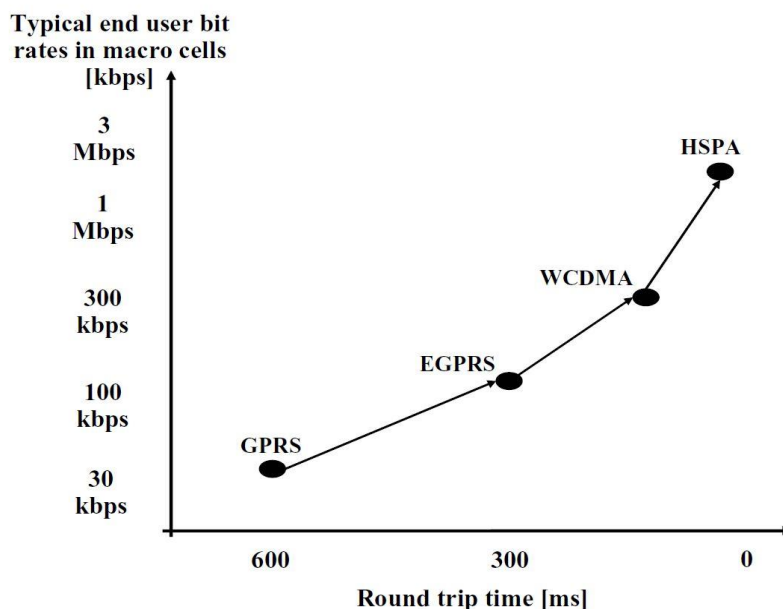


Figure 13: Radio capability evolution [18]

HSPA is deployed on top of the WCDMA network either on same or on different carrier frequency. HSPA and WCDMA can share all the network elements in the core and radio network. Obviously the upgrade from WCDMA to HSPA requires new software package and some new pieces of hardware in the base station and in RNC to support higher data rates and capacity [18].

#### 2.4.3.1. ***HSDPA: Main changes to WCDMA***

In HSDPA, shared channel transmission was introduced. New transport channel HS-DSCH (High Speed Downlink Shared Channel) that carries the actual user data with HSDPA. It supports higher order of modulation than traditional Dedicated Channel (DCH). As data are sent from one serving HS-DSCH cell only, so no soft handover is possible. In physical layer HS-DSCH is mapped on the high speed physical shared channel (HS-PDSCH).

HSDPA provides Adaptive Modulation and Coding (AMC) to adjust the data rate to the available channel quality. It is a link adaptation which makes use of the channel fluctuation. It allows switching among a set of modulation/coding scheme (MCS) with different transmission rates, the data rate of AMC system is enhanced in favorable channel conditions and is reduced when channel condition degrades. Higher level of modulation techniques were introduced where WCDMA used only QPSK (Quadrature Pulse Shift Keying). QPSK, 16QAM (Quadrature Amplitude Modulation) and 64QAM modulations are used in HSAP.

Hybrid Automatic Repeat Request (HARQ) is an enhanced type of ARQ (Automatic Repeat Request) error control method which includes the error correction capability in addition of error detection for further improving the performance. In HARQ procedure, receiver sends an ACK (Acknowledgement) to if the received packet is without error and sends NACK if an error packet is received also stores the packet. When a retransmitted packet arrives, receiver combines it with the stored packet and tries to decode the combination.

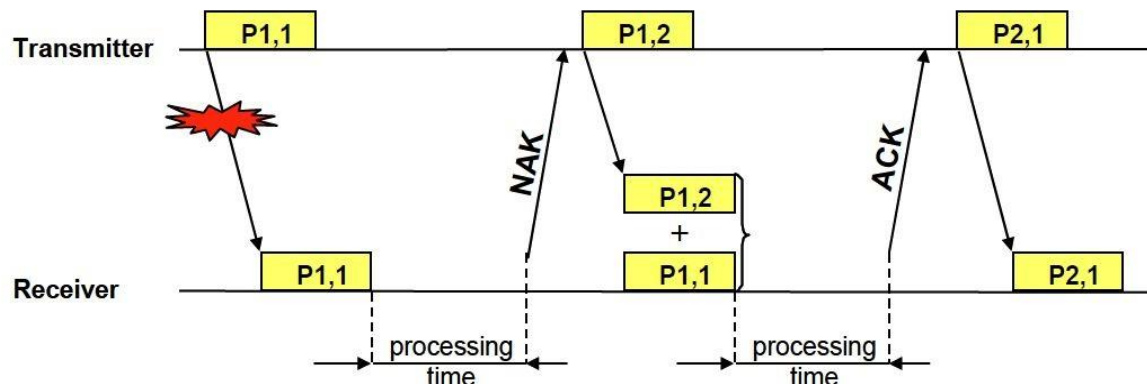


Figure 14: HARQ procedure

HSDPA have shorter Transmission Time Interval (TTI) than WCDMA. It is 2ms for HSDPA where, WCDMA it was 10ms, 20ms, 40ms or 80ms [18].

Besides, HSDPA introduced two additional physical control channel named, HS-SCCH (High Speed Shared Control Channel) and HS-DPCCH (High Speed Dedicated Physical Control Channel). ‘Fast channel-aware scheduling’ controls to which user, the HS-DSCH transmission is directed. This is applied in NodeB and takes into account the radio channel condition. And also, no fast power control is required in HSDPA.

#### 2.4.3.2. *HSUPA: Main changes to WCDMA*

As like HSDPA, HSUPA also have those new features, e.g. HARQ, Fast Scheduling, and Short TTI. And also HSUPA introduced new transport channel named, Enhanced Dedicated Channel (E-DCH). Unlike HS-DSCH, soft and softer is possible in E-DCH. And also, E-DCH is not shared between users.

### 2.5. *Network Architecture for 3G femtocell*

In this thesis main focus is on 3G femto standardized by 3GPP with air interface WCDMA /HSPA. In these section key points of network architecture for 3G femto is discussed to give reader an adequate knowledge about the femto based 3G network architecture.

### 2.5.1. Description of the Architecture

In Table 2 already mentioned the terminologies for 3G femto technology defined by 3GPP. The architecture for 3G femto is based on UMTS architecture with some additional UTRAN architectural enhancements according to the need to support femto technology. This architecture uses HNB and HNB-GW in place of NodeB and Radio Network Controller (RNC) utilized in UMTS architecture. Figure 15 shows the 3G femtocell logical architecture defined by 3GPP 25.467 [14].

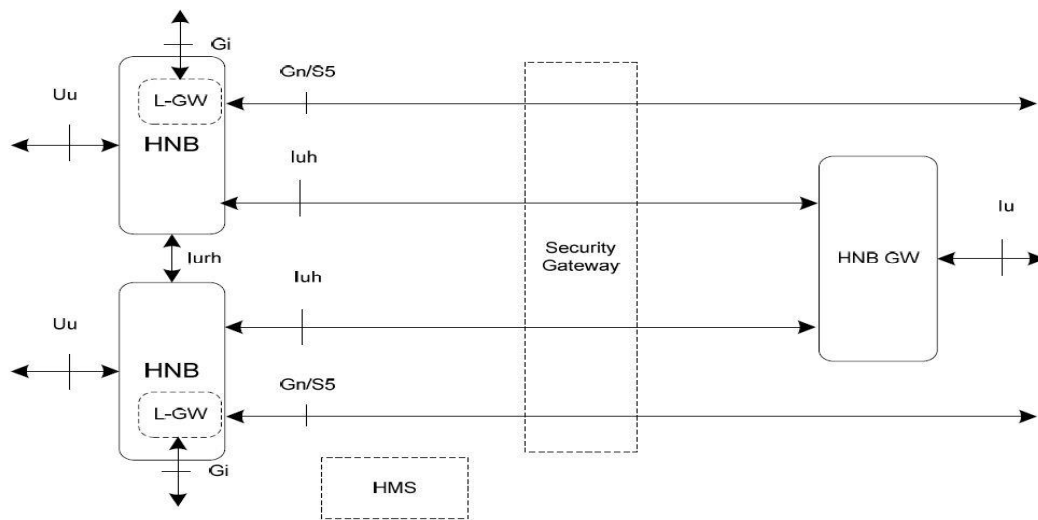


Figure 15: Logical network architecture for 3G femtocell [19]

As like UMTS architecture, Uu interface connects the User Equipment (UE) with HNB. Uu is the standard radio interface between UE and HNB for WCDMA. As mentioned early, HNB is the low power access point which operates in licensed spectrum and provides the coverage and capacity.

3GPP defines a new interface called Iuh interface for connecting HNB to HNB-GW which provides the control and user plane functionalities. For the user plane it includes the basic functionalities like, Radio access bearer management, Radio resource management, mobility management and security etc. For control plane Iuh interface includes functionalities like, HNB registration, UE registration to HNB and error handling.

Iurh is a direct interface which connects one HNB to another HNB. Gi is the interface towards the residential/ IP network. Gn/S5 interface towards Security gateway (SeGW).



HMS functionality is based in TR-069 [20] family of standards. In this architecture, HMS set of functionalities includes the discovery of HNB-GW, location verification of HNB and assignment of serving elements to the serving network.

Iu interface connects HNB-GW with the core network. HNB-GW aggregates numbers of HNB to the core network. Iu interface functionality is split into two interfaces Iu-PS and Iu-CS. Through Iu-PS interface HNB-GW interworks with circuit switch signaling to standard MSC and packet switch signaling to standard SGSN (Serving GPRS Support Network) through Iu-CS simultaneously.

To manage and terminate secure Internet Protocol Security (IPSec) tunnels between HNB and HNB-GW, 3G femto architecture uses Security gateway (SeGW). When mobile traffic is exposed to public access network, SeGW ensures protection against potential security threats and network attacks. Generally, SeGW in 3G femtocell architecture is somehow vendor specific, but in some cases it comes as an integrated solution within a HNB-GW.

Functional architecture of 3G femtocell network is divided in the UTRAN and the core network elements which provide the radio related functionality and call routing, switching along with the management of data connections to external networks respectively. Figure 16 shows the high-level functional architecture of 3G femtocells.

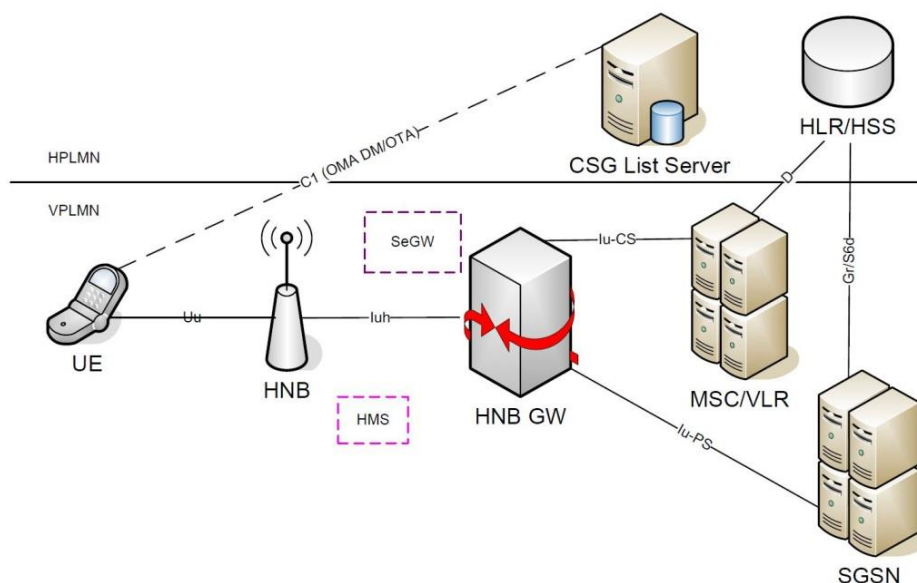


Figure 16: Functional network architecture for 3G femtocell [21]

### 2.5.2. Interfaces and protocols

Apart for Radio Access Network Application Part (RANAP) there are two new protocol sub-stacks in Iuh in 3G femtocell architecture. Figure 17 shows the Iuh general protocol stack. Those two new protocol sub-stacks in Iuh are named as RUA (RANAP user Adaptation Part) and HNBAP (HNB Application Part). To be mentioned Uu is the protocol interface between UE and HNB while Iuh is the interface protocol between HNB and HNB-GW.

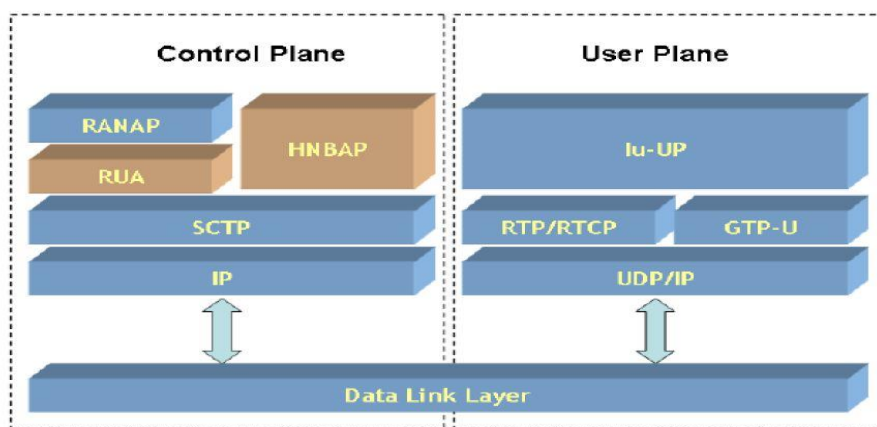


Figure 17: Iuh general protocol stack [21]

RUA supports the UTRAN functions in the HNB which requires RANAP.

- Transparent transfer of RANAP procedures
- Error handling for general errors which do not have specific error messages
- Elementary procedures including
  - Connect
  - Direct transfer
  - Disconnect
  - Connectionless
  - Transfer
  - Error indication

Functions supported by HNBAP specific to HNB are

- HNB registration
- UE registration

- Error handling for general errors which do not have specific error messages
- Elementary procedures including
  - HNB registration
  - HNB de-registration
  - UE registration
  - UE de-registration

### 2.5.3. *Architecture functional description*

#### 2.5.3.1. ***HNB***

HNB is considered as a plug-and-play customer device. It uses the subscriber's broadband backhaul to connect to the operator's core network. HNB have set of very important functionality. It provides RAN connectivity using the Iuh interface, terminates secure connection for Iuh towards SeGW. HNB supports RNC like functions. It discovers the HNB-GW and determines the address of the serving HNB-GW for a particular HNB. HNB reports its HNB identity location information and operation parameters to HNB-GW. It performs UE registration by conveying UE identification data to HNB-GW in order to perform access control between UE and HNB-GW.

#### 2.5.3.2. ***HNB-GW***

According to 3GPP, RAN functionality is distributed between HNB and HNB-GW. In a femto network HNB-GW is used to provide functions like, link security, control and aggregation. HNB-GW terminates Iuh from HNB and appears as a RNC to the core network suing Iu interface. HNB-GW supports HNB registration and UE registration over Iuh interface. It performs paging optimization, where filtering of paging message is done in order to avoid paging distribution to HNBs/CSG cells where the UE is not registered. NAS node selection and re mapping of transport address is also HNB-GW functionality.

#### 2.5.3.3. *SeGW*

SeGW takes care of the security of the communication from or to HNB. It terminates secure tunneling for TR-069 as well as Iuh. It provides HNB with access to the HMS and HNB-GW. SeGW is also responsible for the authentication of HNB.

#### 2.5.3.4. *HMS*

HNB Management system (HMS) is used to provide Operation Administration Maintenance and Provisioning (OAMP). It facilitates HNB-GW discovery. It provisions configuration data to the HNB and performs location verification of HNB, assigns appropriate serving elements.

#### 2.5.3.5. *CSG List server*

It's an optional function which allows the network to update Closed Subscriber Group (CSG) lists on CSG capable UEs.

