TAMPERE UNIVERSITY OF TECHNOLOGY

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TOPOLOGY AND INTERFERENCE ANALYSIS IN MACROCELLULAR ENVIRONMENT

Master of Science Thesis

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ABSTRACT

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In the present day, mobile based data services have become increasingly popular among end users and businesses and thus considered as one of the important issues in the telecommunication network, because of its high demand. The telecommunication industry is continuously striving to fulfil this demand in a cost-efficient manner. Fundamentally, the performance of a mobile communication network is constrained by the propagation environment and technical capabilities of the network equipment. The target of radio network engineers is to design and deploy a mobile network that provides effective coverage and capacity solution with a profitable implementation cost. In order to reach this target, careful examination of radio network planning and choosing the right tools are the key methods. Network densification is considered as a feasible evolutionary pathway to fulfil the exponentially increasing data capacity demand in mobile networks.

The objective of this thesis work is to study and analyse the densification of classical macrocellular network, which is still the dominant form of deployment worldwide. The analysis is based on deep ray-tracing based propagation simulations in the outdoor and indoor environment, and considers two key performance metrics; *cell spectral efficiency* and *area spectral efficiency*. For analysing the impact of network densification, different cell densities, obtained from varying the inter-site distances are considered. Furthermore, the network is assumed to be operating in a full load condition; an extreme condition in which the base stations are transmitting at full power. From the simulations, it has been illustrated that as a result of densifying the network, the inter-cell interference increases, which reduce the achievable cell spectral efficiency. The system capacity, on the other hand, is shown to improve due to the increase in the area spectral efficiency, as a result of high-frequency re-use, in the outdoor settings. Nevertheless, it is observed that the densification of macrocellular network experience inefficiency in the indoor environment; mainly arising from

coverage limitation due to extreme antenna tilt angles. This calls for sophisticated methods such as base station coordination or inter-cell interference cancellation technique to be employed for future cellular network. For fulfilling the indoor capacity demand in a cost-efficient manner, the operators will be required to deploy dedicated indoor small cells based solutions.

PREFACE

This Master's thesis is carried out in the Department of Electronics and Communications Engineering at Tampere University of Technology.

I would like to thank my thesis supervisor Syed Fahad Yunas for his continual patient assistance that he provided throughout the research work. I would like to show my gratitude to my Examiner Prof. Jukka Lempiäinen.

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Tampere, August 2014

Rahman, A. F. M. Muzahidur

CONTENTS

TERMS AND DEFINITIONS

ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Patnership Project
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Service
EDGE	Enhanced Data Rates for GSM Evolution
IMT-2000	International Mobile Telecommunications-2000
WCDMA	Wideband Code Division Multiple Access
UMTS	Universal Mobile Telecommunications System
HSDPA	High Speed Downlink Packet Access
HSUPA	HIgh Speed Uplink Packet Access
HSPA	High Speed Packet Access
HSPA+	High Speed Packet Access Evolution
ITU	International Telecommunication Union
IMT-Advanced	International Mobile Telecommunications-Advanced
IP	Internet Protocol
LTE	Long Term Evolution
WiMAX	Worldwide Interoperability for Microwave Access
NMT	Nordic Mobile Telephone
NTT	Nippon Telephone and Telegraph Company
AMPS	Advanced Mobile Phone System
ETACS	European Total Access Cellular System
D-AMPS	Digital Advanced Mobile Phone System
PDC	Personal Digital Cellular
CDMA	Code Division Multiple Access
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
SC-FDMA	Single Frequency Division Multiple Access
SDMA	Space Division Multiple Access
FDD	Frequency Domain Duplexing

TDD	Time Domain Duplexing
VoIP	Voice over Internet Protocol
MS	Mobile Station
UE	User Equipment
MSC	Mobile Switching Stations
CN	Core Natwork
PSTN	Public Switched Telephone Network
PDN	Packet Data Network
PLMN	Public Land Mobile Network
FCC	Federal Communications Commission
BS	Base Station
UTD	Uniform Diffraction Theory
ISD	Inter-site Distance
CAD	Computer Aided Drawing
WI	Wireless Insite
SBR	Shoot and Bouncing Ray

SYMBOLS

S	No. of Channels, delay spread
N	No. of Cells
C	Capacity of a network
i, j	Non-negative integer
RF	Radio Frequency
Q	Co-channel use ratio
R	Cell Radius
D	Distance Between the co-channels, average delay
SIR	Signal to Interference ratio
$P(\tau)$	Channel power delay profile
f	Frequency [Hz]
Δf_c	Coherence bandwidth
B	Breakpoint distance
λ	Signal Wavelength
h_{BTS}	Base Station height
h_{MS}	Mobile station height
σ	Conductivity [S/m]
P_R	Received signal power
P_T	Transmit power
L	Path loss
r	Distance between transmitter and receiver
k,n,K	Constants
A, B	Constants
d	Distance between BS and MS
C	Propagation Slop term, Shannon capacity
C_m	Area type correction factor
G_h	The horizontal azimuth pattern
φ	Horizontal angle relative the main beam direction
$\O$	Negative elevation angle relative to horizontal plan
$HPBW_h$	Horizontal half-power beamwidth
FBR_h	Front-to-back ratio
G_m	Maximum antenna gain
G_v	Vertical (elevation) angle

$\boldsymbol{HPBW_v}$	Vertical half-power beamwidth
$\boldsymbol{SLL_v}$	Side lobe level
$\boldsymbol{d_{site}}$	Inter-site distance
$\boldsymbol{A_{cell}}$	Dominance area
$\boldsymbol{Ø_{etilt}}$	Electrical tilt angle
$\boldsymbol{r_{cell}}$	Cell range
$\boldsymbol{EIRP}$	Effective isotropic power
$\boldsymbol{\rho_{cell}}$	Cell density
$\boldsymbol{W}$	Bandwidth
$\boldsymbol{\Gamma}$	Signal-to-interference ratio
$\boldsymbol{S_j}$	Received signal of the serving cell site at j^{th} receiver point
$\boldsymbol{P_n}$	Noise figure of receiver
$\boldsymbol{\eta_{cell}}$	Cell spectral efficiency
$\boldsymbol{\eta_{area}}$	Areq spectral efficiency
$\boldsymbol{C_k}$	Average area
$\boldsymbol{N_s}$	Total number of active serviced channels per cell

1. INTRODUCTION

Since the early days, wireless communication has been influencing every aspect of modern life in the form of anywhere, anytime connectivity. At the beginning of 1990, the successful launch of GSM provided the breakthrough in mobile communication, which started the era of the modern mobile communication. GSM is considered as the Second Generation (2G) mobile communication system and one of the first systems to employ digital transmission technique. The main objective of the GSM was to provide speech services, but it had a strong limitation for providing high bit rate data connectivity. Initially, it was enough to offer adequate quality of speech with the constant data rate of 8 kbps. Later, a common demand for more innovative mobile services like video telephony, content streaming, positioning services and multimedia messages lead to a problem of insufficient 'data rate' and 'capacity' requirements. Hence, new techniques were needed to fulfill these packet data transmission capacity demands. The limitations related to the data handling capabilities of GSM, were later improved with enhancements in the digital transmission techniques, introduced in General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE).

In 1999, 3GPP (3rd Generation Partnership Project) released the *UMTS* standard, as one of the candidate technologies for fulfilling the *IMT-2000* system requirements. The UMTS is based on an entirely new radio interface technology known as *Wideband Code Division Multiple Access* (WCDMA). In the initial release specifications, known as Release 99 (R99), the UMTS system offered data rates of up to 384 kbps. Later on, this was significantly improved with further enhancements in the air-interface (in both downlink and uplink directions) introduced in later releases; R5 specification introduced HSDPA (High Speed Downlink Packet Access) which offered improvement in the downlink data rates, while in R6 specifications, HSUPA (High Speed Uplink Packet Access) was introduced which brought about enhancements in the uplink data rates. The improved system, based on R5 and R6, is jointly referred to as High Speed Packet Access (HSPA), which supports broadband data speeds of approximately 14.4 Mbps in downlink and 5.76 Mbps in uplink direction. A further evolution of HSPA technology, which is known as Evolved HSPA or simply HSPA+, utilizes multi-antenna techniques to provide data rates of up to 168 Mbps and 21.1 Mbps in the downlink and uplink direction respectively. In order to cope with the increasing capacity demand, the International Telecommunication Union ITU, released specifications for IMT-Advanced systems that provided data rates of up to 1 Gbps in the downlink direction. The IMT-Advanced systems represent the fourth generation (4G) of mobile networks, based on simplified Internet Protocol (IP) packet switch network. Already, the Long Term Evolution (LTE) system and Worldwide Interoperability for Microwave

Access (WiMAX) are marketed as 4G technologies. The downlink peak rates for LTE specification is 300 Mbps and uplink rates 75 Mbps.

The amount of data capacity demand is predicted to increase by 1000x by year 2021 [1]. In order to fulfill this demand in a cost-effective manner, mobile operators will have to look for ways to utilize the available spectrum resources in an extremely efficient manner. Fundamentally, the main mechanisms to increase the network capacity are increased link and radio resource management efficiency together with utilization of wider bandwidth and decreasing the cell size, i.e., having dense network configuration with small cells. The idea of enhancing the system capacity through network densification can be dated back to late 1940s when the cellular concept was introduced [2]. The initial adoption of the concept, however, was slow at first but started to gain serious attention when 2G networks were introduced. Since then, network densification has been viewed as a feasible pathway towards network evolution.

The main target of the thesis is to evaluate the impact of macrocell site densification on the *cell* and *system* level capacities in outdoor and indoor environments, and also to evaluate whether macrocellular densification is a feasible pathway for mobile network evolution. In essence, the study aims to find answer to the question; *how much system capacity gain can we achieve through macrocellular network densification*?

This Master of Science thesis is organized in two division, theoretical background, and results analysis. Chapter 2 introduces basics of cellular concept. In chapter 3, we look at the radio propagations phenomena that have a significant impact on the performance of a cellular network. In chapter 4, the system model has been described elaborately. The results and analysis have been covered in Chapter 5. Chapter 6 provides the conclusions based on the result analysis.

2. CELLULAR CONCEPT

The main idea behind the cellular concept was to support large number of users within a limited spectrum. Through efficient utilization of the spectrum over the network coverage area, the network can support more simultaneous users than would be possible without deploying cellular solution. This chapter provides the discussion on the basics of a cellular system and its evolution.

2.1 Brief History

In 1897, Guglielmo Marconi demonstrated the ability to communicate wirelessly with the sailing ships on the English Channel using radio waves. This was a huge invention in the history of wireless communications, after which there was no looking back. The progress in wireless communication has achieved remarkable improvement during the last couple of years. Inevitably, cellular radio technology has had an enormous impact on our daily lives and it still continues to do so.

The first telephone service was started in 1946 in USA with 120 kHz system bandwidth and 3 kHz user bandwidth [3]. This technology was implemented using a single high-powered transmitter deployed on a large tower mast and supported few simultaneous users with limited mobility. In 1970, Bell laboratories introduced a cellular concept with the development in radio frequency hardware [4]. A new era was augmented in wireless communication with the beginning of this development. Verne H. MacDonald published a journal article on “The cellular concept” in 1979 [5]. In the same year Nippon Telephone and Telegraph Company (NTT) established their first cellular system supporting 600FM duplex channels, with each channel occupying 25 kHz channel bandwidth in the 800MHz frequency range [3, 4]. In Europe in 1981, the Nordic Mobile Telephone (NMT) system was developed. The system supported 200FM duplex channels, each occupying 25 kHz channel bandwidth in the 450MHz spectrum range. In 1983, and1985, two virtually identical cellular systems were developed in U.S.A and Europe respectively. The US system was named Advanced Mobile Phone System (AMPS) and the European version was referred to as European Total Access Cellular System (ETACS) [3, 4]. In 1990, the first ever Pan European digital cellular standard GSM (Global System for Mobile) was deployed with 900MHzband. This system was dedicated for all European cellular telephone service [3]. Apart from GSM, other notable 2G systems that were deployed during that time period were;

- D-AMPS (Digital AMPS) and CDMA One, mainly deployed in the North America and,

- PDC (Personal Digital Cellular), deployed in Japan.

The second generation radio networks were based on either TDMA (Time division multiple access) or CDMA (Code division multiple access) multiple access [4]. Figure 2.1, illustrates the chronology of mobile phone systems; in the early days; starting with the first ever analog mobile telephony system, developed in 1946, and ending with the introduction of first ever second generation (2G) digital mobile telephony system, the GSM in 1990.

