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TAMPERE UNIVERSITY OF TECHNOLOGY

WAQAS UL HASAN ANSARI

IMPACT OF FEMTOCELL BACKHAUL LIMITATION ON PERFORMANCE OF MACRO-FEMTO HETNET

Master of Science thesis

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ABSTRACT

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This thesis is a techno-economical study which focuses on addressing the exponentially rising data capacity demand through network densification. The study is based on the two popular deployment strategies; Macrocellular networks and Macro-Femto heterogeneous networks, deployed in a suburban type environment with modern houses. The main aim of the dissertation is to investigate the impact of network densification on *capacity*, *energy-* and *cost-efficiency* of the network, while considering different femtocell backhaul connectivity limitations.

The network performance is evaluated for both indoor and outdoor scenarios. A comparative analysis between the macrocellular and macro-femto network is done by increasing the density of the macrocells, femtocells and the operating frequency spectrum. The capacity is enhanced by increasing the density of the cell sites in the network but operators want to generate profit and want to adopt a cost effective solution to cater the problems. The results show that increasing the density of low-cost, low-powered femtocell access points (FAPs) in the network can solve the problem of 1000x future data capacity demand while keeping the CAPEX and OPEX of the network relatively lower than legacy pure macrocellular deployments. The deployment of the FAPs both in indoor and outdoor environments enhances the network capacity.

This study helped in providing results, understanding and insight of both technical and techno-economical aspects of different mobile network deployment and densification solutions. Furthermore, the outcome of the thesis will give some guidelines for network vendors and mobile operators in evolving their network in future.

PREFACE

This Master of Science thesis has been written for the completion of my M.Sc degree in Electrical Engineering from Tampere University of Technology. The research was carried out during the year 2015 at the Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland.

I would like to thank my supervisor M.Sc Syed Fahad Yunas for guiding me to carry out and complete this research. I learned a lot from his academic and technical expertise in the field of wireless communications. His valuable experience helped me a lot in learning and exploring new things.

I extend my gratitude and pay warmest regards to my parents and sisters. Their support and encouragement is continuous source of motivation.

In the end, I would like to thank every person who helped me in this study especially my friends; Salman, Hamza Ehtisham, Adnan, Ali, Qutab and others. I thank all of them for their encouragement and motivation.

Tampere, November 2015

Waqas ul Hasan Ansari

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LIST OF ABBREVIATIONS AND SYMBOLS

2G Second Generation

3G Third Generation

3GPP 3rd Generation Partnership Project

4G Fourth Generation

AMPS Advanced Mobile Phone System

ARQ Automatic Repeat-reQuest

AuC Authentication Center

BTS Base Transceiver System

CDM Code Division Multiplexing

CDMA Code Division Multiple Access

CEPT Conference of European Posts and Telegraphs

CN Core Network

CP Cyclic Prefix

CS Circuit Switch

DCF Discounted Cash Flow

DPM Dominant Path Model

DSL Digital Subscriber Line

EIR Equipment Identity Register

EIRP Effective Isotropic Radiated Power

eNB Evolved Node B

ETSI European Telecommunication Standard Institute

EUTRAN Evolved UMTS Terrestrial Radio Access Network

FAP Femtocell Access Point

FDD Frequency Division Duplexing

FDMA Frequency Division Multiple Access

FPGA Field Programmable Gate Array

FPLMTS (Future Public Land Mobile Telecommunications Systems

GGSN Gateway GPRS support node

GSM Global System for Mobile

HetNet Heterogeneous Network

HLR Home Location Register

HPBW Half Power Beam Width

HRPD High Rate Packet Data

HSPA High Speed Packet Access

HSS Home Subscriber Server

IP Internet Protocol

IRC Interference Rejection Combining Receiver

ISD Inter-Site Distance

ISI Inter-Symbol Interference

ITU International Telecommunication Unit

KPI Key Performance Indicator

LOS Line of Sight

LTE Long Term Evolution

MIMO Multi-Input Multi-Output

MME Mobility Management Entity

MS Mobile Station

MSC Mobile Switching Center

NMT Nordic Mobile Telephone

NPV Net Present Value

NSS Network and Switching Subsystems

OFDMA Orthogonal Frequency Division Multiple Access

OSG Open Source Group

OSS Operation and Support Subsystems

PDN Packet Data Network

PIR Parallel Interference Cancellation

PS Packet Switch

PSTN Public Switched Telephone Network

QoS Quality of Service

RACE Research into Advanced Communications in Europe

RAN Radio Access Network

RNC Radio Network Controller

RNS Radio Network Subsystems

SAE System Architecture Solution

SDMA Spatial Division Multiplexing Access

SIC Successive Interference Cancellation

TACS Total Access Communication System

TDD Time Division Duplexing

TDM Time Division Multiplexing

TDMS Time Division Multiplexing Access

UMTS Universal Mobile Telecommunications Services

UTRA Universal Terrestrial Radio Access

VLR Visitor Location Register

VoIP Voice over IP

WCDMA Wideband CDMA

WiFi Wireless Fidelity

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

1. INTRODUCTION

This chapter briefly describes the background of the wireless systems and its evolution. The motivation of the research is discussed along with the scope of the thesis. The chapter concludes by providing the outline of the thesis.

1.1 Background and Motivation

The history of wireless networks dates back to the era when the communication was done maily through smoke signaling, torches and flashing mirrors etc. These primitive communication techniques were then replaced by the telegraphs which were invented in 1838 by Samuel Morse following the invention of the telephone which was a significant breakthrough in the communication systems. Radio technology kept on evolving making it possible to transmit the signals over a longer distance with low cost and low power equipment and with better service quality, which made it accessible to public and targeted the mass market.

Wireless communication is by far the most rapidly flourishing sector of the telecommunications. With the accelerated growth in the subscribers, the number of mobile devices have also grown exponentially and now more than 2 billion mobile users exist worldwide. Cellular networks have been evolving ever since to cater the demands of coverage and capacity. Wireless networks are, nowadays, deployed almost everywhere, replacing the old conventional wired telephony system. Additionally, Wireless Local Area Networks (WLANs) have also been deployed to provide seamless data access to virtually everyone on the planet. Earlier cellular systems were limited in capacity and coverage and inefficient in utilizing the frequency spectrum hence they were able to provide service to a mere few users in the coverage region.

The first generation of cellular networks appeared in 1983 which were based on analog technology. The second generation cellular systems, based on digital technology, was deployed in early 1990s. The motivation to evolve from analog system to the digital one was enhanced capacity, lower costs, improved throughput and power efficient equipment. The second generation technology offered basic telephony services but with the passage of time, there was a need to introduce a system that could fulfill the emerging demands of the users such as email, internet browsing, video streaming and online games etc.

In order to cater for the rising capacity demands, 3GPP (Third Generation Partnership Project) introduced UMTS (Universal Mobile Telephone System) and LTE (Long Term Evolution) which are able to provide high data rates, low latency and much higher spectral efficiency compared to the previous standards.

1.2 Scope of the Thesis

Keeping in view the drastic increase in the subscribers' footprint, experts have predicted that the data growth will be 1000× by the year 2020 [3]. Around 25 billion interconnected devices are estimated to be present by 2020 and there will be approximately 7 billion smart phones forecasted between the year 2013-2017 [3]. New advancements are being done in the existing network technologies to support the exponential increase in the capacity to improve the efficiency of the networks, keeping the cost and energy aspects affordable. Different technologies are employed to increase the capacity of network like evolved 3G/4G/Wi-fi, Heterogeneous Networks (HetNet) and Intelligently Access 3G/4G/Wi-Fi. Recently small cells have been introduced as a low cost, low powered alternative solutions to enhance the capacity and coverage in the indoor environment.

The extreme densification of a network has been identified as a key methodology to 1000× capacity problem which means small cells will have to be deployed virtually everywhere. The network-level capacity can be significantly increased using this strategy. This implies that capacity is directly proportional to the number of base stations deployed in certain area. But increasing the base stations is not always feasible because there are various factors that need to be addressed. The major concern for any operator is the cost factor that has to be controlled in order to compete with other operators and provide service to the users at affordable price.

In the cellular networks, it has been contemplated that 60% to 90% mobile traffic is generated by indoor users [4]. Mobile operators have so far been providing service to the indoor users by the conventional macrocellular base stations. It has been reported that the most of the complaints related to poor coverage come from the indoor users [4] The reason for the poor coverage in the indoors is deterioration of the signal strength as it penetrates through the walls and other obstruction to reach the receiver. To overcome this issue, operators may densify the existing network, i.e. increase the number of macro- and micro- base stations or introduce the more recent technology. *Femtocells are small cellular base stations, typically used by an end user to connect to the mobile operator's network via their broadband connection. Femtocells offer more than just improved mobile reception with better security, they also expand location and presence awareness and improve battery life* [5]. The issue of poor indoor coverage can be addressed by using the femtocell technology as they are placed indoors and provide excellent coverage. However, due to their small coverage area, they are needed to be deployed in an ultra dense fashion to provide seamless coverage throughout the whole indoor environment. Thus, not only coverage is improved, the capacity is also enhanced. Nevertheless the ultra-dense deployment of indoor femtocells also triggers cost and energy concerns for the mobile operators.

In this thesis, the main objective is to investigate the impact of the femtocell backhaul limitation on the performance of femtocells networks in indoor and outdoor environment. As mentioned earlier, the femtocells connect to a mobile operators core network using end user's broadband connection as the backhaul. Hence, the data throughput is limited by the connection speed of the broadband backhaul connection, which in turn impacts the offered capacity.

The key factors that are considered for the analysis are:

- Network Capacity
- Energy Efficiency
- Cost Efficiency

The analysis is done for a suburban scenario and the connectivity speeds considered in the analysis for the femtocell backhaul are taken to be [2, 4, 8, 16, 32 and 100] Mbps. This set of data rates is formed in such a way that it ranges from low to ultra high speed internet connection. A report published by Akamai Technologies in fourth quarter (Q4) of the year 2014 reveals the top ten average data rates of internet broadband connections around the world [2]. Table 1.1 enlists the top ten countries with respect to their average data rates.

Table 1.1 *Global Average Broadband Connection Speeds [2]*

No.	**Country/Region**	**Q4'14 Avg. (Mbps)**	**YoY Change**
1	South Korea	22.2	1.6%
2	Hong Kong	16.8	37%
3	Japan	15.2	16%
4	Sweden	14.6	34%
5	Switzerland	14.5	21%
6	Netherlands	14.2	15%
7	Latvia	13.0	25%
8	Ireland	12.7	24%
9	Czech Republic	12.3	8.4%
10	Finland	12.1	33%
-	**Global**	**4.5**	**20%**

From the statistics given in the Table 1.1, it is evident that the top country with the highest average broadband data connection is South Korea (22.2 Mbps). Some under-developed countries have average broadband speed as low as 0.7 Mbps (Libya). Finland has the average internet speed of 12.1 Mbps. This implies that the internet connection speed of the backhaul link in the femtocell networks play a pivotal role.

Apart from the backhaul limitation, the thesis also studies the impact of femtocell market penetration on the overall network capacity. The results are then compared with pure macrocellular densification. For the analysis, the femtocell market penetration have been assumed to be [0, 5, 10, 15, 20, 25, 50, 75 and 100]% penetration rates of the femtocells in the network to analyze different market scenarios.

1.3 Previous studies on network densification

Various studies have been done regarding the densification of networks and techno-economic issues in the past. The concept of enhancing of network capacity by densification of networks dates back to 1940's when D.H. Ring proposed the idea of cellular system [6], [7]. Later on, multiple publications were published on the concept of cellular networks to address the capacity demands and the problem of spectral congestion [8].

Due to massive growth of mobile users over the past decade, the drastic increase in capacity demand urged researchers to devise other low cost capacity enhancing solutions in parallel with the conventional wireless mobile networks. Low cost and low power small cells gathered much attention of the telecom industry. The first case of such small cell site was reported in 1990 by Alcatel [9]. The word 'femtocell' was first used around year 2005 bythe industry referring to a small, stand-alone and self managing home base station. Femtocell standardization started in 2007 initiated by the Femto Forum later changed into Small Cell Forum [10].

Some research articles related to the densification of network to enhance the network capacity and referred in [11] and [12]. This study is an extension of the research done in the article [13] which is performed using the deterministic ray-based methods utilizing the 3-D propagation model unlike the previous studies which are based on empirical models.

1.4 Outline of the Thesis

The remaining sections of the thesis are listed as below:

- Chapter 2: This chapter describes the cellular concept in detail. Starting with the history of the cellular networks, it continues to explain multiple access techniques, interference issues and capacity enhancing techniques. In the end, the general architecture of different 3GPP standards are discussed.
- Chapter 3: In this section, radio propagation related aspects are briefly discussed. Different propagation environments are described that are used in the analysis of this thesis. Propagation models are also explained to calculate the path loss in the propagation environment.
- Chapter 4: This chapter explains the system model and analysis methodology. It also includes the deployment strategies used in the analysis and all the parameters used in the simulation are described. The key network performance metrics are also explained in detail.
- Chapter 5: In Chapter 5, the results from the simulations are analyzed and discussed in detail.
- Chapter 6: This chapter includes concluding remarks along with the future work related to this thesis.

2. CELLULAR CONCEPT

The early mobile radio system was designed such that it could cover a large coverage area with one transmitter radiating at high power using an antenna fixed on a tall structure. The cellular network concept was a leading discovery to resolve the issues of limited spectral efficiency and network capacity. It successfully offered enhanced capacity without any major technical change. In cellular concept, high-powered transmitter is replaced with several low powered transmitters which provide radio coverage to small zones of the service area. Every base station is assigned a chunk of channels from the total available channels to the system. In order to curtail interference, base stations in the close proximity are allocated different group of channels. As the users increase in a particular area, number of base stations can be increased, thereby increasing the number of channels without expanding the radio spectrum.

The cellular concept forms the base of all state-of-the-art wireless communication systems.

2.1 Brief History of Cellular Systems

The earliest cellular telephone systems can be dated back to 1920s. The systems in those days had limited features, functionality and mobility. The commercial deployment of cellular networks started in the late 1970s. Since then, the advancement in mobile communications technology has increased exponentially. The initial deployments of cellular networks were based on the variations of analog technologies and standards. Some of the well known analog cellular systems are introduced below:

- Advanced Mobile Phone Service (AMPS): It was initially a United States standard but later adopted by other countries such as Australia, Far-East, Brazil and South Korea. It operated in the 800 MHz band. Later on, a Narrowband

AMPS (NAMPS) was introduced by Motorola, which was adopted by USA, Russia and other countries. NAMPS was an interim standard between first and second generation based on analog technology. The only difference it had with AMPS was that the voice channel of 10 kHz instead of 30 kHz in NAMPS.

- Total Access Communication System (TACS): It is a variation of AMPS that was initially deployed in the UK then later adopted by other countries like Spain, Italy and the UAE. It operated in the 900 MHz. A variation of TACS, known as JTACS, was later adopted by Japan.
- Nordic Mobile Telephone System (NMT): This standard was introduced in the Scandinavian countries initially which used to operate also in the 900 MHz band. NMT-450 and NMT-900 systems were later deployed by a lot of countries in Europe, Australia and Asia.

In 1982, the Conference of European Posts and Telegraphs (CEPT) created a study group which developed a pan-European standard for a mobile telephone system. The group was named as Groupe Special Mobile (GSM). The main objective of this group was to overcome the limitations and issues encountered in the analog standards at that time. The new system had to fulfill the new criteria set by CEPT in the following aspects:

- Spectrum Efficiency
- Superior Speech Quality
- Support for new range of services
- Support of international roaming
- Lower costs of mobiles, infrastructures and services

Later, the study group was later merged into to the European Telecommunication Standard Institute (ETSI), which released phase 1 of GSM specification in 1990. GSM now stands for Global System for Mobile Communication. The GSM standard, which was initially developed for Europe only, has been deployed worldwide now.

To meet the ever increasing demands of telephony, there was a need to enhance the current capabilities of GSM. The development of mobile technologies was ventured by international standards developing entities such as the Third Generation Partnership Project (3GPP).

"Third Generation" (3G) is an advanced interpretation of the previous mobile technologies which has been deployed almost worldwide today. The motivations to deploy the 3G network technology were as following:

- Capacity limitation of existing networks
- Demand for high-speed data connections
- Demand for more mobile data centeric services
- Wireless multimedia services
- Desire to access data anywhere and anytime
- Wireless multimedia services
- Seamless service environment - wireless, wire-line, home, office, on the move.

Work on 3G mobile communication had already started in International Telecommunication Union (ITU) in the 1980s. In 1990s, 3G standard was named as Future Public Land Mobile Telecommunications Systems (FPLMTS) which was later changed to International Mobile Telecommunications for year 2000 (IMT-2000) by the ITU.

The initial research on 3G was carried out in Europe, in the EU funded project called 'Research into Advanced Communications in Europe (RACE)'. In Europe, 3G was named as 'Universal Mobile Telecommunications Services (UMTS)'. In early 1998, ETSI selected Wideband CDMA (WCDMA) as the technology for UMTS in paired spectrum utilizing Frequency Division Duplexing (FDD) and Time Division CDMA (TD-CDMA) for the unpaired spectrum using Time Division Duplexing (TDD).

In UMTS, the network architecture is divided into two logical sub-networks, i.e. core network (CN) and Radio Access Network (RAN). An open interface connects the CN and RAN. The network architecture was evolved enabling the smooth transition between 2G and 3G to accommodate existing and new technologies. 3GPP released several specification based on this evolution.

The initial version of the 3G standard failed to achieve the promised high-speed data connection as the data rates were much lower in reality compared to the peak data rates mentioned in the standard. Genuine efforts were done to boost up the data rates of 3G systems. 3GPP introduced High Speed Packet Access (HSPA) [14] technique which supported both data and voice services on the same 5 MHz carrier. Voice over Internet Protocol (VoIP) was also proposed which offers both data and voice service on the same channel.

Later, due to increasing capacity demand, a new radio access technology was introduced based on Orthogonal Frequency Multiple Access (OFDMA) by 3GPP and 3GPP2 which has similar network architecture as of Mobile WiMAX. This system was named as evolved universal Terrestrial Radio Access (evolved UTRA) [15] and it is also commonly known as Long Term Evolution (LTE). The main objective of LTE is to offer enhanced data-rate, low latency and packet optimized access technology with flexible bandwidth deployments [16]. Along with Frequency Division Multiplexing (FDD) and Time Division Multiplexing (TDD), LTE supports half duplex FDD which results in low cost User Equipment (UEs). The user equipment does not need to transmit and receive simultaneously in half duplex FDD unlike full duplex FDD which prevents the requirement of an expensive duplexer in UE.

This standard could support maximum data rates up to 326 Mbps with 4 x 4 MIMO (multiple input and multiple output) using 20 MHz bandwidth [17]. The uplink data rates were bound to 86 Mbps because MIMO in uplink was not yet introduced in the initial LTE standard. In addition to the enhanced throughput, LTE systems also provide double or quadruple the cell spectral efficiency as compared to Release 6 HSPA system. Same advancements were also observed in cell-edge data rates. The LTE system offers low latency in the network, i.e. a packet transmitted from the network to UE takes less than 10 ms.

In late 2009, LTE Advanced was introduced and it was standardized by 3GPP as 3GPP 10 release [18]. LTE Advanced focuses on higher capacity. Its main focus is to provide high bit rate in a cost effective manner while fulfilling the requirements set by ITU for IMT Advanced (4G). LTE Advanced offers higher spectral efficiency from 16 bps/Hz in Release 9 to 30 bps/Hz in Release 10, enhanced data rates, improved performance at the cell edges and increased number of simultaneously active subscribers [19]. The new features proposed in LTE Advanced are Carrier Aggregation, enhanced use of multi-antenna techniques and support for relay nodes.

2.2 Fundamentals of Cellular Communications

The frequency spectrum for mobile communications is limited and very expensive. With billions of mobile phones around the world, it is necessary that an allocated frequency spectrum is efficiently re-used again and again without any mutual interference of one cellphone to another.

2.2.1 Frequency Reuse

In radio propagation phenomenon, the strength of the radio signal decays with distance, which means, practically, the coverage area of a cell is limited. Hence the same frequencies can be reused after a certain 'safe' distance in another base station without causing any significant interference. This phenomenon is known as 'Frequency Reuse', which forms the basis of cellular systems.

Traditionally, cellular systems needed to have a smart allocation mechanism and reuse of channels in the whole coverage area. Every base station was assigned a band of radio channels for its corresponding cell. The neighboring base stations were assigned the channels that were entirely different from the adjacent cells.

Figure 2.1 shows the idea of frequency reuse. Cells labeled with the similar alphabets and pattern operate on the same frequency. The coverage area of a cell is approximated by a hexagonal shape. In practice, however, the actual coverage area of a cell varies significantly and is not a perfect hexagonal shape, due to surrounding terrain.

While using the hexagon model to represent coverage areas, BTSs are either shown in the center of the cell or on the cell edge. Usually, center-excited cells use omni-directional antennas and directional antennas are used for edge-excited cells. Base stations are usually not deployed precisely as they are depicted in the hexagonal arrangement due to the practical limitations.