#### 2.5.3.6. *SGSN*

SGSN (Serving GPRS Support Network) provides access control for CSG capable UEs; this function is used to decide whether a CSG capable UE can access a CSG cell.

### 2.6. *Current Market Status and Forecast*

Since 2007 small cell market is being active when Sprint launched their first consumer femtocell service. After that many operators have been adopting this new technology and overall usage is increasing day by day. Fact is, between October and November 2012 the number of small cells deployed overtaken the number of macrocells [22]. According to the report published in February 2013 by Small cell forum, there are 46 commercial services and total 60 deployment commitments. It also adds, nine of the top 10 mobile operators worldwide are offering femtocells services. Including Sprint and Vodafone, several operators have been reported deployments with 100s of thousands of femtocell [22].

Informa Telecoms & Media estimates, the small cell market will generate US\$22 billion by 2016. Juniper Research - June 2012 claimed small cells will account for a steadily increasing proportion of offload data over 2012 – 2016, reaching over 12% by 2016. Mobile experts –

February 2012 claimed, 70 million small cells will be shipped by 2017. Dell'Oro Group – September 2012 claimed, the small cell market will almost quadruple by 2016.

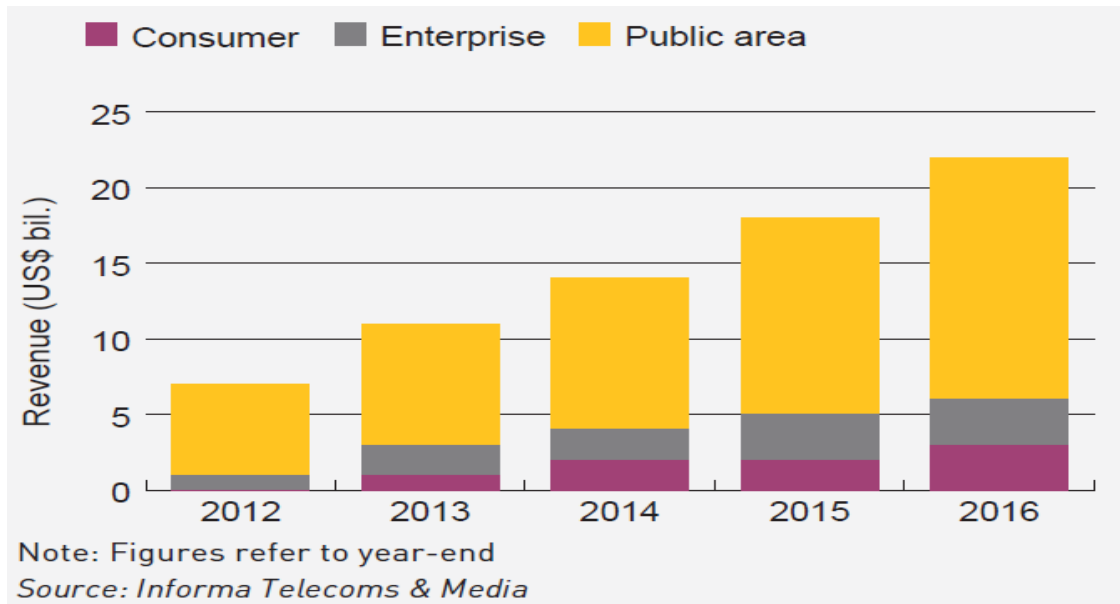


Figure 18: Global, small cell revenue forecasts by category [22]

### 3. DEPLOYING SMALL CELLS

The term ‘Small cell’ is covering a large portion of future HetNet. Operators can choose their own strategy of selecting and deploying small cells. In this study main focus in on femtocell, because as mentioned earlier, femtocell are being studied more and trying to replace the other small cells. That is, femtocell can also be used as microcell and metrocell. With some modifications femtocell can be deployed outdoor and can be used for coverage expansion along with the specific benefits of femtocell. In this section, system configuration and implementation aspects are discussed.

#### 3.1. System Configuration

According to the operator’s plan and revenue target, the system can be deployed with different strategies. In general, the system constitutes with conventional microcellular NodeB providing coverage for both outdoor and indoor environments, and HNBs are deployed to extend the macro NodeB coverage and enhance the capacity.

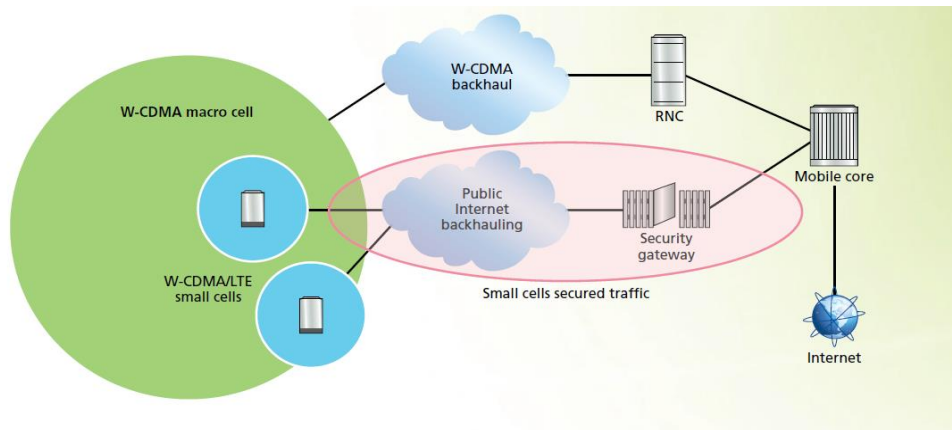


Figure 19: High-level view of typical small cell deployment [23]

In the system, there are two types of UE; Microcellular UE (MUE) which is connected to the network via macro NodeB, and Femtocell UE (FUE) which is connected to the network via femtocell access point. According to the channel quality available for the UE, it selects the best channel. But if the femocell is a closed access femtocell then an outsider UE cannot connect to the femtocell even it it gets better channel condition from the femtocell. For open access and hybrid access femtocell UE connects to the best server.

Femtocell deployment can be two types, private femtocells and neighborhood/ outdoor femtocells. Private femtocell is deployed indoor, so the coverage is actually restricted to indoor area and enhance the indoor coverage and capacity. On the other hand, neighborhood femtocell can be deployed on the roof-top of a house. This type of femtocell are generally open access femtocell and the coverage is for both the indoor and outdoor.

Densification of base station with frequency re-use gives the highest capacity gain. Deployment of femtocell can be an attractive option for densification with frequency re-use for providing the highest capacity gain. With a smaller cell range (100m) low power femtocell can be perfect for coverage and capacity expansion. To maintain and deploy network with neighborhood femtocells requires some additional awareness and architectural assumptions. Self-Organizing Network (SON), mobility and interference management, automatic neighbor relation, dynamic allocation of resources and synchronization are the most important architectural issues for outdoor deployment of femtocells. Dedicated spectrum is needed for both the private and neighborhood femtocells. In this study and simulation assumptions, both types of deployment were considered. Simulation results for both indoor and outdoor deployed femtocell were studied.

For the backhaul of femtocell there are two different options. The backhaul can be wired (traditional method, using DSL connection/fiber line), and wireless (connected to the macro NodeB wirelessly). In the next section the backhaul options and possible selection strategies are discussed more detail.

### **3.2. Backhauling**

One of the great challenges of deploying small cells/ femtocells is the capacity of the backhaul. It brings new challenges to the operator's backhaul planning and operations teams. To maintain the proper end-to-end QoS for the users and deliver maximum business benefit to the operator deployment of femtocell based network is very beneficial. But to meet the actual expectation with this deployment, high performed end-to-end backhaul in terms of speed and delay variation is highly recommended [24].

Backhauling for traditional femtocell is described with the existing DSL connection. In this scenario femtocells are backhauled via the available wire-line broadband access link to a

femto gateway node and the mobile operator's core network. But as mentioned earlier, for the emerging markets no fixed line is available and deployment of new wired line fiber infrastructure is quite difficult and very costly. In that case, proposal can be raised for wireless backhaul. For the selected case study no choice than wireless backhaul in terms of cost, availability and affordability.

Wireless backhaul has its own advantages, no need to run cabling between locations. Wireless solutions need only equipment at the small cell and point of presence, which can help to reduce cost and improve the speed of deployment. However, wired link is more predictable and provides higher capacity [25].

The purpose of backhaul is to connect the small cell to the core with the required quality of service. Backhaul requirements depend on the use case for the small cell, though there are some basic requirements for small cell backhaul. Whether backhaul is wire line or wireless, those requirements should be taken care of. Table 5 describes some basic requirements for small cell backhaul.

Backhaul Requirement	Compared to Macrocells	Notes
Cost	Cheaper	Cost per link should be lower. Cost per bit may be similar.
Capacity	Traffic load is lighter but burstier	Small cells generate less backhaul traffic than multi-cell/mode/band macrocells, but the traffic is much burstier.
Scalability	More scalable	Faster growth requires rapid deployment despite shorter lead times.
Latency	More delay tolerant	Delay sensitivity depends on service level expectations. Femtocells are designed to cope with lower quality connections. Femtocell handover is less important.
Availability	"Five Nines" not needed	Small cells will form an offload underlay to a higher-availability macrocell.
Size & Weight	Smaller and lighter stations	Small cells require deployment in locations with limited space availability. Compact backhauling solution is essential.
Access to Backhaul	More difficult	Small cells are close to users – on the street and indoors, relatively far from backhaul sites. These sites are harder to reach than tower-based macrocells.
Installation & Commissioning	Faster, simpler, cheaper	Consumer femtocells are plug-and-play. Femtocell backhauling should also work this way.

Table 5: Summary of small-cell backhaul requirements [26]



### 3.2.1. *Wireless backhaul*

Some solution providers (e.g. Ericsson, Ceragon) are already researching and providing wireless backhaul solutions for small cells. The NGMN Alliance is also dealing with this issue and providing solutions. As stated before, backhaul requirements depend on use cases and also deployment scenario. Some popular solutions of wireless backhaul for small cell deployment are discussed below:

- ***Traditional Microwave:*** Traditional licensed microwave wireless link can be an attractive solution for backhauling femtocell. Where distance and availability are crucial, microwave provides the best solution with 1Gbps capacity. Operational frequency varies from 6-57GHz. Ceragon provides licensed microwave wireless links for backhaul aggregation, in addition it can be used to back-up wire line backhaul links if needed. NGMN also provides backhaul solution for small cells with microwave technology.
- ***Licensed millimeter wave (E-Band):*** This solution is preferable for dense urban region and provides very high capacity up to 1.2Gbps. Ceragon offers this solution with an operating frequency range 70-80GHz. As narrow beam-width is used, so it offers higher reuse factor. Abundance of the spectrum and light licensing scheme makes this solution more attractive, but this solution performs well for only line-of-sight (LoS) situation.
- ***Sub 6GHz Microwave:*** This solution supports both point-to-point and point-to-multipoint scenarios. It is a medium capacity (200Mbps) solution, yet works for near-line-of-sight and non-line-of-site situations (NLoS). For point-to-point backhauling, reuse/ usage of access frequencies are possible. Both the licensed and unlicensed spectrum can be used. Sub 6GHz microwave solutions for point-to-multipoint scenario could be best solution for emerging market scenario. It works for non-line-of-sight (NLoS) in both licensed and unlicensed spectrum. Single hop transmission ensures lower delay and this type of link ensures that the sum of access link capacity will never overload the system uplink. Figure 20 shows sub 6GHz point-to-multipoint solutions offered by Ceragon (<http://www.ceragon.com/>).



Figure 20: Sub 6GHz point-to-multipoint backhaul solution [26]

A wireless backhaul solution with non-line-of-sight and near-line-of-sight capabilities means that the PoP does not need to be visible from the small cell. As small cell access points are ideal solution for last-mile backhaul and deployed indoors, so near-line-of-sight and non-line-of-sight solutions are much dependable. Microwave frequencies have higher wall penetration loss so, not suitable for NLoS. But the frequencies below or equal to 6GHz are better choices for small cell deployment.

In addition to those mentioned wireless backhaul solution types, *Satellite* and *TV white space* technologies can also be considered as backhaul for small cell. But those are not relevant options for this thesis that is why those are not described in detail.

### 3.2.2. *Wire-line backhaul*

Wired connectivity could be through copper line or fiber line connectivity. Using copper twisted pair telephone structure the throughput can be achieved about hundreds of Mbps for small distances. And even for 1Km distance 50Mbps is achievable, which is sufficient for HSPA [20]. However using fiber connectivity, gives even more throughput (Multi Gbps). Internet Service Provider's (ISPs) existing line are also used for backhauling of small cell. But at some level private ISPs that supply the backhaul particularly if the femtocells are open access might be forced to carry additional traffic. These ISPs will end up responsible for a large portion of all mobile traffic if femtocells become popular enough, and the ISPs might rise up the price for this cooperation [27].

Backhauling discussion can be summarized with Figure 21. In this figure all the solution types for backhauling the small cells are illustrated. Both wire line and wireless solutions are available mentioned, and according to selected area scenario and deployment plan, option can be chosen.

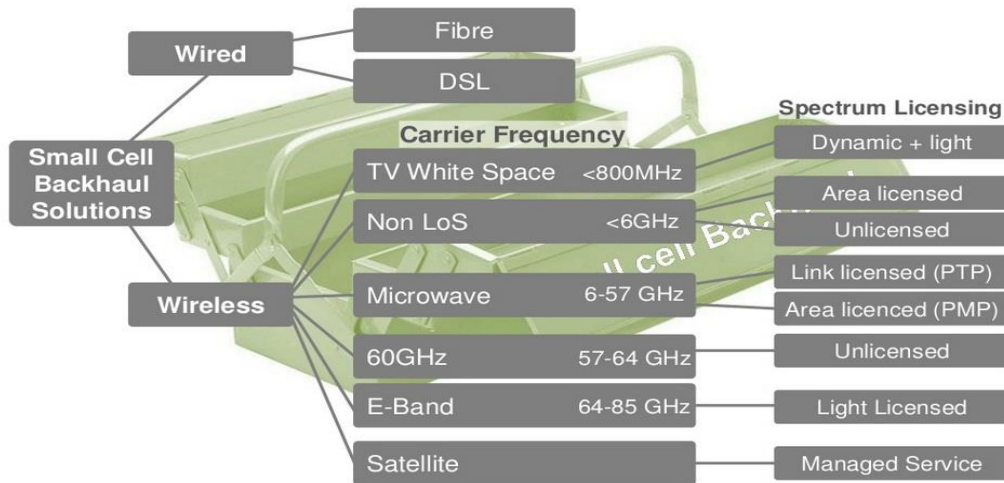


Figure 21: Small cell backhaul solution types [25]

### 3.3. Access control and Mobility strategies for UE

In section 2.2 classification of femtocells according to the access method is already discussed. Referring to that discussion, access to femtocells can be based on three possible methods namely closed, open and hybrid access methods. In closed access mode, a list of subscribers is maintained with name of Closed Subscriber Group (CSG). Only those UEs who belong to the CSG can access that femtocell. In open access and hybrid access method, any UEs can access the femtocell, though open access method is totally open for all UEs with the same priority and hybrid access method maintain some sophisticated analysis to share the available resources.

3GPP release 8 and beyond have specific means by which UE is able to distinguish between the two cell types (macrocell and femtocell) [28]. With those specifications UEs are smart enough to make decision whether to connect/ reconnect to the femtocell or to the macrocell with pre-defined cell ranking rules (3GPP, 2009a). In case of closed access method, HNBs broadcast a CSG Identity (CSG ID) while UE maintains a list of eligible CSG IDs. The

access control procedures for HNBs are managed by the HNB-GW or the core network (3GPP, 2009c).

To support mobility of UEs, proper handover specifications are important. For femtocell deployed network, from the femtocell point of view, there could be three types of handovers.