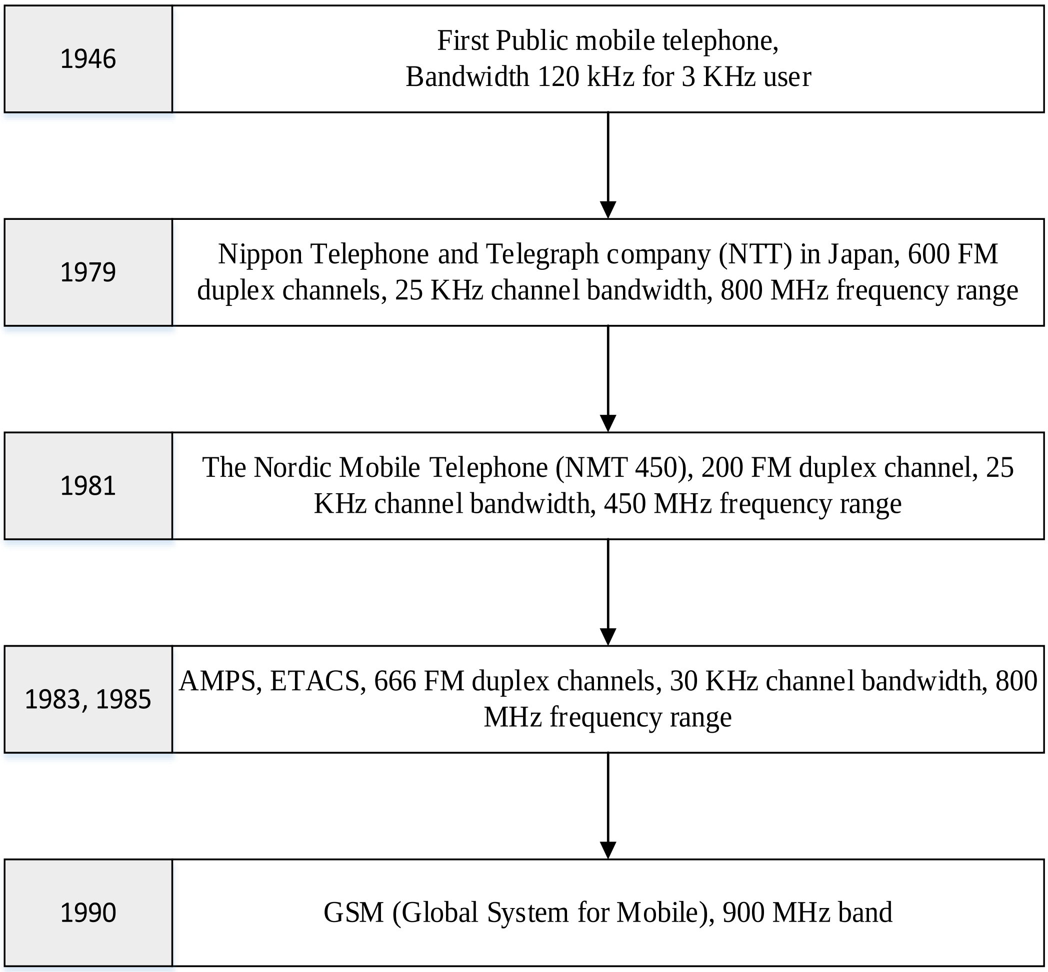

Figure 2.1 *Evolution of Mobile Telephone System from analog to digital system*

After year 2000, mobile cellular systems evolved into third generation i.e. 3G technology. The basic aim of introducing 3G cellular systems was to offer high speed data services. Internet access, communication using voice over Internet Protocol (VoIP), voice-activate calls are some examples of types of services supported by the 3G system.

2.2. Cellular System

Figure 2.2 shows the basic cellular system structure. A cellular system in its general form mainly consists of mobile stations (MS) or user equipment (UE), base-stations (BS), and mobile switching centers (MSC) also known as the core network (CN). The MSC/CN is responsible to connect all MS/UE to the external networks, e.g., a *Public Switched Telephone Network* (PSTN), a *Packet Data Network* (PDN) or another *Public Land Mobile Network* (PLMN) [12]. The base-station plays a pivotal role in connecting the subscriber to the mobile network. It acts as a bridge between mobile station and the switching/routing center.

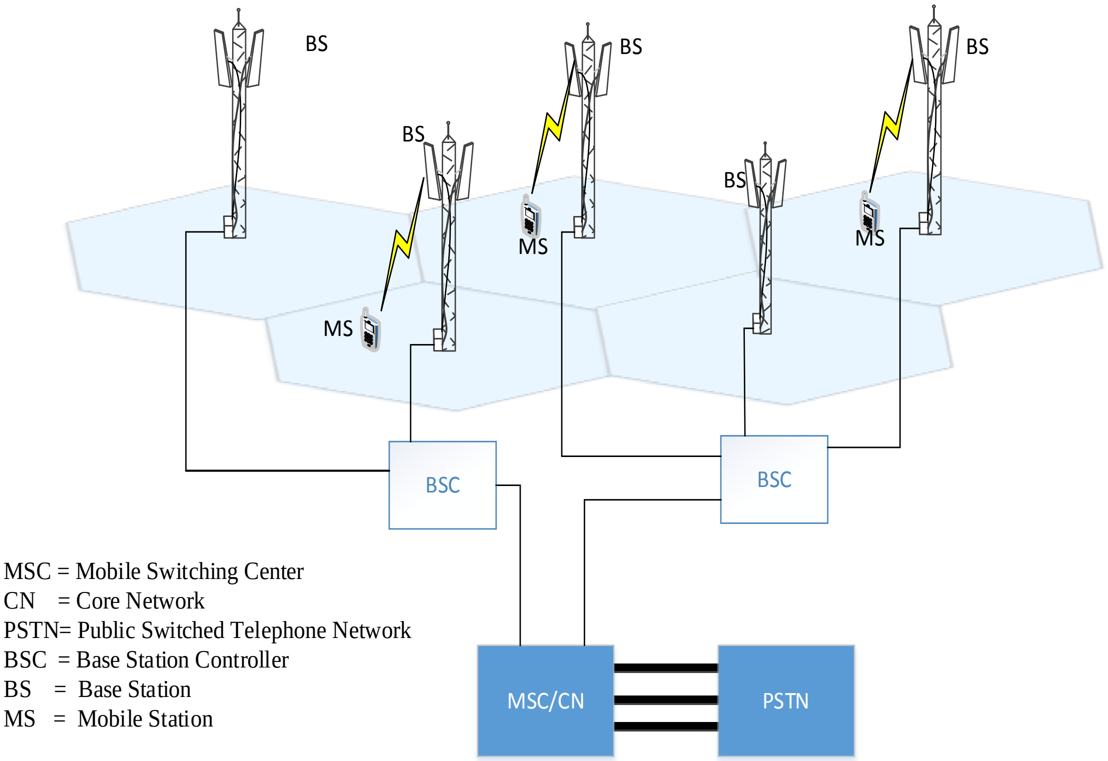

Figure 2.2 *Basic cellular system structure [4]*

2.3. The Need For Cellular System

The first ever mobile radio telephony system, also referred to as the pre-cellular '0G' system, was deployed in St. Louis (USA) by Bell Telephony Systems (nowadays AT&T) in 1946. The system was analog in nature and constituted a central base station installed on a very high tower mast. A high-power transceiver provided service to the users over a distance of 25 - 30 km. Initially, the system supported only 3 channels, i.e., 3 analog carriers, which meant that at most 3 subscribers/users could make a telephone call in a single time instance.

Later, the number of channels was increased to 32, as more spectrums were granted by the Federal Communications Commission (FCC). Nevertheless, due to the limited number of channels, the system soon reached its capacity – with the subscriber continuously experiencing busy lines. Further increasing of the system capacity through adding more spectrums was not a viable option. Hence, in order to eliminate the problem of congestion in a cost-effective manner, Bell Telephony Systems came up with the idea of a cellular concept. A large geographical area, instead of being served by a single high-power transceiver, was divided into several smaller regions, known as cells/sector [4]. Further, each of these cells or sectors was thus served by a low-power transceiver. The cellular concept was a major breakthrough in solving spectral congestion and system capacity problems. As such it forms the basis for modern mobile communication network design that we witness today.

2.3.1 Frequency Reuse

Radio spectrum is a scarce resource and a key asset of a country. The spectrum is usually managed by the country's telecom regulatory, which is responsible for licensing the spectrum to different government and eligible commercial entities, as well as monitoring of the spectrum usage to ensure compliance. Mobile operators, through a competitive and an expensive auction process, are allocated a small portion of the available spectrum, which supports a limited number of channels. Thus, in order to accommodate more users over a certain geographic area, cellular network operators are required to utilize the available spectrum resource as efficiently as possible in order to maximize the coverage and capacity. In a typical cellular communication network, the allocated spectrum is usually divided into carrier/channel groups. Each of the base stations is assigned a certain number of channels from the channel groups which are to be used within a small geographic location called cells. Adjacent cells are assigned complete different channel sets as compared to the neighboring cells in order to avoid interference. In wireless networks, the magnitude of a transmitted signal tends to decrease as it propagates farther away from the transmitting base station, thus limiting the coverage area of each cell. Hence, the same set of frequency channels can be allocated to another base station, after a certain reuse distance. The design methodology of selecting and allocating of groups of channel such that the channels can cover the entire cellular BS within the system is called frequency reuse. Figure 2.3.1 illustrates the concept of frequency reuse. The cells with the same color represent co-channel cells. In the example scenario, the neighboring or adjacent cells are allocated different channel set, in order to keep the interference within tolerable limits.

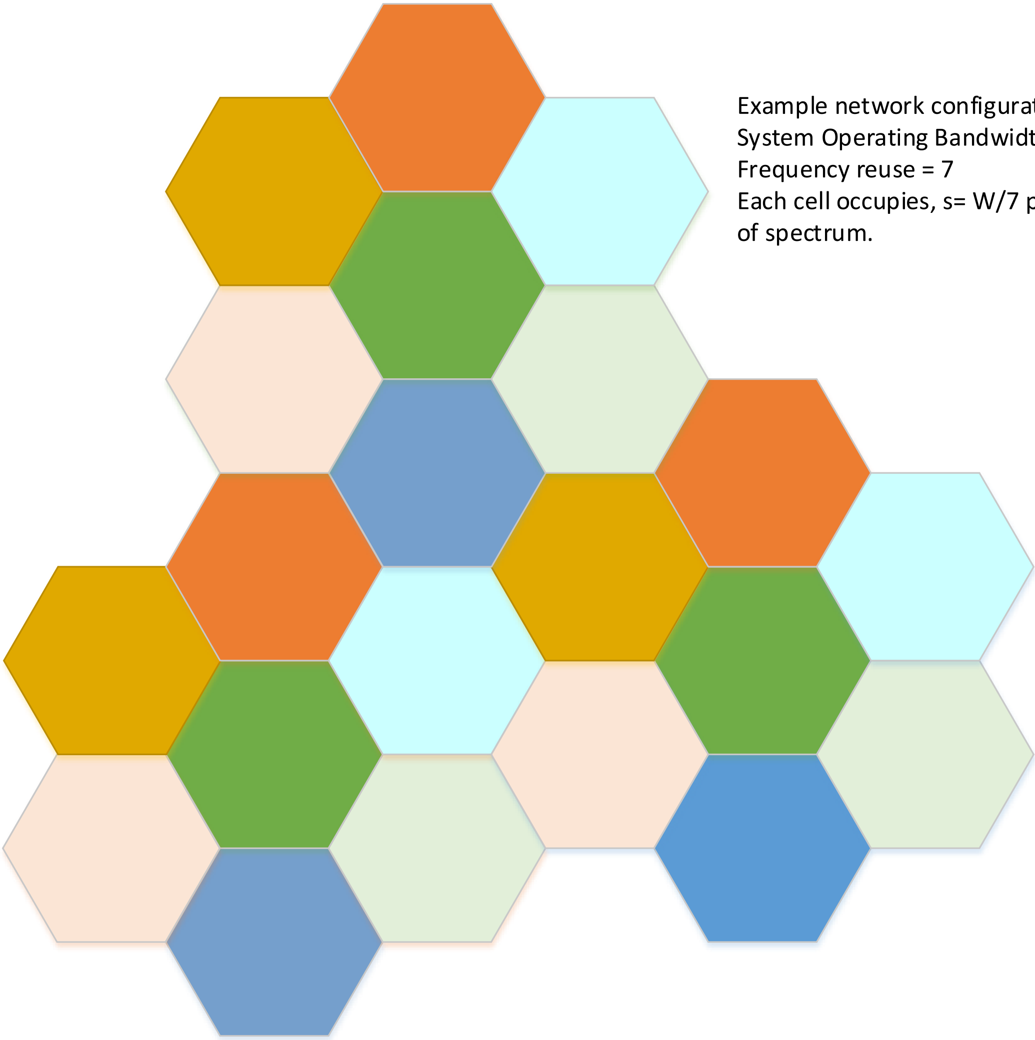

Figure 2.3.1 *Frequency reuse concept. Cells with same color use the same set of frequency channels.*

As an example case, consider a cellular mobile network is composed of N cells. Suppose there are a total of X duplex channels that the cellular network can utilize. If each of the cell in the network is allocated s channels (where $s<X$), and if S channels are divided among N number of cells such that all the channels are unique and disjoint, then total number of channels can be expressed as:

$$X = sN \tag{2.1}$$

N cells that utilize all the available channels are termed as a *cluster*. If the available frequency channels are replicated M times then the capacity of the network which is denoted as C can be formulated as:

$$C = M \cdot s \cdot N = MX \tag{2.2}$$

From the equation (2.2) it can be deduced that cellular capacity is directly proportional to the number of times a cluster is duplicated in the network's coverage area. One of the important parameters commonly used in cellular network system is called frequency reuse factor which is equal to *1/N*.