To get an idea of the concept of frequency reuse, assume a cellular system having 'S' number of usable channels. All the cells are allotted a group of 'k' channels where

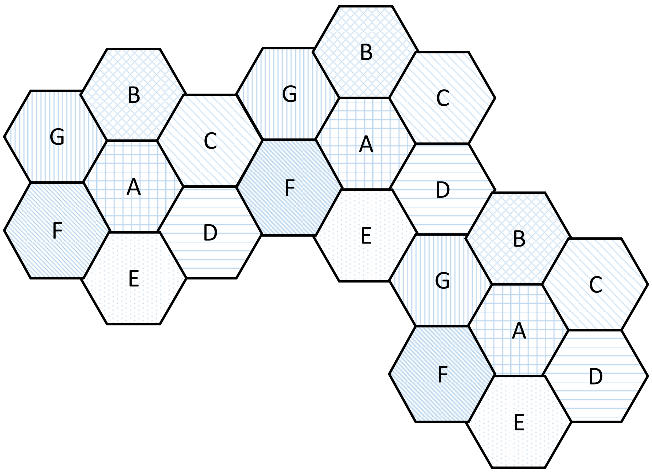

Figure 2.1 *Illustration of frequency reuse concept*

$(k < S)$. Furthermore, the total S channels are divided among 'N' number of cells into different and separate channel groups having identical channels. As such, the total number of radio channels are [20]

$$S = kN \tag{2.1}$$

The N cells which use the whole group of all the frequencies is called a cluster. If this cluster is repeated M times in a systems, the total number of channels, in terms of capacity *'C'* can be written as

$$C = MkN = MS \tag{2.2}$$

From equation 2.2, it is shown that capacity of the cellular network is directly related to the number of clusters repeated in the coverage area. 'N' is termed as a cluster size and it is usually taken as 4, 7 or 12. The capacity of the system can be increased by decreasing the cluster size N while keeping the size of the cell constant, in this way; more clusters are required to cover a given region hence higher capacity is attained. A large cluster size implies that the co-channel cells are situated far apart, whereas, a small cluster size indicates that the distance between the co-channel cells is less. Thus, the factor N tells about the threshold of interference that a BTS or a mobile station can withstand while maintaining the speech quality. Ideally, the value of N should be the smallest to have a maximum capacity of the given area. All the cells of a cluster are allotted *1/N* of the accessible channels in the network and this factor *1/N* is called *frequency reuse factor.* Nowadays, the advancement in mobile communications technology allow deployment of frequency-reuse 1 systems, which is also considered in this thesis.

2.2.2 Multiple Access Techniques

Frequency spectrum, as mentioned earlier, is a limited resource. Hence, it is imperative to utilize it as efficiently as possible. Multiple access techniques allow large number of users to access the limited spectrum resource in an efficient manner.

In wireless cellular systems, subscribers in each cell send and receive data simultaneously to the base station. The primary objective in the mobile cellular network is to enhance the channel capacity, i.e. support the maximum number of calls in a given spectrum without any adverse impact on the quality of service. Some of the well known multiple access techniques are listed below:

1. Frequency Division Multiple Access (FDMA)
2. Time Division Multiple Access (TDMA)
3. Code Division Multiple Access (CDMA)
4. Orthogonal Frequency Division Multiple Access (OFDMA)
5. Spatial Division Multiple Access (SDMA)

Frequency Division Multiple Access (FDMA)

In FDMA, each user is assigned an individual channel. From Figure 2.2 , it is shown that a unique frequency channel is allocated to each user. These frequency channels are assigned to the user on demand when they request for service. During a call, the same frequency channel cannot be shared with any other user. In FDMA, the frequency channel remains idle and cannot be used by other users even if it is not utilized. FDMA channels have narrow bandwidth, e.g. 30 kHz in AMPS, and it is usually implemented in narrowband systems. Intersymbol Interfernece (ISI) is low in FDMA systems because symbol duration of a narrowband signal is large as compared to average delay spread [21]. Since transmitter and receiver operate at the same time, duplexer is used in FDMA mobile unit which results in increased cost of FDMA subscriber units and base stations. Sharp RF filtering is required in FDMA systems to minimize the adjacent channel interference.

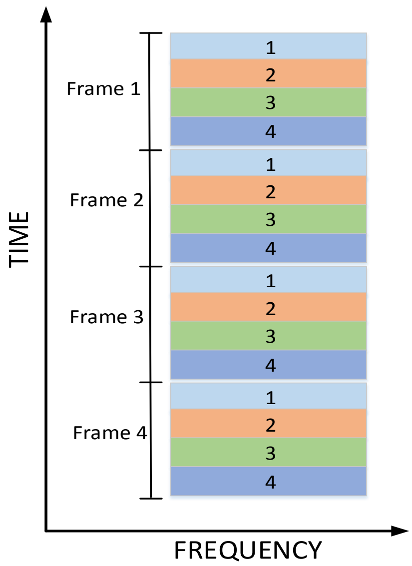

Figure *2.2 Channels in FDMA*

Time Division Multiple Access (TDMA)

In the digital systems, the transmission is not done continuously because subscribers in the network do not use the bandwidth constantly. In such case, TDMA is the access technique that complements FDMA. The GSM standard uses TDMA technique. In TDMA, a user can utilize the entire bandwidth but for a specific span of time. Usually, the bandwidth in TDMA is split up in fewer channels unlike FDMA and the users use the entire bandwidth during the time slot allotted to them.

TDMA distributes one frequency channel among the users in which each user transmits and receives on its allotted non-overlapping time slot as shown in Figure 2.3.

The number of time slots in a frame is dependent on many factors like available bandwidth and modulation scheme etc. Unlike in FDMA, TDMA has a discontinuous transmission occurring in small blocks. This causes the transmitter to be turned off when the user does not transmit which saves the battery. Different number of time slots can be allocated to different users per frame in TDMA scheme. In this way, the bandwidth can be allotted to different users on demand by reallocating time slots on preference.

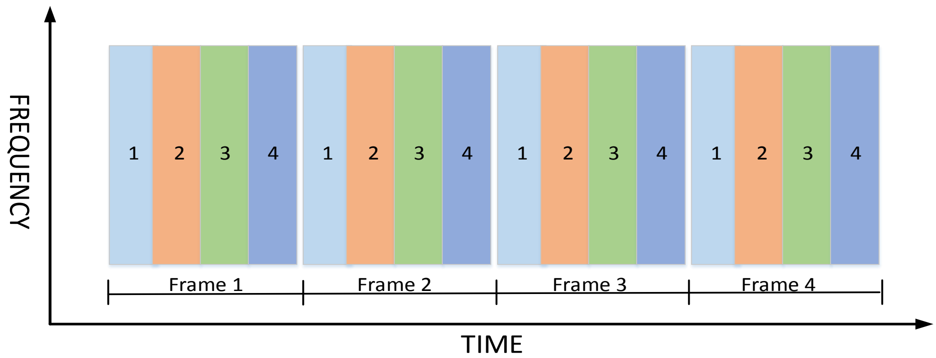

Figure *2.3 Channels in TDMA*

Code Division Multiple Access (CDMA)

In CDMA, the end users communicate by using the same frequency resources simultaneously, however, each user is assigned a unique code that distinguishes them from one another. CDMA uses a spread spectrum technique where a spreading signal, having a large bandwidth and uncorrelated to the actual message signal, spreads the narrow band signal. CDMA works on Direct Sequence Spread Spectrum (DS-SS) in which the message signal is multiplied by a Pseudo Random Noise Code. Every user is allocated a unique code which is orthogonal to every other code allocated to other subscribers in the network. To identify the user, the receiver has to keep this unique code in order to identify the user, the receiver must know the code utilized by the transmitter.

Due to multipath communication in a cellular system, self interference arises due to delayed replicas. The delay causes the spreading sequence lose its orthogonality, hence in de-spreading, information from other users arises and act as interference. In TDMA and FDMA, orthogonality can be preserved by having reasonable time or frequency guard-bands respectively.

The other problem that CDMA suffers from is the near-far problem. The signals nearer to the BTS are received with more power than the signals coming from far away due to low attenuation as shown in Figure 2.4. This problem arises when the signals received from the mobile phone closer to the BTS masks the signals received from a farther mobile. This near-far effect combined with imperfect orthogonality causes severe interference. To overcome this issue, accurate and fast power control mechanisms are used to ensure the communication with little or no interference.

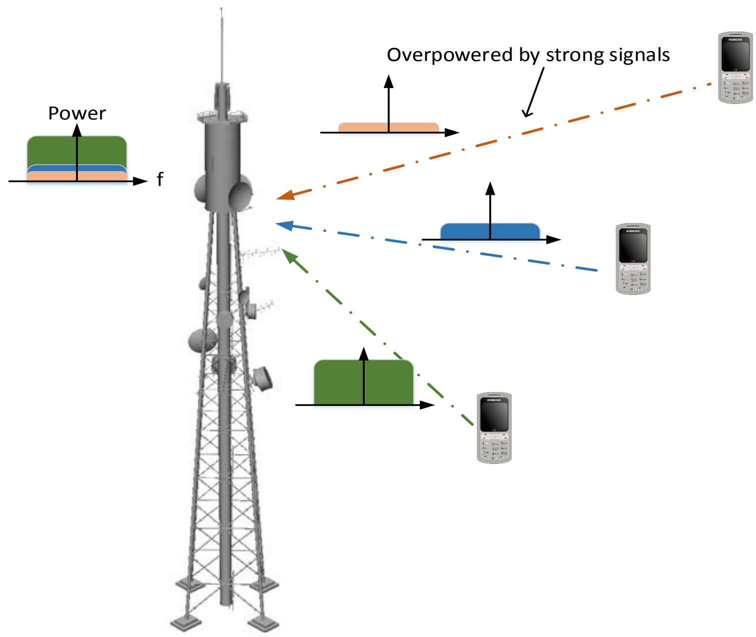

Figure 2.4 *Near-Far problem in CDMA*

Orthogonal Frequency Division Multiple Access (OFDMA)

OFDM is fundamentally considered a digital modulation technique instead of a multi-user access technique. One stream of bits is transmitted on a single communication carrier using a string of OFDM symbols. Nevertheless, OFDM can be used with multiple access schemes like time, frequency or coding. OFDMA operates on various closely placed sub-carriers. These sub-carriers are further split up and form smaller group of carriers called sub-channels. The sub-carriers which are used to model sub-channels must not be adjacent to each other. OFDMA multiplexes the data streams of various users on the downlink sub-channels and uplink multiple access by the uplink sub-channels.

The multiple access is acquired by allotting various OFDM sub-channels to multiple users. In uplink, a transmitter is assigned one or more sub-channels but in downlink, a sub-channel may be transmitted to various receivers. OFDMA has a large symbol duration that enhances the delay spread and the introduction of cyclic prefix (CP) completely cancels the inter-symbol interference (ISI). CP is a redundant replica of the last samples which is affixed at the beginning of the data block illustrated in Figure 2.5. The ISI can be effectively mitigated if the cyclic prefix is kept longer than the channel delay spread.

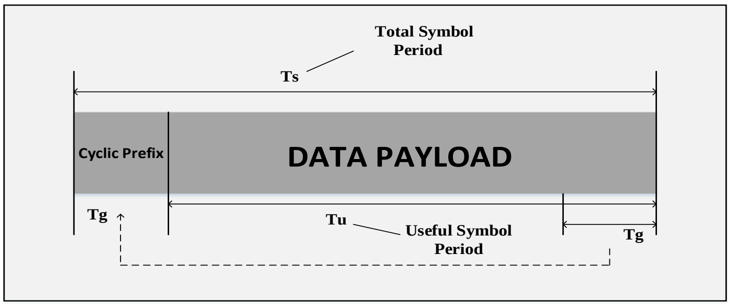

Figure 2.5 *Cyclic Prefix*

The structure of OFDM and OFDMA symbols is similar. In OFDMA, each symbol consists of sub-carriers and those sub-carriers are further divided into data sub-carriers that carry information, pilot sub-carriers as reference frequencies, DC sub-carriers as the center frequency and guard sub-carriers to keep the distance between the OFDMA symbols as demonstrated in Figure 2.6.

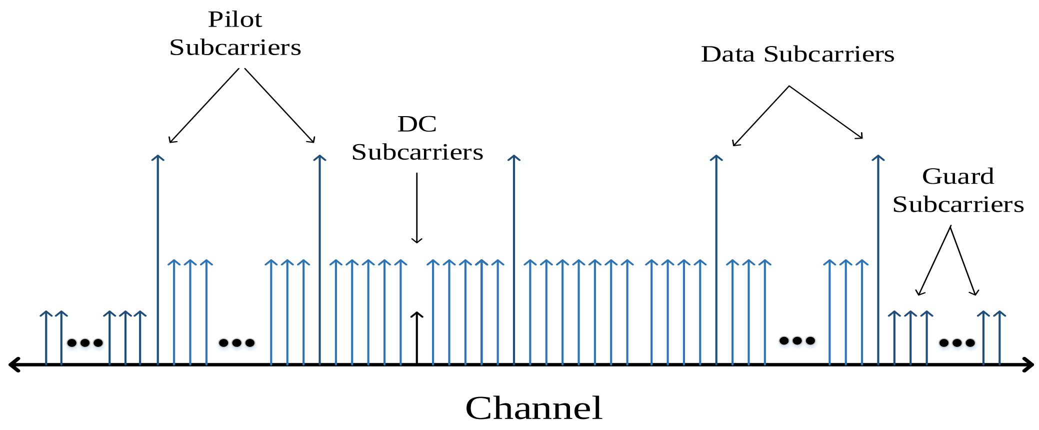

Figure 2.6 *Structure of sub-carriers in OFDMA*

Single-carrier FDMA is a frequency division multiple access scheme, also known as Linearly precoded OFDMA (LP-OFDMA), which performs discrete Fourier transform (DFT) prior to the conventional OFDMA processing. SC-FDMA has drawn great attention as an alternative to OFDMA due to its reduced peak-to-average-power ratio (PAPR) in uplink channel which enhances the transmit power efficiency with reduced cost of power amplifier in the mobile terminal. SC-FDMA has been adopted as the uplink multiple access scheme in 3GPP LTE [22], [23]. Figure 2.7 illustrates the comparison between OFDMA and SC-FDMA channels.

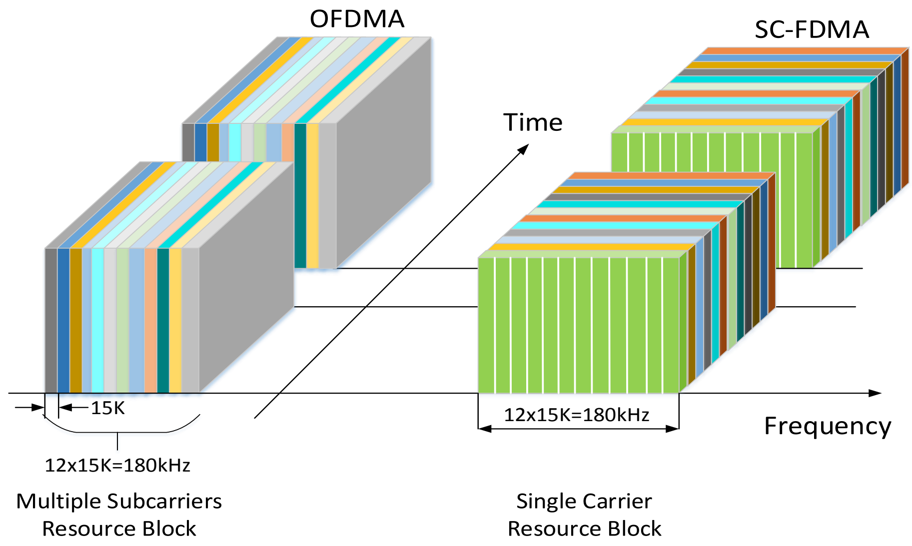

Figure 2.7 *Illustration of OFDMA vs SC-FDMA channels*

Spatial Division Multiplexing Access (SDMA)

In SDMA, the users are spatially separated in order to optimize the frequency spectrum usage. Primarily, SDMA reuses the same frequency in different cells throughout the network. SDMA serves the users by same or different frequencies using spot beam antenna, shown in Figure 2.8 . However, the cells should be sufficiently separated in order to avoid co-channel interference. This limits the frequency reuse factor because the coverage area can be divided into limited number of sufficient separated cells. Recently, a more advanced approach called Single Path Multiple Access (SPMA) is used to enhance the capacity of the coverage area. *"SPMA utilizes the characteristics of independent propagation paths for particular geographical location in the coverage area of mobile network"* [24]. In mobile communications, when radio waves traverse between transmitter and receiver through only one path, the frequency resources can be reused in a coverage area as small as 1 m $\times$ 1 m, thus, as a result, the capacity of the network increases significantly.

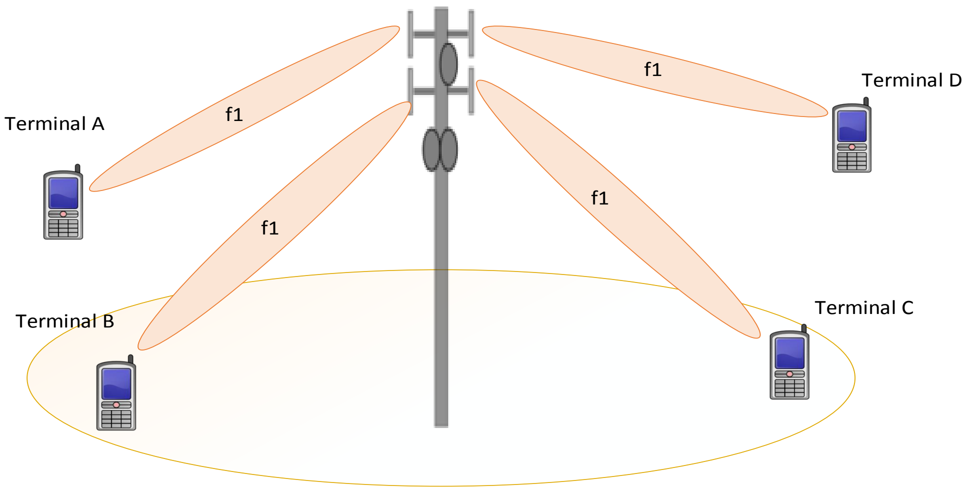

Figure *2.8 Illustration of SDMA concept*

2.2.3 Duplex Communication

A duplex communication is a point-to-point communication between two connected devices that can communicate in both directions to each other. A duplex system has two paths and with each path, the information is carried in only one direction. Two types of duplex systems are used in communications; half duplex and full duplex.

- **Half duplex system**: A half duplex system is a two way communication system that allows the non-simultaneous bidirectional communication. One user can send the information at a time only. Second user will only be able to transmit information when the first user finishes transmitting. The user is only able to transmit or receive data at a time. Walkie-talkie is a classical illustration of half duplex communication that uses 'push-to-talk' and 'release-to-listen' for two way communications. Figure 2.9 shows the concept of half duplex systems.

Figure 2.9 *Half Duplex Communications*

- **Full duplex system**: A full duplex system is a two way communication system that allows two way simultaneous communication between the users. This is achieved by two concurrent but individual channels to both the users as shown in Figure 2.10. In full duplex systems, the transmission does not appear to be sent until it is received and an acknowledgment has been sent back by the receiver.

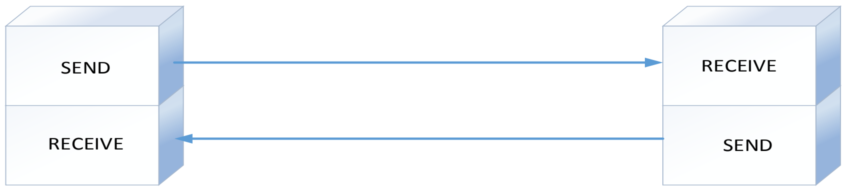

Figure 2.10 *Full Duplex Communication*

Full duplex communication can be implemented using two duplexing methods:

- Frequency Division Duplexing (FDD)
- Time Division Duplexing (TDD)

Frequency Division Duplexing (FDD)

FDD is a technique which utilizes two different frequencies for transmitting and receiving. In mobile cellular network, one set of the frequency spectrum is allocated for the uplink communication which transmits data from the mobile station to the base station. Another set of frequency is used for the downlink communication for the transfer of information from base station to the mobile user. Simultaneous bidirectional transmission is possible because of the two independent channels. To keep the self-interference under threshold level, the two frequency bands are separated by a frequency offset. FDD is efficient in case of symmetric data. FDD makes radio network planning easier and more efficient because base stations do not interfere with each other since they transmit and receive in different sub-bands. Figure 2.11 demonstrates frequency division duplexing and guard band.

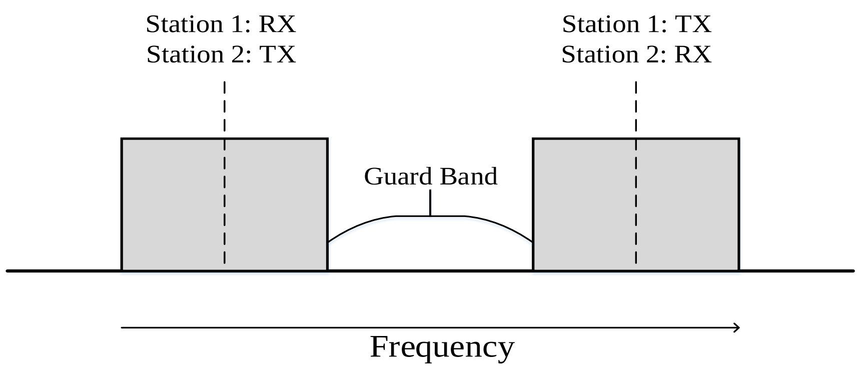

Figure 2.11 *Frequency Division Duplexing illustrating guard band*

Time Division Duplexing (TDD)

TDD uses the same frequency for both uplink and downlink. It shares the frequency band by allotting the time slots for transmitting and receiving. The data transmitted is in serial binary form whether it is voice, video or mobile data. A time slot can be 1 byte long or a frame of multiple bytes. In TDD system, the time slots for uplink and downlink are often of same time period; nonetheless, the system can be asymmetrical as well. The real advantage of TDD is that it works on only single channel of frequency spectrum. There are no guard-bands, hence the spectrum is utilized more efficiently.