- ***Hand-in or Inbound Handover:*** When handover occurs from the macrocell network to the femtocell network. UE entering to office or home, handover from the macrocell to the femtocell is needed. Hand-in is a bit critical handover to handle without modifying devices and core network components. In 3G based heterogeneous network many numbers of femtocells with same Primary Scrambling Code (PSC) might present in the network under a macrocell. To identify the correct femtocell for the handover is difficult for the macrocells, this confusion is known as PSC confusion. To resolve this problem, Observed Time Difference (OTD) technique can be used [8].  $\Delta$ OTD is the femtocell timing relative to macrocell which is unique for a particular femtocell within a macrocell. In this technique UE reports the  $\Delta$ OTD and PSC ID, then macrocell combine these two and identify the right femtocell. This technique works for Release 9 and beyond UEs. The method for identifying femtocells are well defined within Release 9 of 3GPP standards, as initially 3GPP specifications focused on only Hand-Out or Outbound handovers.
- ***Hand-out or Outbound Handover:*** When handover occurs from femtocell devices to macrocell system. 3GPP Release 8 specifications define procedures for femtocell to macrocell handovers (3GPP, 2009). This is most like macro cell to macro cell handover. If no direct interface is available (wire-line backhauling) between these two then core network takes care of this type handovers. When UE comes out from the area of femtocell, it has no other options than macrocell that is why this handover is less complex [29]. Only thing need to take care about is the handover time should be as less as possible.
- ***Femto to femto handover:*** When UE exits one femtocell area and enters another femtocell area then femto to femto handover occurs. As mentioned in the network

architecture, there is a direct interface to connect two femtocells. Iurh interface takes care of this type of handover.

### 3.4. *Other Operational Aspects*

#### 3.4.1. *Spectrum allocation*

WCDMA networks started at 2100MHz band in Asia and Europe and at 1900MHz in USA [17]. But to maintain the larger coverage area WCDMA/HSPA are been deployed using lower frequency bands e.g. 850MHz and 900MHz band. As WCDMA/HSPA specifications have been designed with backward compatibility to make the deployment and up gradation easier, WCDMA/HSPA can operate in the same band as GSM using 850, 900 and 1900MHZ band. Figure 22 shows WCDMA/HSPA frequency variants by region.

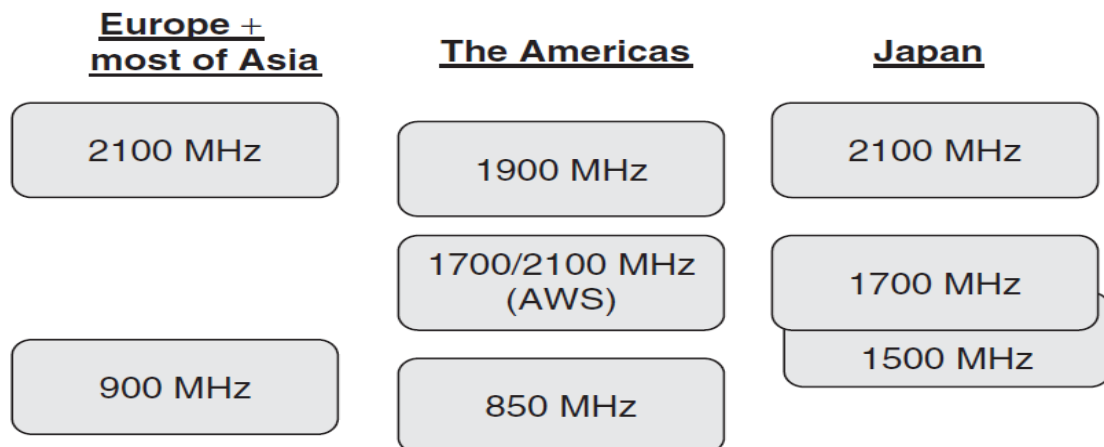


Figure 22: WCDMA/HSPA frequency variants [17]

3G femtocells can actually use the same frequency band of WCDMA/HSPA. So the macrocell and HNB operates in the same frequency band. But two different techniques can be adopted to allocate the licensed spectrum between macrocell and femtocell.

- **Orthogonal deployment/ partitioning:** Total licensed spectrum is divided into two parts and separated for macrocell and femtocell use. In this approach cross layer interference between macrocell and femtocell is neglected as they use separate frequency bands. According to the traffic load and user mobility, spectrum allocation

can be either statically or dynamically. But orthogonal deployment results inefficient use of radio spectrum which is extremely expensive. So not recommended for cost effective network planning.

- ***Co-channel deployment/ Reuse one partitioning:*** In this approach both the macrocell and femtocell use the same frequency spectrum, which means reuse factor is one or full reuse. This approach ensures more efficient use of available spectrum, but the interference condition in network is more severe and challenging than the orthogonal deployment. In WCDMA system, Self-organizing networks (SON) technology is the key factor to avoid the cross and co layer interference in the network [11].

Another approach can be used for partitioning the spectrum. In this approach total spectrum is available for macrocell use, but a portion of the total spectrum is also used by femtocells. Figure 23 generates better idea about the discussed spectrum allocation approaches.

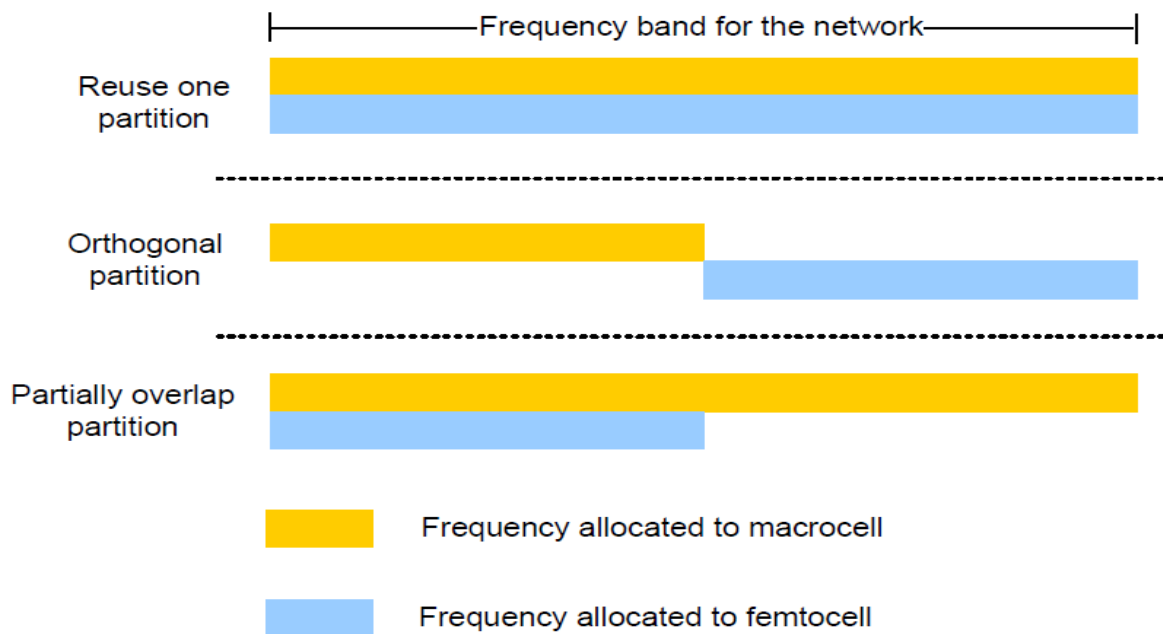


Figure 23: Frequency partitioning techniques [19]

### 3.4.2. *Self-organizing networks (SON)*

Deployment of HetNet increases the number and types of cells used in the network and with this the interdependency among those parameters increases as well [10]. Self-organizing networks (SON) is a key aspect which makes the HNB deployment easier, cost efficient and better performed. If SON is a life cycle, measurement, self-configuration, self-optimization and self-healing are the phases of that life cycle [11]. As most of the time operator doesn't know the number and location of the small cells, these four phases take care of the network plan and optimization which makes operator's life easier.

Via measurement, HNB takes necessary information from the network to access the network. Measurements are taken from different sources and different raw data are processed. A newly added HNB sets up its software and parameters and makes itself available using self-configuration. According to measured data, self-configuration is done and even an existing HNB can use self-configuration technique when a new HNB is placed near to it. After self-configuration, it does the measurements again, and according to the measured data HNB performs self-optimization. Using the knowledge of the environment, the coverage and capacity can be optimized [10]. Controlling and changing transmit power by itself is a great way of self-optimization. The overall network performance can be improved by decreasing transmission power [30]. HNB transmit power control should be a trade-off between the HNB performance and the interference towards close by macrocell users.

Based on 3GPP studies the allowed output power of HNB is limited to

- < +20 dBm for 1 transmit antenna
- < +17 dBm for 2 transmit antennas
- < +14 dBm for 4 transmit antennas
- < +11 dBm for 8 transmit antennas, Release 10.

Dynamic power control/ calibration should be used to get the proper performance. In dynamic power control method, HNB listens to the radio environment to make measurements of current noise and power levels. Based on this measurement HNB will adjust its maximum transmit power to a level where it causes only an acceptable amount of interference. Figure 24 shows how dynamic power control improves the network performance.



Figure 24: Dynamic power calibration mitigating pilot pollution [31]

Self-healing is another important phase of SON. When network faces some difficulties e.g. damaged HNB self-healing resolves those issues. It can adjust the network without the damaged HNB by self-optimization technique. Self-healing takes care about sleeping-cell detection, cell outage compensation, root cause analysis and alarm correlation. Figure 25 focuses on the main functionality of SON.

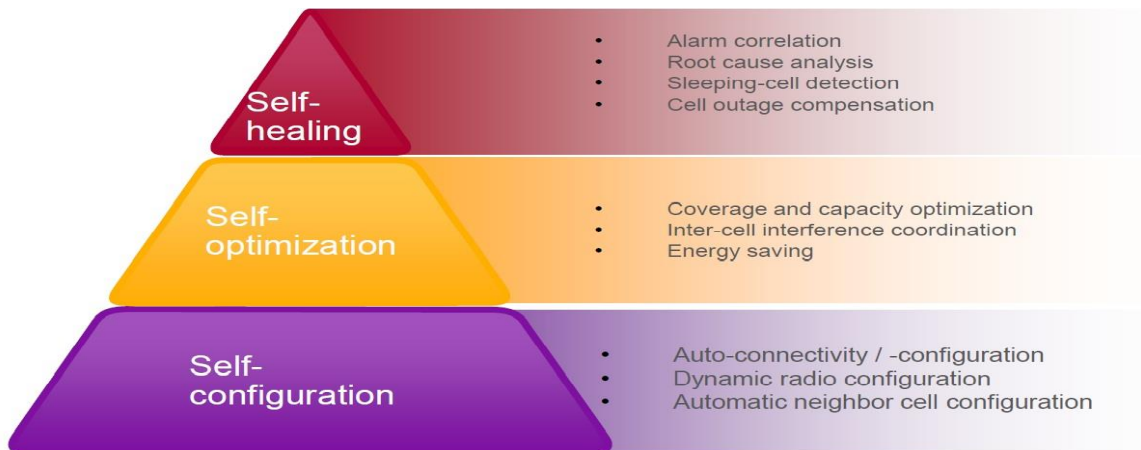


Figure 25: Main functionalities of SON [32]

SON technology reduces the need of operator maintained lower level configuration and optimization, which decreases the CAPEX and OPEX. The network monitors its performance itself and adapts for the optimal performance. Still some level of network plan and optimization is required.



## 4. SYSTEM SIMULATION METHODOLOGY

### 4.1. *Area details*

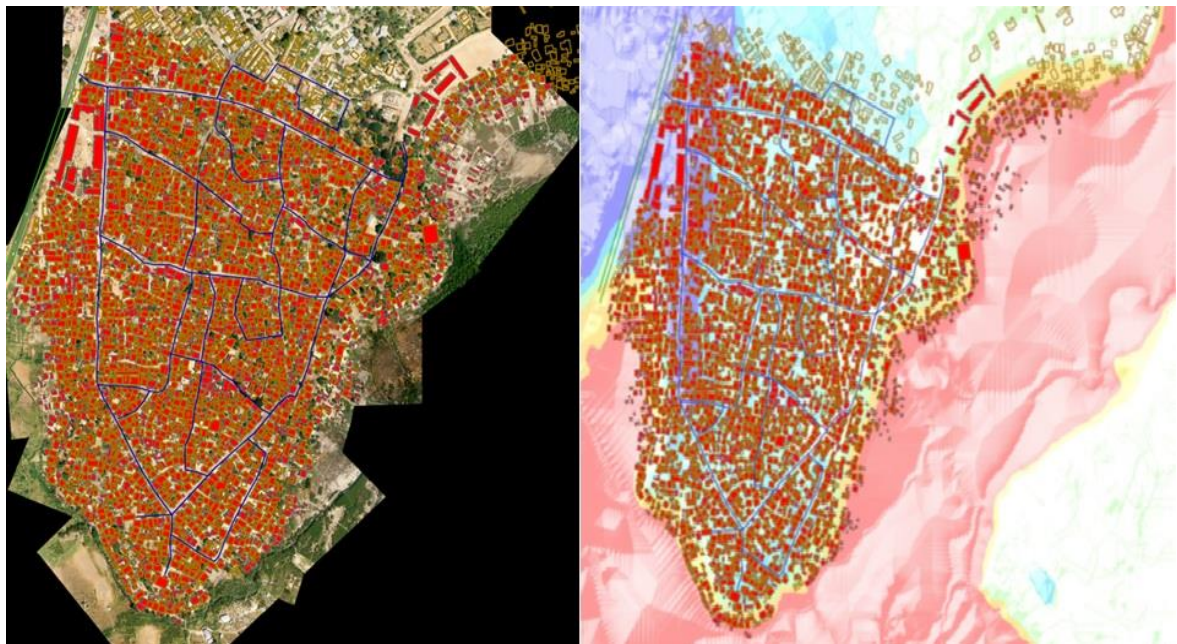
The purpose of this study is to investigate the best way to bring up the available affordable broadband to the mass, particularly to the low-income suburban region. As mentioned earlier, it's challenging from the operator's point of view to establish a network in low potential area as they cannot expect much revenue from there. Recent days in Africa, it is becoming a common scenario that surrounding an urban area low income unplanned settlement is growing. World Bank study shows in Tanzania 17% of the total population are living on such unplanned densely populated suburban area, which is actually just beside of a higher potential area. In this study one such slum area was selected to investigate the deployment performance gain.

There is a ward in Dar es Salam city of Tanzania, named Hanna Nassif is the selected area for this study. The studied 1Sq Km area is a slum located aside of a planned urban area. Such area allows planning heterogeneous network, where macrocells are mostly targeted to the higher revenue area and brings up the profit. However, small cells can be planned lower potential area for complete coverage. Two macro sites with 6 cells were planned with reasonable location, where most of the cells targeting the urban area, and selected slum area were covered by less number of cells from macro sites and random deployment of femtocells/HNB.

The population of the area is estimated about 20000 – 30000 with 3056 buildings within only 1Sq Km area. Topographical difference is 19m. Building height data was not exactly available, but as it is a slum area in the African nation so most of the buildings or house can be assumed one storied. Figure 28 shows some houses or buildings from selected area. For being more realistic 10% of the buildings were assumed two storied buildings. Building area and locations are estimated as exact data which matches the Google earth view as well.



*Figure 26: Google earth picture (bird's eye view) of the selected (red line) slum area*



*Figure 27: Satellite image and clutter with topography picture with building data on it [33]*



Figure 28: Some pictures of houses in the selected area “Hanna Nassif – Dar es Salaam”

## 4.2. Tools

To do the simulation for selected area, two different tools were used. WinProp – developed by AWE-Communications and Matlab static simulator. In this section details of those tools are described.