Since the network coverage is divided, typically, into *hexagonal* cells, thus, due to the geometry of a hexagon, only specific values of clusters are possible. The cluster size N can be mathematically calculated as following:

$$N = i^2 + ij + j^2 \tag{2.3}$$

where, i and j are non-negative integers.

2.3.2. Channel Assignment

In order to efficiently utilize the resources of a cellular network, certain algorithms for radio channel assignment are used, which enables the frequency reuse scheme to fulfill with the targeted increase in the network capacity and at the same time minimize the interference to a desirable level. Channel assignment strategies can be classified in two categories. The categories are termed as *fixed* or *dynamic* channel assigning strategies. The opted strategy significantly affects the performance of a network, particularly in the method how the call is handed off from one cell to another.

In the fixed network system, each cell is allocated a fixed set of channels. If in a certain time period, the number of subscribers exceeds the allocated number of channels in the cells, the call is blocked, and in that situation the subscriber cannot make a call. Several methods are used to combat the situation. One of the known methods is *borrowing* strategy. In this method when the resource of the cell is exhausted the *MSC* borrows a channel from the neighboring cell and the assigns it to the overloaded cell.

In dynamic channel assignment strategy, voice channels are not permanently allocated to specific cells. Instead whenever a call is made, the serving base station requests a channel from the MSC. The MSC allocates a channel to the BS following an algorithm resolving the situation in such a way that future blocking probability is mitigated.

2.4 Multiple Access Schemes

Many schemes are employed for allocating resources to multiple users such that the users can communicate simultaneously using the same medium, and hence, the process is termed as "multiple access". The orthogonality of the signals from different users is of primary importance in order to avoid interference and cross talk. Every multiple access scheme has its benefits and drawbacks and affects the radio resource and mobility management of the radio network. In the following section the five most commonly used multiple access schemes *FDMA* (Frequency Division Multiple Access), *TDMA* (Time

Division Multiple Access), *CDMA* (Code Division Multiple Access), *OFDMA* (Orthogonal Frequency Division Multiple Access) and *SDMA* (Space Division Multiple Access) would be described long with two basic duplexing techniques. A system is classified as *narrowband* and *wideband* system depending on the available bandwidth allocated for the subscribers. The narrowband relates the bandwidth of the single channel to the expected coherence bandwidth of the channel. In narrow band FDMA, a user is allocated to our users operating in vicinity and if FDD is opted then the system is termed as FDMA/FDD. In narrow band TDMA enables the use of the same channel but a unique time slot is assigned to each user on the channel, thereby spreading small users in a single channel in time domain. Generally for narrow band TDMA a large numbers are allocated utilizing wither FDD or TDD (Time Domain Duplexing), each channel is shared implementing TDMA. Such systems are termed as TDMA/FDD and TDMA/TDD access systems. In wideband systems the transmission bandwidth of the operating systems is much larger than the channel's coherence bandwidth. Therefore, systems adopting wideband is not affect significantly by the multipath fading within a wideband channel. Frequency selective fading occurs only in a small part of the signal bandwidth. Table 2.1, lists some of the cellular communications systems with corresponding multiple access schemes and duplexing methods.

Table 2.1 *Multiple Access techniques used in different wireless communication systems [4]*

Cellular System	Multiple Access Scheme with Duplexing technique
Advanced Mobile Phone System (AMPS)	FDMA with FDD
Global System for Mobile (GSM)	TDMA with FDD
Digital AMPS (D-AMPS)	TDMA with FDD
Personal Digital Cellular (PDC)	TDMA with FDD
cdmaOne (IS-95)	CDMA with FDD
Universal Mobile Telecommunication System (UMTS)	CDMA with FDD or TDD
CDMA2000	CDMA with FDD or TDD
Long Term Evolution (LTE)	OFDMA (Downlink) and SC-FDMA (Uplink) with FDD or TDD

2.4.1 Frequency Division Multiple Access

As Figure 2.4.1 shows FDMA (Frequency Division Multiple Access) is a method of enabling individual users to use individual channels by assigning a different frequency band or channel to different users. The channels are assigned to a user upon request of the service. During the period in which the user occupies the channel it cannot be used by any other user. In FDMA systems, the users are given a channel which consists of a pair of frequencies; once frequency is for the forward channel and the other is for the reverse channel. In a GSM network adjacent channels are separated by 200 kHz frequency band but additional guard bands are allocated to avoid interference. FDMA allows full orthogonality between the channels if proper guard bands are applied. In doing so strong interference immunity can be attained. One of the drawbacks of FDMA scheme is that in order to attain linearity, complex equalization schemes requires to be implemented.

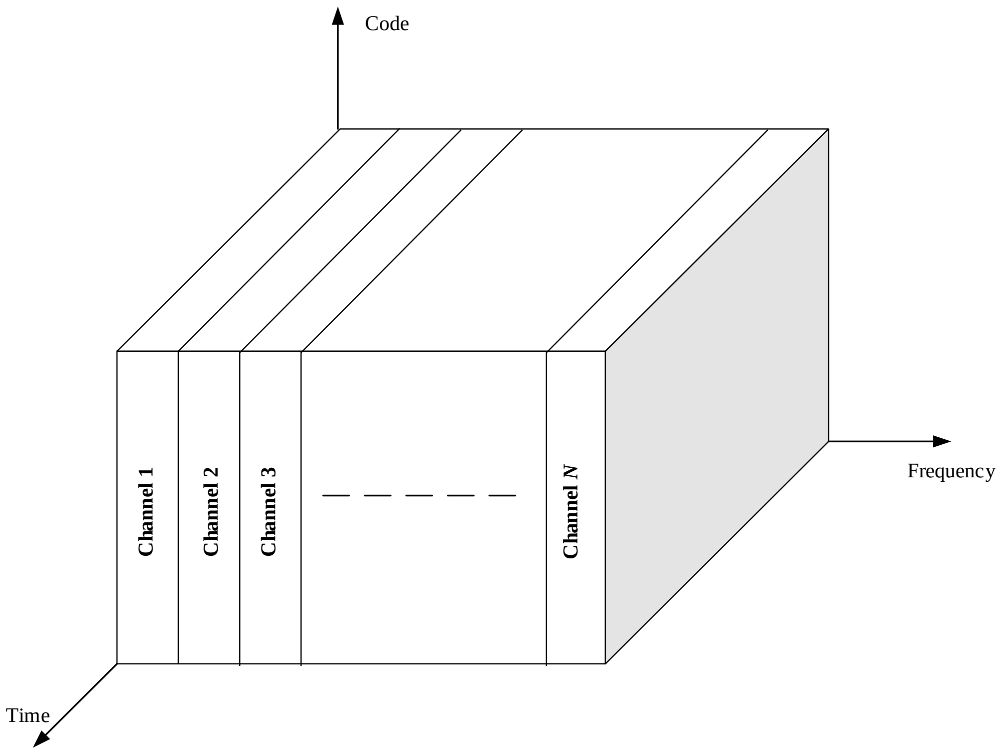

Figure 2.4.1 *Frequency Division Multiple Accesss (FDMA)[4]*

2.4.2 Time Division Multiple Access

Time division multiple access (TDMA) is a method of dividing the radio spectrum into slots. In each time slot a single user is allowed to either transmit or receive. Figure 2.4.2 depicts how each user occupies a cyclically repeating time slot. The channel is allocated to a particular user for a particular time slot that is repeated every frame, where N time slots comprise a frame. Therefore, the simple structure of TDMA comprised of frames which are transmitted in bursts in the transmission medium. A frame is hence, a time period that is divided into smaller time slots that carry the traffic payload of the users existing in the network. The basic form of TDMA is implemented using a frame level synchronization which is accomplished by comparing with the reference bursts. In additional to the reference bursts preamble bits are allocated at the beginning of each traffic burst to enable the correct carrier phase. Typically TDMA also consist of guard bands which basically a specific delay between the time-slots in order to combat the delay variation from users in the network. Therefore, in practice the time slot occupies a longer time period that it is required to transmit a particular payload, hence, the technique is inefficient, but nevertheless is required to make the method practically implementable [4].

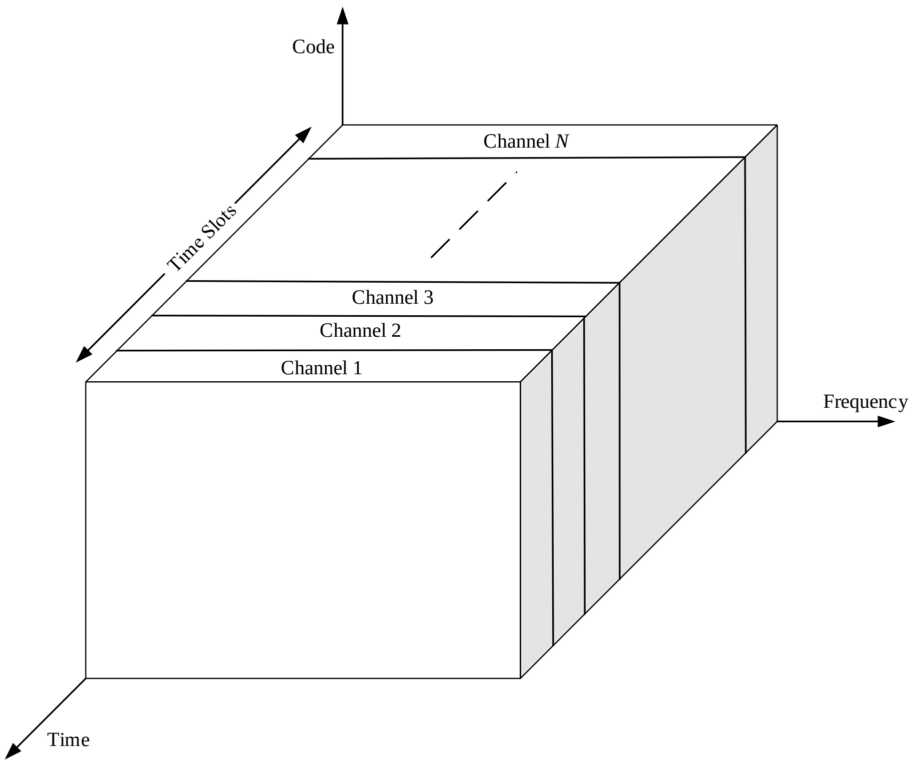

Figure 2.4.2 *Time Division Multiple Access (TDMA)[4]*

2.4.3 Code Division Multiple Access

Code division multiple access (CDMA) systems, the message signal which is a narrow band signal is multiplied with a very large bandwidth signal called the spreading signal. The spreading signal is basically a pseudo noise code the chip rate of which few orders of magnitude greater than the data rate. All users in a CDMA system as illustrated in the figure 2.4.3 uses the same carrier frequency and transmit simultaneously. Each user is assigned a unique pseudo random codeword which are approximately orthogonal to one another. Frequency reuse in CDMA systems is ideally 1.The receiver only requires toper form a time correlation operation to detect the desired codeword only. The rest of the code words appear as noise because of de-correlation. The receiver needs to know the code word to detect the message signal. The different users possess orthogonal codes having a low correlation between each other as much as the network condition permits. Hence, each user can operate independently.

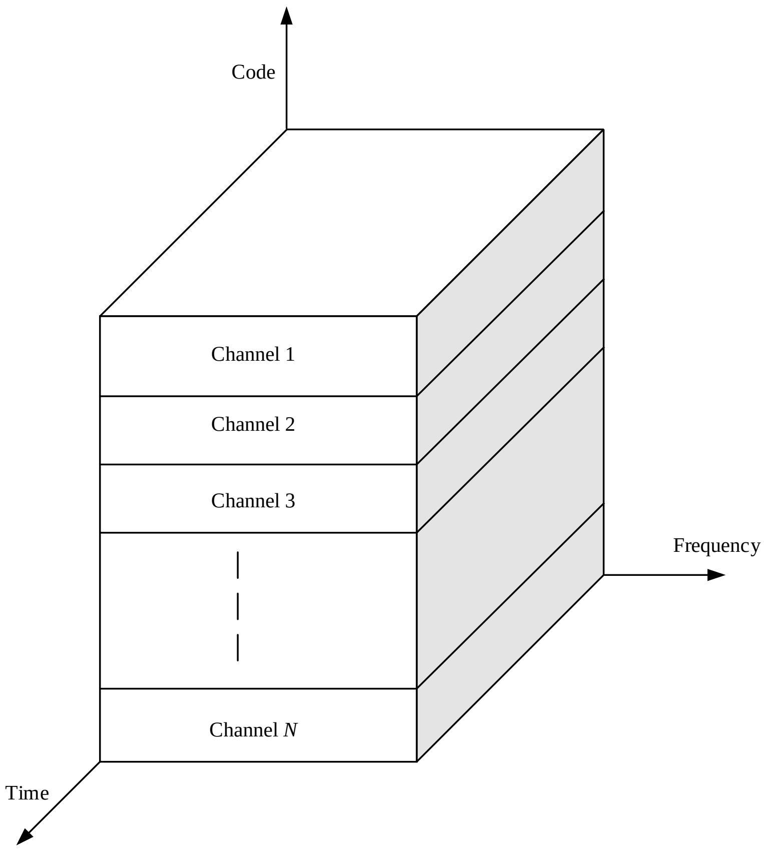

Figure 2.4.3 *Code Division Multiple Access*

Channels that suffer time–varying multipath distortion or jamming due to narrow band interference should implement CDMA. However, CDMA suffers from near-far and partial correlation problem. Near far problem occurs when the transmitter located far away gets blocked a transmitter that is transmitting very close to the base station due to much weaker signal reaching the base station from the distant transmitter. To cope with the problem power controlling schemes are used. Such problem does not exist in TDMA and FDMA since the transmitters either transmits in different times or the desired signal can be filtered using appropriate bandpass filter. As the network becomes more congested the interference level increases which results in degradation of network capacity and coverage, this particular phenomenon is known as soft capacity and cell breathing. In networks that implements TDMA and FDMA are limited by time and frequency slots but in case of CDMA the limitation is 'softer' since it is depended on the available codes and the interference that originates due to the increasing number of subscribers [4]. Figure 2.4.3 illustrate CDMA scheme.