The TDD systems need very precise and accurate timing and synchronization, both at the transmitter and receiver, to make sure that the time slots do not overlap with each other to cause interference. Timing is often synchronized with the atomic clock standards. To prevent overlap, guard times are needed between the two slots. Figure 2.12 shows the time division duplexing.

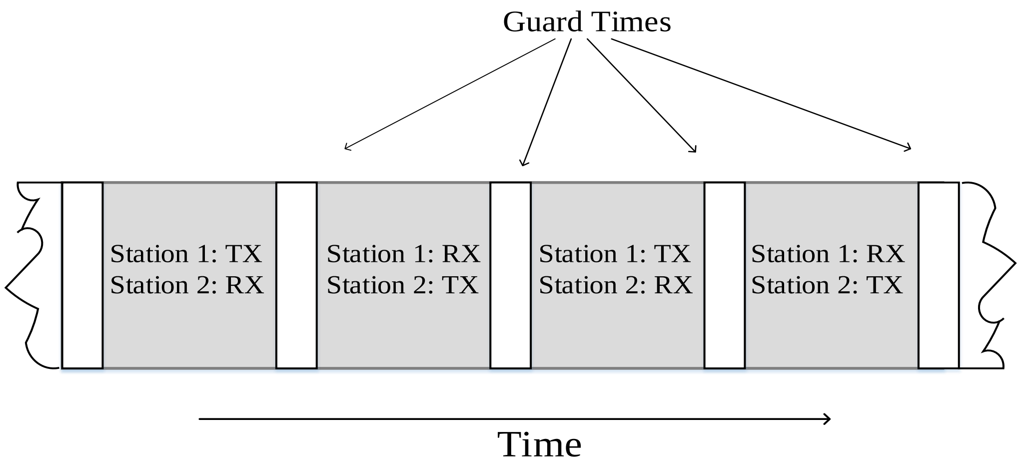

Figure 2.12 *Time Division Duplexing illustrating guard times*

2.3 Interference and Capacity

The most dominant factor that affects the performance of a cellular system is interference. The interference can be caused from another mobile in the same cell, a mobile user from the adjacent cell, the base stations transmitting on the similar frequency, or some other devices working on the same frequency. Interference in urban areas is severe due to the large number of base stations and greater RF noise floor. The major bottleneck in enhancing capacity of a network is interference which degrades the radio channel conditions. There are two dominant types of interference which are caused within a system known as *co-channel interference* and *adjacent channel interference*. Another form of interference is *out-of-band* interference, which comes from external sources e.g., a competing carrier operating its network in an adjacent frequency band, or some other non-ideal devices emitting noise into the mobile carrier's frequency band etc. These type of interference are usually handled by the regulatory authority of that region.

2.3.1 Co-Channel Interference and Capacity

In the frequency reuse technique, several cells in the network operate on the same frequency. These cells are termed as co-channels and the interference caused by phenomenon is called co-channel interference. Co-channel interference cannot be decreased by increasing the transmit power, unlike thermal noise, because increasing the power rises the interference in the neighboring co-channel cells. Geographically, co-channel cells must be isolated enough from each other so that there is no co-channel interference. Figure 2.13 shows a typical cell layout in a network.

When the size of the cells is almost same and the transmit power of the base stations is also same then the co-channel interference does not depend on the transmit power and it turns into a function of cell radius (R) and distance between the origin of closest co-channel cells (D). As the ratio D/R is increased, the distance between co-channel cells is increased. Thus, by keeping far apart the co-channel cells, the interference can be reduced. Co-channel reuse ratio, Q, is dependent on the cluster size. For a hexagonal geometry

$$Q = \frac{D}{R} = \sqrt{3N} \tag{2.3}$$

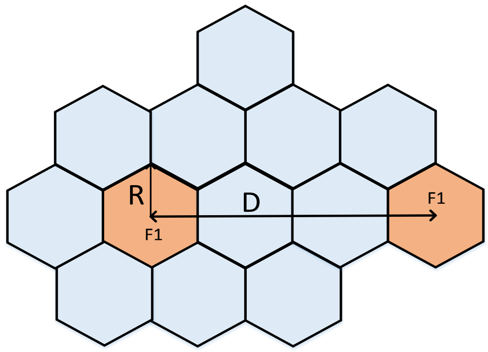

Figure 2.13 Cell layout illustrating cell radius R and co-channel distance D.

Capacity of the area will be higher if Q is small since the cluster size N is small. And if Q is large, the transmission quality is improved due to less co-channel interference. In practical design, a trade-off is done between these two factors.

2.3.2 Adjacent Channel Interference

Interference caused by the neighboring channels operating on the same frequency as the serving cell is known as adjacent channel interference. It is caused by the imperfection in the receiver filter due to which the nearby frequencies mix with the desired frequency band. The interference can be very severe if the adjacent channel user transmits close to the subscriber's receiver and the receiver tries to receive transmission from the base station at the same time. This is also called near-far effect, where a nearby transmitter catches the subscriber's receiver.

Adjacent channel interference can be mitigated by using sharp filters and employing appropriate channel assignments. Adjacent channel interference can be reduced considerably if the channel frequencies in the specific cell are separated far enough. Therefore, rather than using channels made up of adjoining frequencies in a cell, channels are assigned in a way that the frequency separation between them is maximum.

2.4 Classification of Base Station Types

The requirement of the base station depends on the type of environment (outdoor or indoor), coverage and capacity. Different types of base stations are deployed according to the coverage and capacity requirements in an area. Three types of base stations are explained below, however, only macrocellular and femtocells fall within the scope of this thesis.

2.4.1 Macrocellular

Macrocells are known as wide area base stations and their coverage usually ranges upto 35 km [25]. Macrocells are used to cover a large area for the mobile service provisioning, however, due to the large size of the cell, the capacity of the cell is not high. Macrocells provide radio coverage by using a single, tall and high power transmitter. Antennas used in macrocells are mounted on the tall infrastructure or poles. Macrocell base stations are less energy efficient due to their huge size. Several macrocells are used in a wide area to provide coverage to the subscribers.

2.4.2 Microcellular

A microcell is a cell with relatively shorter coverage area and it is served by a transmitter of low power. Microcells are used in areas such as malls, airports, sporting events etc. A microcellular base station has comparatively lower transmit power and it provides coverage to an area upto 2 km [25]. Microcells are usually deployed in urban environment where the users experience bottleneck in macrocellular network due to lack of capacity.

2.4.3 Femtocells

Femtocells are small cells which are used in residential buildings and offices to provide enhanced indoor coverage and capacity. In order to achieve higher data rates in the indoor environment, the signal strength from the macrocellular base stations is not enough due to wall penetration losses and other types of attenuation. Femtocells provide excellent signal strength in the indoors, thereby providing higher speed connectivity. Femtocells are connected to the mobile network by utilizing the conventional end user internet connection e.g. Digital Subscriber Line (DSL)or Fiber optic connection. This scheme avoids the extra overhead of expenses that makes the installation of the femtocells very cost effective.

There are numerous benefits of using femtocells for both the mobile operators and the users. Femtocells are easy and cheap to install due to their small size and very low power consumption. The capacity of the network can be significantly increased by deploying the femtocells in the indoor environment.

The femtocell system has a simple architecture. It comprises of the following elements [26]:

- Femtocell
- Internet router
- DSL internet connection
- Mobile operator's core network gateway

Femtocell installed in the premises of the household or the office is connected via network gateway which provides the connectivity to the femtocell through DSL connection.

3GPP has developed a standard to define the architecture of femtocell network so that it can be implemented worldwide. Furthermore, 3GPP standardized the network elements and interfaces for the femtocell networks [27].

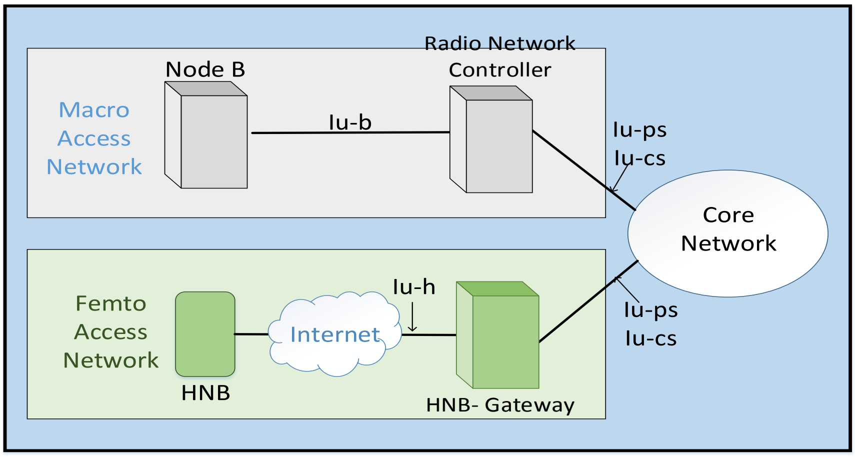

Figure 2.14 *Femtocells Network Architecture*

Figure 2.14 illustrates the femtocell network architecture. 3GPP defined three main network elements for the femtocell architecture:

- **Home NodeB (HNB)**: Home node B is a term for femtocell access points (FAPs) as used in 3G UMTS networks. It has the capability as the normal Node B of the UMTS network and the radio resource management functions of Radio Network Controller (RNC)
- **HNB-Gateway (HNB-GW)**:HNB-GW is an element that connects the femtocell with the core network via standardized interfaces Iu-h and Iu-ps or -cs. HNB-GW has the following functions:
  - Authentication and certification of the data. It makes sure that the data transmitted or received should reach the correct destination.
  - HNB-GW is a channel through which all the HNBs are connected to the core network. It accumulates the data from the HNBs and passes onto the core network.
  - HNB-GW also supports the advanced features like clock synchronization distribution and other IP based synchronization like NTP, IEEE1588 and IETF NTP etc.

Interference in Femtocell network

Interference is a key issue that needs to be addressed in a femtocell network. Femtocells use the spectrum which has already been assigned to the mobile operator but their deployment is ad-hoc based, i.e. no network planning has been done before deploying the femtocells which may introduce severe interference. This interference can cause not only poor service to the users of the femtocell network but also to the subscribers of the main network. If the interference issues are not resolved, they will invalidate the great advantages of coverage and capacity that femtocells provide. A significant amount of work has been done to minimize the interference in femtocell networks so that they can be deployed across the world.

There are number of interference scenarios that femtocell may experience while providing service in the network. Severe interference problems arise when femtocells operate on the same carrier frequency. Interference is not very significant when the carrier frequency is different. Using the same carrier frequency offers great spectral efficiency but it also brings great challenges in dealing with the interference issues.

The main interference issues are listed below [28]:

- **Interference from indoor femtocells to the outdoor base stations**: this happens when the femtocells and the macrocellular base stations operate on the same carrier frequency. Interference caused by this affects the service which results in the deterioration of the service quality.
- **Interference from outdoor base stations to indoor femtocells**: this interference happens when the macrocellular base stations are transmitting on the same frequency as the femtocells. This also decreases the service performance in the network.
- **Inter-cell interference**: this interference is introduced when the femtocells are placed in close proximity of each other. When the femtocells are closely placed to each other, they increase the level of background noise that reduces the sensitivity of each femtocell.
- **Interference offered by user equipment**: this interference arises when the user equipment transmits at higher power and the information is transmitted to more than one base stations. Though the coverage indoors is poor and

the signals may be attenuated due to the wall losses, still there will be some signals from the femtocells that may interfere with the base stations that will increase the noise level at the base station.

Femtocell mode of operation

Femtocells are usually configured to work in a closed-access model, *Closed Subscriber Group (CSG)*, to bar unwanted users from connecting to the femtocell network. This prevents the femtocell network from unknown mobile users who can exploit the network capacity without permission of the owner. Another mode of operation is *Open Subscriber Group (OSG)* where any subscriber can connect to the femtocell network. Lastly, femtocell network can be operated in a hybrid mode which combines characteristics of both OSG and CSG. In hybrid mode, any subscriber can connect to the femtocell network but preference is given to the registered users [29]. However, in this thesis, the mode of operation for the femtocell network is taken to be OSG.

2.5 Backhaul Limitation in Femtocell Networks

Femtocell APs are connected to the network by a broadband internet line that connects them to the internet and the operator's core network. The broadband access gateway connects the FAPs to the Femto gateway in HPLMN core network via an IP based broadband connection as shown in the Figure 2.15.

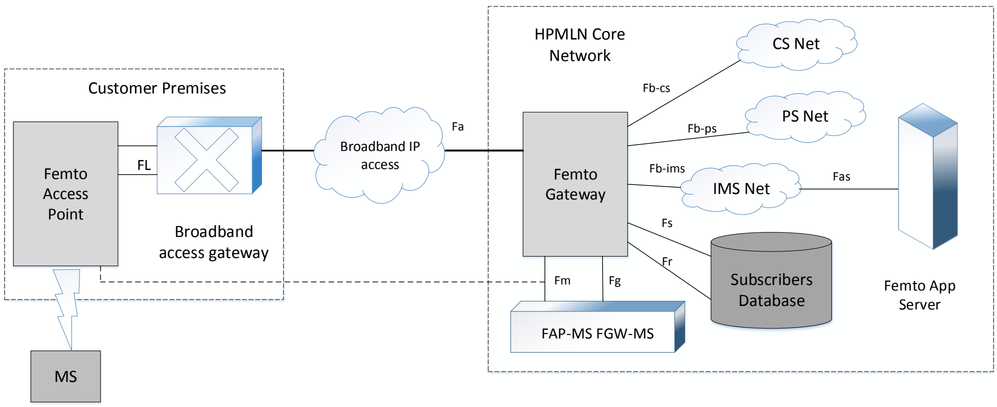

Figure 2.15 *Femtocell network architecture illustrating backhaul link*

The femtocell access point is a device which interacts with the mobile user on a wireless air interface. FAPs operate on a very low power and are connected to the core mobile network via a broadband interface like fiber, DSL or cable. Using the femtocell services, the subscribers can avail improved indoor coverage and enhanced bandwidth availability. The femtocell gateway communicates with the FAPs on a broadband access network which further connects it to the core components of the mobile network as shown in Figure 2.15. In order to receive enhanced capacity offered femtocell network, the backhaul broadband connection plays a very crucial part. This means that the data connection speed that a user can avail in a femtocell network depends on the backhaul channel connectivity speed which connects the mobile user to the main network. The backhaul link works as a backbone for the femtocell network users because the connection speed limitation on the channel will determine the data connectivity speed regardless how wide is the bandwidth offered by mobile operator.

The mobile operators need to provide a secure and scalable broadband IP interface to the femtocells in femtocell networks. There are three types of interface that are used to connect the femtocell in the user's premises with the mobile core network [30].

- **Iu-b over IP**: Typically, the FAPs are connected to the Radio Network Controllers (RNCs) via Iu-CS (Circuit Switched) or Iu-PS (Packet Switched) interfaces already existing in macrocellular networks. The CAPEX for this interface is low because the mobile operator can leverage existing RNCs. Lack of scalablity is the drawback in this interface and it has also been not standardized yet.
- **IMS/SIP**: The internet media sub-system or Session Initiation Protocol interface provides a core network existing between the mobile operator and the femtocells. The IMS interface changes the subscriber's data into IP packets using the SIP protocol and apply Voice over IP (VoIP) mechanism. This technique is scalable and standardized, however, there is a disadvantage of the cost while upgrading and maintaining the two networks for macrocells and femtrocells.
- **RAN gateway based UMA**: Radio Access Network (RAN) gateway lies between the mobile network and the IP network using Iu-CS/PS interface. Between femtocells and the RAN gateway, there exists a protocol called Unlicensed Mobile Access (UMA)which transports the femtocell traffic over the internet by using secure IP tunneling.

Femtocell works as same as 3G/LTE networks work on the handset, but in this case, the femtocell becomes the terminal point for the call. The signals get processed and converted into IP packets using VoIP. The VoIP traffic is transmitted to the wireless carrier's core network through a secure VPN. Technically, it is similar as Skype and other VoIP services [31]. So if the broadband network's connection speed is high, there is no problem supporting high data rates and enhanced Quality of Service (QoS) for the subscribers.

2.6 Capacity Enhancing Techniques

One of the most challenging aspects that the operators face in the network is to cope with the increasing capacity of the network. Global mobile data traffic is expected to grow 26 times between 2010 and 2015 according to Global Mobile Data Traffic Forecast update by Cisco Systems [32]. The exponential growth in smart phones and other broadband devices have forced the operators to make never-ending efforts to increase the capacity. There are many constraints in the process of increasing the capacity. Operators not only need to fulfill the increasing capacity demands but they also have to do it in a cost-efficient manner in order to stay competitive.

2.6.1 Bandwidth

The first factor to increase the channel capacity is the bandwidth. Increasing the bandwidth of the system enhances the capacity. This is the reason that all modern wireless technologies use wider channel bandwidths e.g., 4G LTE uses 20 MHz bandwidth which is four times the bandwidth of WCDMA (5 MHz). Meanwhile, LTE-A specification aims to have a bandwidth of 100 MHz by using a phenomenon called Carrier Aggregation. In carrier aggregation, the operators are assigned a group of non-adjacent and distinct frequency channels which are orthogonal in nature which they can use to increase the channel bandwidth. Carrier aggregation is more commonly used in LTE-A standard in which five groups of 20 MHz channels combine to offer 100 MHz LTE-A bandwidth. Figure 2.16 shows the concept of Carrier Aggregation.

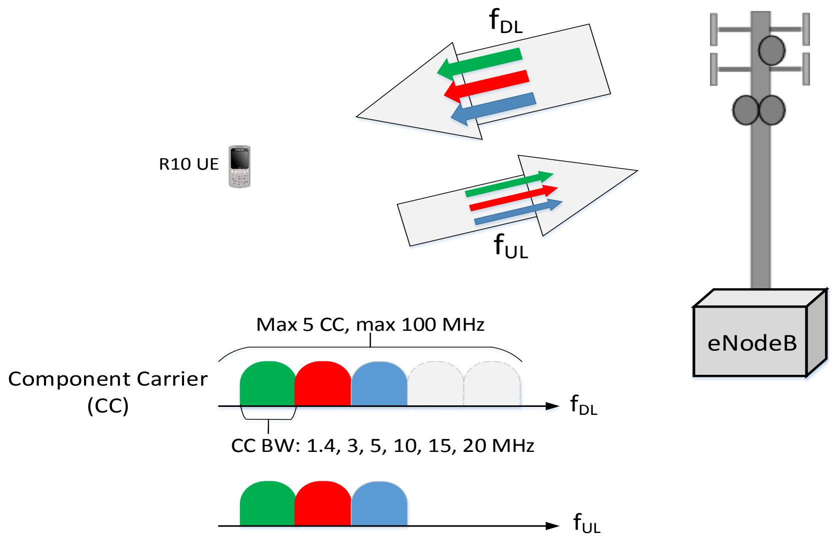

***Figure** 2.16 Illustration of Carrier Aggregation using FDD in LTE-Advanced*

2.6.2 Signal to Interference-plus-Noise Ratio

The wireless network capacity cannot be increased indefinitely, rather it is limited by Shannon capacity bound. Shannon capacity theorem defines the capacity of the channel as the maximum throughput of the system at which the information can be transmitted over a channel with very low error probability [33]. In other words, Shannon limit sets the physical limit on a transmission channel in terms of data transmission. The capacity of an Additive White Gaussian Noise (AWGN) channel can be written as [33]:

$$C = Wlog_2(1 + SINR) \quad bits/sec \tag{2.4}$$

where W is the bandwidth of the channel and SINR is the *Signal to Interference-plus-Noise ratio*. In wireless communications, the RF spectrum is limited and expensive source, hence, it is descriptive to write the capacity in terms of the rate at which the data is transmitted.

From equation 2.4, it is evident that capacity is directly proportional to the Signal to Interference-plus-Noise ratio (SINR). This means that capacity can be increased by increasing the SINR. However, there is an extent to which SINR can be increased.

2.6.3 Interference Cancellation

The capacity can also be increased by reducing the interference which results in greater values of SINR. Spectral efficiency can be increased by canceling the interference caused by the neighboring cells. Cellular interference is of two kinds, interference caused within the same cell and the interference introduced by the adjacent cells. Antenna beamforming is used to improve signal levels and mitigate interference, hence, the network capacity can be improved by using directive antennas [34], shown in Figure 2.17.

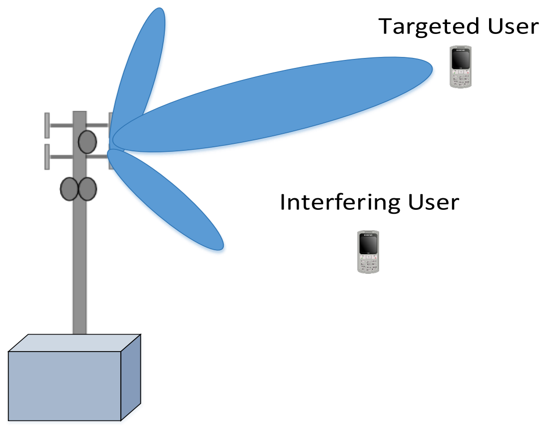

Figure 2.17 *Antenna beamforming*

The interference cancellation techniques have been employed in modern cellular networks to minimize the effect of interference e.g. WCDMA network uses the Parallel Interference Cancellation (PIR) and Successive Interference Cancellation (SIC) at the base station to reduce interference and LTE system uses Interference Rejection Combining Receiver (IRC) for the interference cancellation at the base station [33].