AWE-Communications (<http://www.awe-communications.com>) was founded in 1998 and these days main focus is on developing software tools for wave propagation and radio network planning. To do so, AWE-Communications is partnering with Alcatel-Lucent, Nokia, Nokia Siemens Networks, Vodafone, Aircom and many more. Together with several partners AWE-Communications was able to develop a software package named WinProp for propagation modeling in different scenario (rural, urban, indoor, tunnels, etc..) and for network planning of different air interfaces (LTE, 3G, 2G, WiMAX, etc..).

### 4.2.1. WinProp

- **Radio Network planning aspects:** In WinProp various commonly used air interfaces are pre-defined, additionally user can define individual properties of the air interfaces to adapt it to the requirements which makes it user friendly and increases usability. WinProp offers static, Monte-Carlo and dynamic network simulators. Beside coverage and capacity planning it allows network simulations with analysis of delays, performance of algorithms. To combine different environments (outdoor and indoor)

polygonal cylinder surrounding the indoor building database is used. When indoor coverage is measured both the outer and inner wall are considered.

For coverage planning, different transmission modes can be defined, e.g. bandwidth, MCS, data rate, SINR target, TX power etc. Coverage maps with all the performance indicators (cell assignment, best server, channel quality, SINR, etc.) can be generated by WinProp. Maximum data rates, and maximum received power can be calculated accurately [8].

For capacity planning, WinProp computes throughput, maximum data rate, packet delays, QoS etc. based on coverage analysis and traffic assumptions (which can be defined by user). Overloaded cells can be detected easily and optimization is also possible. Newer technologies to improve capacity like MIMO and beam forming are also supported and their impact can be calculated [8].

- ***Wave Propagation aspects:*** Better performed and very fast propagation models are available in WinProp for wave propagation calculation in different propagation scenario. Empirical and semi-empirical models, 3D ray tracing, Dominant path model (DMP), Guided Wave Tracing (GWT) are included in the WinProp propagation engine. For accurate calculation, predictions are made considering topographical, clutter, urban building, 3D objects and walls etc. It allows conversion of various types of databases, and editors are also available for user defined database. To perform the measurement accurately between outdoor and indoor a special measurement campaign is used. First step is to verify and the models to describe the propagation from base stations on the outside to mobile station on the inside [34]. Next step is to describe the conditions under which the signals of a femtocell penetrate from the inside to the outside [34]. And also signal propagation of femtocell in indoor is also considered.

To do all the planning calculation and supporting user defined availability WinProp uses some different programs. As mentioned before, WinProp is a software package with different programs for different purposes. Among the below five programs, in this thesis study first two were used.



- ProMan – Wave propagation models and Radio network planning
- WallMan – Graphical editor for vector database
- TuMan – Graphical editor for tunnel database
- AMan – Graphical antenna editor for 2D and 3D patterns
- ConMan – Connectivity simulator for sensor and MESH networks

#### 4.2.1.1. *ProMan*

ProMan – Propagation Manager is a program of WinProp software suit which does the network simulation and planning part. Including all the important parameters of radio channels, ProMan predicts the pathloss between transmitter and receiver. As mentioned earlier, it supports all popular air interfaces and propagation model to do the prediction. ProMan allows user defined base station location and parameters and gives prediction accordingly. All the necessary databases (e.g. topography data and building vector data) can be defined by the user while starting a new project and all the calculation is done on that description. The user interface is very user friendly and simple to work with. Figure 29 presents graphical user interface of ProMan.

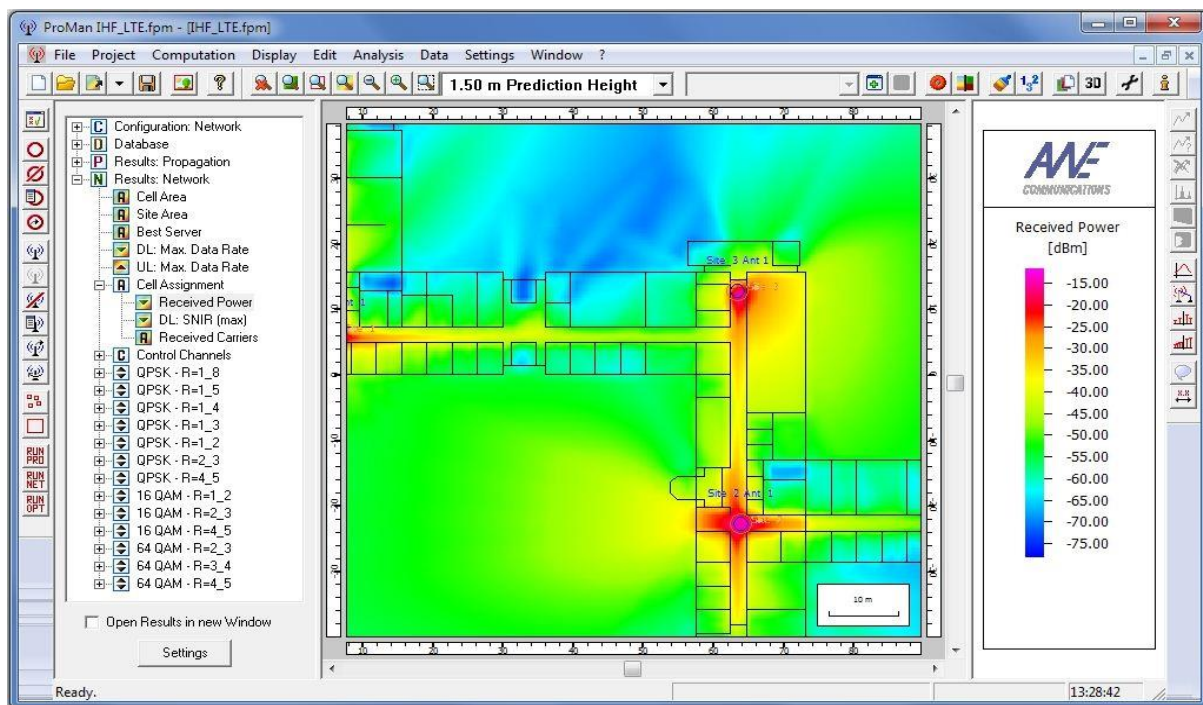


Figure 29: Graphical user interface of ProMan

In this study using ProMan network design was done manually for the selected area. Base station location and parameters can be defined by users and measured data can be analyzed by ProMan. In this study propagation calculation was done and with the measured data performance gain between different deployment scenarios was calculated.

#### 4.2.1.2. *WallMan*

WallMan program provides a graphical interface to define building database and convert them to various format. It allows to create own database or edit existing data. All individual buildings in the database are considered as individual objects and WallMan stores all the information about those objects. The database describes each building with wall segments with three dimensional coordinates of each corner. All the materials of the wall and objects inside the building can also be defined individually and also considered during the propagation prediction. And especially the 3D view of the database allows detecting any error in the database. For heterogeneous study WallMan is very useful as it allows creating own building with different material and different shapes, and propagation can be calculated putting base station/ HNB inside the building.

In this study 5% of the existing buildings were replaced by manually designed buildings with WallMan to put the HNB inside and observe the accurate results and impact.

### 4.3. *Simulation Models, Assumptions and Parameters*

#### 4.3.1. *Propagation model*

Currently available or traditional models have some disadvantages and accuracy could have been improved. A new model for prediction was needed as; Models should not depend on each micro – details in the vector database. Processing time has to be short as computing hundreds of path (Ray tracing model) with small contribution in the transmission. Depending on these requirements, Dominant Path Model was introduced with some reasonable solutions.

Figure 30 shows the comparison between different models. Empirical model must lead to error as direct path is only calculated and sometimes it is the lowest contributing path. In Ray – tracing model hundreds of paths are calculated to be much more accurate. But most of the cases only 2 or 3 rays contribute more than 95% of the energy [34].

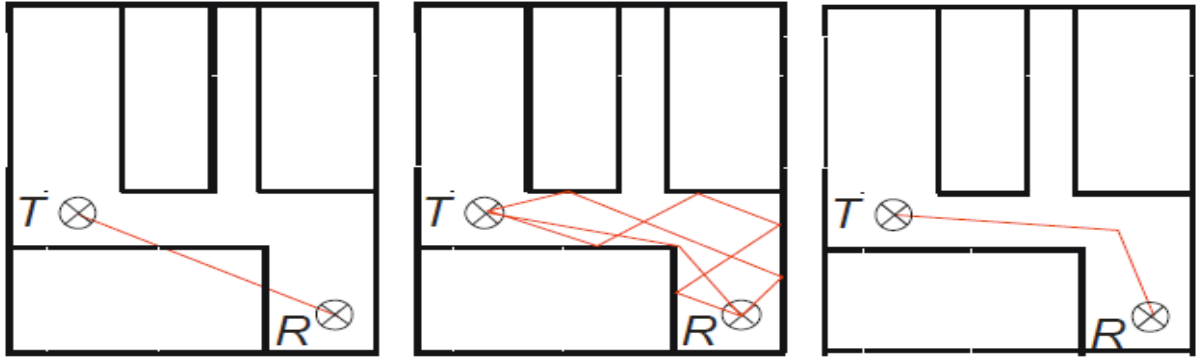


Figure 30: Empirical models use direct path (left), Ray tracing uses many paths (middle), DMP uses the most dominant path [34]

In DMP model, it determines the dominant path and predicts the pathloss along those dominant paths. To determine the dominant paths some criteria like, a small number of interactions, short paths, and a small number of transmission are considered. By adjusting weight more than one path can be calculated for each pixel [35]. But if only one path per pixels can be determined (the most dominant one), then the computation time becomes more less and model works efficiently. For indoor scenario this model works much efficiently than others as well. Figure 31 shows Ray – tracing and DMP model principles for indoor scenarios. The model works in both 2D and 3D. For multi floor indoor prediction 3D calculation is necessary and can be done by DMP model.

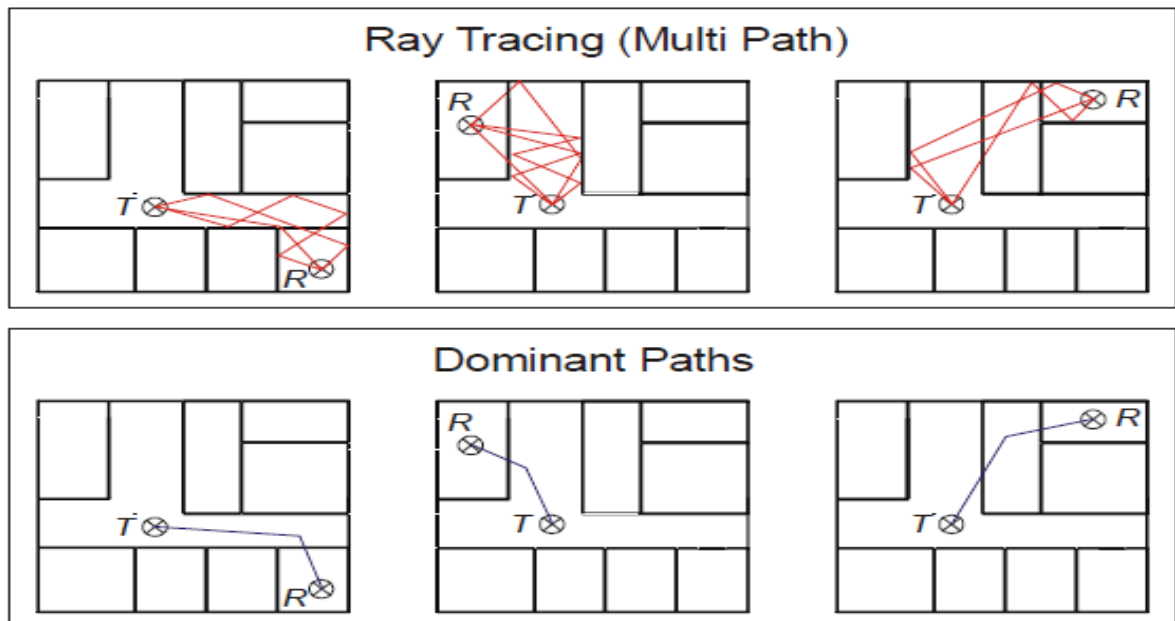


Figure 31: DMP and Ray – tracing for indoor scenarios [34]

Basic algorithm of DMP can be described with determining the dominant path and calculating the path loss along with the path. Figure 32 shows the basic algorithm. According to the example scenario in the Figure 32, the dominant path from the transmitter to the receiver must be via convex corners. Then the tree diagram can be presented and it shows there are more than one path between transmitter and receiver. Then the best path is determined. Comparing the path losses of those paths the best path can be determined. Pathloss is calculated using Equation 1.

$$L = 20 \cdot \log \left( \frac{4\pi}{\frac{\lambda}{m}} \right) + 20 \cdot p \cdot \log \left( \frac{d}{m} \right) + \sum_{i=0}^n \alpha(\varphi, i) - \frac{1}{C} \sum_{k=0}^c w_k$$

Equation 1: Pathloss calculation equation for DMP.

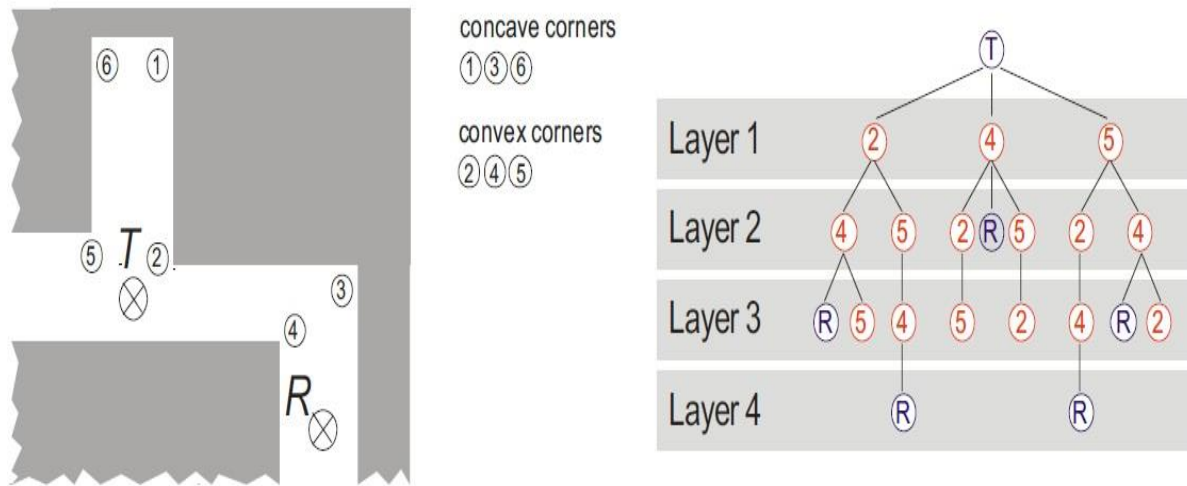


Figure 32: Basic algorithm of DMP. Urban scenario (left) with buildings (grey) and corners, Tree structure to select the Dominant path (right) [36]

DMP takes very less time both for pre-processing and prediction. And it gives the most accurate prediction comparing to others. [35] have some very interesting results while comparing prediction results with measurement from a study done by AWE – Communications. Another study [34] shows the comparison of preprocessing and computation time between different models. That study results are shown in Figure 33 and Table 6.