2.4.4 Orthogonal Frequency Division Multiple Access

OFDMA (Orthogonal Frequency Division Multiple Access) was first proposed for the return channel in CATV (Community Antenna Television) [5]. OFDMA is an OFDM (Orthogonal Frequency Division Multiplexing) based multiple access. OFDM is the most widely used system for broadband communications, both wired and wireless. In OFDM system available bandwidth is divided into sub-carriers. These subcarriers are orthogonal because the peak of one sub-carrier coincides with the nulls of the other subcarriers, which help to avoid the use of frequency guard band which increases spectral efficiency. OFDM transmits data in parallel by multiplexing the data on these orthogonal sub-carriers. This allows dividing the high-speed signal into several slower signals and transmits them in parallel through separated narrow frequency bands. In OFDMA all the subcarriers are grouped into different sub-channels. These channels are assigned to different users. Orthogonality among the sub-carriers gives advantage to avoid interference between users. It provides greater efficiency and flexibility in the allocated system resources [6].

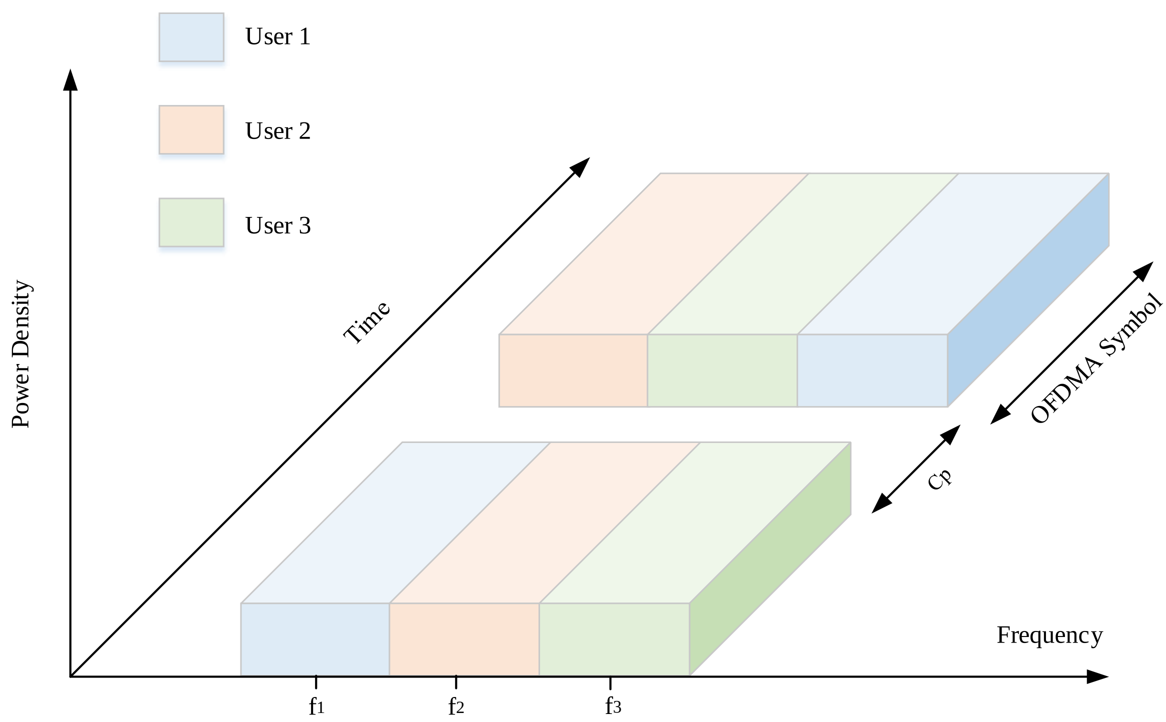

Figure 2.4.4 *User allocation example in OFDMA*

In Figure 2.4.4**,** a simple user allocation in OFDMA has been showed. The entire system bandwidth is divided into three different sub-bands and three users are multiplexed to those sub-bands.

OFDMA was chosen as the medium access techniques for 3GPP LTE downlink. For the 3GPP LTE uplink another multiple access was chosen, it is called Single Frequency Division Multiple Access (SC-FDMA) [7]. SC-FDMA allows multiple accesses with a complexity similar to that OFDMA. SC-FDMA has better capabilities in terms of envelope fluctuations of the transmitted signal [8]. SC-FDMA has better efficiency in power consumption than OFDMA. SC-FDMA is an appropriate technology for the uplink transmission because its complexity focuses on the receiver end.

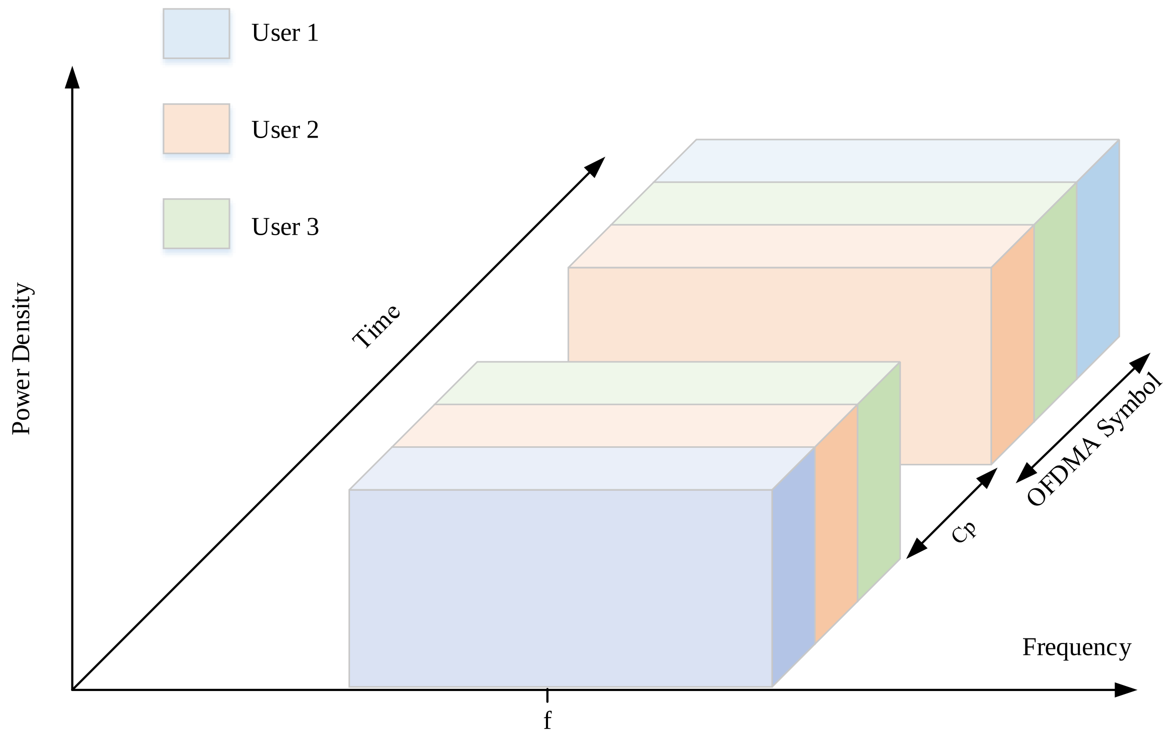

Figure 2.4.5 *User allocation example in SC-CDMA*

In Figure 2.4.5 shows a simple example of user allocation in SC-CDMA. Figure 2.4.4 and 2.4.5 shows the obvious difference between OFDMA and SC-FDMA. OFDMA transmits signals from three users in parallel, one per sub-carrier. On the other hand SC-FDMA transmits signals from three users in series at three times the rate, with a single carrier.

2.4.5 Spatial Division Multiple Access

Spatial division multiple access (SDMA) is a special form of Multiple Access scheme which utilizes the spatial separation of the users to efficiently use the available frequency spectrum in the network. In a basic form of SDMA the cellular network uses the same frequency throughout the network. SDMA is used to control the radiated power to each user. Different user is served using different spot beam antenna. The areas are served by using the same or different frequencies. Nevertheless to mitigate co-channel interference the cells are required to be separated sufficiently. This imposes a limitation in the number of cells a network is divided and thereby, restricts the frequency re-use factor. However, by using frequency reuse within the cell the capacity of the network can be improved. In practice it is not feasible to use a single transmitter within the receiver beam width. Therefore, it is necessary to use other multiple access technique in conjunction with SDMA.

When the network utilizes frequency reuse TDMA or CDMA is used in conjunction to SDMA and when different frequency is used FDMA technique is adopted. Figure 2.4.4 illustrates SDMA skim.

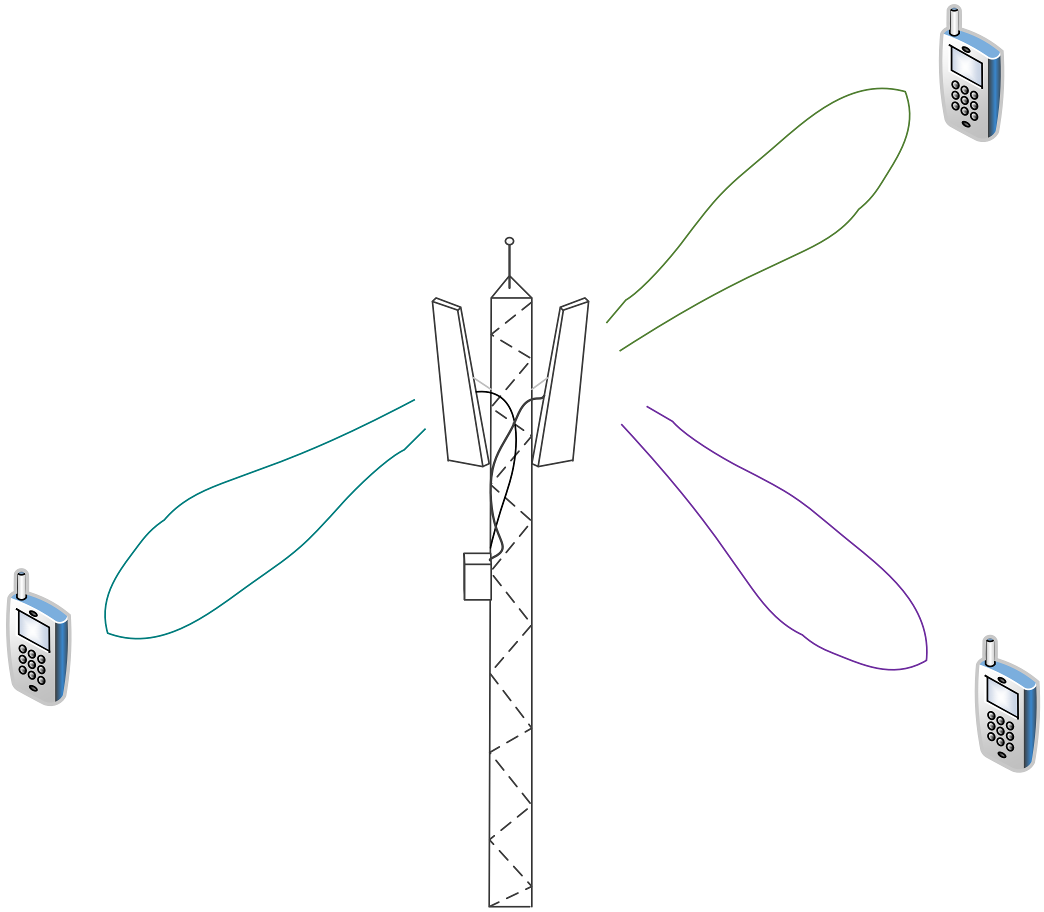

Figure 2.4.6 *SDMA (Space Division Multiple Access)*

2.5 Duplex Communication:

In mobile communication systems separating traffic in uplink and downlink directions, respectively is known as duplex communication method. Duplex communication allows the subscriber to receive the signal from the base station and send the signal to the base station simultaneously. As an example in a telephone network, a subscriber can talk and listen at the same time. Before duplexing the channel was known as simplex channel. In that channel, signal could only be sent in one direction.. The difficulty of the simplex channel was to send back error or control signal back to the transmit end. Duplexing is the method by which the traffic in the uplink and downlink are separated from one another. There are basically two types of duplexing systems. One is known as *Half duplex* and another one is known as *Full Duplex.* In half duplex, communication can possible in two ways, but only one communication is possible at a time. If one transmission starts from one end then the other end cannot transmit anything before first one stop transmitting. In walkie-talkies this kind of communication is used. In Full Duplex communication is possible to the both direction at same time. Full duplex sometimes referred to simply as *duplex*. The most commonly used duplexing schemes are frequency division duplexing (FDD) and time division duplexing (TDD). Figure 2.5 illustrate the simplex, half duplex and full duplex scheme.