2.6.4 Multiple Antenna Systems

The capacity of the system can also be increased by increasing the number of antennas at transmitter and receiver's side. Thus, the spatial dimension is exploited to increase the capacity of the system. More data can be transmitted simultaneously by having more antennas which results in enhanced capacity. There are N_t antennas at the transmitter side and N_r on the receiver's end as shown in the Figure 2.18. This scheme is called Multi-Input Multi-Output (MIMO) systems.

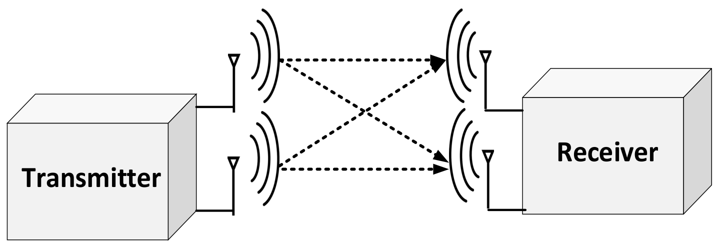

Figure 2.18 *Illustration of MIMO system between a base station and UE*

2.6.5 Network Densification

As the subscribers grow in the network, the total number of channels allotted to that particular cell becomes inadequate to provide service to the new users. To adjust new subscribers in the coverage area, there is a need for new techniques in cellular design to accommodate more channels in the system. In order to enhance the capacity of cellular network, techniques like sectoring, cell splitting, and coverage zone approaches are used. The cellular system grows in an orderly manner using the cell splitting. In sectoring, interference is further reduced by using directional antennas and enhancing the frequency reuse of channels in the network. Using the cell splitting technique, the capacity of the system is increased by increasing the number of base stations. In sectoring, base station antenna placement strategies are done to enhance capacity by reducing co-channel interference.

Cell Sectoring

Cell sectoring is one of the technique to densify the existing network. Figure 2.19 illustrates a network with omni-directional sites.

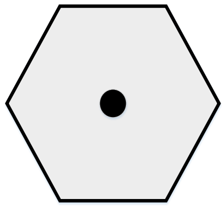

Figure 2.19 *Illustration of omni-directional cell site*

In order to increase the network capacity, the omni-directional antenna can be replaced with directional antennas, each serving a portion of the cell, as shown in Figure 3.4.. Sectorization tends to decrease co-channel interference by using highly

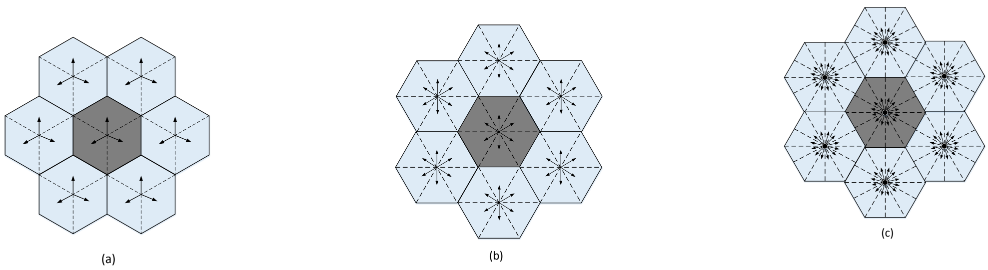

Figure 2.20 *Illustration of a) 3-sector, b) 6-sector and c) 12-sector cell sites.*

directive antennas. A cell site can normally have 3 sectors, however, it can be increased to 6 sectors and even 12 sectors using narrower beamwidth antennas. Recent findings reported in [35] , however, reveal that the system capacity increases up until 6 sectors. Further densification to 12 sectors start to degrade the SINR performance which have negative impact on the overall network capacity.

Cell Splitting

In cell splitting, the coverage area of a traffic congested cell is divided into several smaller cells. Each of the cell is served by a separate base station. This enhances the frequency re-use of the system thereby increasing the network capacity. Each of the small cell is served by a base station with reduced antenna height and low transmit power. Figure 2.21 illustrates the cell splitting technique.

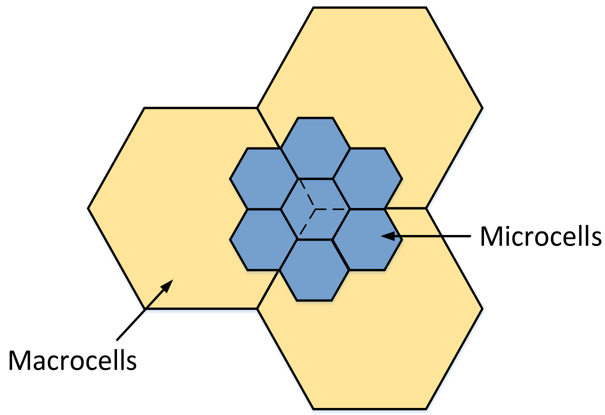

Figure 2.21 *Illustration of cell splitting technique*

3. RADIO PROPAGATION IN CELLULAR SYSTEM

In cellular systems, the mobile communication is much complicated as compared to the fixed radio network communication where the base station and receiver station are stationary and usually in line of sight (LOS) to each other. In mobile communications, however, the mobile terminal is generally at a very low height, not more than few meters above the ground. The obstacles and reflecting surfaces in the surrounding environment have substantial impact on the propagation channel in mobile communication. The behavior of the radio channel keeps changing as the mobile terminal changes its position. The radio channel between a transmitter and a receiver can change from a simple line of sight path to the one which is obstructed by buildings, trees and other obstacles. Generally, statistical propagation models are used to determine the path loss of the mobile radio channel, i.e. no specific terrain data is taken into account and channel parameters are modeled as stochastic variables. There are three propagation phenomena, which are mutually independent, listed as follow:

- **Multipath propagation**: The transmitted waves from the transmitter take several paths to reach the receiver along with the direct path. These wave components, also called *multipath components*, are either reflected from building, trees, or other infrastructure and obstructions to reach the receiver. Depending on the relative phase differences, the wave components may combine constructively or destructively at the receiver which causes rapid instantaneous fluctuation in the received signal strength. This phenomenon is known as 'fast fading'. Multipath propagation is small scale effect on the received signal.
- **Shadowing**: Shadowing is caused by the obstructions between the transmitter and receiver due to which the received signal power degrades and may cause the mean signal power levels to fluctuate over longer period of time. This phenomenon is known as *slow fading*. Shadowing has a medium scale effect on

the received signal i.e., the slow fading phenomenon due to shadowing cannot be observed unless the receiver or transmitter is displaced over couple hundred meters.

- **Path loss**: It is the gradual decrease in the average received signal power with increasing distance from the transmitter. The attenuation in the average received signal level is caused by free space propagation, due to the geometry of the path profile, unlike the local propagation mechanisms which are determined by terrain characteristics in the immediate surroundings of the antenna. The path loss has a large scale effect.

3.1 Propagation Environment

Radio propagation relies upon the propagation environment. Propagation environment is classified into three categories; *urban, sub-urban* and *rural*, as shown in the Figure 3.1 [36].

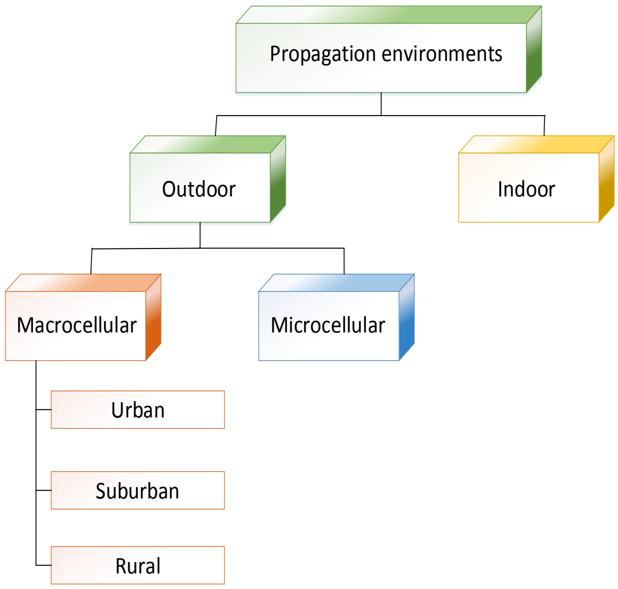

Figure 3.1 *Types of propagation environments*

These environment types are divided on the basis of constructed (buildings) or natural (trees, hills) obstacles, which may change in size and density. Typically, the propagation environment is termed as *macrocellular* when the base station antenna is mounted above the rooftop level and usually in *microcellular* environment, the base station antenna is below the rooftop level. Radio propagation environments are segregated based on the following [36]:

- Morphography type (urban, sub-urban, rural)
- Base station antenna location (above or below the rooftop level)
- Mobile station location (outdoor or indoor)

In the macro-, micro- cellular and indoor environment, the radio wave propagation can be characterized by *angular spread, delay spread, fast and slow fading properties* and *propagation slope.*

3.1.1 Macrocellular Environment

In mobile cellular networks, a macrocell is a cell that provides coverage to a large geographical area by a single high power base station. The antennas used in macro-cells networks are mounted above the average roof-top level or average height of obstacles in the surrounding environment. In a typical macrocellular environment, the angular spread [1] is between 5^o to 10^o and delay spread [2] is between 10 - 15 μs [36].

3.1.2 Microcellular Environment

Generally, microcellular environment exists in urban scenario where the buildings are three or four floors high and the base stations are located in high capacity areas. The base station antennas are mounted below the average rooftop level which allows the frequency resources to be used more often because lower height of the antenna prevent the waves to propagate farther due to tall buildings/obstructions. In this way, each base station covers a small coverage region and frequencies can be reused many times. In mirocellular environment, the typical value of angular spread is 45^o and the delay spread is between 1 μs - 5 μs [36].

[1] Angular spread defines the deviation of the signal incident angle [36].
[2] Delay spread is the amount of variation of multi path components [36].

3.1.3 Indoor Environment

The indoor propagation environment is much more complex than outdoor environment. Due to the presence of objects and obstructions in close vicinity, the radio signal from transmitter to receiver traverses through various paths, making the indoor propagation environment quite rich in terms of scattering and multipath propagation. Usually the receiver is in non line-of-sight (NLOS) from the transmitter. Hence, in addition to multipath fading, the radio signals are also subjected to attenuation caused by doors, walls and/or floors. This is the reason behind poor indoor coverage problem, that has been the top most complaint of the subscribers since the early days of commercial cellular networks. As the network capacity and data throughput directly depend on the signal quality, thus, when designing the network, radio design engineers take into account the additional outdoor to indoor wall penetration loss, in their path loss calculations. Traditionally, the wall penetration loss values have been in the range of 10 - 25 dB [36]. However, in a bid to improve the thermal insulation of buildings, the construction industries in Europe have started to use modern construction materials which are negatively affecting the radio signal propagation into the buildings. A recent study has reported building penetration losses up to 35 dB in modern constructions [37], [38]. One way to overcome, the high wall penetration loss is by densifying the outdoor macro or micro layers. Another approach is based on a more recent local area indoor femtocell technology. Due to being located inside the buildings, they are well positioned for delivering proper indoor coverage and are less prone to increasing outdoor-to-indoor wall penetration losses.

Figure 3.2 illustrates macro-, micro- and femtocells and their coverage areas.

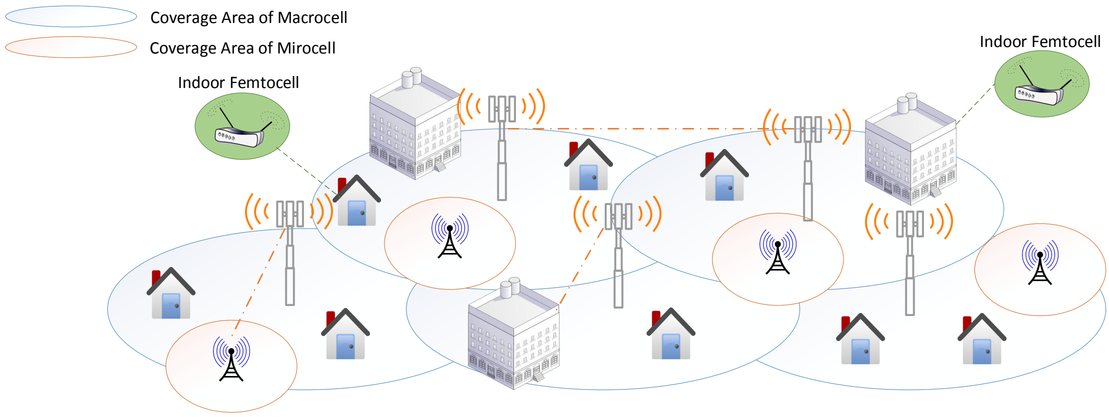

Figure *3.2 Illustration of Macrocells, Microcells and Femtocells*

3.2 Propagation Models

In mobile radio communications, it is vital to determine the behavior of radio wave propagation in a particular terrain. Propagation models predict the path loss or average received power for a particular frequency utilizing the geographical information provided for that terrain. Using propagation models, optimization of the cell coverage area is possible while reducing the intercell interference [39]. In cell coverage area planning, radio engineers aim to identify the radio signal strength at the receiver end. In a given environment, the path of radio wave is haphazard and the received signal comprises of both LOS and NLOS waves, thus NLOS wave components may (partially) cancel the LOS wave which results in path loss. Knife-edge type obstacles introduce diffraction loss where the radio signal diffracts causing the multipaths. Furthermore, reflected waves also significantly degrade the performance of the network therefore, radio networks are planned in such a way that these losses are minimized.

3.2.1 Empirical models

The attenuation along the transmission path results in a path loss which limits its coverage area. In the initial phase of network planning, it is very important to calculate the path loss. In order to quickly determine the coverage area of a base station site, without conducting time consuming and costly field measurements, empirical propagation models are used.

Empirical models are typically equations derived from massive field measurements using regression methods. These models are developed for system specific parameters, specific communication systems, and types of environment. In wireless network design, the selection of an appropriate propagation model is the first step. Okumara-Hata and COST 231-Hata are the most widely used empirical models to calculate path loss in frequency bands below 2 GHz [40]. For the new wireless systems that operate on higher frequencies, i.e. above 2 GHz, several new models have recently been developed e.g. Stanford University Interim (SUI) model computes path loss for systems operating below 11 GHz [41].

- **Okumura-Hata Model**: The Okumura-Hata model was developed in 1968 by Okumura which was later simplified by Hata in 1980. This model can be used only for the distance less than 20 km from the transmitter. However, the model does not consider the terrain profile between the transmitter and receiver, i.e. obstructions, hills, buildings etc. Furthermore, the model takes, as input, only four parameters hence the computation time is very short.

  These parameters are:

  - Frequency (150 MHz - 1500 MHz)
  - Distance between transmitter and receiver (1 km - 20 km)
  - Transmitter's antenna height (30 m - 200 m)
  - Receiver's antenna height (1 m - 10 m)

The path loss in Okumura-Hata model is calculated by the following equation [42]:

$$L_u = 69.55 + 26.16 log_{10} f - 13.82 log_{10} h_B - C_H + [44.9 - 6.55 log_{10} h_B] log_{10} d \quad (3.1)$$

where
L_u = path loss [dB]
h_B= height of the base station [m]
f = frequency [MHz]
C_H= mobile antenna correction factor
d= distance between base and mobile stations [km]

The mobile antenna correction factor, C, is calculated by the following expressions:

$$C = 2log_{10}^2\left(\frac{f}{28}\right) \tag{3.2}$$

for suburban environment,

$$C = 4.78log_{10}^2 f + 18.33log_{10}^2 f + 40.94 \tag{3.3}$$

for open environment and,

$$C = \begin{cases} 3.2log_{10}^2(11.75h_B) - 4.79, & largecities, f \geq 300MHz \\ 8.29log_{10}^2(1.54h_B) - 1.1, & largecities, f < 300MHz \\ (1.1log_{10}f - 0.7)h_B - (1.56log_1 0 f_B - 0.8), & mediumorsmallcities \end{cases}$$

for urban environment.

Empirical models are generally used for macrocellular environment because they are rather accurate in environments with same characteristics. These models are easy to use and take less amount of time due to low complexity of input parameters, however, empirical models are less accurate and require tuning for different environments.

3.2.2 Semi-empirical models

Semi-Empirical models take more parameters of propagation environment into account for predicting the field strength as compared to empirical models [43]. Usually, the direct beam between transmitter and receiver is taken but in addition to that, number of walls and wall penetration losses are also evaluated for the calculation. Available measurement data is used to calibrate the values of different parameters. The prediction capability of the model increases with the higher number of parameters as compared to empirical models. Figure 3.3 shows the radio wave traversing from transmitter to the receiver after reflection from walls.

COST-231 Walfisch-Ikegami model is a classical example of semi-empirical models. This model is the combination of the two models proposed by J. Walfisch and F. Ikegami and further developed by COST 231. This model is designed to make coverage prediction in the frequency range from 800 MHz to 2000 MHz. It has been mainly used for coverage prediction of GSM 1900 MHz in Europe. The path loss

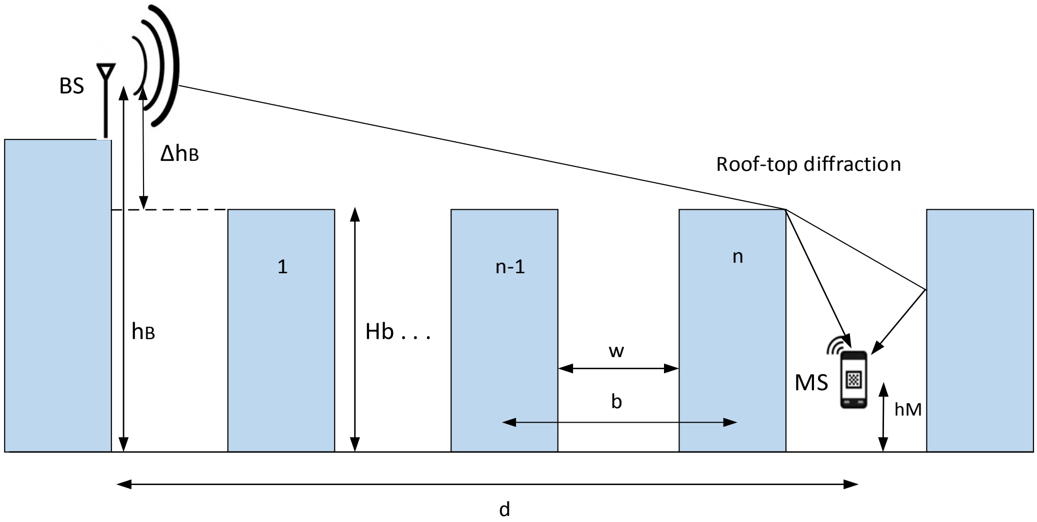

Figure 3.3 *Illustration of transmitted wave to the receiver after reflection from walls.*

given by this model is [44]:

$$L(dB) = L_f + L_{rts} + L_{msd} \tag{3.4}$$

Where,
L_f= free space loss [dB]
L_{rts}=rooftop-to-street diffraction and scatter loss [dB]
L_{msd}=multi-screen loss [dB]

These transmission losses can be calculated by the following equations:

$$L_f = 32.4 + 20log.d + 20log.f \tag{3.5}$$

where d is distance and f is frequency. Roof-to-top scatter loss can be calculated by the following expression where W is width of the roads.

$$L_{rts} = -16.99 - 10logW + 10logf + 20log(h_r - h_m) + L_{ori} \tag{3.6}$$

L_{ori} is the orientation loss which is determined by the expression below where ϕ is incident angle relative to the street.

$$L_{ori} = \begin{cases} -10 + 0.354\phi & for \quad 0^o \leq \phi \leq 35^o \\ 2.5 + 0.075(\phi - 35^o) & for \quad 35^o \leq \phi < 55^o \\ 4.0 - 0.114(\phi - 55^o) & for \quad 55^o \leq \phi < 90^o \end{cases}$$

$$L_{ms} = L_{bsh} + k_a + k_d logd + k_f logf + 9logb \tag{3.7}$$

where L_{ms} is multiscreen loss, b is the mean value of building separation and k_a, k_d, and k_f are empirical correction factors.

L_{bsh} is the shadowing gain which is achieved when the base station is higher than the rooftops. It can be calculated by the following expression:

$$L_{bsh} = \begin{cases} -18log(1 + \triangle(h)) & for \quad h_{base} > h_{roof} \\ 0 & for \quad h_{base} < h_{roof} \end{cases}$$

The COST-Walfisch-Ikegami model includes a lot of parameters related to the surrounding environment, hence, it gives relatively more accurate results compared to empirical ones. The path loss is affected by varying the parameters like base station height, roof height, street width etc., in a given scenario. The model is valid for base station height from 4 m to 50 m, mobile station height from 1 m to 3 m, and distance between the transmitter and receiver from 200 m to 5 km.

Semi-empirical models require more precise characterization of the propagation environment. Though they provide relatively accurate results compared to the empirical models, but they require more time for computation.

3.2.3 Deterministic Models

Deterministic models use ray optical propagation models to predict the field strength. Unlike empirical and semi-empirical models that require separate propagation models for indoors and outdoor path loss prediction, deterministic models are applicable in both scenarios. Deterministic models yield quite accurate results as they take into account the detailed environment models (e.g. building layouts, street orientation, type of material used etc.) and simulate real wave propagation phenomenon like scattering, reflection, diffraction and penetration.