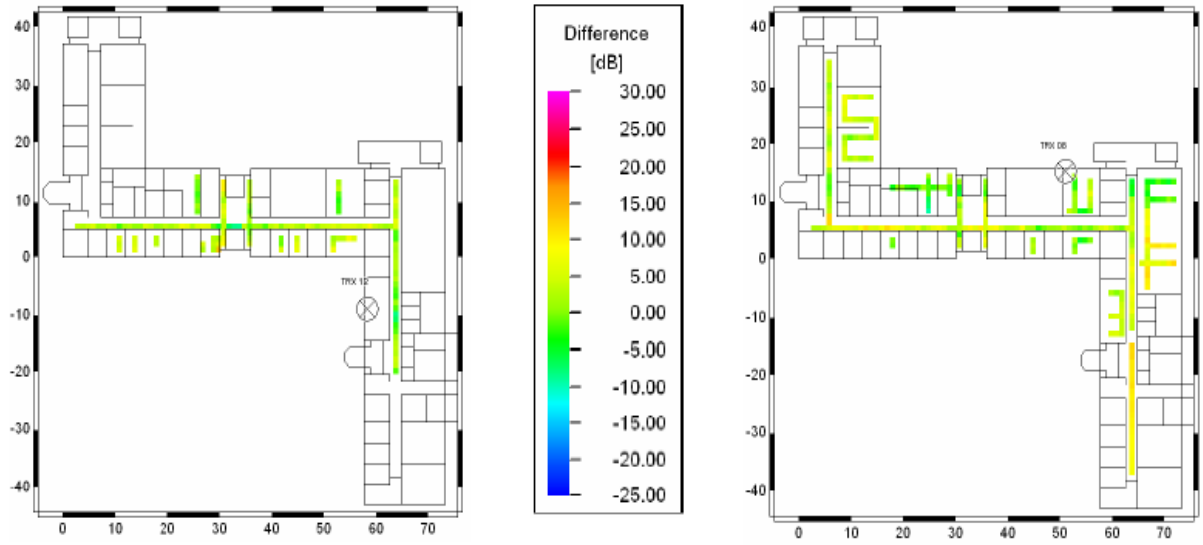


Figure 33: Difference between prediction and measurement for Dominant Path Model for two different sites [34]

Site	Computation times (PC with AMD™ Athlon™ 2800+ CPU and 1 GB RAM)			
	Intelligent Ray Tracing		Urban Dominant Path	
	<i>Preprocess.</i>	<i>Prediction</i>	<i>Preprocess.</i>	<i>Prediction</i>
1	24 hours, 34 min	127 s	some seconds	20 s
2		80 s		39 s

Table 6: “Computation time” comparison between Intelligent Ray Tracing and Dominant Path Model [36]

Key simulation assumptions and parameters are given in Table 7. In section 2.4, it is already stated that, this study is on 3G femtocell as WCDMA/HSPA network deployment is already popular in African nations and ramping up the internet access via mobile devices [3]. Figure 34 shows the broadband penetration percentage and a subscriber segment in the study area. ‘Midterm’ signifies up to 2015 and ‘Long term’ signifies beyond 2015. 3GPP WCDMA/HSPA FDD air interface is already available in WinProp and different carrier frequency was available to define. As higher frequency spectrum is already popular, so 2GHz range carrier frequency was selected to observe the performance.

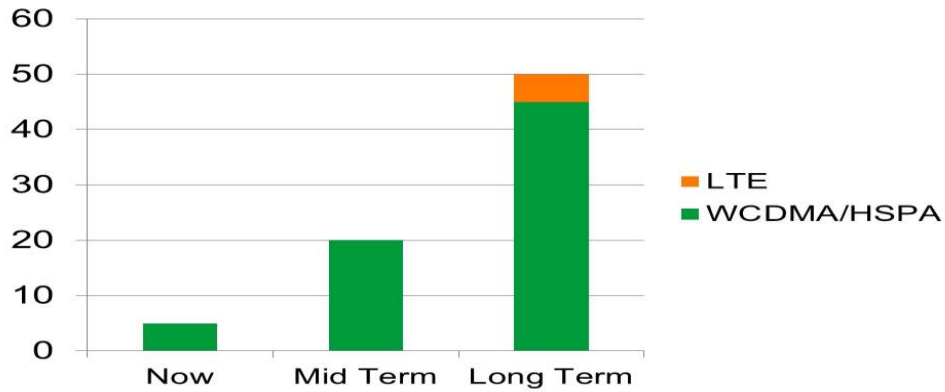


Figure 34: Broadband penetration percentage vs subscriber segment in study area [21]

Parameter	Values/ Assumptions
Air Interface	DL/UL center 2112.5/1922.500 MHz Single 5 MHz carrier, 3840 kchips/s
Simulation	2.5 resolution, 1.5 m prediction height
Propagation Modeling	Urban Dominant Path Model Combined Network Plan (CNP) enabled Waveguiding considered
Macro Node B (MNB)	2 sites, 3 sectors per site 37.8 dBm Tx power (10% power for common pilot) 10 m height
MNB Antenna	Kathrein 742 212 65° HPBW 18 dBi antenna gain
Home Node B (HNB)	Omnidirectional 20 dBm Tx power (10% power for common pilot) 1.5 m height (indoor) or 1 m above rooftop
User Equipment (EU)	Omni directional 1 dBi antenna gain 1 dB body losses, 6 dB noise figure
Orthogonality Factor	0.7
Load Factors	DL: 30% - 80% for MNB, 50% for HNB UL: 4 dB noise rise
Building Penetration Losses	10 dB outer walls 10 dB ceiling/ Floor 8 dB indoor walls
Building Heights	3 m (90% of buildings) and 6 m (10%)

Table 7: Simulation assumptions and parameters

Two macro node B was placed with reasonable parameters according to the selected area environment. HNB was deployed randomly in both possible scenarios; e.g. indoor and outdoor (roof top). To put the HNB indoor, observe indoor performance and the impact on outdoor the HNB deployed buildings were replaced by transparent WallMan made buildings as mentioned in section 4.2.1.2. Load factors were varied for MNB for different number of HNB deployment as HNB offload traffic from MNB.

Directional antenna used for MNB, model “Kathrein 742 212” with 65° Half – power Beam Width (HPBW) and 18dBi antenna gain Figure 35 is the horizontal and vertical pattern of the used antenna. For HNB, omnidirectional antenna defined by WinProp was used.

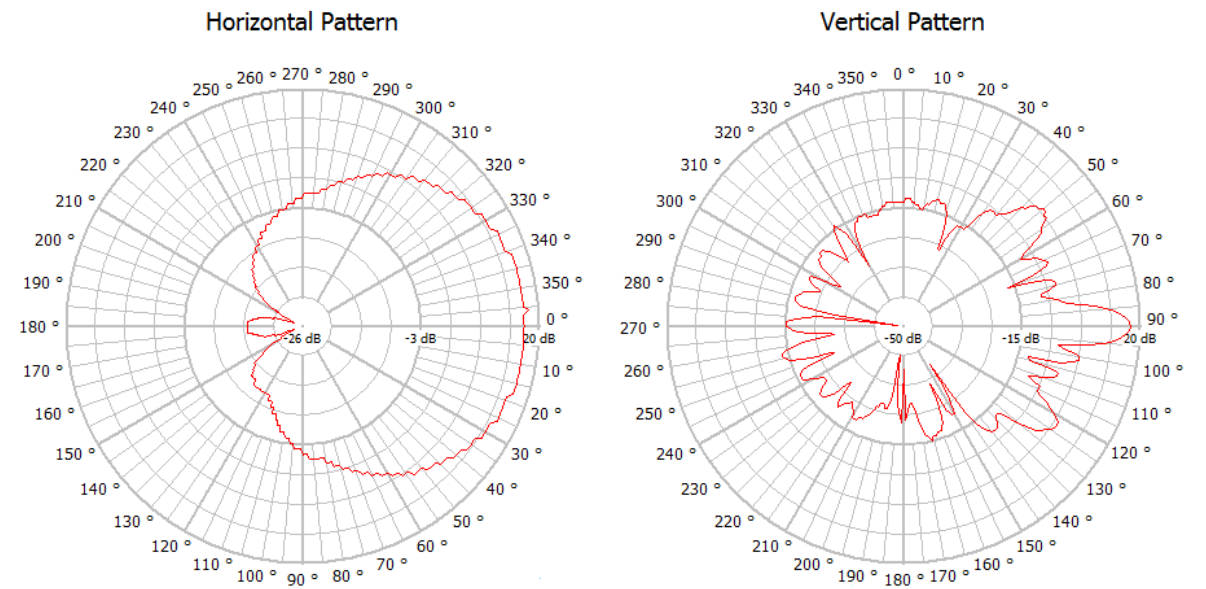


Figure 35: Horizontal and vertical pattern of the directional antenna used for MNB (Kathrein Manual)

This study is focused on the access part of the network and performance gain of different deployment scenario. Backhaul capacity of the nodes (MNB and HNB) is not considered as study here and assumed to be perfect. Considering backhaul is not a bottleneck, only the performance in the access part was studied. Wireless backhaul for HNB can be another interesting topic to study or future study of this work. Different wireless backhaul options for HNB are discussed in section 3.2. Selecting best option with performance analysis and comparison could be fruitful study for such emerging market HetNet deployment.

#### 4.4. *Different deployment strategies*

To study the performance gain with the femtocell penetration (percentage of buildings having HNB) different deployment scenario was simulated. All the deployments were compared to Macro - only case. In Macro - only case two MNB was considered only no HNB were placed. Then increment in the femtocell penetration was deployed. As selected area is such low – income area and user has to buy the HNB for own, so in this study only 0.5%, 1% and 2% femtocell penetration were considered to be more realistic. In every case, HNB was placed both indoor and rooftop so study the difference. So the main deployment scenarios are;

- Case 1: Macro – only (2 MNB)
- Case 2: 0.5% femtocell penetration: Macro – 10 FemtoIN (2 MNB, 10 HNB placed indoor)
- Case 3: 0.5% femtocell penetration: Macro – 10 FemtoRT(2 MNB, 10 HNB placed rooftop)
- Case 4: 1% femtocell penetration: Macro – 30 FemtoIN(2 MNB, 30 HNB placed indoor)
- Case 5: 1% femtocell penetration: Macro – 30 FemtoRT(2 MNB, 30 HNB placed rooftop)
- Case 6: 2% femtocell penetration: Macro – 60 FemtoIN(2 MNB, 60 HNB placed indoor)
- Case 7: 2% femtocell penetration: Macro – 60 FemtoRT(2 MNB, 60 HNB placed rooftop)

In every case the location of the two MNBs remains same. For indoor and outdoor HNB deployment, HNB was placed in the same building, but with different height. For rooftop HNB the height depended on the height of the building. HNB is placed 1m above on the roof. So, for rooftop deployment if the building height is 3m, HNB is placed at 4m and at 7m if the building height is 6m. Figure 36 gives more clear idea about the deployment strategies.

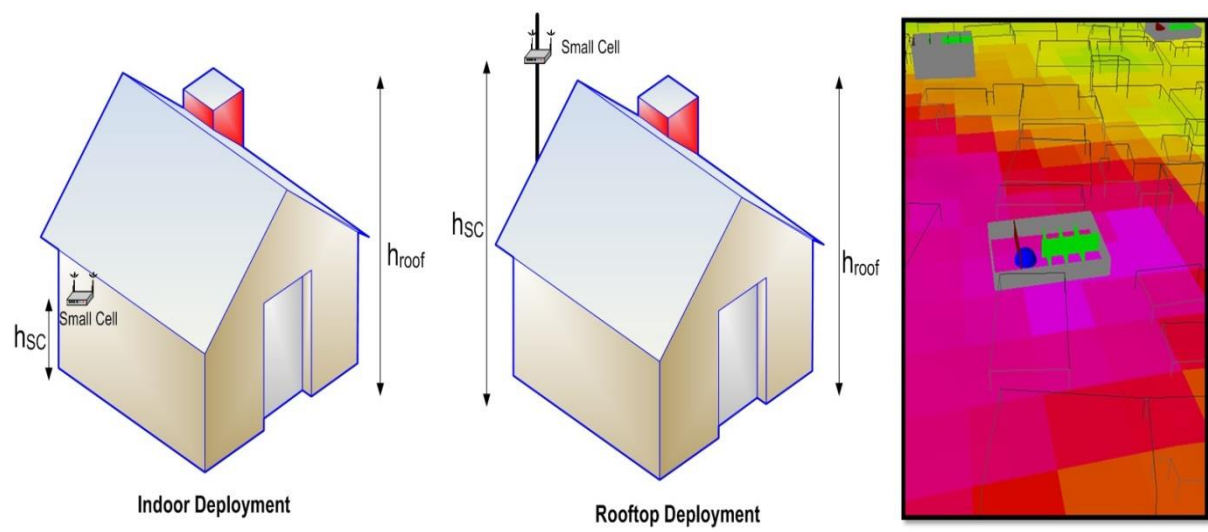


Figure 36: Small cells deployment strategies (Rooftop and Indoor) and WinProp image with the building and cell location (Indoor)

## 5. SIMULATION RESULTS

WinProp generated results in the selected area are discussed in this section. The obtained results for each different deployment scenario is elaborated and compared to each other. All the performance related important parameters e.g. Pathloss, Maximum DL throughput (voice and data), Maximum UL throughput (voice and data), Best Server, Cell area, Interference limited area, Coverage probability (in terms of different category of HSDPA scheme) were observed. The number of multicodes supported, length of the inter-TTI (Transmission Time Interval) gap during HS-PDSCH reception and overall radio channel condition are the main parameters to define the categories. Different categories support different modulation and coding schemes, which influences the data rate. The results were calculated for both Propagation related parameters and Network related parameters. Figure 37 shows one sample result of simulation in the selected area. Both the indoor and outdoor performances are considered and investigated. For better view “Cell Area” is shown in Figure 37.

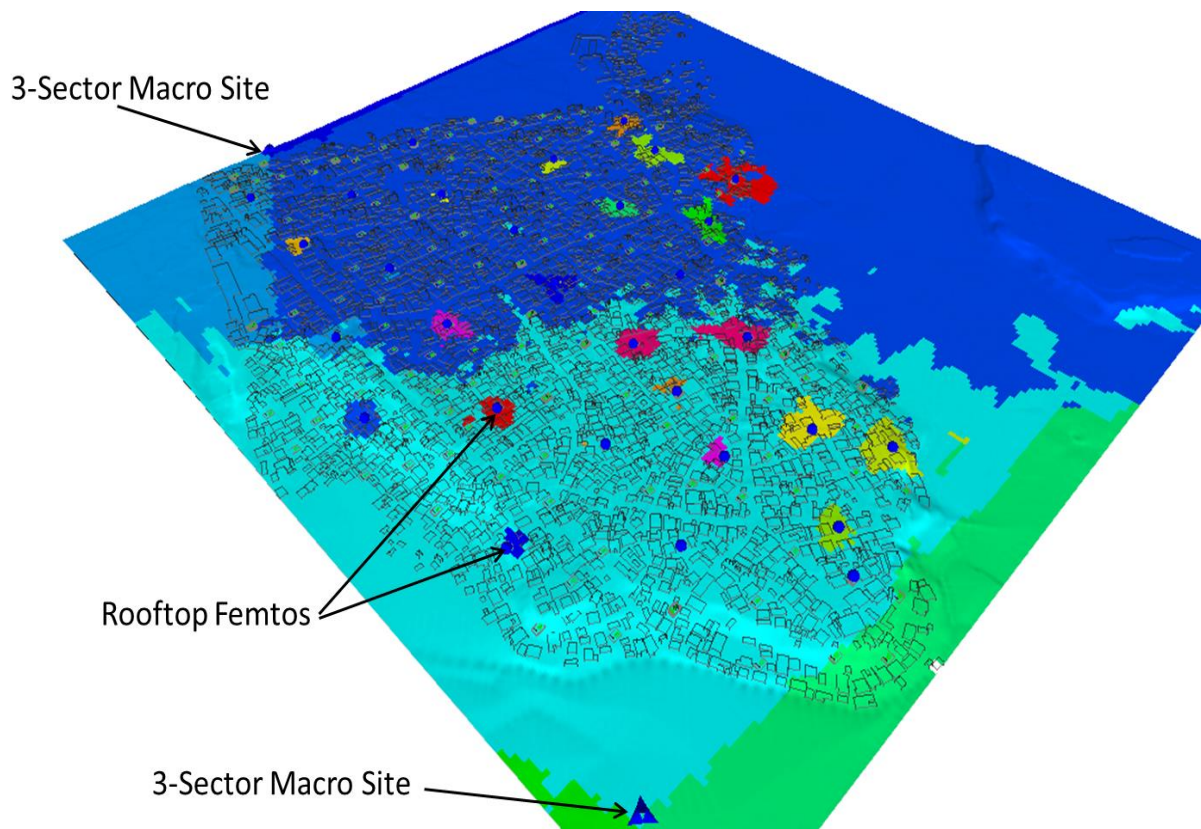


Figure 37: “Cell Area” plot of deployment scenario “Macro – 30 FemtoRT”



### 5.1. Propagation Modeling Results

Different deployment scenarios were observed to compare the performance gain and to predict the best of them. Several issues affected the total network performance, among them HNB position (indoor or outdoor) and percentage of HNB in the network created the mentionable differences between different deployment strategies. As HNB is low power base station, it actually operates with low transmitting power that could not penetrate the home wall much. So when HNBs are placed in rooftop the coverage area of the HNB increases much than when placed in indoor. And also a rooftop HNB doesn't serve indoor as much as an indoor HNB does.