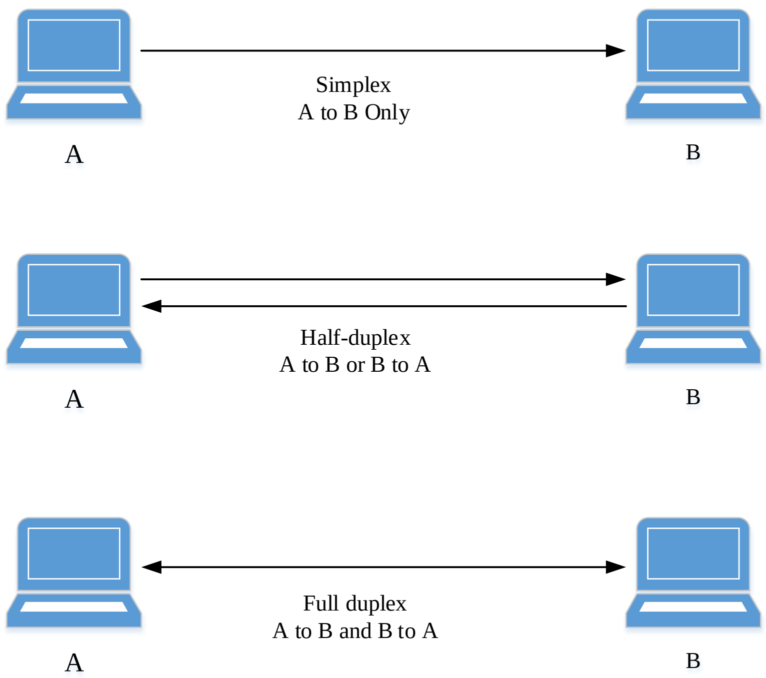

Figure 2.5 *Simplex, Half duplex and Full duplex*

2.5.1 Frequency Division Duplexing

In FDD different frequency band is allocated for the uplink and downlink channels, which provides the full utilization of the capacity of the channels for both directions in the sense of utilizing the entire allocated spectrum in each direction. In the United States AMPS standard, the reverse channel operates exactly 45 MHz lower than the forward channel. FDD is prominently used in analog radio systems.

Figure 2.5.1 *Frequency Domain Duplexing (FDD)*

2.5.2 Time Division Duplexing

In TDD same frequency is shared in the uplink and downlink in time domain that is it shares a single radio channel in time, for a part of the time slot the channel is used to transmit to the base station to the mobile and the remaining part of the time slot is used to transmit from the mobile to base station. As TDD uses only one frequency the allocated channel uses unpaired band whereas in FDD two paired bands for uplink and downlink would be used. Application of TDD can provide a more spectral efficient system compared to FDD but at the cost of lower capacity. TDD is only implementable in digital transmission formats and digital modulation and is very timing sensitivity. TDD is hence used for indoor or small area wireless applications.

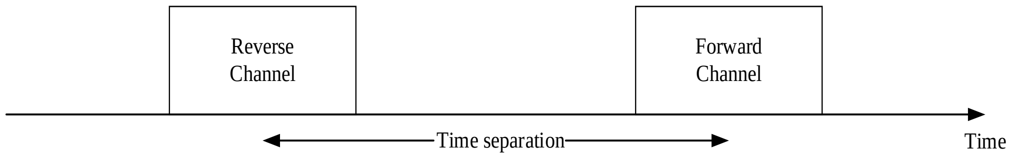

Figure 2.5.2 *Time Domain Duplexing (TDD)*

2.6 Interference and Capacity

Interference is parameter of major concern when it comes to the performance of a wireless network. Some the sources of interference could be; another mobile phone in the same cell, the progressing call in a co-channel cell, base stations operating in the same frequency or some other system unintentionally leaking energy in the cellular frequency band. The interfering signal when interferes with the voice channels, it produces cross talk. When the interfering signal leaks into the network's control signal missed and blocked calls may occur due to errors in the digital signaling. Interference is one of the major constraints when it comes to increasing the capacity of the network and is responsible for calls being dropped. The two prominent form of system-generated cellular interference are *co-channel interference* and *adjacent channel interference*.

2.6.1 Co-channel interference and System Capacity

When same frequency used in neighboring cells in order to implement frequency reuse, the cells using the same frequency is called co-channel cells and the interference between the signals of the cell is called *co-channel interference*. Unlike thermal noise where the noise is mitigated by using higher transmit power; *co-channel interference* has an opposite effect on the interference level. In order to decrease the co-channel interference, the co-channel cells needs to be physically separated to provide the desired isolation.

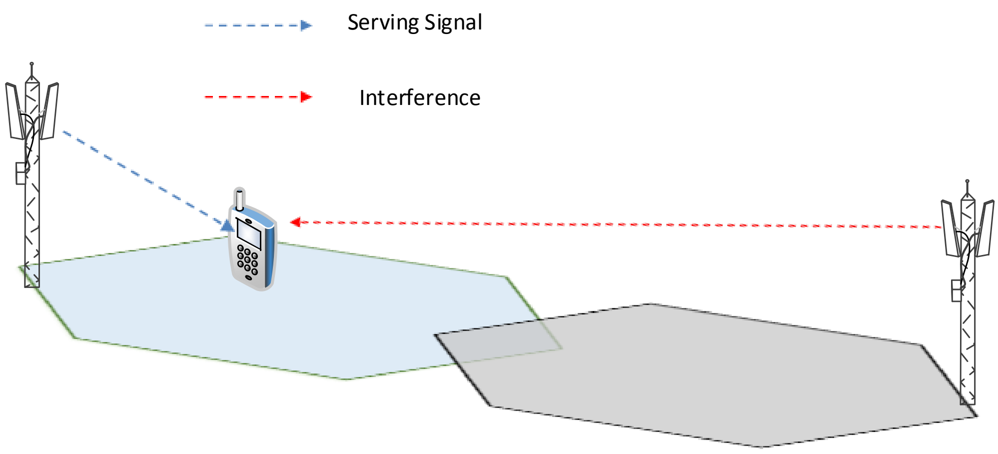

Figure 2.6.1 *Illustration of co-channel interference*

The co-channel interference becomes a function of the distance between the co-channel cells *D* and the radius of the cell *R*, when the cell radius and the transmit power in each of the cell is the same. If the ratio of D to R is increases the physical separation of the cells increases as a result of which the co-channel interference decreases. The co-channel reuse ratio Q is expressed as

$$Q = \frac{D}{R} = \sqrt{3N} \tag{2.4}$$

Smaller value of Q will provide larger network capacity since the cluster size N is small whereas a higher value of Q improves the transmission quality since, higher value of Q mitigates co-channel interference. Attaining the optimum trade-off is a challenge which the network engineers need to deal with.

2.6.2 Adjacent Channel Interference

When adjacent signal leaks into the desired signal the interference is called adjacent channel interference. This type of interference takes place due to imperfect receiver filters which is not able to stop the nearby frequencies to pass in to the pass band. The interference becomes particularly significant when the adjacent channel user is transmitting very close to the subscriber's receiver when the receiver is attempting to receive the desired channel from the base station. This effect is termed as near-far effect since the nearby transmitter captures the subscriber's receiver. Adjacent channel interference can be reduced by using filters which has sharper pass band and by proper channel assignments.

2.7 Improving Coverage and Capacity in Cellular Systems

When the demand for the wireless services increases, the available number of channels are unable sustain the required number of users. In situation like this the network designers needs to provide more channels per unit coverage area. The techniques that are adopted to increase the capacity of the cellular system are cell splitting, sectoring and coverage zone approaches.

2.7.1 Cell Splitting

Cell splitting enables a systematic growth of a cellular system. Cell splitting is the process of subdividing a congested cell into smaller cells, with each base station having its own but correspondingly reduced antenna height and transmits power. Cell spitting increases the number of times that a channel can be reused and thereby, increases the capacity of the cellular system. By defining cells with smaller radius than the original cell and allocating smaller cells between the existing cells which is also known as microcells, the capacity of the cellular system is increased since now there are additional number of channels per unit area. Therefore by rescaling the system the capacity of the existing network can be increased. If the co-channel reuse ratio is kept constant and the cell radius is decreases cell splitting increases the number of channels per unit area.

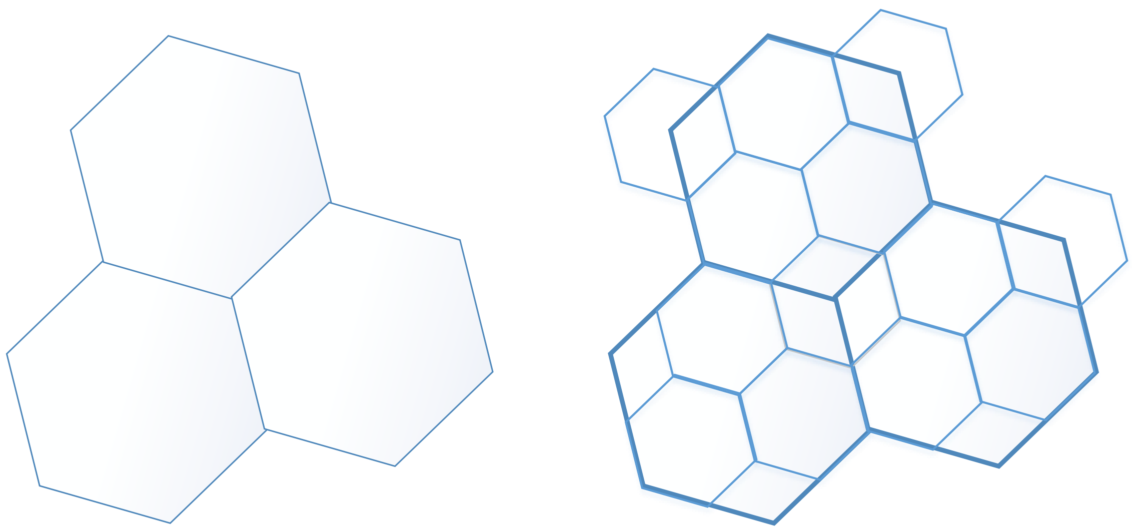

Figure 2.7.1 *Illustration of Cell splitting*

If the cell radius is decreased by a multiple of half to cover the whole area, four times more cells are required approximately. Figure 2.5 shows a cell splitting scenario. Here the base stations are placed at the corner of the cells. Therefore, new base stations are required for the microcells.

2.7.2 Sectoring

Sectoring, as mentioned before, is another method to improve the capacity of the system. In sectoring, the cell radius is kept constant but the D/R ratio is decreased, i.e., as the radius is kept constant, the distance between the cells using the same frequency decreases, which consequently reduces the cluster size. This can be resulted by increasing signal to interference ratio (SIR). In sectoring directional antenna is used to improve the SIR. The network capacity is improved by decreasing the number of cells in a cluster which consequently increases the frequency reuse. However, the transmit power needs to be reduced such that interference can be reduced.

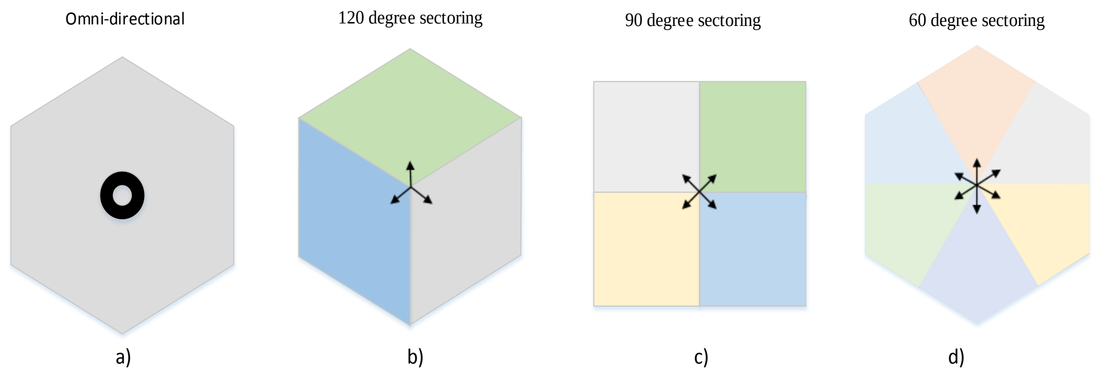

Figure 2.7.2(a) Omni-directional (b) 120º sectoring (c) 90º sectoring (d) 60º sectoring.