There are two ways to approach ray optical modeling; ray tracing and ray launching. Both models come with their pros and cons. Ray tracing calculates all rays for each receiving point individually using image theory and makes sure consideration of each wall as well as a constant resolution [43]. This individual processing takes more time than ray launching method where the rays are launched from the transmitter with a continual increasing angle and traversed till they reach the receiver point. Figure shows the illustration of ray tracing and ray launching concept. Ray optical models are accurate but also extremely time consuming, compared to empirical and semi-empirical models, because all the possible rays must be computed.

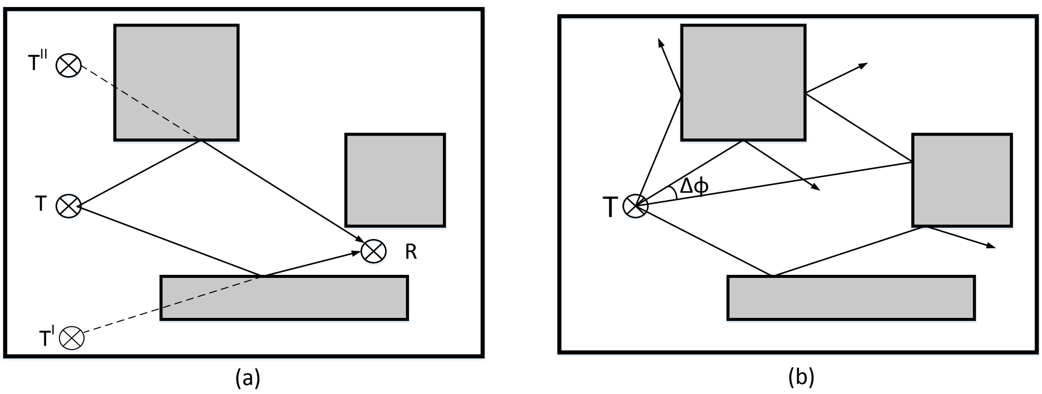

Figure 3.4 *Illustration of a) ray tracing, b) ray launching propagation models*

Another deterministic model called Dominant Path Model (DPM) is used to predict the path loss. This model is used in our analysis and it is explained in Section 4.2.

4. SYSTEM MODEL AND ANALYSIS METHODOLOGY

This chapter describes the system model and analysis methodology used in the performance analysis of heterogeneous network deployment in suburban environment. First the propagation environment is described, which is followed by propagation model and antenna model in Section 4.2 and 4.3, respectively. The deployment strategies are described in Section 4.4. Finally, the simulation parameters and performance metrics used in the analysis, are described at the end.

4.1 Scenario Description

The analysis is done in a suburban type environment. A block of 20 (2 floors) houses is repeated throughout the network to keep the homogeneity, as shown in Figure 4.1. The dimensions of each house is 10 m $\times$ 10 m $\times$ 5 m (length $\times$ width $\times$ height). In each block, the houses are separated by a street of width 5 m, while the inter-block separation is set at 15 m. The analysis is done for both indoor and outdoor environments. For the indoor plan, no specific floor plan has been assumed, i.e. there are no interior walls to obstruct the indoor wave propagation, except for the floor or ceiling. Moreover, the radio wave transmission is affected by wall penetration loss..

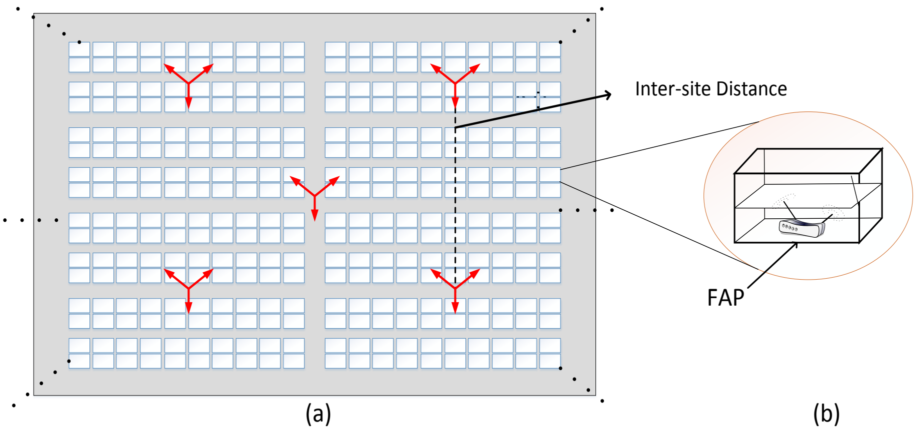

Figure 4.1 *Suburban scenario used in the analysis*

4.2 Propagation Model

For modeling the outdoor and indoor propagation channel, a deterministic propagation model has been used in the analysis. Deterministic models, as described in the previous chapter, are computationally intensive and very time consuming due to the fact that they try to model all the ray paths at the receiving point. Some of the most popular deterministic models are *ray-tracing* and *ray-launching*. All the rays are accumulated at that point to acquire the received power. In general, almost 95% of the received signal energy is carried by only 2 or 3 ray paths [45]. Hence, considering only the dominant paths serves the purpose which is not time consuming like other deterministic models [45]. Moreover, slight variation or inaccuracies in the map database also lead to incorrect prediction by traditional ray-tracing models, which results in inaccurate prediction. The Dominant Path prediction Models are less prone to such inaccuracies in the map database, and hence are most suitable and convenient to use. As such, DPM model provides relatively quite fast propagation prediction results with accuracy comparable to the traditional ray-based models.

The DPM calculates the results in two steps:

- Identify the dominant paths
- Predict the path loss of those dominant paths

Figure 4.2 illustrates the concept of dominant path phenomenon. It is evident

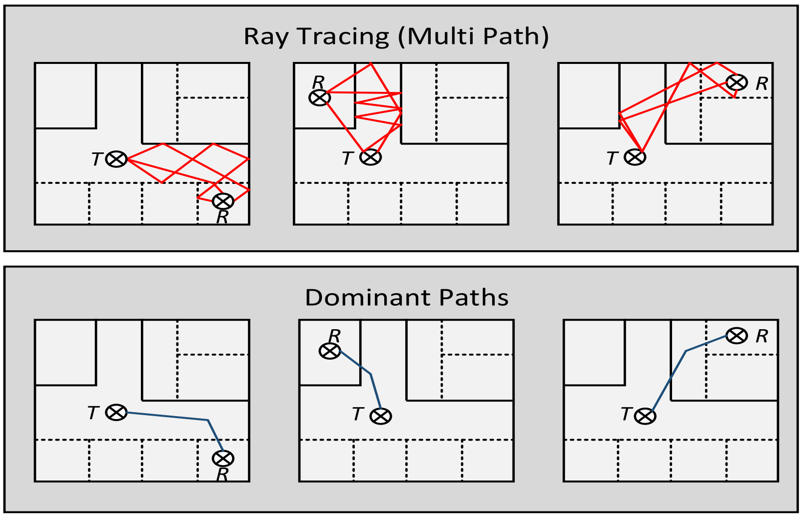

Figure 4.2 Comparison of traditional ray tracing and Dominant Path Model.

that ray tracing computes all the multipaths between the transmitter and the receiver which makes it complex and highly time consuming. On the contrary, the dominant path model only considers the dominant path(s) between the transmitter and receiver which carries 95% of the signal power, hence significantly reducing the computation time.

The path loss of the dominant ray along the path is calculated by the formula [18]:

$$L = 20.p.log(d) + \sum_{i=1}^{n} f(\varphi, i) + \sum_{j=1}^{m} t_j - \alpha \tag{4.1}$$

where L is the loss in dB, d is the distance covered by the ray in meters, $f(\varphi, i)$ is a loss due to interaction in dB, α is the wave-guiding factor, the value of p lies on the visibility status between the transmitter and the current pixel point under prediction.

4.3 Antenna Model

An electrically down-tilted directional antenna is used for the macrocellular sector antenna. The specifications for the antenna model are taken from [46] because efforts have been made to make a physical antenna model and the parameters of it can be matched with the data sheets of the real antennas. The horizontal (azimuth) gain is modeled as [46]:

$$G_h(\varphi) = -min \left[12 \left(\frac{\varphi}{HPBW_h} \right)^2, FBR_h \right] + G_m \tag{4.2}$$

where $\varphi, -180° \leq \varphi \leq 180°$ is the horizontal angle relative to the main beam of antenna, $HPBW_h$ is the half power beam width in horizontal direction, FBR_h is the horizontal Front-to-back ratio and G_m is the gain of the antenna. The vertical gain component is computed by the following expression [46]:

$$G_v(\theta) = -max \left[12 \left(\frac{\theta - \theta_{etilt}}{HPBW_v} \right)^2, SLL_v \right] \tag{4.3}$$

where $\theta, -90° \leq \theta \leq 90°$ is a negative vertical angle relative to the horizontal plane. $HPBW_v$ is the vertical Half power beam width, SLL_v vertical slide lobe level and θ_{etilt} is the electrical down-tilt angle.

The antennas used for indoor femtocell access points (AP) are conventional omnidirectional antennas. The parameters for the macrocellular antenna model used for the simulation are listed in the Table 4.2 [13]. The effective isotropic radiated power (EIRP) of a macrocell antenna is 61 dBm (43 dBm + 18 dBi) and the EIRP of the femtocell access point (FAP) is 22.2 dBm (20dBm + 2.2 dBi) [13].

4.4 Deployment Strategies

In the scope of this thesis, two common deployment strategies are employed for the analysis of indoor and outdoor environment. These strategies are listed as follows:

- Pure Macrocell network
- Pure Femtocell network
- Heterogeneous Macro-Femto network

4.4.1 Pure Macrocell network

The pure macrocell network is deployed in a hexagonal manner. The distance between the base stations called an inter-site distance (ISD) is taken as [1732, 866 and 433] meters. Cell density per km^2 is calculated by the following expression [47]:

$$\rho_{cell} = \frac{1}{A_{cell}} \tag{4.4}$$

where A_{cell}(per km^2) is the dominance area of the cell and it can be calculated as:

$$A_{cell} = \frac{\sqrt{3}}{6}(d_{site})^2 \tag{4.5}$$

d_{site} is the inter-site distance, i.e. distance between the two base stations in a network. The cell densities for all the ISDs for the above mentioned deployment strategies used in the analysis are given in Table 4.1.

4.4.2 Pure Femtocell deployment

In this strategy, the users in the network are served by indoor femtocells only. In case of ultra-dense network, which means each house is deployed with a femtocell, the cell density of the FAPs 3125 cells/km^2 [13]. However, the analysis is done such that the density of the FAPs varies from 5% to 100% in the network area. Moreover, the connectivity speeds for the femtocell backhaul are considered as [4, 16 and 100] Mbps. FAPs are considered to be running in an Open Source Group (OSG), which means that the external macrocell users can connect to the indoor femtocell AP whenever it enters the dominance area of the indoor FAP.

4.4.3 Heterogeneous Macro-Femto Network

The third strategy considers deployment of both macrocell and indoor femtocell access points. The femtocell access points are deployed within the dominance area of the macrocellular cell site, thus forming a heterogeneous network. Both deployment layers (macro and femto) operate on the same carrier frequency, hence called *co-channel* deployment. Furthermore, in the analysis, for the hetnet deployment, for each macrocell ISD the femtocell deployment varies from 0 % (meaning no femtocellular deployment) to 100 % i.e. every house has a separate indoor femtocell deployed.

Table 4.1 *Cell densities for different ISDs with different femtocell penetration rates*

Deployment Strategy	**Femtocell (%)**	**Cell Density (cells/km^2)**		
		1732 m	**866 m**	**433 m**
Macro only	**0**	3.5	13.9	55.4
Macro-Femto HetNet	**5**	160	171	212
	10	316	327	368
	15	472	483	524
	20	629	640	680
	25	785	796	837
	50	1566	1577	1618
	75	2347	2358	2399
	100	3129	3140	3180

The general simulation parameters are listed in Table 4.2. Moreover, to determine the receiver thermal noise floor, a 20 MHz bandwidth is assumed (stemming from 3GPP Long Term Evolution, LTE).

Table 4.2 *General Simulation Parameters*

Parameter	Unit	Value
Operating Frequency	MHz	2100
Bandwidth(W)	MHz	20
Transmit power	dBm	Macrocell: 43, Femtocell: 20
BS antenna type		Macro (Directional), FAP(Omni-directional)
BS antenna beamwidth, $HPBW_{h,v}$		Directional (65°/6°), Omni (360°/90°)
BS antenna gain, G_m	dBi	Macrocell: 18, Femtocell: 2.2
UE antenna type		Halfwave dipole
UE antenna gain	dBi	2.2
BS antenna height, h_{BS}	m	Macrocell: 30, Femtocell: 2
UE antenna height, h_{MS}	m	2 (relative to floor level)
Receiver noise figure	dB	9
Receiver noise floor level,P_n	dBm	-92
Propagation environment		suburban
Propagation model		Dominant Path Model
Building dimensions	m	10 × 10
Building height	m	5
Indoor floor plan		Open space
External wall penetration loss	dB	30

4.5 Analysis Methodology

The major concern of any mobile operator is the cost factor while deploying a new network or upgrading an existing one. In the analysis, we have chosen *energy* and *cost* efficiency to be studied in detail to analyze the feasibility of investigated deployment strategies. Moreover, the impact of femtocell backhaul speed limitation on the overall network capacity is also analyzed, in pure femtocell and macro-femto HetNet deployment scenario.

For simplicity, the propagation environment in the simulation model is kept homogeneous. The analysis is done considering the performance statistics from the dominance area of the middle macro cell site and all the femtocells deployed within that area. The analysis is then normalized over the area of 1 km^2. The following key performance indicators are analyzed a suburban type environment:

- **Network Capacity**
- **Energy Efficiency**
- **Cost Efficiency**

4.6 Cell and Network Area capacity

For the analysis, the network is assumed to be operating at full load, i.e., all the base stations are transmitting at full power. In this case, the cell spectral efficiency, η_{cell}, is defined as cumulative bit rate per Hz that a cell can offer under given radio propagation environment and interference conditions [13]. The average network capacity η_{area} can be determined by the expression [13]:

$$\eta_{area} = \rho_{cell} \times \eta_{cell} \tag{4.6}$$

ρ_{cell} is the number of cells per km^2, i.e. cell density and η_{cell} is the average cell capacity which can be computed by Shannon's capacity theorem.

$$\eta_{cell} = W \langle log_2(1 + \Gamma) \rangle. \tag{4.7}$$

where W is the bandwidth, the factor Γ is the signal-to-interference-noise ratio and $\langle . \rangle$ refers to the averaging. It is clear from the above expression that cell capacity is directly proportional to the SINR. Lower SINR values yield low cell capacity and vice versa. Interference causes the SINR to drop down because the signals from other sources deteriorate the signal quality. This interference can be caused by co-channel macro- or co-channel femtocells. An illustration for interference condition in a macro-femto hetnet is shown in Figure 4.3. A user equipment (UE) may endure interference from either co-channel macro layer, co-channel femto layer or both macro and femto layers. The interference conditions are further explained as following [1] :

- *Interference Conditions - Macro-only deployment:* The UE experiences interference from other co-channel macrocells in macro-only deployment. The

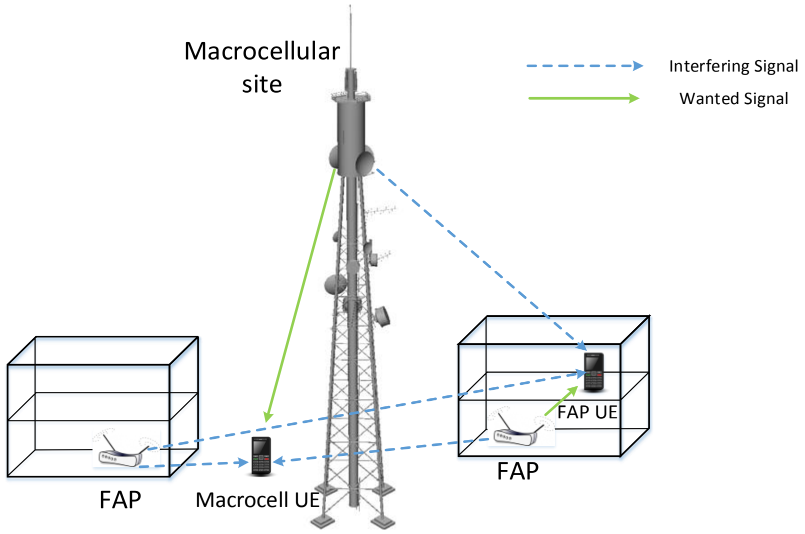

Figure 4.3 *Interference experienced by UE in co-channel Macro-Femto network [1].*

SINR for this case is given by the following expression [1]:

$$\Gamma_j = \frac{S_j^{Macro}}{\Sigma I_{i,j}^{Macro} + P_n} \tag{4.8}$$

where S_j^{Macro} is the signal power, of the serving macrocell, received at the j^{th} UE, $I_{i,j}^{Macro}$ is the interferer signal power of i^{th} macrocell received at j^{th} UE and P_n is the noise floor which includes noise figure of the UE as well.

- *Interference Conditions - Femto-only deployment:* In a femto-only deployment case, the UE experiences interference from the co-channel femto cell access points which are deployed in the close vicinity of the serving femtocell. The *SINR* for this case can be expressed as follow [1]:

$$\Gamma_j = \frac{S_j^{Femto}}{\Sigma I_{k,j}^{Femto} + P_n} \tag{4.9}$$

where S_j^{Femto} is the signal power, of the serving FAP, received at the j^{th} UE, $I_{i,j}^{Femto}$ is the interferer signal power of k^{th} femtocell received at j^{th} UE and P_n is the noise floor.

- *Interference Conditions - Macro-Femto deployment:* In this scenario, it is assumed that the UE is either connected to the macrocell or a femtocell. In both cases, the UE experiences interference by other co-channel macro and femtocell base stations. The *SINR* for this scenario is calculated as [1]:

$$\Gamma_j^{Macro} = \frac{S_j^{Macro}}{\Sigma I_{i,j}^{Macro} + \Sigma I_{k,j}^{Femto} + P_n} \tag{4.10}$$

$$\Gamma_j^{Femto} = \frac{S_j^{Femto}}{\Sigma I_{i,j}^{Macro} + \Sigma I_{k,j}^{Femto} + P_n} \tag{4.11}$$

  where Γ_j^{Macro} and Γ_j^{Femto} are the *SINR* values experienced by the j^{th} UE connected to the macrocell and femtocell respectively. The UE is interfered by the co-channel macro- and femtocell transmitters in both cases.

4.7 Energy Efficiency Analysis

With the overwhelming growth in mobile traffic, it is an important concern for the mobile operators to keep their networks energy efficient and reduce the amount of CO_2 emission levels [48]. The studies suggest that CO_2 emission due to the communication technology has already exceeded 2 percent and with the exponential increase in the mobile devices, this figure is drastically rising [48].

Energy efficiency is a key factor in deploying a new network or operating an existing one. Mobile operators need to improve the energy efficiency of the network because it contributes a major chunk of expenditure in the cost as well. A concept of 'Green Cellular Network' has risen which emphasizes on the improvement of energy efficiency in the telecommunication sector and now it has become one of the most significant KPIs [49]. Although deployment of small cells promise to cater the increased demands of capacity but there are some serious questions regarding the implication of energy efficiency.

The most common method to measure the energy efficiency of a network is to calculate the bits per Watt ratio. This means that number of bits transferred per unit Watt gives the energy efficiency. The energy efficiency is calculated for the whole network so the unit used for the energy here is 1 kW. This method is applicable to calculate the energy efficiency when the network is running under full load. The energy efficiency of a network can be calculated by the following expression [13]:

$$E_{eff} = \frac{\eta_{area}}{P_{km^2}} \quad [bits/Hz/kW] \tag{4.12}$$

where η_{area} is the total network capacity normalized to 1 km^2 area, and P_{km^2} is the power consumed by the network elements (e.g. base stations) in the area of 1 km^2. This methodology is applicable to both macrocellular and femtocell networks.