Indoor performance can be highly improved by placing a HNB in that building and it doesn't impact on the outside of the building much. Though, it has some impact on the surroundings. But when HNB is placed on rooftops, it has a much larger cell area than indoor HNB. A rooftop HNB covers much more area than an indoor HNB. So expected off-loading is available for both the deployment strategies, but as rooftop HNB has a larger cell area so this deployment can actually offload much traffic comparing to indoor HNB.

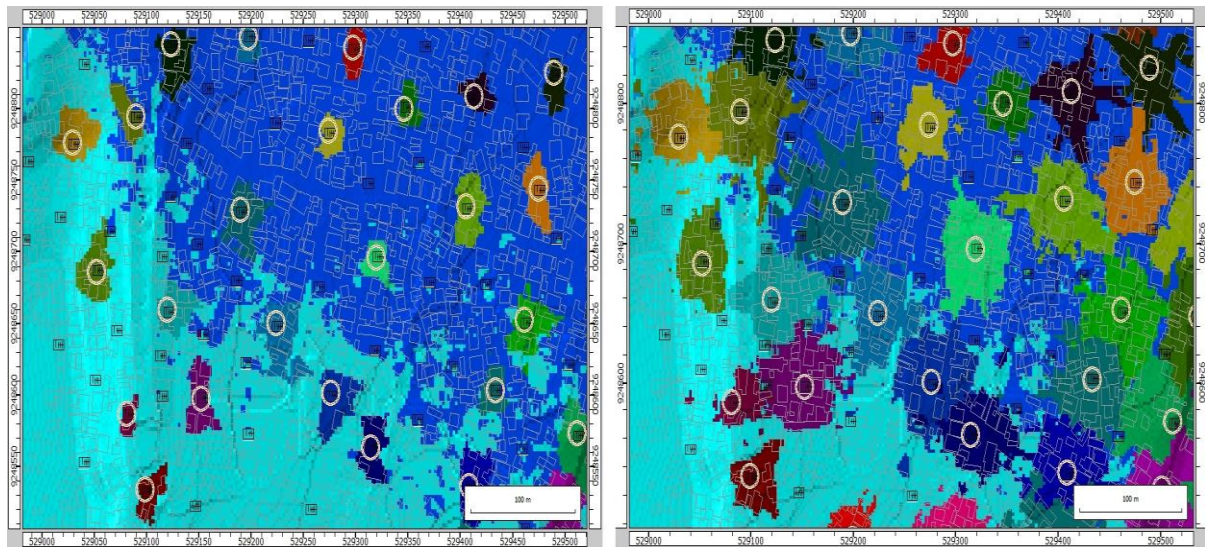


Figure 38: Cell area plot for a specific area with same number of HNB place indoor (left) and HNB placed rooftop (right), circle showing the HNB positions

Figure 38 shows a remarkable difference of cell area between indoor deployment and rooftop deployments. By controlling the transmit power of HNB the cell area can be adjusted as well.

Another illustration explains the difference between indoor and rooftop deployments. Figure 39 and Figure 40 show the signal power difference of HNB between rooftop deployment and indoor deployment for two different HNB. In this context, difference means the numerical value difference between two different results for each pixel. These illustrations give clear idea about the fact that, inside the building users can get better signal strength when HNB is placed indoor. The signal power difference is like 5 – 10 dB inside the building but outside the building the power difference is large, even up to 30 dB is available. The scenario is very different inside the building and outside the building. Even with the same transmitting power, just because of the placement of HNB it can vary the cell area very much. Pathloss plot also shows same the kind of difference between rooftop and indoor placed HNBs. Figure 41 and Figure 42 shows pathloss calculation plot for a particular area with three different deployments. For only macro case, there was no HNB in that area and only server was the long distant MNB. Then one HNB was placed indoor one building which improves the coverage area there and mostly inside the building is improved. And then that HNB is placed on the rooftop of that building. Now a larger area is getting good signal from the HNB. Pathloss calculation is very important for calculating the other parameters. And from these figures clear illustration of the network performance can be assumed for three different deployments.

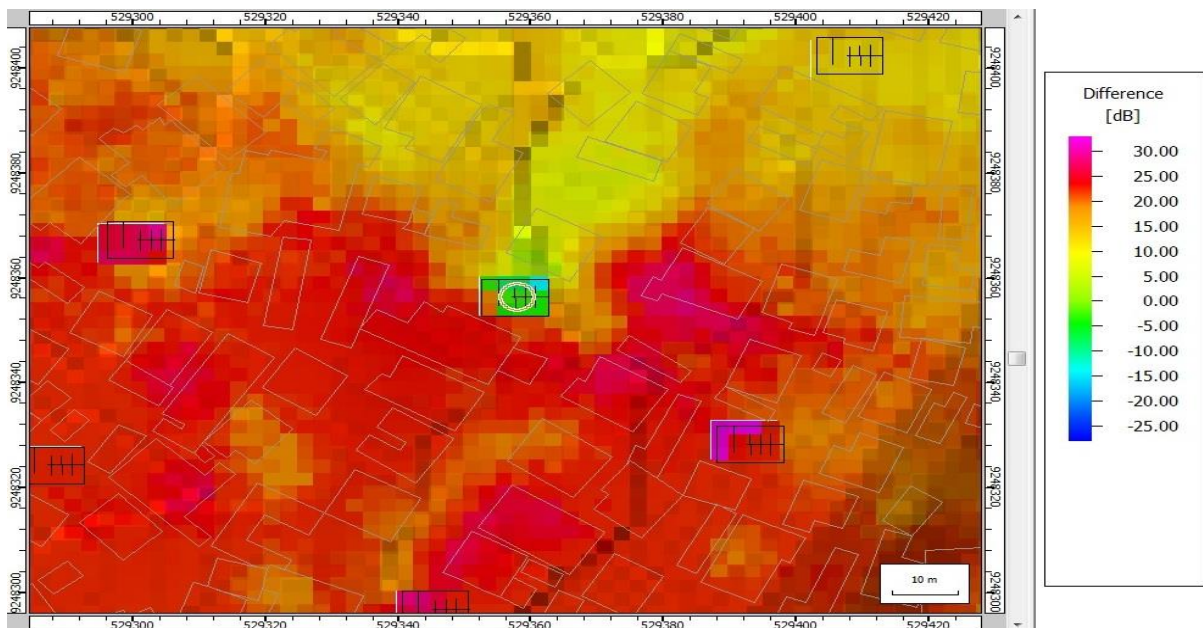


Figure 39: Signal power difference plot between HNB rooftop and HNB indoor



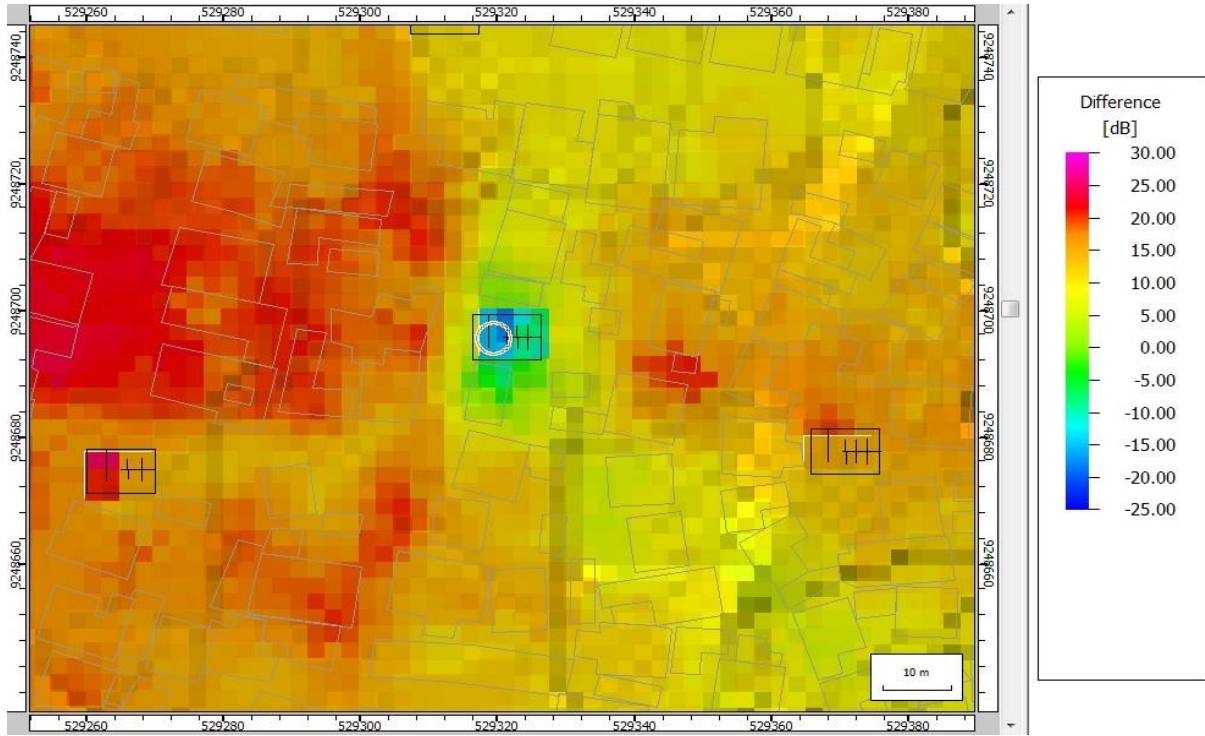


Figure 40: Signal power difference plot between HNB rooftop and HNB indoor for another HNB

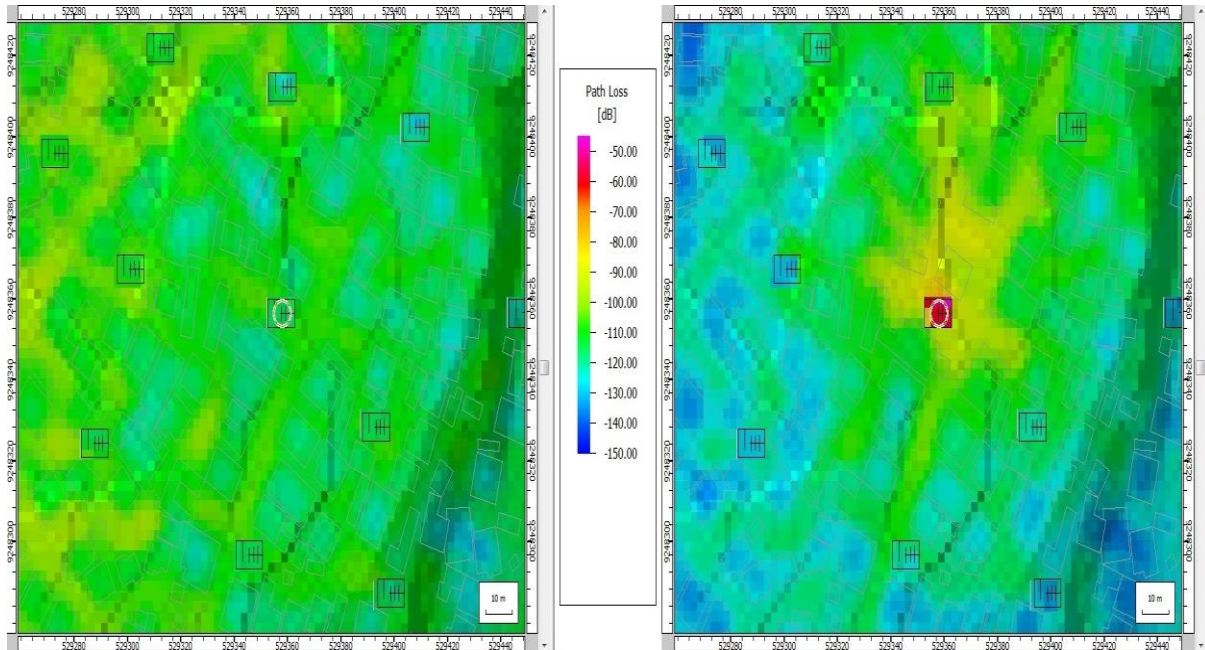


Figure 41: Pathloss maps for Macro only (left) and HNB indoor (right) on same area

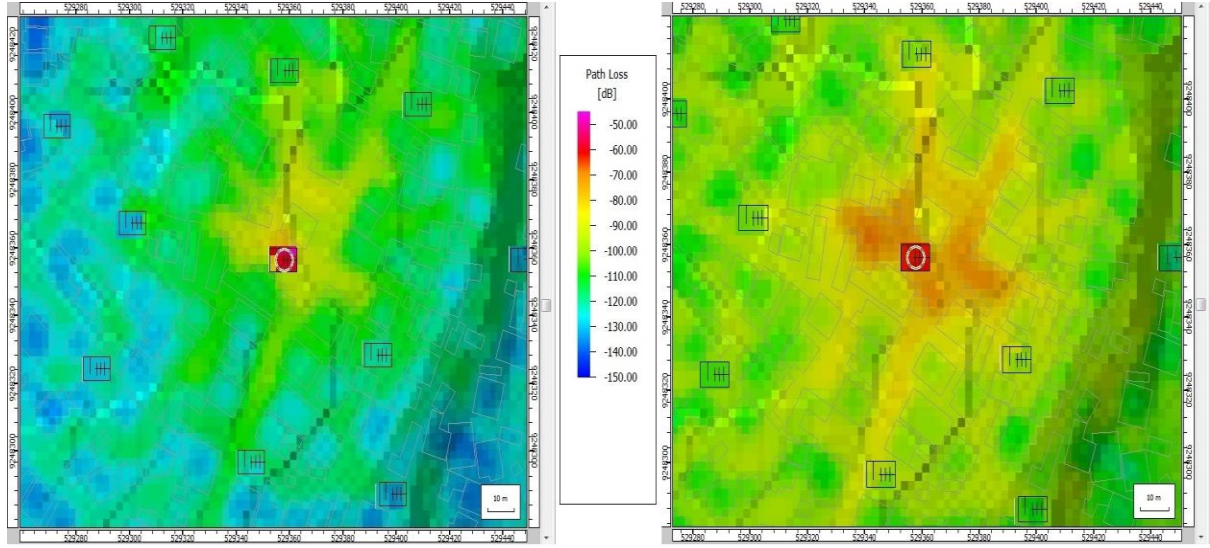


Figure 42: Pathloss maps for HNB indoor (left) and HNB rooftop (right) on same building

It is already clear that putting HNB indoor and rooftop have different impact on the network and both the strategies are improving the overall network than Macro-only case. In terms of coverage extension, capacity improvement and better indoor coverage HNB deployment is very useful.