By sectoring co-channel interference is decreased in a cellular network by replacing the Omni-directional antenna with several directional antennas in a cell. Each antenna radiates within a specified sector of cell. This technique of using directional antennas to decrease the co-channel and consequently increasing system performance is called sectoring. The amount of sectoring that needs to be employed depends on how much co-channel interference the network experiences.

2.8 Different type of tessellation

On the basis of large coverage area, the total number of radio channels available to a mobile radio system will not provide satisfactory service. Simultaneously using radio channels in small coverage areas or cells can provide satisfactory service within a metropolitan on a large coverage area basis. But these small areas or cells are separated in a distance to prevent co-channel interference. In order to distinguish these distances between the cells introduces the term cell layout. The geographical layout for cell shape is needed for systematic system design. However, the radio coverage of a cell is determined from propagation prediction models [4]. The equal regular polygons which cover such region are known as tessellation. These polygons are not overlapping with each another [10]. The approximations to the interference limited small coverage cells are provided by tessellations, which is defined on propagation statistics [11]. There are four cellular network layers based on geometric shapes (tessellation).

- Triangle
- Square

- Hexagonal and
- Clover-leaf layouts

The different cell layouts are realized by relative position of the cell sites and the respective sector orientation, as shown in Figure 2.7.

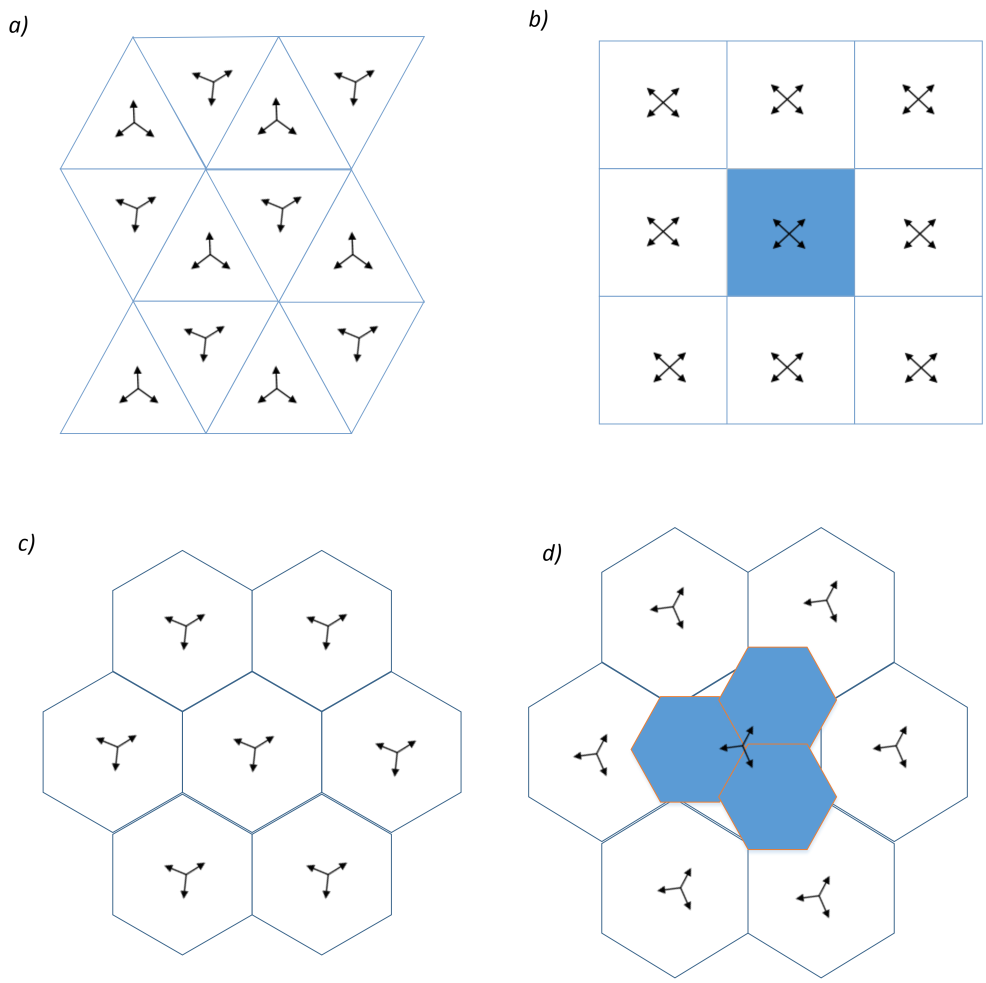

Figure 2.8 *a) Triangle, b) Square, c) Hexagon, and d) Clover-leaf layouts*

The coverage area of a base station is normally represented by circle. Hexagonal layouts closely approximate circle and for this reason hexagonal layouts are usually used to depict cells. Hexagonal layouts cover the largest area than the other layouts. Considering frequency reuse factor, Valerio Palestine proposed alternative frequency plans in hexagonal-shaped cellular layouts [12], which is called clover-leaf layouts. He also showed that the coverage of clover-leaf layouts is preferable from the point of view of efficiency in terms of channels per site [13].

Based on the system level studies conducted [14], the clover-leaf layout is shown to be superior among the other layouts in terms of overall performance. In our topology and interference analysis study, we use clover-leaf layouts because of the efficiency of this layouts over the other layouts (triangle, square, traditional hexagonal).

3. RADIO PROPAGATION IN CELLULAR SYSTEM

In wireless communication *radio propagation* is the behavior of a radio wave when it travels from a transmitter to a receiver. During the propagation, radio waves are affected by different physical phenomenon that might occur due to; interaction with physical obstacles, natural events, and different kinds of propagation environment. In order to characterize or model these phenomenons and quantify their impact on the radio waves, different propagation models are utilized. This chapter provides an overview of the propagation environment, the physical phenomenon impacting the radio waves, and the different models to characterize those phenomenons.

3.1 Propagation Environment

This radio propagation environment can be broadly classified into macrocellular, microcellular, and indoor environment, based on the relative height of the transmitter antenna with respect to the average roof-top height in the surrounding environment. In the following sections we provide a brief overview of each of these environments, and how they affect the radio waves.

3.1.1 Macrocellular environment

In macrocellular environment, the height of the transmitting antenna is above the average roof-top building. Hence, in such an environment, the radio signals tend to propagation quite far away. In a typical macrocellular network, the cell range can vary from 1 km to 20 km. Macrocellular deployment is the still the dominant form of deployment worldwide, as it provides wide area ‘blanket’ coverage in the mobile operators network area, whereas, the microcellular deployment, introduced in the next section, fulfill the capacity demands in hotspot areas.

3.1.2 Microcellular environment

In microcellular environment, the height of the transmitting antenna is at or below the average roof-top building. This limits the effective range of the cells, as the surrounding buildings act as obstacle. In a typical microcellular network deployment, the antennas are deployed at street level e.g. on street lamp posts. As such, the cells deployed in microcellular environment have a typically cell range of 250 m to 1 km. Due to being located at the street level, the base stations transmit at low power levels as compared to macrocells. Microcells, due to small cell size, are usually deployed in hotspot areas to increase the system capacity.

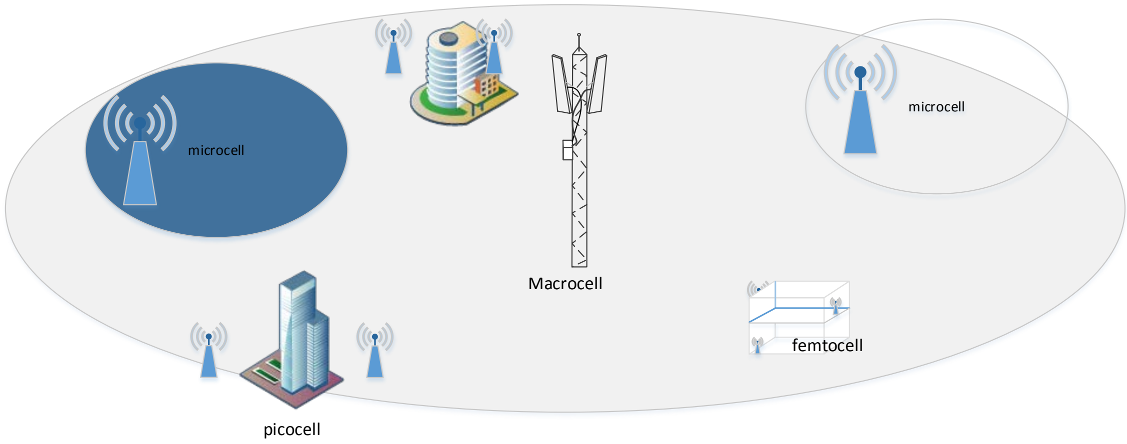

Figure 3.1 *Example of macro, micro and indoor (pico, femto) cellular system*

3.1.3 Indoor environment

Indoor radio channels do not suffer from the effect of snow, rain clouds etc. as do outdoor radio channels. The indoor environment is effected by the building size, shape, structure, layout of rooms. Construction materials of the building mainly effect indoor propagation environment. Wave propagation inside a building is more complicated than outside environment, we can say that a factory building is quite different than an office building [15]. The deployment of BS antenna's in indoor environment is configured in such a way that it minimize the strong attenuation faced by the signal from the walls, floors, ceilings and other obstacles in the coverage area and improve the capacity of the system.

3.2 Mobile radio channel

In a typical mobile cellular environment, radio waves, travelling from a transmitter to a receiver, usually traverse different propagation paths. This propagation mechanism is generally known as *multipath propagation* [16]. At the receiving end, different replicas of the original transmitted signals are received, with different phases and amplitudes. Consequently, the received signal is a sum of all the replica signal components, which are summed together incoherently. This summation happens in either a constructive manner or destructive manner, depending upon the relative phase of each replica signal component. This results in fast fluctuations in the amplitude of the received signal, and the phenomenon is referred to as *fast-fading*.

The main reasons for the multipath propagation are *reflection*, *diffraction* and *scattering* in a mobile communication system. Reflection happens due to the bigger dimension of the surface as compared to the wave length of the radio signal. Reflections can happen from any kind of surface like walls, buildings and even from the earth surface. Diffraction happens because of the sharp edges of the obstacles. Several secondary waves created from the edge of the surface. Diffraction depends on the phase, amplitude and polarization of the incident wave [4]. Scattering happens when signal travel through obstacles, whose dimensions are smaller than the wavelength of the signal. Scattering usually occur when the radio signal strikes upon rough surfaces, or small objects. [4].

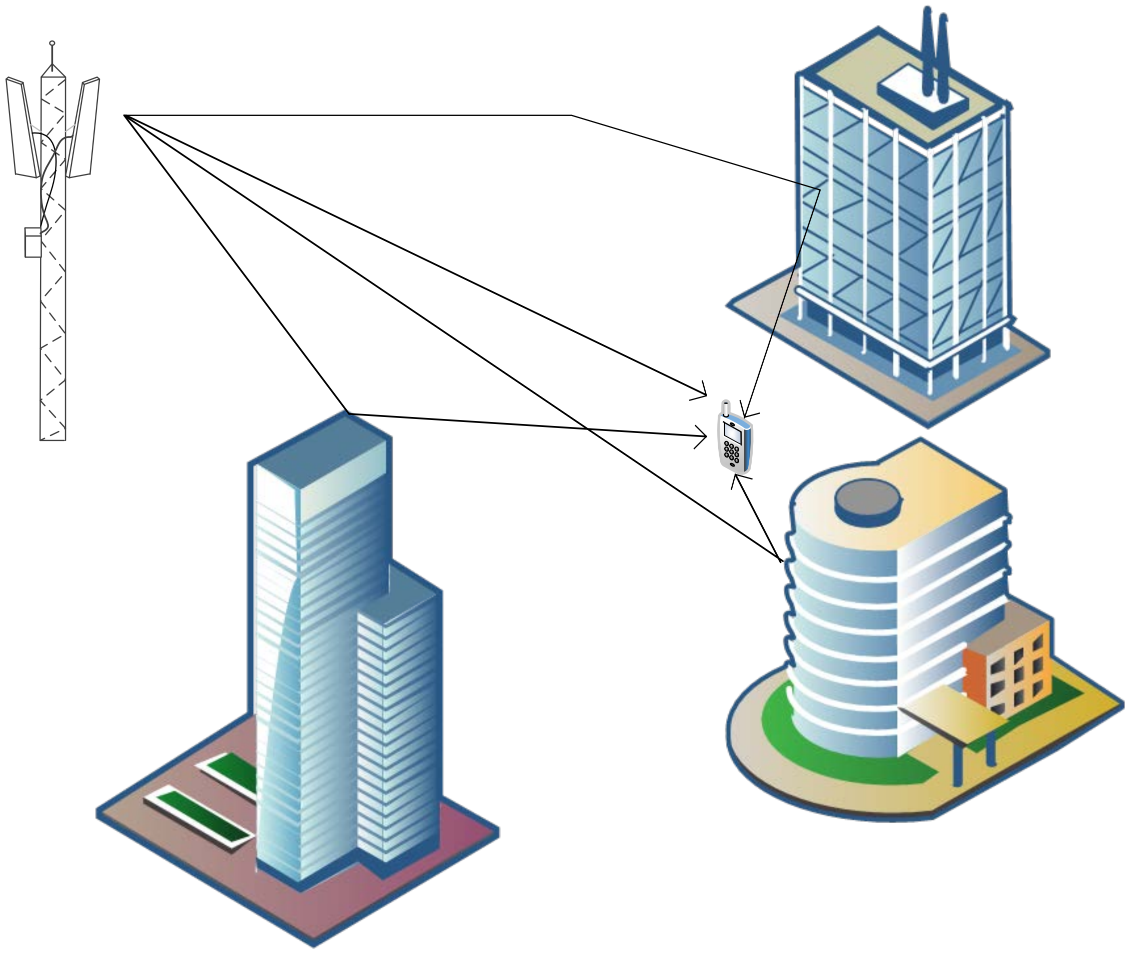

Figure 3.2 *Multipath Propagation*

In addition to multipath propagation, few other parameters that describe the radio propagation environment are *angular spread*, *delay spread*, *coherence bandwidth*, and *propagation slope*.