4.7.1 Power Consumption Model for Macrocell Base stations

The parameters for power consumption model of the macrocellular base station are taken from a data sheet developed by Alcatel Lucent [50]. Power consumption in the network depends on the load of the traffic supported by the base stations, in peak hours, the network is expected to consume more power. Hence, in the power calculation, load factor is also included to obtain optimum results. The expression is given as [50]:

$$P_{BS(macro)} = P_{const} + P_{load}.F \tag{4.13}$$

In the above expression, P_{const} is the constant load of the base station regardless of any load e.g. rectifier, fiber optic link, air conditioning unit etc. On the other hand, P_{load} is the load induced by the power amplifier, transceiver, and digital signal processing units. F is the load factor whose value lies between 0 (minimum) and 1 (maximum). In our analysis, we have assumed the base station to be operating at full load. The general parameters for the macrocellular base station are given in Table 4.3. The values for the macrocell base station power model are taken from [50] except the values for air-conditioning, power amplifier efficiency and fiber optic link. The average efficiency of modern power amplifiers range from 35 % to 65 % [51], [52], hence we have assumed the PA efficiency to be 45%. The power consumption by the air-conditioning unit is not considered because new outdoor pole mounted BTS are reported to have no air conditioning units, thus 0 watts in case of air conditioning units. From the values in Table 4.3, the total power consumption is calculated approximately as 1040 Watts ≈ (1kW)

Table 4.3 *Input Parameters for the Macro BS Power Consumption Model*

Component/Equipment	Unit	Value
Number of sectors		3
Transmit power at the antenna	Watts	20
Power consumption of DSP card	Watts	100
Power Amplifier efficiency	%	45
Power consumption of Transceiver	Watts	100
Power consumption of Rectifier	Watts	100
Power consumption of Fiber-Optic Link unit	Watts	7.5

4.7.2 Power consumption model for Femtocell Access Points

Power consumption model of the femtocell access point can be determined by adding the power utilized by three key interacting blocks of the femtocell base station [53]. The first block is the microprocessor which implements and manages the radio protocols and relevant base band processing. Moreover, it also connects the back haul connection to the core network. The second block is the Field-Programmable Gate Array (FPGA) with some other supporting circuitry to perform functions like data-encryption, authentication of hardware, and NTP. The third block consists of a radio frequency transmitter which is responsible to send and receive signal and power amplifier. The total power of a femtocell base station is given as [53]:

$$P_{femto} = P_{mp} + P_{FPGA} + P_{Tx} + P_{amp} \tag{4.14}$$

where P_{mp}, P_{FPGA}, P_{Tx} and P_{amp} are the power consumption in Watts for microprocessor, the FPGA, the transmitter and the power amplifier respectively. Table 4.4 enlists the parameters for femtocell power consumption model components. The efficiency of the power amplifier is taken to be 20%. The reason is, FAPs are targeted for the mass market and to keep the price affordable for the consumers, inexpensive components are used e.g. lower power efficiency amplifier used in the FAPs are quite cheaper as compared to high efficiency power amplifiers installed macrocellular base stations. Considering all the parameters from [53], the total power consumption of a femtocell base station is calculated as 10 Watts approximately.

Table 4.4 *Input Parameters for Femtocell BS power consumption model*

Component/Equipment	Unit	Value
Transmit power at the antenna	Watts	0.1
Power Amplifier efficiency	%	20
Power consumption of Transceiver	Watts	1.7
Power consumption of Microprocessor	Watts	3.2
Power consumption of FPGA	Watts	4.7

4.8 Cost Efficiency Analysis

One of the key factors in deploying a network is its cost efficiency. Mobile operators strive to provide maximum coverage and capacity to their customers keeping the cost in control and improving the profit margins. This section introduces the cost efficiency model for the all the deployment strategies.

The total cost of the network is comprised of three dominant factors; frequency spectrum, energy and infrastructure [54]. For the analysis, we will compute the annualized Capital Expenditure (CAPEX) and Operational Expenditures (OPEX). The CAPEX includes the initial costs at the time of network deployment like the cost of base stations, transmission equipment, antennas, wires, and infrastructure costs. While the OPEX comprises of running costs like, site rental, transmission line, operation and maintenance costs, radio network planning, billing and customer care costs, interconnection and roaming costs, core network and marketing costs. The total cost of the network can be determined by adding CAPEX and OPEX. Operational costs are dominant in the overall cost structure of the network [55] which are extended to the life-time period of the network while CAPEX is the initial cost at the time of network deployment or upgrading. The calculation for CAPEX and OPEX are done using a Discounted Cash Flow (DCF) analysis. DCF has appeared to be the best method to evaluate corporate equities and investment opportunities. The DCF gives the discounted present value equal to the future value of the business project using appropriate discount factor which gives the net present value (NPV). Net present value is the accumulated present value of incoming and outgoing cash flows over a time span. The mathematical expression of NPV is given as [55]:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \tag{4.15}$$

where T is the study period (usually 8 years in case of base stations value depreciation), CF is the cash flow over the period of time 't' and r is the discount rate. Table 4.5 enlists the CAPEX and OPEX for both macrocell base stations and femtocell access points. The approximate values for the costs are taken from [56]. From the statistics provided in the table, it is evident that the cost of macrocell base stations as compared to FAPs is very high. FAPs are low cost WLAN access points which can be found in commercial market at very cheap cost. The operational cost for FAPs is also very low, the only running expense is the cost of backhaul connectivity which is approximately 40 euros per month.

To calculate the NPV of the base stations, it is presumed that the mobile operator has deployed the network as a Greenfield project where the network has been deployed in the first year and the CAPEX is calculated for only first year. The total cost for the macrocell base station over the span of 8 years with the discount of 10% is determined as 104k€and for the femtocell access point, it is calculated as 3.3k€.

Table 4.5 *CAPEX and OPEX for Macro- and Femto- base stations*

CAPEX	**Macrocell BS**	**Femtocell AP**
Base station equipment	10 k€	0.1 k€
Site deployment cost	5 k€	0 k€
Total CAPEX	**15 k€**	**0.1k€**
OPEX	**Macrocell BS**	**Femtocell AP**
Site rent (lease)	5 k€/year	0 k€/year
Leased Line rent (backhaul)	2 k€/year	0.5 k€/year
Operation and Maintenance	7 k€/year	0 k€/year
Total OPEX	**14 k€/year**	**0.5 k€/year**

Once the total cost structure of the base station is known, the cost efficiency of both macrocell and femtocell networks can be calculated. Cost efficiency is generally identified by cost-bit ratio efficiency for different deployment strategies and it is expressed as:

$$c_{eff} = \frac{\eta_{area}}{T_{cost/km^2}} \qquad [bps/Hz/kEuro] \tag{4.16}$$

where η_{area} is the average network capacity and T_{cost/km^2} is the total cost of the base stations in the network normalized over 1 km^2.

The main aim of this thesis is to study the impact of backhaul limitation on the performance of energy and cost efficiency of indoor femtocell based cellular network deployment and compare it with pure macrocellular network deployments. As discussed earlier in this section, the performance of the femtocells is dependent on the quality of broadband link. Higher connectivity speeds of the backhaul link lead to better performance and high data rates in the femtocells. The analysis on energy and cost efficiency is done with a set of different connectivity speeds of the backhaul broadband connection. The backhaul connectivity speeds that are used for the analysis in this thesis are [4, 16, & 100] Mbps. This is done because generally, houses are connected via a limited internet connection. Moreover, as discussed earlier, the simulations have been done for different femtocell market penetration rates, i.e., [5, 10, 15, 20, 25, 50, 75 & 100]% in a macro-femto hetnet. The deployment of femtocells is done using Monte Carlo [1] method, in which femtocells are randomly placed a 100 times in a given area for each market penetration percentage. In this way, the femtocells in the network are uniformly distributed.

[1] Monte Carlo simulation is a method to explore the sensitivity of a system by varying parameters within statistical constraints. The results from the simulation are analyzed to determine the characteristics of the system [57].

5. RESULTS AND ANALYSIS

The analysis in this section is based on the post processing of the results from the simulation done in suburban environment discussed in section 4.1. The analysis starts with focus on behavior of RSSI, SINR and spectral efficiency in both indoor and outdoor environments. Then, network area capacity, cost and energy efficiency results are illustrated and analyzed in detail with emphasis on their trend varying with the density of FAPs in the network.

5.1 RSSI, SINR and Average Spectral Efficiency

The RSSI and SINR have been calculated on the cell edge (10th percentile values) in order to determine the user experience where the signal strength is very weak, prone to co-channel interference and quality of service is poor. In this way, we get to know the user experience in the worst conditions.

Received Signal Strength Indicator (RSSI) is an indicator of the received signal power. RSSI is one of the factor that affects the channel quality in communication, higher values of RSSI lead to good coverage and hence the radio channel quality, provided the interference level is constant. Figure 5.1 shows the RSSI for suburban indoor scenario in macro-femto het-net.

x-axis shows three inter-site distances for which the calculations have been done and y-axis shows the RSSI levels in dBm. The graph shows nine different lines that represent percentage of femtocells' density in the network starting from 0% to 100%. The figure shows RSSI levels for the macro-femto network with different macro inter-site distances (ISDs) i.e., 1732 m, 866 m and 433 m. Moreover, for each macro ISD, the femtocell penetration varies from 0% (i.e., pure macrocellular deployment) to 100% (i.e., ultra-dense femtocells deployment in which each house has a single femtocell AP deployed on first floor). We see that the RSSI improves as we increase the density of FAPs in indoor environment. The ultra dense network

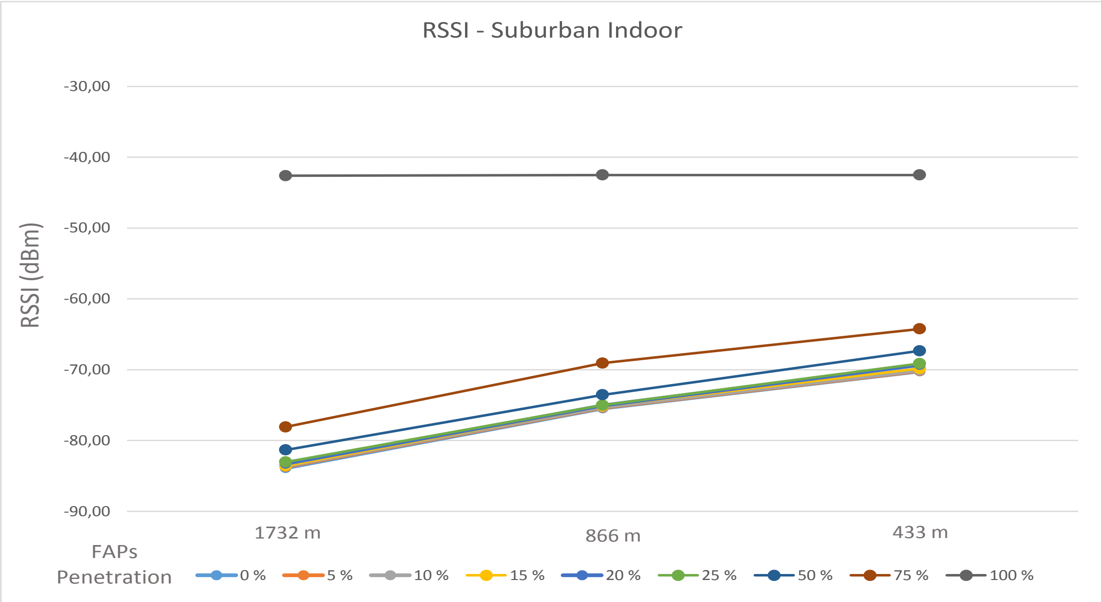

Figure 5.1 10^{th} *percentile values of RSSI for Suburban Indoor Environment*

with 100 % FAPs has the best RSSI level which helps in achieving higher SINR and good spectral efficiency. This happens because ultra dense het-net with 100 % FAPs provide coverage virtually everywhere indoors which results in high RSSI values. Figure 5.2 shows the RSSI levels for outdoor scenario.

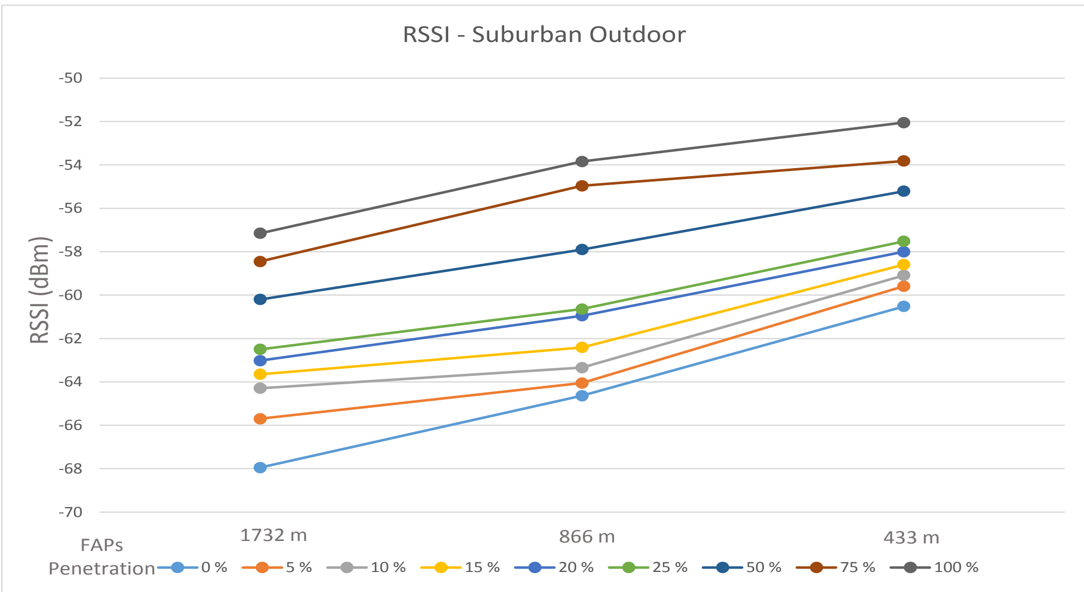

Figure 5.2 10^{th} *percentile values of RSSI for Suburban Outdoor Environment*

From the figure, we see that the RSSI levels for the outdoor are slightly less than indoors. The reason for having lower outdoor coverage levels as compared to the indoor coverage is due to the fact that at the cell border region, femtocells are serving the outdoor users as well, because they are dominant as compared to macrocells. However, due to wall penetration losses, the signal from indoor femtocell attenuates, hence we see relatively lower RSSI in the outdoors. Signals propagating from indoor femtocell network to outdoor network are attenuated due to wall penetration loss and hence the RSSI is not as strong as it is in the indoor femto network.

Signal to Interference-plus-Noise ratio is a quantity to determine the theoretical upper bound on channel capacity in wireless communication systems [58]. SINR is the ratio of signal power and interference power with noise. It is used to determine the quality of the wireless channel and SINR decreases as the receiver moves away from the transmitter and vice versa. Figure 5.3 shows the SINR levels of macro only and macro-femto Het-Net indoor network.

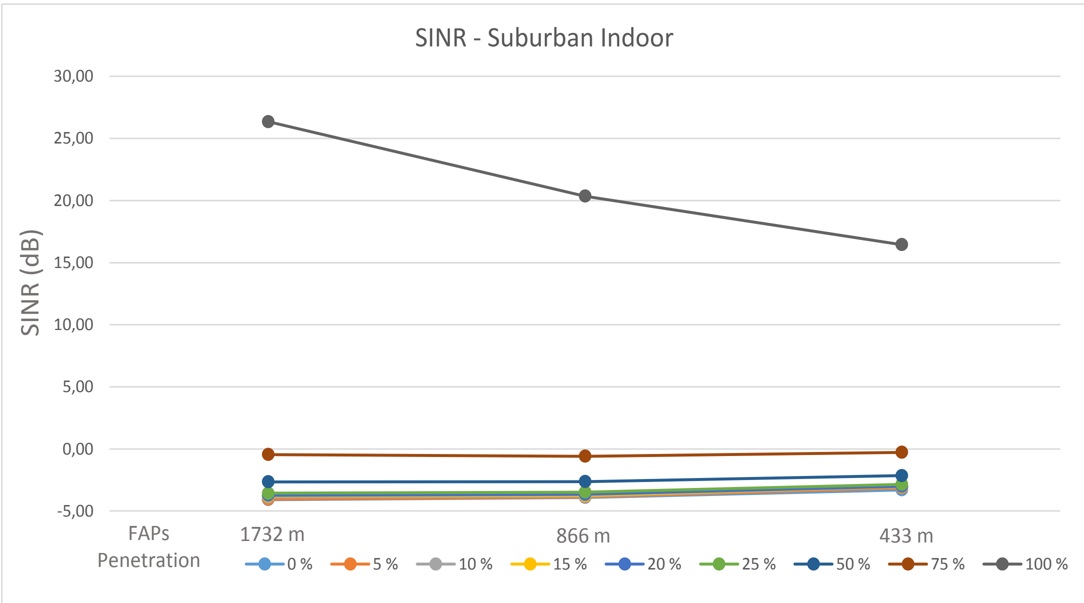

Figure 5.3 10^{th} *percentile values of SINR for Suburban Indoor Environment*

From Figure 5.3, we see that SINR offered by the three macro only networks (ISD 1732, 866 and 433) m is almost the same. Although, dense macro only network (ISD 433 m) should have higher levels of SINR but that doesn't happen because high frequency reuse in this case causes co-channel interference and SINR does not increase. However, the deployment of femtocells causes SINR levels to rise, as shown from the results, SINR increases as the density of FAPs increases and ultra dense network of ISD 1732 m with 100% FAPs has the highest values of SINR. ISD 433 m has comparatively lowest SINR because the dense macro network causes co-channel interference, hence even being the most dense hetnet, SINR offered by it is the lowest. The reason for highest SINR values in ISD 1732 m is the FAPs that provide excellent coverage in the indoors with strong RSSI levels. Though the the indoor femto only network is ultra-dense in this case, co-channel interference in indoors does not affect the values of SINR due to the small coverage range of FAPs in each house. Moreover, indoor radio coverage is isolated by the walls in each house, that prevents from further interference among FAPs deployed in each house. Figure 5.4 illustrates the SINR values for the sub-urban outdoor scenario.

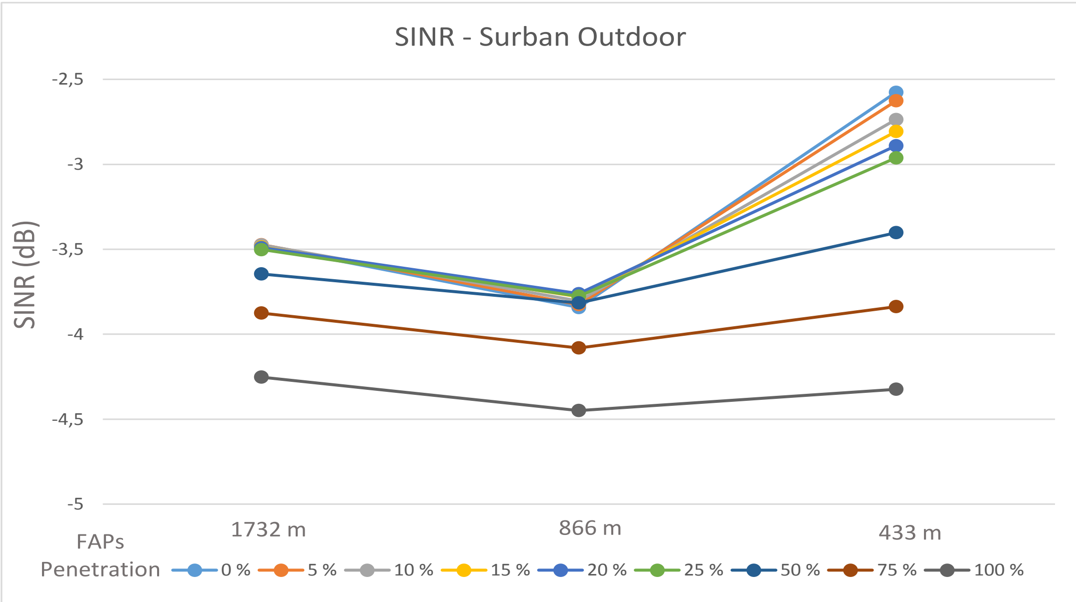

Figure 5.4 10^{th} *percentile values of SINR for Suburban Outdoor Environment*

As discussed earlier, the femtocells are dominant in the cell border region. That is why, a trend of improved SINR is observed as the density of FAPs is increased. However, as the femtocell penetration is increased, the interference level in the outdoor environment increases, which degrades the SINR performance.

Spectrum Efficiency is defined as the bit rate of an information that can be sent over the channel with frequency of 1 Hz in a communication system. Figure 5.5 shows the average spectral efficiency of the network in a suburban indoor scenario which is direct mapping of SINR values shown in Figure 5.3 using 4.7.

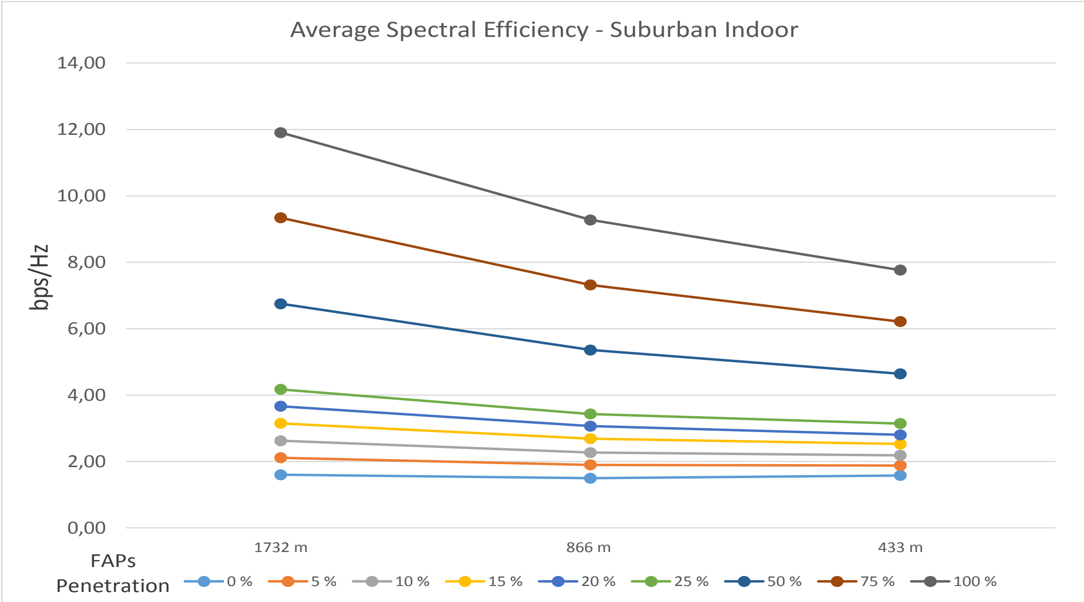

Figure 5.5 *Average Spectral Efficiency values for Suburban Indoor Environment*

In the indoor environment, FAPs are dominant serving cells and contribute in achieving high spectral efficiency. As seen from the figure, the spectral efficiency increases as the density of the FAPs increases. Looking at the trend of the graph, we can observe that the average spectral efficiency decreases when density of macrocell base station increases. Co-channel interference increases as the number of macro cells sites increases which results in lower spectral efficiency. That is why het-net with ISD 1732 m has the highest spectral efficiency as compared to other two networks (ISD 866 & 433 m).