## 5.2. Network Performance Results

Now focus on the impact of femto penetration (percentage buildings having HNB) and deployment strategy in the network performance. With the increment of the femto penetration the overall network performance increases almost drastically. Two parameters can be used here to observe the improvement, maximum achievable “ $E_c/(N_0+I_0)$ ” and “DL maximum throughput”. The  $E_c/(I_0 + N_0)$  describes the situation before despreading. Accordingly  $I_0$  includes the full interference power density of the own cell (independent of the defined orthogonality factor) as well as the interference power density of the neighboring cells and the noise power density.  $E_c$  is the energy per chip. And, DL maximum throughput results describe the overall peak DL throughput which is possible considering the defined network with various transmission modes and possibly multiple carriers in a particular pixel.

$E_c/(N_0+I_0)$  in the network varies with different deployment strategies. When HNB is placed indoor the performance indoor improves largely and users get a better experience. The network scenario changes with the location of the HNB and number of HNB in the network.



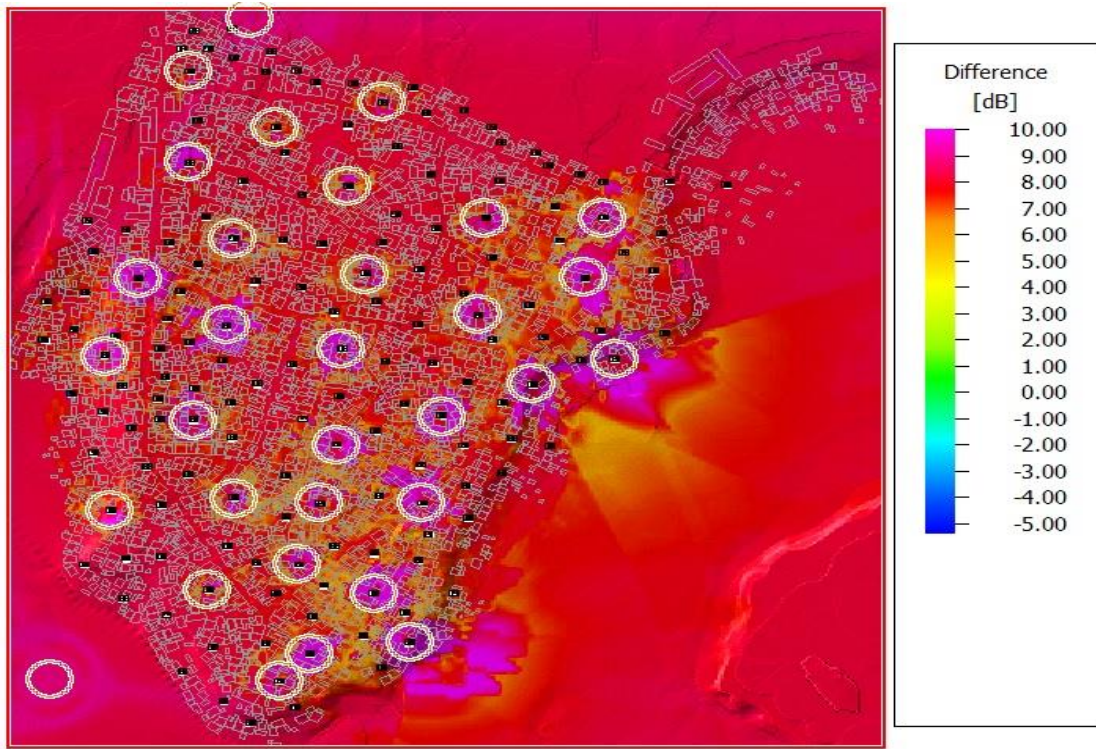


Figure 43:  $E_c/(N_0+I_0)$  value difference between 30 Femto indoor deployment and rooftop deployment.

Figure 43 shows the difference plot of HNB indoor placement and rooftop placement. This plot clearly shows some reasonable difference between two different strategies. When HNBs are placed indoor, as like the propagation results the inside the buildings are getting better quality signal. When HNBs are placed rooftop the surrounding of the building gets better performance too. But inside the building it's poorer than before. Rooftop HNB has a larger cell area so there is some possibility to increase interference in the network as well. When number of HNB in the network increases the probability of creating interference also increases with the rooftop deployment. Figure 43 shows some obvious difference in the network performance due to different deployment strategy and introduced interference is discussed later.

And also these performances vary with the number of HNB in the network. As the number of HNB in the network increases the overall performance of the network gets better. Frequency reuse with cell densification gives the performance gain we already discussed and in this simulation results also reflects that statement logically.

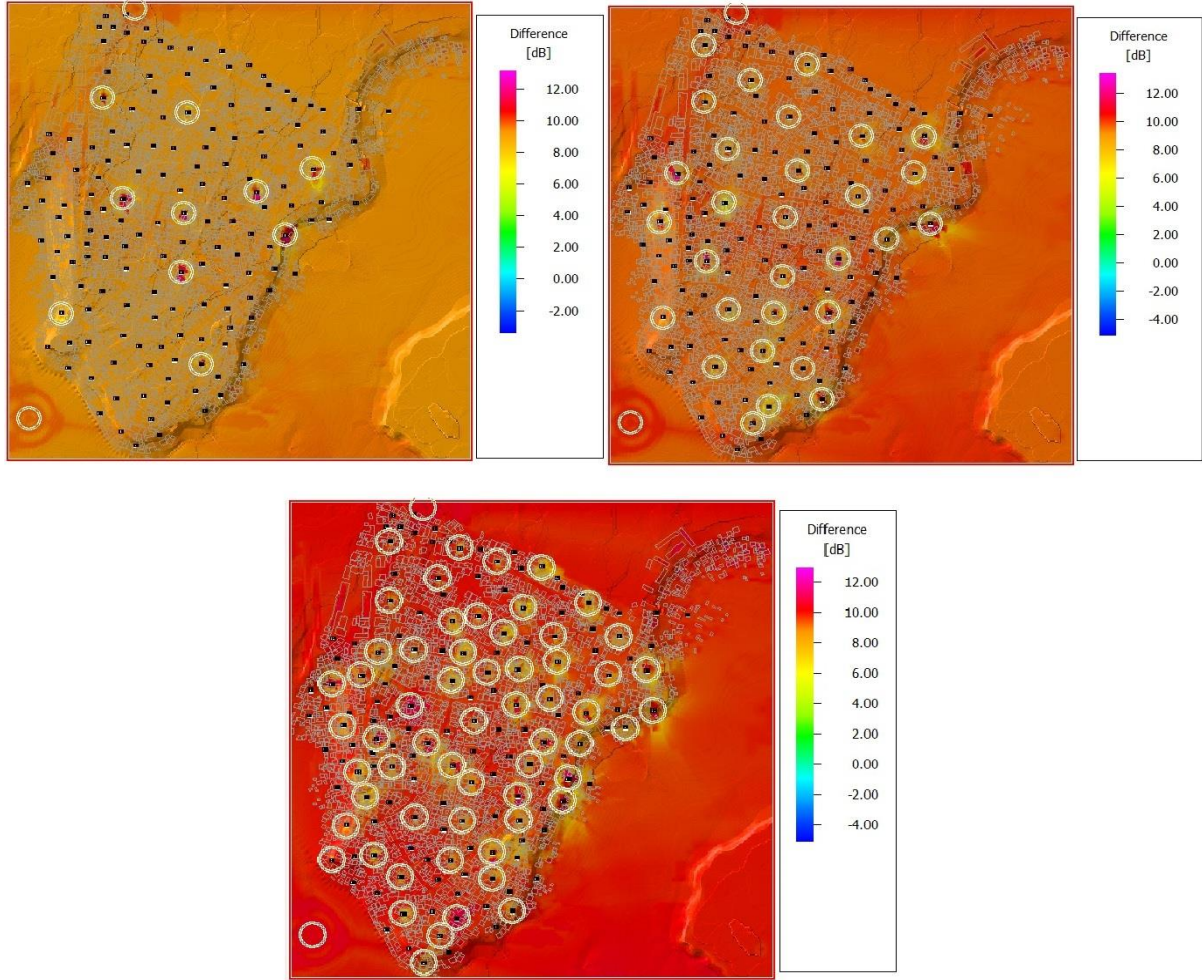


Figure 44:  $E_c/(N_0+I_0)$  value difference between deployment case 2 (Macro – 10 FemtoIN) and case 1 (Macro – Only) (top left), case 4 (Macro – 30 FemtoIN) and case 2 (Macro – 10 FemtoIN) (top right), case 6 (Macro – 60 FemtoIN) and case 4 (Macro – 30 FemtoIN) (bottom)

Figure 44 shows in every case of increment in the HNB penetration the overall network performance is better than the previous deployment. And that difference is quite remarkable. With the network performance in terms of  $E_c/(N_0+I_0)$ , the other network parameters like available DL throughput, data rate and coverage probability of different HSPA categories also varies.

Femto penetration improves the performance in terms of available maximum DL throughput also. Overall network throughput, maximum achievable, poor throughput area, was improved with the femto penetration. Inside the buildings and surroundings which have HNB in it, having far better performance than Macro – Only case. And the cell edge users are getting far better performance with HNB deployed.

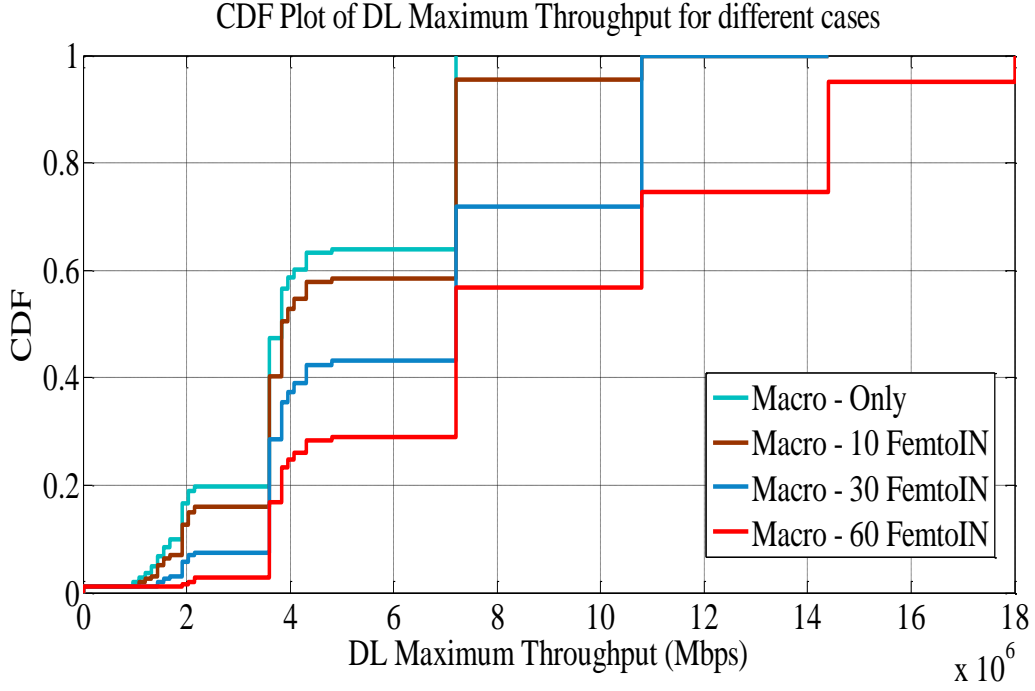


Figure 45: CDF plot of DL maximum throughput for different deployments; (FemtoIN: Indoor Femto, FemtoRT: Rooftop Femto)

Figure 45 illustrates the DL maximum throughput for 4 different cases. WinProp uses some discrete value while calculating DL throughput, like: 3.6Mbps, 7.2Mbps, and 10.8Mbps. That is why the CDF looks staircase. No continuous values of throughput, it makes the CDF with steps. However, as like previous Figure 44 this also shows the performance improvement with the femto penetration increment in the network.

Now we can dig down to the numerical values of the stated results. The performances of different deployment strategies in terms of maximum DL throughput are tabulated below. Table 8 shows details of Maximum DL throughput for different studied cases. As like the CDF plot this table also shows the remarkable performance difference between different types of deployment strategies. In every case of HNB indoor deployment, the network performance gets better with the increased number HNB in the network. But after some extent rooftop HNB deployment with the larger cell area it creates interference and affects the network performance. This fact is discussed more detail in the next section.

Different deployment cases	Percentage of Areas for different Peak DL Throughputs			
	$\leq 4$ Mbps	$\geq 7.2$ Mbps	$\geq 10.8$ Mbps	$\geq 14.4$ Mbps
Case 1 (Macro – Only)	60%	36%	0	
Case 2 (Macro – 10 FemtoIN)	50%	42%	5%	0
Case 3 (Macro – 10 FemtoRT)	52%	42%	5%	0
Case 4 (Macro – 30 FemtoIN)	35%	56%	28%	0
Case 5 (Macro – 30 FemtoRT)	45%	44%	22%	0
Case 6 (Macro – 60 FemtoIN)	25%	72%	26%	5%
Case 6 (Macro – 60 FemtoRT)	50%	46%	12%	3%

Table 8: Maximum DL throughput details for different deployment strategies

#### 5.2.1. Performance gain

CDF of DL maximum throughputs for all the cases are plotted in the Figure 46. With the increment in femto penetration network performance is being gradually improved. To compare the results more numerically, gain was calculated relative to the primary deployment scenario (Case 1, Macro – only). Figure 47 shows the CDF of DL throughput gain of all the cases over Macro – only case. 2% femto penetration is giving even up to gain 5 for some points. Among all the deployments, Case 6 (Macro – 60 FemtoRT) is giving the best gain overall. And Figure 48 is the bar plot coverage probability (probability more than 90%) for different HSPA categories for all the different deployment strategies. Increment in femto penetration gives an extensive gain in every parameters of the network. All these plots are giving a clear idea about the impact and improvement of the network performances with femto penetration in the network. But one very interesting findings from these figures is rooftop deployments are performing poorer than indoor deployments. This is because indoor users are getting much higher throughput when femto is placed indoor. Yet, when HNB is placed rooftop, cell area increases and probability of interference in the network increases which degrades the network performances.