Angular spread is the deviation of the angle at which the signal is incident at the receiving antenna. The spreading of the angle is greater in indoor and microcellular environments than in macro cellular situation.

Delay spread is the measure of a richness of multipath in a propagation environment. Since the signal components take different routes to reach the receiver, due to the multipath propagation, their arrival time is different. The difference in the arrival time between the earliest signal component (usually signal arriving from direct path) and the last significant multipath component is measured by RMS delay spread and is calculated from the channel power delay profile *P(τ)* as:

$$S = \sqrt{\frac{\int_0^\infty (\tau - \mathrm{D})^2 P(\tau)\,\mathrm{d}\,\tau}{\int_0^\infty P(\tau)\,\mathrm{d}\,\tau}} \tag{3.1}$$

where *D* is the average delay. In micro cellular environment, the delay spread value is smaller in comparison to macro cellular environment [17].

The coherence bandwidth Δfc defines the spectrum range in which two frequency components experience the same or correlated fading. For the signals to experience *uncorrelated fading,* the frequency separation of two signals has to be equal or greater than the coherence bandwidth of the channel. The coherence bandwidth is expressed as:

$$\Delta f_c = \frac{1}{2\pi S} \tag{3.2}$$

where, *S* is the delay spread.

Attenuation is strongly environment dependent. For instance in urban environment, where there are many buildings and other towering structures, the attenuation is much higher than in rural environment. *Propagation slope* is a parameter which is employed to indicate attenuation experienced in a particular environment and it basically illustrates the signal attenuation as a function of distance and the unit of the parameter is dB/dec. In wireless propagation environment, the propagation exponent (γ) is 25-40 dB/dec and in free space environment γ equals 20 dB/dec. The propagation slope between base station and the mobile station varies as the distance between them increases. The propagation slope up to a certain distance is approximately equal to 20 dB/dec (i.e. free space). After a certain distance, the slope is affected by the propagation environment. The distance when the propagation slope transition from free space propagation slope to environment-dependent slope is called *breakpoint distance,* and is calculated as following [18]:

$$B = 4\frac{h_{BTS} h_{MS}}{\lambda} \tag{3.3}$$

where h_{BTS} is the height of the base station antenna and h_{MS} the height of the mobile station and λ is the signal wavelength. The breaking point is an essential parameter which needs to be taken into account in cellular radio network planning [19].

Table 3.1 illustrates typical values for angular spread, delay spread, slow fading standard deviation and propagation slope in different surroundings at GSM 900MHz frequency band.

Table 3.1 *Typical values for angular spread, delay spread, slow fading standard deviation and propagation slop in different surrounding at GSM 900 MHz frequency band*

Environment type	**Angular spread [º]**	**RMS delay spread [μs]**	**Slow fading standard deviation [dB]**	**Propagation slope [dB/dec]**
Macrocellular				
Urban	5-10	0.5	7-8	40
Suburban	5-10		7-8	30
Rural	5	0.1	7-8	25
Hilly rural		3	7-8	25
Microcellular	40-90	<0.01	6-8	20
Indoor	90-360	<0.1	3-6	20

3.3 Propagation Models

A Radio propagation model is a mathematical model, which is defines the behavior of radio wave propagation as a function of wavelength, distance, frequency, height and other states. Radio propagation models, depending upon how they are derived, are mainly classified into *empirical model*, *semi-empirical or physical model,* and *deterministic model*.

3.3.1 Empirical Model

An Empirical model is derived from extensive field of measurement campaigns. This model is suitable for macro cellular network. The empirical models take into account the information related to propagation environment, frequency, and antenna height. The main goal of these models is to predict the *path loss*. *Path loss* describes the signal strength loss as a function of distance. Simple empirical path loss has given below [20]:

$$\frac{P_R}{P_T} = \frac{1}{L} = \frac{k}{r^n} \tag{3.4}$$

where, $P_R$is the received signal power,$P_R$the transmit power, L is the path loss, r is the distance between a transmitter and a receiver, and k, n are constants of the model. In decibels this model is referred to as *power law model* [20]:

$$L = 10n \log r + K \tag{3.5}$$

Where, $K = -10\, log_{10} k$ is a constant. n is the path loss exponent and depends on antenna heights and the environment.

There are several other well-known empirical propagation models e.g., *clutter-factor model, Okumura-Hata model, Lee model, Ibrahim and Parsons model.* Out of these models, the most widely used propagation model is the *Okumura-Hata model.*

The Okumura-Hata model is mostly used in macro cellular networks. The model is based on extensive field measurement campaign carried out by Mr. Okumura in 1968. The field measurements were later formulated into a mathematical model by Mr. Hata in 1980 [21]. Okumura-Hata model was initially valid for carrier frequencies in the range of 150 MHz to 1500 MHz. Later on, the COST 231, a European project, extended the model to include frequency range up to 2000 MHz. Although, widely used, there are some limitations in terms of base station antenna height, mobile station antenna height, and distance between BS and MS. The model is valid for base station height in the range of 30 m to 200 m, and for mobile station antenna height from 1 m to 10 m. The distance between base station and the mobile station must be in between 1 km to 20 km.

The Okumura-Hata model is formulated in the following way:

$$L = A + B\log_{10}(f) - 13.82\log_{10}(h_{bs}) - a(h_{ms}) + [C - 6.55\log_{10} h_{bs})]\log_{10} d + C_m \qquad (3.6)$$

Where;

L is the path loss [dB],

A, B are the constant(initial offset parameter), values given in Table 3.1

f *f* is the frequency, (150 MHz $\leq$ f $\leq$ 2000 MHz),

h_{bs} is the base station antenna height,(30m $\leq h_{bs} \leq$ 200m),

h_{ms} is the mobile station antenna height,(1 m $\leq h_{ms} \leq$ 10m),

d is the Distance between *BS* and *MS*,(1 km $\leq$ d$\leq$ 20km),

C is the *Propagation slope term*

C_m is *Area type correction factor* (-25 dB up to 30 dB)

Table 3.2 *Value for the parameter A and B with respect to Frequency range*

Frequency Range	Initial offset Parameter	
150 MHz- 1500 MHz	A	69.55
	B	26.16
1500 MHz- 2000 MHz	A	46.3
	B	33.9

Mobile station height h_{ms} depends on the size of the city. For small/ medium size city the height is formulated as follows:

$$a(h_{ms}) = (1.1log_{10}(f) - 0.7) - (1.56log_{10}(f) - 0.8) \tag{3.7}$$

And for Large city:

$$a(h_{ms}) = 3.2(log_{10}(11.75h_{ms}))^2 - 4.97 \tag{3.8}$$

3.3.2 Semi-empirical model

In contrast to empirical models, the semi-empirical model take into account more detailed information related to the propagation environment, in order to predict the field of strength. As such, the semi-empirical models are more accurate than empirical models, however, at the expense of slightly more computational time. In semi-empirical model, penetration losses of the wall are taken into account for calculation [3]. Diffraction is a critical mechanism in this model. These models are suitable for small macrocells and microcells. Followings are different types of semi-empirical model:

- The Allsebrook-Parson model
- Cost 231/Walfisch-Ikegami model
- Rooftop Diffraction
- The Flat edge model etc.

The Allesbrook-Person model was the first semi-empirical model that attempt to provide physical basis for urban prediction models [20]. Cost 231/Walfisch-Ikegami model is the combination of the Walfisch-Bertoni model and Ikegami model [20]. Cost/Walfisch-Ikegami model take the characteristics of the city structure into account (heights of the building, width of the roads, building separation etc.). There are limitations for the Cost 231/Walfisch-Ikegami model:

- Carrier frequency range between 800 MHz to 2000 MHz
- Base station antenna height between 4 m to 50 m
- Mobile station antenna height between 1m to 3 m
- Distance between BS and MS 0.02 km- 5 km

The flat edge model is simplified by assuming that all buildings are in same height and have equal spacing [20].

3.3.3 Deterministic Propagation model

In deterministic model, radio wave propagation is estimated analytically. Detailed information related to the propagation environment such as material parameters, 3D building plan etc. are very important and lead to very accurate propagation prediction results. Usually two types of approaches have been introduced in deterministic model:

1. Numerically solving electromagnetic formulas
2. Applying ray optical method

Ray optical method is most widely used method but it needs more computing time and power. The ray optical method is implemented using either *ray tracing* or *ray launching* techniques. In r*ay launching,* the field strength is summarized at all receiver points. The ray search is stopped when energy reaches to maximum interactions. *Ray tracing* technique is based on geometrical optics and *uniform diffraction theory* (UTD).

4. SYSTEM MODELING

This chapter introduces the system model that has been used for the simulation and result analysis. The chapter starts with the description of the simulation environment and the cell layout. This is followed by a brief overview of the simulation tool and propagation model used for the simulations. The mathematical model for modeling the antenna pattern is described next. Finally, the average inter-site distances (ISD), corresponding to different site densities is presented.

4.1 Simulation environment and cell layout

A fictive city based on Manhattan type grid model is used as the simulation environment. The model emulates a dense urban environment, where the buildings are identical in dimensions and are aligned into rows and columns, as shown in the figure 4.1.

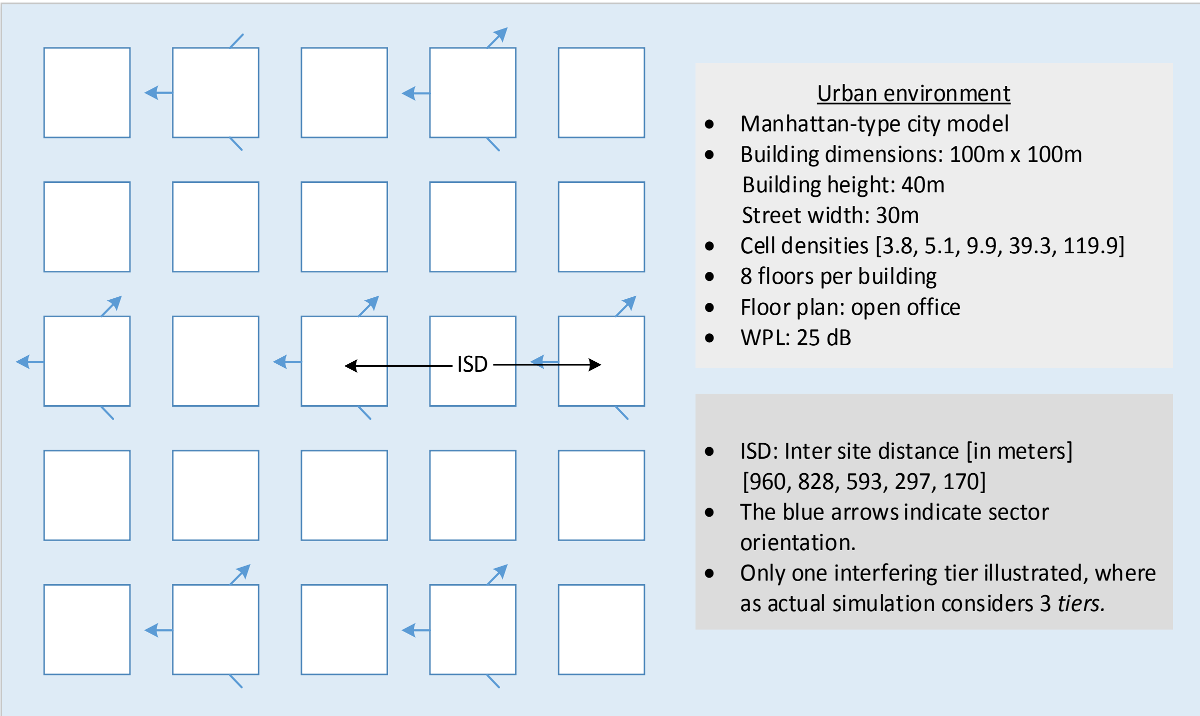

Figure 4.1 *Manhattan grid city model*

We use a hexagonal cellular network layout as the basis for deploying the macrocellular network. However, due to the deployment of the cell-sites on the roof-top of the buildings, the actual network layout is determined by the Manhattan grid environment, and thus does not follow a pure hexagonal pattern. Figure 4.1 shows an aerial view of a Manhattan grid city model that has been used in the simulation environment. In the figure, only the first interfering tier is illustrated, whereas the actual number of tiers varies with different *ISD* scenarios. The blue arrows show the sector antenna positions and orientations. The white square boxes shown in the Figure 4.1 are buildings that were used in the simulation.