A similar calculation has been done for the outdoor environment and the results are shown in Figure 5.6.

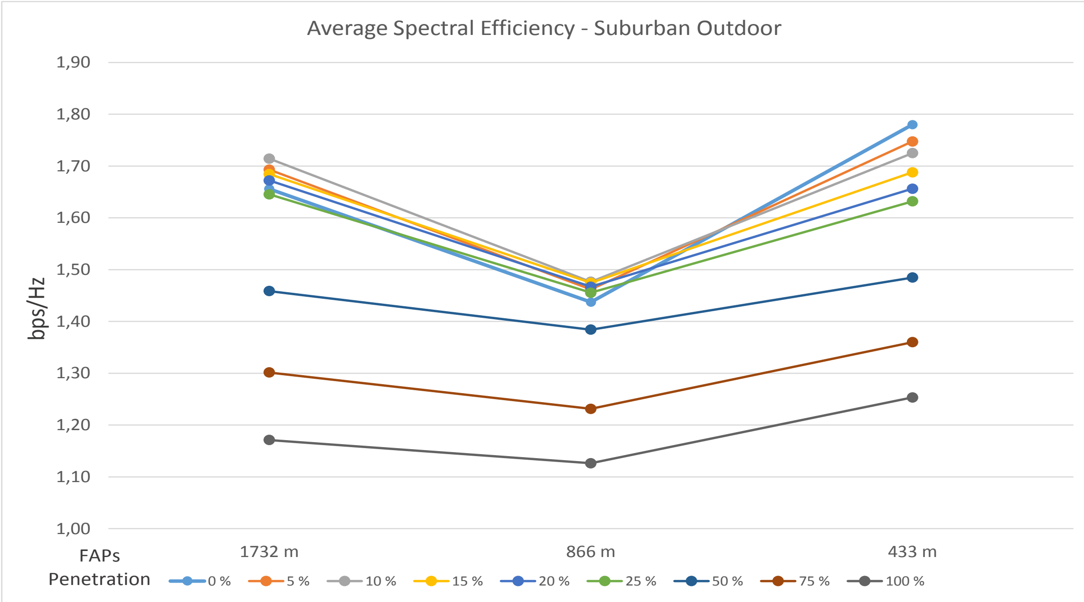

Figure 5.6 *Average Spectral Efficiency values for Suburban Outdoor Environment*

The results in Figure 5.6 show that average sectral efficiency in suburban outdoor environment is much lesser than indoor scenario. The reason for the good spectral efficiency in the indoor environment, as compared to the outdoor environment, is because of the good coverage due to close proximity of the femtocells and better interference protection from the external walls. The indoor femtocells are well shielded from external interference, both outdoor base stations and neighboring femtocells, due to the external walls which attenuate the interfering signals when they penetrate inside the building.

For the indoors, we have indoor FAPs which provide better coverage, but for the outdoor, due to being far away from the macro base station, at the cell edge, the FAPs get more dominant servers as we increase the FAPs penetration. The indoor FAPs present at the cell edge of macrocells have relatively higher signal levels, but, due to wall penetration losses, their signal strength are relatively weak as compared to indoors as shown in Figure 5.4 and also the interference in the outdoor environment is more noticeable. This interference comes from macrocells and neighboring femtocells. That is why, we see relatively poor SINR condition in the outdoor environment, as compared to the indoor environment which consequently has an affect on spectral efficiency.

5.2 Indoor capacity, cost- and energy- efficiency analysis

In a typical mobile network, indoor users are served mainly by the outdoor macro base stations. Due to this *outside-in* mechanism, indoor users may suffer from poor coverage, low quality of service and reduced data throughput because the signals from outdoor network suffer from wall penetration loss and get attenuated. There is a popular hypothesis, majority of the network traffic, around 65-70%, is generated by the indoor users. In order to provide seamless quality of service, macro only network will be not sufficient to serve indoor users in near future due to massive growth in users and overall mobile capacity demand. To overcome this bottleneck, operators have started to introduce indoor small cells which are helpful in addressing the capacity and coverage issues experienced by indoor users.

In this thesis, we consider pure macrocell (ISD 1732m) as the baseline deployment scenario and use it as a benchmark to analyze and compare pure macrocellular densification and HetNet (macro-femto) deployment scenarios with varying femtocell penetration. The analysis is done in the following steps:

i. Analysis of the baseline macro only ISD 1732 m network.

ii. Comparison and analysis of baseline network with densified macro-femto het-net.

iii. Comparison and analysis of densified macro-femto network with macro only network operating at higher frequencies.

iv. For the performance analysis, we consider three metrics; network capacity, energy-efficiency and cost-efficiency.

The aim of the comparative analysis to determine which technique gives the best solution by providing maximum network area capacity, lowest cost and minimum energy consumption. The analysis is done such that the calculations for the area capacity, cost efficiency and energy efficiency are done using the varying spectrum bandwidth (5, 40 and 100) MHz for macro only network and the backhaul connection link of the femtocells is taken as (4, 16 and 100) Mbps for both indoor and outdoor suburban scenarios.

5.2.1 Pure macrocellular densification indoor analysis

In this section, we look at the performance analysis of a pure macrocellular network densification. The cell densities for different inter-site distance (1732, 866 and 433) meters are 3.5, 14.5 and 55.4 cells per sq. km respectively. The analysis starts by keeping the operating bandwidth fixed at 5 MHz, which is typical for UMTS network all over the world, and increasing the cell density in a macrocell network. The results show that the area capacity offered by the baseline macrocell ISD 1732 m network is 0.028 Gbps. This is the least dense network configuration that we have considered in the study which offers the cost and energy efficiency parameters as shown in Table 5.1.

Table 5.1 *Network Capacity, Cost & Energy efficiency @ 5 MHz spectrum*

Macro Only	Bandwidth = 5 MHz		
	1732 m	**866 m**	**433 m**
Area Capacity (Gbps)	0.02	0.10	0.43
Cost Efficiency (kbps/€)	0.23	0.21	0.22
Energy Efficiency (Mbps/W)	0.023	0.021	0.022
Total cost per area (k€/km^2)	121	482	1924
Area power consumption (kW/km^2)	1.2	4.8	19.2

As we can see from Table 5.1, the area capacity increases as we increase the density of the macrocells in the network. In order to further enhance capacity of the network, there are several pathways for network evolution. One way is to increase the operating bandwidth of the system, however this is a costly option and a free spectrum resource might not always be available as UHF band is already congested. The second method is to increase the base station density. This method forms the basis of this thesis as well. Analyzing the pure macrocellular densification, we can see that for indoor environment, although the network capacity increases with increase in macro base station density, however, the increase in network capacity is not high enough to offset the corresponding increase in network energy consumption and cost of deployment. Hence, we see a decrease in the overall energy- and cost-efficiency i.e. from ISD 1732 m to ISD 866 m. A slight improvement in energy- and cost-efficiency can be observed when further densifying the network from ISD 866 m to ISD 433 m. Nevertheless, the overall efficiencies are still lower than the baseline ISD 1732 m scenario.

Hence, in order to increase the network capacity through network densification, mobile operators require base stations that consume lower power and are less costly to deploy as compared to their legacy counterpart i.e., macro base stations. Small cell solutions e.g. femtocell access points are hence identified to fulfill these criteria. However, the problem with small cells is that due to having small coverage range compared to macrocells (typically 10 m to 100 m), they are required to be deployed in order of magnitude to have a seamless and consistent coverage. This again triggers energy- and cost-efficiency concerns. In the following section, we compare the pure macrocellular densification with HetNet macro-femto densification and analyze whether HetNet deployment strategy is a energy- and cost-efficient pathway for the mobile operators to evolve their networks. In other words, we use this technique to find out which deployment strategy is beneficial for the operator; increasing the density of macrocells only or deploying femtocells in the network.

5.2.2 Macro-Femto cell densification indoor analysis

In this section we look at the network densification based on low cost and low power indoor femtocells as an alternative deployment solution to increase the network capacity. In this analysis we assume that the indoor femtocell solutions are utilizing residential (consumer) grade internet connection as a backhaul to the core network. As such, we also analyze the impact of femtocell backhaul limitation in terms of different connectivity speeds on the overall network performance. We have compared the baseline macro only network with ISD 1732, Table 5.1, with the heterogeneous macro-femto network by varying the density of femtocells from 5% to 100% penetration rates. In indoor environment, femtocells are dominating serving cells and they offer a very good spectral efficiency due to excellent indoor coverage and good SINR. We start off the analysis with the lowest penetration rate (5%) of the femtocells in the network considering the femtocell backhaul limitation as 4, 16 and 100 Mbps. Table 5.2 shows the efficiency parameters of macro-femto network with 5% femtocell penetration.â

If we compare the key performance metrics of macro-femto heterogeneous network considering only 5% penetration rate of the femtocells, as shown in Table 5.2, and

Table 5.2 *Macro-Femto Het-Net Capacity, Cost and Energy Efficiency @ Femtocell penetration = 5%*

Macro-Femto Network	**Backhaul Limitation**	**Spectrum = 5 MHz**		
		1732 m	**866 m**	**433 m**
Area Capacity (Gbps)	**4 Mbps**	0.63	0.68	0.84
	16 Mbps	1.68	1.61	1.98
	100 Mbps	1.68	1.61	1.98
Cost Efficiency (kbps/€)	**4 Mbps**	1.005	0.68	0.34
	16 Mbps	2.65	1.61	0.81
	100 Mbps	2.65	1.61	0.81
Energy Efficiency (Mbps/W)	**4 Mbps**	0.23	0.10	0.04
	16 Mbps	0.61	0.25	0.096
	100 Mbps	0.61	0.25	0.096

compare those values with performance values of pure macrocellular network, given in Table 5.1, it is evident that for the ISD 1732 m, the area capacity increases almost 22 times as compared to the baseline macro 1732 m network just by introducing 5% femtocells in the network while the femtocell backhaul connectivity speed is limited to only 4 Mbps. The area capacity is increased with higher femtocell backhaul connectivity speeds. Hence, it is observed that overall network capacity performance in this case is limited by the femtocell backhaul limitation. Furthermore, for macrocellular deployment, no backhaul limitation is assumed.

In this scenario, the frequency spectrum is kept constant i.e. 5 MHz. Same trend is observed in case of cost and energy efficiency parameters. Cost efficiency is improved around 5 times while energy efficiency is increased by 10 times as compared to pure macro only network. The deployment of the femtocells in the network helps in improving the average spectral efficiency that results in enhanced area capacity and other parameters. Femtocells are low cost and work efficiently together with the macrocellular network. This shows that efficiency of the network can be enhanced without spending huge costs on procuring additional spectrum or increasing costly macro-base stations. Femtocells do not only enhance the network performance economically but they also provide a better user experience, good indoor coverage and very high data throughput because FAPs offer good RSSI levels indoors that results in good SINR levels and spectral efficiency. Macrocells, being far from the receivers at the cell edge, have poor RSSI levels indoors which degrades the quality of service.

Figure 5.7 shows the trend of the area capacity of suburban indoor scenario for different penetration rates of femtocells in the network starting from 0% penetration

(Macro Only) to 100% femtocell penetration (Macro-Femto Network) extremely dense het-net with three femtocell backhaul connectivity limits of 4, 16 and 100 Mbps while the operating frequency of 5 MHz is used. It is important to note that the capacity graph with 0% femtocell deployment has no limitation on the connectivity speeds unlike higher percentages because the macro only network is independent of any backhaul limitation. The x-axis shows the femtocell backhaul limits, y-axis shows the network capacity in Gbps and z-axis shows the ISDs (1732, 866 and 433) m. The percentage values on top of the bars show the percentage of deployment of femtocells in the network.

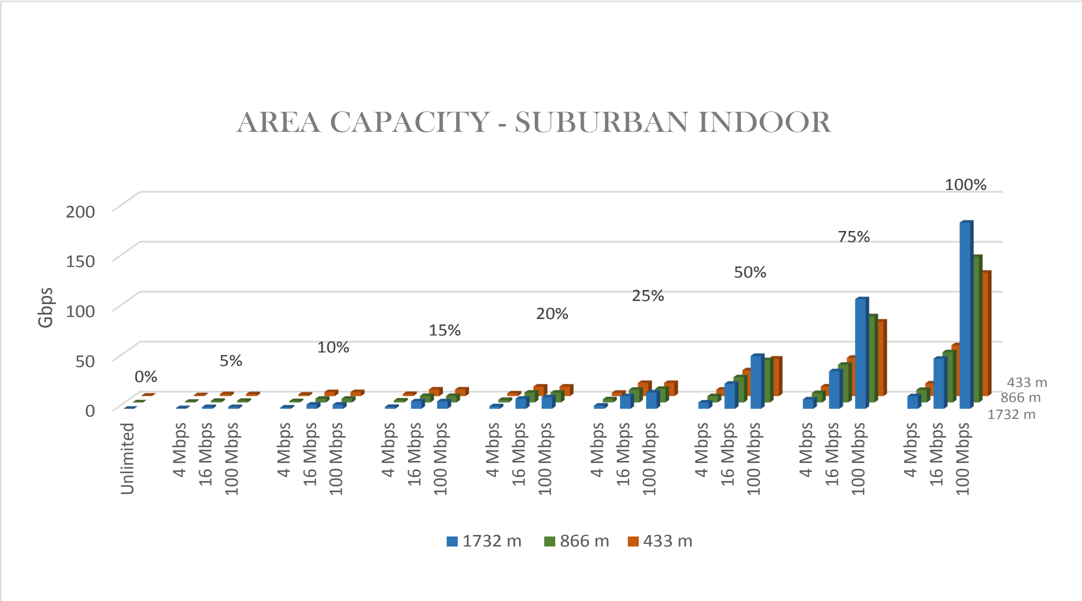

Figure 5.7 *Network Capacity - Suburban Indoor*

From Figure 5.7, we can see the trend of increasing capacity as the femtocell density increases. It is evident that 100% deployment of femtocells in the macrocell network with ISD 1732 meters yields the highest capacity. Ideally the capacity offered by the het-net with ISD 433 m should be the highest but dense deployment of the macrocell base station results in co-channel interference due to which the average spectral efficiency decreases and hence the overall area capacity decreases. The performance of ISD 433 m network can be improved to some extent by using a different frequency spectrum for macro- and femtocells layer or using the Intercell Inerference Coordination techniques (ICIC) which is beyond the scope of this thesis.

To increase the capacity of the network, we can increase both the density of macrocellular base stations as well as femtocell access points. The technique with highest capacity and lowest cost will be ideal and feasible for the operators to implement. We now analyze how does densification of the femtocell and macrocell base stations effect the cost and energy efficiency. From the values in Table 5.1, it can be seen that as we decrease the inter-site distance (ISD) i.e. increase the density of macro-cellular base stations, the area capacity increases but with the added costs of new base stations. Using the frequency spectrum at 5 MHz, densified macro only network at ISD 433 m yields cost efficiency as 0.228 kbps/€. If we increase the density of femtocells in the baseline network of ISD 1732 m, the cost efficiency is much more better than it is in macro only network. The cost of the femtocell access point is 100 times less than a macrocell base station which makes it very cost effective and provides an excellent indoor coverage with enhanced capacity gains. Moreover, FAPs operate on very low power i.e. they have low OPEX which, in case of macro base stations, constitute a huge chunk of expenses. Figure 5.8 illustrates the cost efficiency with the same attributes as in Figure 5.7.

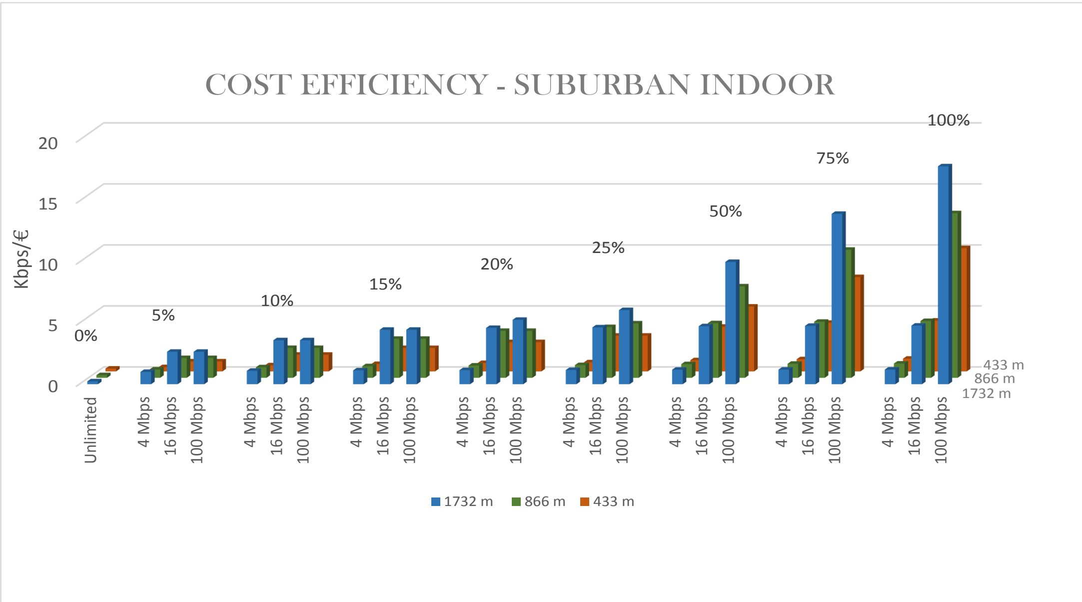

Figure 5.8 *Cost Efficiency - Suburban Indoor*

As shown from Figure 5.8, a similar trend is observed for the cost efficiency as it was observed for the area capacity. Since cost is the most important factor that an operator has to take care in deploying a new network or upgrading an existing one, it is crucial to find out the optimum solution that offers the best deal, i.e. enhanced capacity and low cost. Having virtually no OPEX, femtocells take a lead in providing a cost effective and enhanced capacity solution. Macro-femto het-net deployment with the ISD 1732 m offers the most cost efficient solution because increasing the density of macrocellular base stations increases the cost factor, both CAPEX and OPEX, which makes het-net of ISD 433 m the least cost efficient compared to het-net with ISD 1732 m and ISD 866 m, with varying femtocell penetration. Bits transferred per euro are increased drastically when the penetration percentage of the femtocells increases in the macro-femto het-net as shown in the figure.

Looking at the energy consumption statistics, we can determine that the bits transferred per watt are much higher in case of macro-femto heterogeneous network than in macro only deployment. The energy efficiency improves 27 times if we compare macro only and macro-femto het-net with 5% penetration of femtocells at ISD 1732 m. Figure 5.9 shows the trend of energy efficiency for different densities of femtocells in het-net network starting from macro only network (0%) to extremely dense het-net i.e. 100% deployment of femtocells in the network.

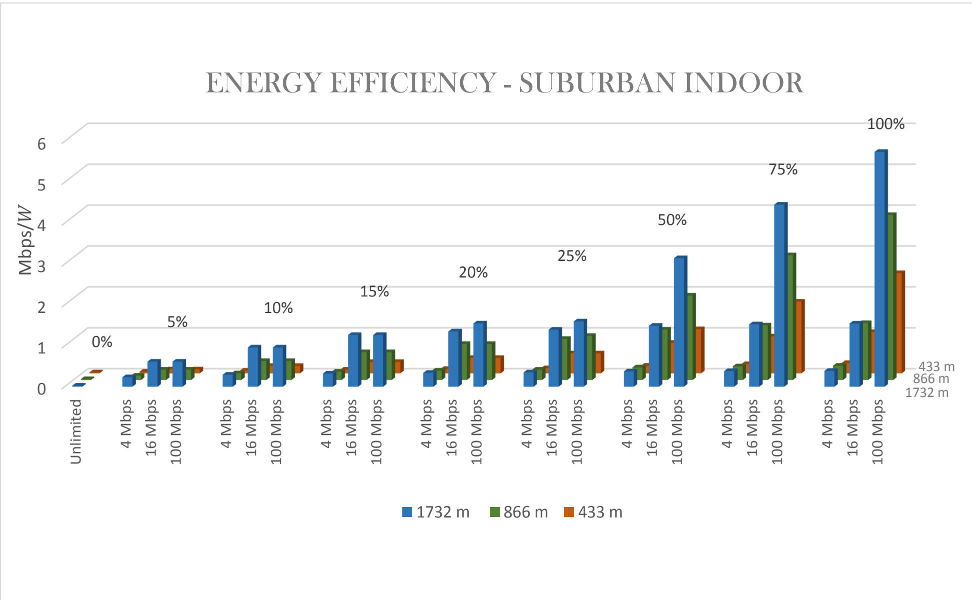

Figure 5.9 *Energy Efficiency - Suburban Indoor*

Energy consumption is a factor that cannot be ignored while operating a network because it contributes a major part in running costs of the network. Operators try to implement energy efficient solutions to cut their costs and keep the environment green and clean. In this study, we have calculated the energy efficiency of the pure macrocellular network and determined how it is effected by the deployment of femtocells in the network. From Figure 5.9, the het-net of ISD 1732 m provides the most energy efficient solution which implies cost effectiveness that we already had seen in the statistics discussed in the cost efficiency part. Femtocell access points consume very low power due to their very small size, the energy consumption of the FAPs is 10 times lesser than a macrocellular base station which saves a lot of energy as well as cost.