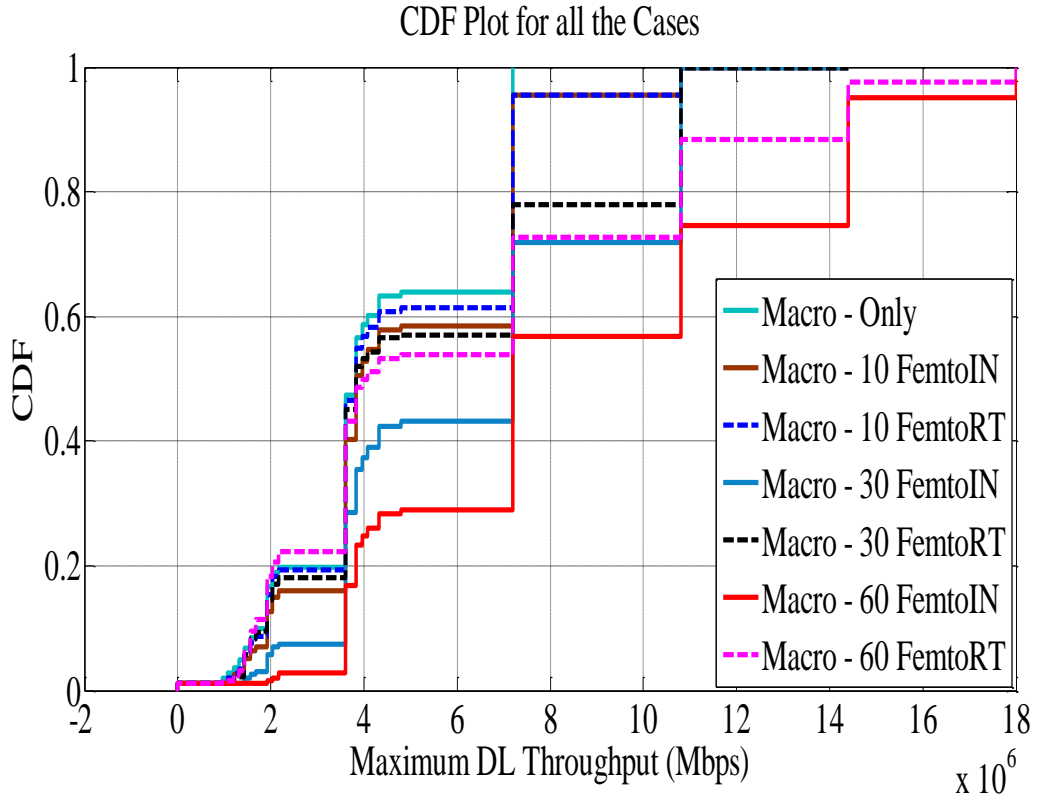


Figure 46: Maximum DL throughput CDF for all cases

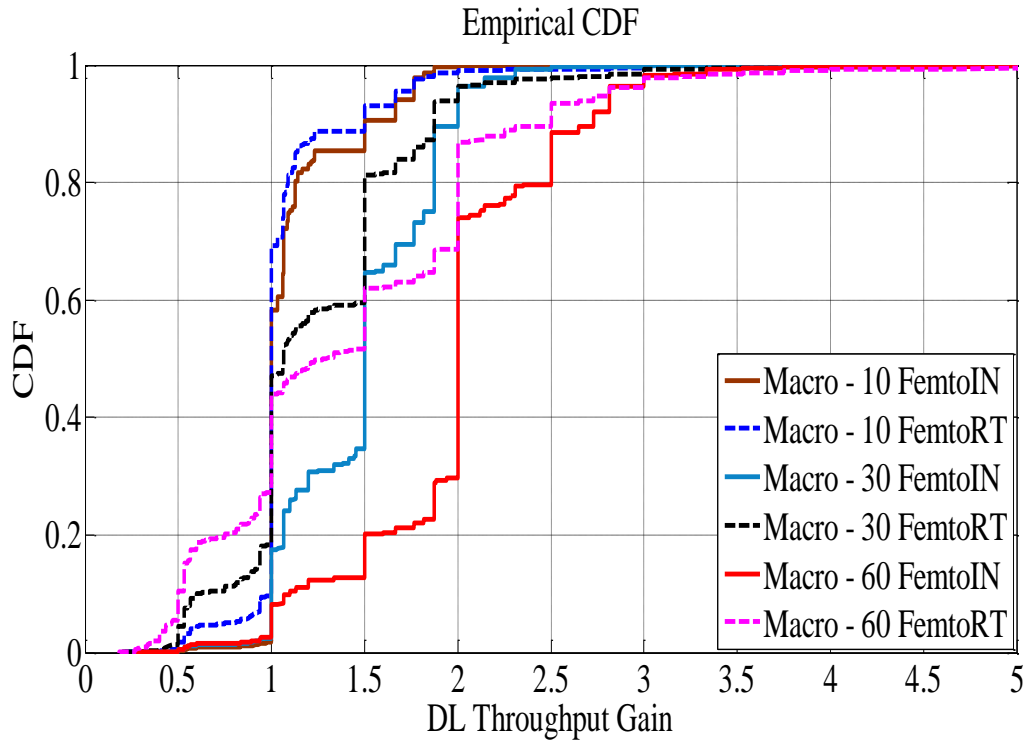


Figure 47: Peak throughput gain for different femto deployment scenarios relative to Macro-Only case

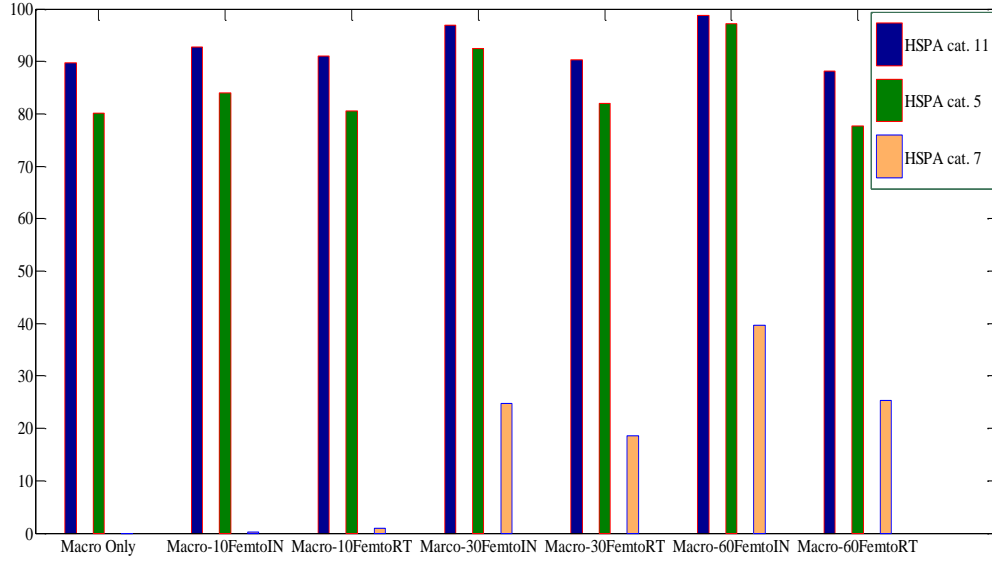


Figure 48: Coverage probabilities for HSPA Category 11, 5 and 7 schemes in the simulated area

Figure 48 is the bar plot of coverage probability for different HSPA categories. Different categories require different level of signal quality and gives different level of performances. Appendix section gives more detail about the different categories. Among the three categories in the figure, category 7 requires the highest level of signal quality. And category 7 can be considered as available after 2% of femto penetration in the network for this study. Category 11 and category 5 is available for all the deployment strategies, but probability varies. Here again, with the increment of HNB in the network, the availability of different HSPA categories increases. Yet, the indoor and outdoor deployments give different performance and some level of degradation for outdoor deployment is clear from the figure. This degradation or poor performing fact for all the rooftop cases can be described with the interference in the network. As discussed in section 5.1, rooftop deployments are increasing the cell area largely so it creates interference with existing MNB and even neighbor rooftop HNB. Figure 49 is the CDF plot of pilot interference level in the network for different deployment strategies. The multipaths from the serving base stations and the multipaths from the other neighboring base stations create interference in when demodulating a CDMA signal. A substantial portion of the interference on any particular multipath may be from the pilots in the other multipaths included in the received signal. This pilot interference degrades the network performance.



From Figure 49 we can see how in every case rooftop deployments are introducing more interference in the network than indoor deployments. Another interesting fact to observe from this figure is, with the increment in the number of HNB in the network the difference of pilot interference between rooftop and indoor deployment increases. More number of HNB in the network increases the probability of creating interference with neighbor HNB as well. When 10 HNB was placed the difference between indoor and rooftop is not much. As the number of HNB in the network increases the difference and interference due to rooftop deployment increases. Interference adversely affects the capacity of a radio system and the quality of the individual communication links on the system [37].

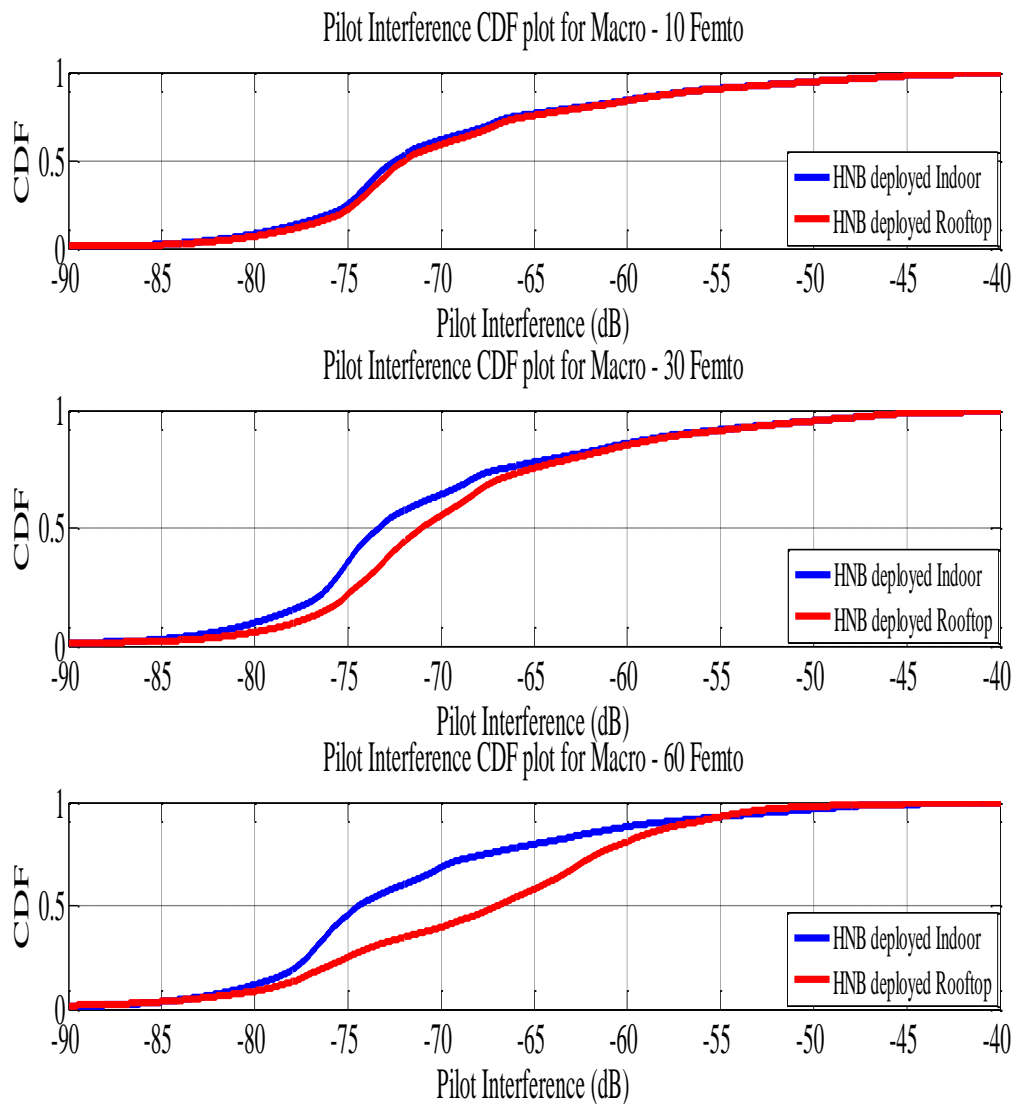


Figure 49: CDF comparison of pilot interference level in the network for indoor HNB and rooftop HNB deployments

As mentioned earlier, in this study no interference mitigation techniques were applied so those obvious introduced interferences in the network degrading the network performance up to some little extent. But from these results this idea is clear that some interference mitigation techniques should be adopted especially when HNB is placed rooftop. Indoor HNB has smaller cell area and coverage remains much inside but to get the benefit of more off-loading with larger cell area by rooftop deployment the interference should be taken care of. General techniques can be the SON which is a very interesting and fruitful advantage of HNB. Deploying HNB rooftop with lesser transmit power can be another simple and smart technique.

Putting HNB in rooftop has some great advantages if the network performances can be taken care. One of the great advantages is rooftop HNB have larger cell area which performs better for off-loading purpose. As wireless backhaul is proposed, so indoor HNB might face weak signal for backhaul as a matter of wall penetration loss. But sometimes rooftop HNB can get Line of Sight (LOS) from the backhaul MNB. Power consumption is also another challenge in HNB based network. Rooftop deployments can give an advantage to this also. Rooftop HNB can be operated by solar power. Though it is also available for indoor HNB but with additional cable.

## 6. CONCLUSIONS AND FUTURE WORK

“Small cells” is being a highly researched topic in recent days. It’s interesting features and usability making is more popular. In urban areas of many developed countries small cells are already available in operation. Among the several small cells the term Femtocell (HNB) is most popular as it is used for enhancing the coverage indoor. In developed countries many offices, households, schools and hospitals are using HNB to experience better coverage using HNB. Third Generation (3G) mobile technologies made the mobile broadband popular in such low- income emerging markets. In this thesis study, main scope was to study the usability of 3G HNB in emerging market environment to bring the mobile broadband to the mass with cheaper solutions. As from operator’s view point it is not profitable to invest much in such areas.

Simulation study highlights the potential benefits of using femtocells in the network for extended broadband connectivity in high density low- income settlements. Deploying HNB in the network ensures improvement in network performances. Indoor users get very good signal quality and higher throughput. Cell edge users with HNB deployed can experience remarkable improvement in the network performance. Comparison between different deployment strategies gives an idea about the performance gain when HNBs are placed in the network. With the femto penetration increment the performance gain increases also. Two different deployment strategies have been studied and potential benefits are clear. Placing HNB rooftop, gives larger cell area which can lead to higher possibilities of off-loading. Indoor HNB performs very well for the indoor coverage and indoor users get massive benefit from HNB.

However, the results and situation might vary with the simulation environments also. In more dense areas with high rise buildings, more number of HNB can be placed without having interference in the network. This study is done on a low clutter area which allows signals to propagate more distances without any obstacles. And also increment of HNB in the network increases the necessity of interference mitigation techniques. But at the end, to bring wireless broadband to the mass, Heterogeneous Network with HNB can give the best solution in terms of service and cost point of view. As femtocells are supposed to be user deployed and

operated so, SON is something very important to be implemented. This simulation study also shows the potential degradation in the network due to interference.

There are large scopes of future work on this thesis. In this study backhaul was expected to be perfect with proper capacity and quality. But it might not be the real scenario so a study about the backhaul can be very interesting as this study focuses on the access part only. Total network performance can be improved by applying advanced interference mitigation techniques. Which can give best optimization between offload and network performance. Other aspects like, energy – efficiency for prolonged off – grid operation, mobile self-backhauling, exploitation of new spectrum bands and innovative business models that enhance feasibility of “Small Cell” deployments in such informal settlements can be also future research scope of this study.

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## APPENDIX – HSPA CATAGORIES

3GPP Release	Category	Max. number of HS-DSCH codes	Modulation <sup>[3]</sup>	MIMO, Dual-Cell	Code rate at max. data rate <sup>[4]</sup>	Max. data rate [Mbit/s] <sup>[5]</sup>
Release 5	1	5	16-QAM		.76	1.2
Release 5	2	5	16-QAM		.76	1.2
Release 5	3	5	16-QAM		.76	1.8
Release 5	4	5	16-QAM		.76	1.8
Release 5	5	5	16-QAM		.76	3.6
Release 5	6	5	16-QAM		.76	3.6
Release 5	7	10	16-QAM		.75	7.2
Release 5	8	10	16-QAM		.76	7.2
Release 5	9	15	16-QAM		.70	10.1
Release 5	10	15	16-QAM		.97	14.0
Release 5	11	5	QPSK		.76	0.9
Release 5	12	5	QPSK		.76	1.8
Release 7	13	15	64-QAM		.82	17.6
Release 7	14	15	64-QAM		.98	21.1
Release 7	15	15	16-QAM	MIMO	.81	23.4
Release 7	16	15	16-QAM	MIMO	.97	28.0
Release 7	19	15	64-QAM	MIMO	.82	35.3
Release 7	20	15	64-QAM	MIMO	.98	42.2
Release 8	21	15	16-QAM	Dual-Cell	.81	23.4
Release 8	22	15	16-QAM	Dual-Cell	.97	28.0
Release 8	23	15	64-QAM	Dual-Cell	.82	35.3
Release 8	24	15	64-QAM	Dual-Cell	.98	42.2
Release 9	25	15	16-QAM	Dual-Cell + MIMO	.81	46.7
Release 9	26	15	16-QAM	Dual-Cell + MIMO	.97	55.9
Release 9	27	15	64-QAM	Dual-Cell + MIMO	.82	70.6
Release 9	28	15	64-QAM	Dual-Cell + MIMO	.98	84.4