One of the capacity enhancing techniques is to increase the system bandwidth. In the next step, we evaluate the macro only network by shifting it from 5 MHz to larger system bandwidth i.e. 40 & 100 MHz. In this way, we are able to compare macro only network utilizing larger bandwidth with macro-femto het-net to find cost-efficient technique to enhance the capacity. Table 5.3 shows the efficiency parameters of macro only network with different ISDs and using larger system bandwidth.

Table 5.3 *Network Capacity, Cost & Energy efficiency @ 40 and 100 MHz spectrum (Macro Only)*

Macro Only	**Bandwidth = 40 MHz**			**Bandwidth = 100 MHz**		
	1732 m	**866 m**	**433 m**	**1732 m**	**866 m**	**433 m**
Area Capacity (Gbps)	0.22	0.84	3.50	0.56	2.10	8.75
Cost Efficiency (kbps/€)	1.87	1.73	1.83	4.68	4.32	4.57
Energy Efficiency (Mbps/W)	0.19	0.17	0.18	0.47	0.43	0.46

From Table 5.3, we can see that as the frequency spectrum is increased, the area capacity, cost and energy efficiency have also improved but this increase in capacity comes at a very high cost because operators spend a fortune to buy a frequency spectrum. Now we compare the values in Table 5.3 with the values in Table 5.2, we see that the network area capacity offered by macro-femto ISD 1732 m network with just 5% FAPs with the lowest backhaul limit of 4 Mbps, operating at 5 MHz spectrum, is around 3 times higher than the capacity of macro only network operating at 40 MHz. The capacity offered by macro only ISD 1732 m network, operating at 100 MHz, is still less than macro-femto network by around 1.5 times. This shows that increasing the density of femtocells in the network is beneficial and enhances the network capacity economically. If we increase the density of macrocells, we see that the capacity starts to increase. Macro only networks of ISD 866 & 433 m operating at 40 MHz offer approx. 1.5 and 5 times more capacity, respectively, than macro-femto het-net operating at 5 MHz with just 5% FAPs. But this capacity is enhanced at the cost of extremely expensive frequency spectrum and added costs of new base stations. Similar scaling of capacity is observed in case of macrocell network operating at 100 MHz. We can increase the capacity of macro-femto network just by increasing the density of femtocells in the network, e.g., increasing the FAPs' density to 50% yields the network capacity, cost and energy efficiency as shown in Table 5.4.

Table 5.4 *Network Capacity of Macro-Femto Het-Net 5 MHz with 50% FAPs*

Macro-Femto Network	Backhaul Limitation	Bandwidth = 5 MHz 1732 m	866 m	433 m
Area Capacity (Gbps)	**4 Mbps**	6.26	6.30	6.47
	16 Mbps	25.05	25.22	25.88
	100 Mbps	52.84	42.24	37.53
Cost Efficiency (Kbps/€)	**4 Mbps**	1.18	1.11	0.91
	16 Mbps	4.74	4.47	3.66
	100 Mbps	10.01	7.48	5.30
Energy Efficiency (Mbps/W)	**4 Mbps**	0.37	0.30	0.18
	16 Mbps	1.48	1.23	0.74
	100 Mbps	3.14	2.06	1.07

We see from Table 5.4 that the network capacity of macro-femto network at ISD 1732 m increases around 28 times if we compare it with the capacity offered by macro only network ISD 1732 operating at 40 MHz and 11 times in case of macro only operating at 100 MHz. This shows that just by increasing the femtocells density, network capacity increases in order of tens because of the excellent spectral efficiency offered by the FAPs. Hence, deploying FAPs indoors offer higher capacity gains without spending huge amount of money on high frequency spectra and extra macrocell base stations.

5.3 Outdoor capacity, cost- and energy-efficiency analysis

Considering the mobile traffic distribution in Section 5.2, around 30-35% of the traffic comes from the outdoor users. And this percentage increases even more in busy hours such as office hours (morning and evening). Till date, outdoor macro network layer have serviced outdoor users due to their low volume but the mammoth growth in network capacity needs in next five years will not be fulfilled by macro base stations alone. To offload traffic from the outdoor base stations, operators need to shift the traffic load from macro base stations to the small cells. In this way, traffic load is distributed between macro and small cell layers which helps in offering good quality of service and enhanced data throughput.

5.3.1 Pure macrocell densification outdoor analysis

For the suburban outdoor scenario, the same approach has been followed as it was done in the case of suburban indoor analysis. In this case, the outdoor macrocellular base stations are more dominant unlike in indoor scenario. As discussed earlier, the indoor environment has good coverage due to close proximity of femtocells, which leads to higher values of SINR and enhanced spectral efficiency, unlike in outdoor environment. However, on the cell edge, femtocells tend to improve the performance of the outdoor network, which is discussed in the next section.

Talking about the network area capacity, we again take macro only network of ISD 1732 m as our baseline which we compare with the macro-femto het-nets. Table 5.5 shows the area capacity, cost efficiency and energy efficiency values of macro only outdoor network while keeping the frequency spectrum fixed to 5 MHz.

Table 5.5 *Network Capacity, Cost & Energy efficiency @ 5 MHz spectrum*

Macro Only	**Bandwidth = 5 MHz**		
	1732 m	**866 m**	**433 m**
Area Capacity (Gbps)	0.02	0.10	0.49
Cost Efficiency (kbps/€)	0.24	0.20	0.25
Energy Efficiency (Mbps/W)	0.024	0.020	0.025

From Table 5.5, it can be seen that the area capacity increases as density of macrocellular base stations increases. The baseline ISD 1732 m macro only network offers an overall area capacity of 0.02 Gbps. In order to see this network's cost effectiveness and capacity related parameters, we compare it with macro-femto het-net operating on the same frequency spectrum with 5% penetration of FAPs.

5.4 Macro-Femto cell densification outdoor analysis

As we have previously done in the suburban indoor scenario, we start analyzing the performance of the network by deploying just 5% femtocells in the network. Table 5.6 illustrates the values of area capacity, cost and energy efficiency with a fixed frequency spectrum of 5 MHz and 5% deployment of FAPs in the network.

Table 5.6 *Macro-Femto Het-Net Capacity, Cost and Energy Efficiency @ Femtocell penetration = 5%*

Macro-Femto Network	Backhaul Limitation	Bandwidth = 5 MHz		
		1732 m	**866 m**	**433 m**
Area Capacity (Gbps)	**4 Mbps**	0.63	0.68	0.84
	16 Mbps	1.35	1.24	1.84
	100 Mbps	1.35	1.24	1.84
Cost Efficiency (kbps/€)	**4 Mbps**	1.005	0.68	0.34
	16 Mbps	2.12	1.24	0.76
	100 Mbps	2.12	1.24	0.76
Energy Efficiency (Mbps/W)	**4 Mbps**	0.23	0.10	0.04
	16 Mbps	0.49	0.19	0.08
	100 Mbps	0.49	0.19	0.08

Looking at Table 5.6, we see that just by deploying 5% FAPs in macro-femto network at ISD 1732 m, the capacity increases about 31 times with the lowest femtocell backhaul connection of 4 Mbps. Similarly, cost and energy efficiency have also been improved by 5 and 10 times respectively. This comparative analysis determines that capacity of the outdoor network can also be enhanced by using indoor femtocell access points. Area capacity offered by highly dense macro network ISD 433 m is still around 2 times less than a macro-femto ISD 1732 m hetnet with deployment of 5% FAPs. However, the results are not improved as indoor suburban environment but it is far more affordable and easy to improve the network efficiency by using femtocells instead of increasing the density of costly macrocellular base stations. Figure 5.10 shows the impact of femtocells density on the outdoor network area capacity.

The x-axis shows the femtocell backhaul connectivity limits of the femtocell network; y-axis shows the area capacity in Gbps and z-axis shows the inter-site distance. The

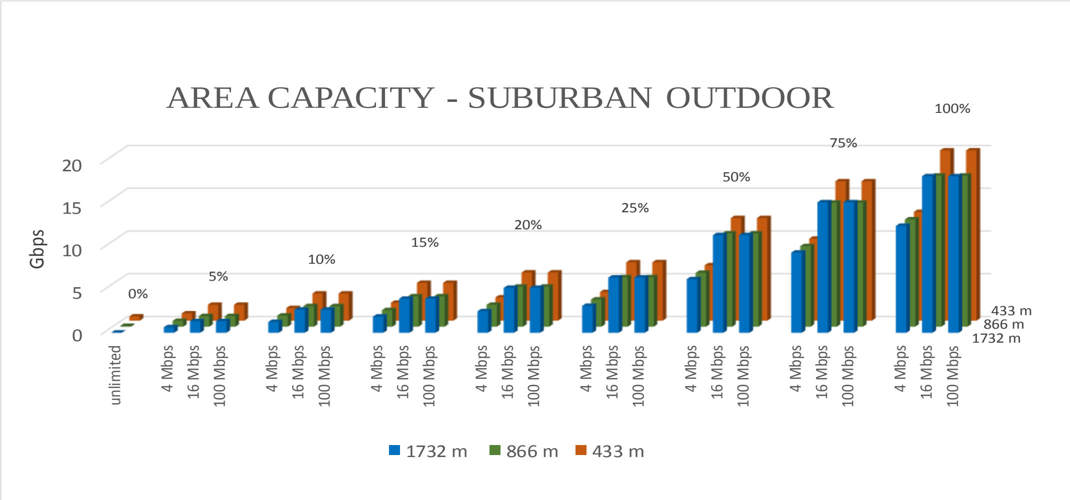

Figure 5.10 *Network Capacity - Suburban Outdoor*

characteristic of the graph is exponential in nature as it was observed in suburban indoor environment but the values are relatively lower than indoors because the radio signal traversing from indoor femtocells to the outdoor network are obstructed by external walls, however, the network performance on the cell edge is enhanced even in the outdoor network due to some coverage given by indoor FAPs. Thus, by using 100% deployment of femtocell access points in the network, we can achieve the area capacity as high as 12.5 Gbps if the maximum allowable connectivity speed of the femtocell backhaul is allowed to 4 Mbps. This value is almost 625 times higher than the network capacity offered by macro only outdoor network with ISD 1732 m.

Cost efficiency is the most important parameter for the operators to determine if the network is practically feasible or not, Figure 5.11 shows the cost efficiency of the macro-femto het-net with the increasing density of the FAPs for different femtocell backhaul limitations.

The x-axis shows the femtocell backhaul connection limits of the femtocell network; y-axis shows the cost efficiency in kbps/euro and z-axis shows the inter-site distances. The bars in the figure do not follow the same trend as it was seen in the indoor scenario. It is interesting to see that macro-femto network with 100% deploy-

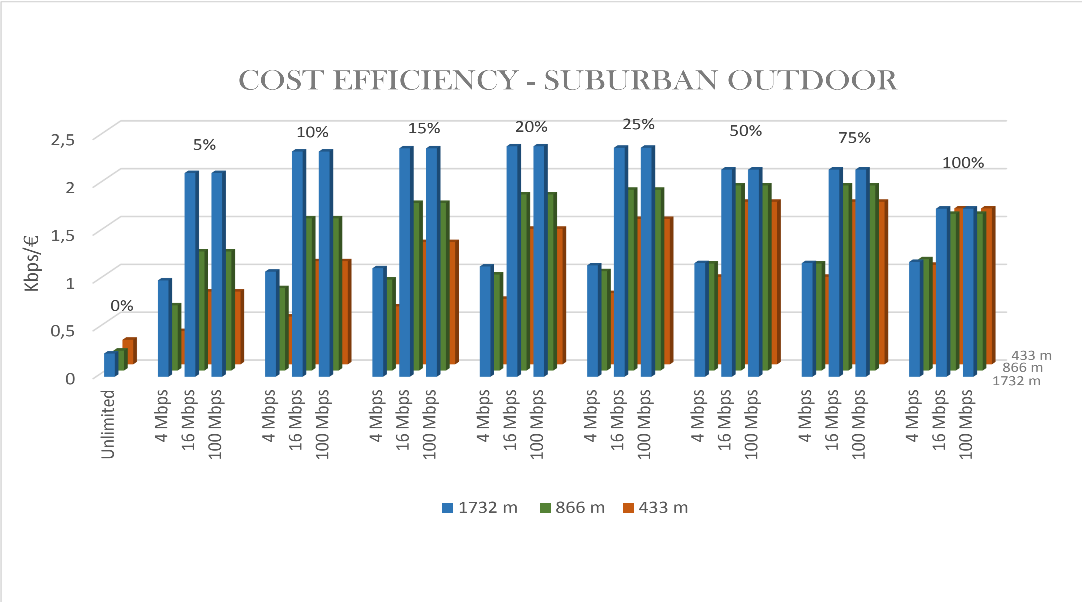

Figure 5.11 *Cost Efficiency - Suburban Outdoor*

ment of femtocells yields the lowest transfer of bits per €. Co-channel interference increases as the density of FAPs increases that degrades the average spectral efficiency. However, such dense deployment of femtocells also increases the spatial reuse thereby significantly increasing the network capacity, as shown in Figure 5.10. The cost or energy-efficiency simply depends on network capacity. Although the outdoor average cell spectral efficiency is decreasing with 100% femtocell penetration, the outdoor network capacity on the other hand is increasing. Nevertheless, this increase in outdoor network capacity is not high enough to offset the additional cost of deploying 100% femtocell, which results in lower cost-efficiency as compared to femtocell with lower penetration rate. Even then, the cost-efficiency is higher than pure macrocellular deployment baseline or in case ISD 433 m. That is why a decrease in cost efficiency is observed as density of femtocells in the network increases.

Now we analyze the energy efficiency parameters to identify the best possible solution for the network that offers highest capacity, lowest cost and least energy consumption. Figure 5.12 demonstrates the energy efficiency of het-net with different densities of femtocells.

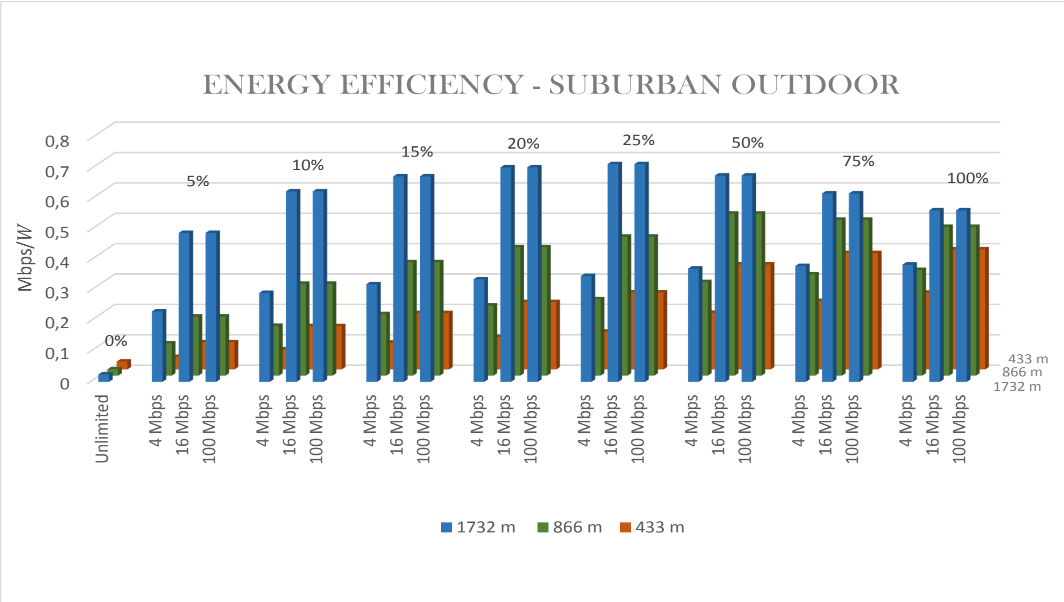

Figure 5.12 *Energy Efficiency - Suburban Outdoor*

The energy efficiency graph follows the same trend as of cost efficiency. Higher densities of FAPs in the network lead to comparatively lower energy efficiency. The values of energy efficiency in the outdoor environment are much lesser than the indoor scenario because the average spectral efficiency offered by the indoor femtocells is a lot higher than it is in the outdoor, reason being, indoor environment has good coverage, resulting in high SINR and spectral efficiency. Moreover, as the number of FAPs increases in the network, energy consumption also increases.

Now we compare the macro-femto outdoor het-net with the macro only network operating on higher frequency spectra i.e. 40 & 100 MHz. Table 5.7 shows the network capacity, cost and energy efficiency of macro only network with different ISDs operating on 40 & 100 MHz.

Looking at the values given in Table 5.7, we see that the network capacity, cost and energy efficiency have improved by shifting the network spectrum to higher spectra. Comparing the results in Table 5.7 with Table 5.6, we observe that the network capacity offered by macro only outdoor network with ISD 1732 operating at 40 MHz is still approx. 3 times less than the capacity offered by macro-femto het-net with just 5% FAPs working on the lowest backhaul limitation of 4 Mbps. This implies that femtocell access points are beneficial for the outdoor scenario as well because

Table 5.7 *Network Capacity, Cost & Energy efficiency @ 40 and 100 MHz spectrum (Macro only)*

Macro Only	**Bandwidth = 40 MHz**			**Bandwidth = 100 MHz**		
	1732 m	**866 m**	**433 m**	**1732 m**	**866 m**	**433 m**
Area Capacity (Gbps)	0.23	0.80	3.94	5.80	2.01	9.86
Cost Efficiency (kbps/€)	1.93	1.66	2.06	4.85	4.15	5.15
Energy Efficiency (Mbps/W)	0.19	0.16	0.20	0.48	0.41	0.51

macro-femto network's capacity is 3 times higher due to higher spectral efficiency offered by femtocells. If we see the cost efficiency, bits transferred per euro in macro only network operating at 40 & 100 MHz are higher than the het-net (5% FAPs, 5MHz) but this improvement comes with the huge costs of frequency spectrum. The network capacity offered by macro only network operating at 100 MHz is relatively high but densifying the outdoor network with FAPs enhances the capacity. Table 5.8 shows the network capacity, cost and energy efficiency with 50% deployment of FAPs in the outdoor network.

Table 5.8 *Macro-Femto Het-Net Capacity, Cost and Energy Efficiency @ Femtocell penetration = 50% operating at 5 MHz*

Macro-Femto Network	**Backhaul Limitation**	**Bandwidth = 5 MHz**		
		1732 m	**866 m**	**433 m**
Area Capacity (Gbps)	**4 Mbps**	6.26	6.30	6.47
	16 Mbps	11.42	10.91	12.01
	100 Mbps	11.42	10.91	12.01
Cost Efficiency (kbps/€)	**4 Mbps**	1.18	1.11	0.91
	16 Mbps	2.16	1.93	1.69
	100 Mbps	2.16	1.93	1.69
Energy Efficiency (Mbps/W)	**4 Mbps**	0.37	0.30	0.18
	16 Mbps	0.67	0.53	0.34
	100 Mbps	0.67	0.53	0.34

Table 5.8 shows that increasing the density of FAPs in the network to 50 percent, the capacity enhances more than the capacity offered by macro only network ISD 1732 operating at 100 MHz. Higher density of FAPs in the outdoor network improves the spectral efficiency which enhances the overall network capacity that exceeds the capacity offered by network of higher frequency spectra.

6. CONCLUSION

In this thesis, we have addressed the solution for 1000x data problem which is likely to happen in year 2020. The study focuses on enhancing the overall network capacity either by increasing the density of the macro only network, operating the same macro only network on higher frequency spectrum or introducing femtocell base stations in the network to identify which scheme is cost effective, energy efficient and offers maximum capacity.

In the study, we have done the analysis to find out the best solution that is cost effective and ideally fits the increasing network capacity demands. We have come to the conclusion that increasing the density of femtocell access points in the network results in enhanced capacity without spending huge costs on extra base stations and frequency spectrum for both indoor and outdoor environments. We evaluated the network from pure macro only to 100% densified het-net with femtocells. The performance of the network is calculated on different FAPs' densities in the network staring from 0% to 100 % femtocells. On the contrary, macrocell densification in the network is much more expensive and doesn't fulfill the capacity demands as required by the exponential growth of users in the market. The results in the analysis show that FAPs performed extremely well in the indoor environment and it is needed to address the poor coverage issues faced by the indoor users. With the good RSSI levels, FAPs also offered high spectral efficiency which enhanced the network capacity.

We also analyzed the macrocellular only network to enhance the network capacity. The macro only network was shifted to operating bandwidth as high as 100 MHz to see how it affects the capacity and what are the cost aspects related to it. We evaluated the macro only network by increasing the density of the macrocellular base stations as well and analyzed the capacity offered by the network, cost effectiveness and energy consumption. We reached the conclusion that operating the macro only network on higher frequency spectra and adding the new base stations in the network enhances the network capacity but this method is relatively expensive as compared to the macro-femto het-net.

Comparing all the statistics, we concluded that femtocells help to resolve the capacity issues which are soon to be confronted by the operators in near future. Results show that as the density of femtocell increases, capacity enhances in both indoor and outdoor networks. This techno-economic analysis is helpful for the industry and mobile operators to predict the capacity needed for their network and determine the solution based on that capacity and cost budget with energy consumption.

The future work will focus on detailed cost modeling of the network considering the cost of frequency spectrum. Moreover, the 5G networks are planned to operate on millimeter wave bands in the future for which more parameters need to be included in the calculations and techniques to control the co-channel interference such as Intercell Interference Coordination (ICIC) techniques.

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