4.2 Wireless InSite Tool and Propagation model

We use a site-specific radio propagation prediction software, called *Wireless Insite (WI),* for the coverage prediction simulations. The tool can predict the impact of buildings and terrain on the propagation of electromagnetic waves. Users are able to define the propagation environment with the help of computer aided drawing (CAD) tool, which is integrated into the software. The tool enables to evaluate the signal characteristics such as path loss, delay spread, direction of arrival/departure and channel impulse response etc., at each location point in the simulation environment. For prediction of radio signals, the tool has suite of propagation models ranging from empirical models to ray-based deterministic models. In the ray-based propagation models, *WI* tool introduces four subtypes: *Urban Canyon, Fast-3D Urban, Full 3D* and *vertical plane*. The subtypes differ from each other in terms of computation speed, applicability to different environment type, and the level of accuracy. The Full 3D model is the only model which includes transmission through surfaces and is applicable to both outdoor and indoor environment. For our simulation study, we utilize the capabilities of Full 3D model.

The Full 3D model in the *WI* tool is the only propagation model which places no restrictions on the shape of the object. It takes into account the impact of three main propagation phenomenon; *reflection, diffraction* and *transmission*/*penetration*. The model is implemented with two different techniques; *Eigen-ray* method *and Shoot and Bouncing Ray* (*SBR*) technique. The Eigen-ray method involves an explicit construction of the ray between the each transmitter and receiver. This method is limited to ray paths with up to a total of three reflections and diffractions (combined). *In* the *SBR* method, rays are shot from the emitting source in discrete intervals and traced correspondingly as they interact (reflect, diffract and transmit/penetrate) through and around the obstacles. Each ray is traced independently and the tracing continues until the maximum number of interactions is reached. Once all the propagation paths have been computed and stored, the field strength for each ray path is calculated. We use the Full 3D model, implemented with SBR, in our simulations.

Although, ray tracing models provide quite accurate results, but the accuracy comes at the cost of higher computation complexity and longer simulation run time. The runtime is dependent upon the input data and the total number of reflections, transmissions (or wall penetrations), and diffractions a single ray can encounter. The SBR method can construct ray paths with up to 30 total reflections and transmissions. The maximum number of diffractions, supported by the tool is 3.In order to keep the calculation time feasible with acceptable level of prediction accuracy, we use an empirical 'hit and-trial' method, which involves simulating with a smaller number of interactions, and then re-simulating the same scenario by steadily increasing interactions and comparing the results. Once the results start to converge with insignificant change, those settings are then selected. In our case, this was observed at 10 reflections, 1 diffraction, and 1 transmission.

To account for the outdoor-to-indoor propagation loss, the exterior wall direct penetration loss is considered to be 25 dB [26, 27]. The corresponding electrical properties of the exterior wall were found empirically by adjusting the conductivity σ , permittivity ε and thickness of the wall, and observing the difference in the average signal level between several outdoor and indoor receiver points.

4.3 Antenna models and positions

For modeling the antenna pattern, an extended 3GPP antenna model is used [22]. The original antenna model, reported in [23], only models the horizontal antenna pattern. The extended model enhances the original model to include a vertical antenna pattern model with an option to set the electrical down tilt. The horizontal (azimuth) pattern, G_h, is given by,

$$G_h(\varphi) = -min\left[12\left(\frac{\varphi}{HPBW_h}\right)^2, FBR_h\right] + G_m \tag{4.1}$$

where,φ; $-180\,^0 \leq \varphi \leq 180\,^0$, is the horizontal angle relative the main beam pointing direction$G_m$isthe maximum antenna gain [dBi],$HPBW_h$ is thehorizontal half-power beamwidth[in degrees], FBR_h is the front-to-back ratio[dB]. The vertical (elevation) angle, G_v, is given by,

$$G_v(\emptyset) = max\left[-12\left(\frac{\emptyset-\emptyset_{etilt}}{HPBW_v}\right)^2, SLL_v\right] \tag{4.2}$$

where,$\emptyset$ =$-90\,^0 \leq \emptyset \leq 90\,^0$, is the negative elevation angle relative to horizontal plan (i.e.$\emptyset = -90\,^0$ is the upward plan relative to the main beam, $\emptyset = 0\,^0$is along the main beam direction, and $\emptyset = 90\,^0$is the downward plan relative to the main beam),$HPBW_v$is the vertical half-power beamwidth [in degrees], SLL_visthe side lobe level [dB], $\emptyset_{etilt}$ is the electrical downtilt angle [degrees]. The antenna parameter values were adopted from [22] except for electrical tilt angles which were based on the average inter-site distances.

The antennas were placed 2 m above the building roof, i.e. 42 m above the ground level. In order to ensure that the transmitted signal is not obstructed by the roof, sector antennas were placed either at corners of the buildings rather than at the center to ensure unobstructed propagation, as shown by blue arrows in Figure 4.1.

4.4 Inter-site distance (ISD)

The cell density of a network depends upon on the Inter-site distance (*ISD*), more specifically on the average inter-site distance ($\bar{d}_{site}$). The *ISD* also defines the *dominance area/best serving area* of a cell, which is described as *the region where a cell provides highest signal level as compared to the other cells*. The dominance area of cell, A_{cell}, *is* given by,

$$A_{cell}[km^2] = \frac{\sqrt{3}}{6}\left(\bar{d}_{site}\right)^2 \qquad (4.3)$$

The cell density, ρ_{cell},[*cells per km*^{2}] and can be obtained by $1/A_{cell}$.

The electrical tilt angle depends on the *ISD*, which specifies the dominance area of a cell. In order to avoid unnecessary interference into neighboring cells, a common technique for managing the interference is to downtilt the sector antennas such that the main beam is focused at the cell boundary. The electrical tilt angle, $\emptyset_{etilt}$, in this study, is calculated geometrically as:

$$\emptyset_{etilt} = \arctan\left(\frac{h_{BS}-h_{MS}}{r_{cell}}\right) \qquad (4.4)$$

where, h_{BS} isthe base station (*BS*) antenna height, h_{MS} isthe mobile station (*MS*) antenna height andr_{cell} is the cell range

Table 4.1 *General Simulation Parameters*

Parameter	Unit	Value
Operating frequency	[MHz]	2100
Bandwidth, W	[MHz]	20
Transmit power	[dBm]	43
BS antenna beamwidth, $HPBW_{h/v}$	[degrees]	Directional(65^o/6^o)
MS antenna type		Half-wave dipole
BS antenna gain	[dBi]	18
MS antenna gain	[dBi]	2
BS antenna height,$\boldsymbol{h_{BS}}$	[m]	42
MS antenna height, $\boldsymbol{h_{MS}}$	[m]	2
Receiver noise figure	[dB]	9
Receiver noise floor, P_n	[dBm]	-92
Propagation environment		Manhattan
Propagation model		3D ray tracing
Building dimensions	[m]	100x100
Building height	[m]	40
Street width	[m]	30
Indoor layout		Open office
Outdoor-to-indoor penetration wall loss	[dB]	25

Table 4.1 gathers the rest of the simulation parameters used in the study. The effective isotropic power (EIRP) in the maximum antenna gain direction is 61 dBm (43 dBm+18 dBm). A 20 MHz bandwidth was assumed for the receiver noise floor level calculation (nominal for LTE).

5. ANALYSIS METHODOLOGY AND RESULTS

This chapter provides an overview of the analysis methodology. The description of the analysis methodology is followed by the discussion on the simulation results.

5.1 Analysis Methodology

In the simulation study, to get the statistical analysis, the receiver points are considered from the dominance area of the center macrocell site. The reason for this consideration is the homogeneity of the simulation environment. The statistical analysis is then normalized to 1 km^2 area. In realistic environment the propagation path loss limits the number of receivable interfering sources at the serving cell and that limits the total interference level. So, it is essential to consider all the interfering cells to assess the effect on the cumulative interference level in the dominance area of a serving cell. In this analysis the situation is more challenging because of the ideal environment. In the simulation the Manhattan grid is used, which is an ideal environment model. The reason behind this challenging scenario is due to *street canyon effect*. In dense urban areas, the signals propagate much further away than the signal travelling in free space [24] because of tunneling effect. This tunneling effect is caused by the walls of the high rise buildings which direct the signals into the alley. As a result, the impact of distant interfering tiers, which was negligible before, become more significant at the serving cell.

5.1.1 Methodology for estimating the number of interfering tires

In the simulation, only those tiers have been considered, that had significant impact on the relative interference level at the serving cell borders, which the worst case scenario. A hit-and-trial method was used to estimate the number of dominant interfering tiers. This method provides reliable and fast estimate of the dominant interfering tires.

Table 5.1lists the average inter-site distance ($\bar{d}_{site}$) and the corresponding electrical tilt angles (θ_{etilt}), cell area (A_{cell}, cell density per km^2 (ρ_{cell}), and the number of interfering tiers used in the simulations.

Table 5.1 *ISDs and corresponding eTilt, Site area, Site densities and Interfering tires*

ISD $\bar{d}_{site}$	**Electrical tilt** θ_{etilt}	**Cell Area** A_{cell}	**Cell density** ρ_{cell}	**Interfering Tiers**
960 m	3.5°	0.26 km^2	3.8 cells/km^2	2
828 m	4.1°	0.2 km^2	5.1 cells/km^2	2
593 m	5.8°	0.1 km^2	9.9 cells/km^2	3
297 m	11.4°	0.03 km^2	39.3 cells/km^2	4
170 m	47.5°	0.008 km^2	119.9 cells/km^2	4

5.1.2 SINR evaluation and mapping to Shannon capacity

In a cellular system, radio propagation conditions play a very important role. It determines the performance of the system. The quality of the radio link is determined by the coverage and interference conditions, which further defines the maximum throughput/users in a cell. As such, the maximum achievable capacity, *C,* according to Shannon capacity bound is evaluated as,

$$C = W \log_2(1 + \Gamma) \tag{5.1}$$

where, W is the bandwidth of the system, Γ is signal-to-interference-noise ratio (*SINR*). *SINR* defines the radio channel conditions. The above equation (5.1) shows us that the cell/area spectral efficiency depends directly onΓ.

The SINR, at a j^{th} receiver point (both outdoor and indoor) is calculated using the following relation:

$$\Gamma_j = \frac{S_j}{\sum_i (I_{i,j} + P_n)} \tag{5.2}$$

where, S_j is the received signal of the serving cell site at j^{th} receiver point, $I_j$is the received power i^{th} interfering cell at j^{th} receiver point, P_n= noise floor level. P_n includes the noise figure of the receiver as well.

In a multi-cellular scenario, the serving cell is determined by the strongest signal level. It means that the cell which has the strongest signal level in an area is considered as the *serving cell* or *best server*, while the other cells are treated as interferers. If we consider the $Pr_{ij}$is the received signal power from the i^{th} cell site at the j^{th} receiver, then the best serving cell for a set of i cells reachable at j^{th} receiver can be found, mathematically, as following:

$$S_j = \arg\max\,(Pr_{0j}, Pr_{1j}, \dots, Pr_{ij}) \tag{5.3}$$

5.1.3 Cell spectral efficiency and Area spectral efficiency

Wireless communication system is a coverage oriented system in where a minimal amount of access service is provided across a defined coverage area. In a cellular network cell spectral efficiency is the maximum number of users per cell that provide required quality of service of that network. On the other hand it refers to the information rate that can be transmitted over a given bandwidth. In the simulation environment all base stations are transmitting at full power at all times. In this scenario, under certain radio propagation conditions, the *cell spectral efficiency*, η_{cell}, is defined as maximum bit rate per Hz that a call can support.

$$\bar{\eta}_{cell} = \left\langle \frac{C}{W} \right\rangle \tag{5.4}$$

In spectrum efficiency it is mandatory to take under consideration the following parameters namely the amount of spectrum utilized, the covered area, the amount of information transmitted, and using time of the spectrum.

The area spectral efficiency is the sum of the maximum bit rates/Hz/unit area by a base station of the cell [25].The area spectral efficiency concept can be introduced by define the reuse distance D [m], which is the distance between two base stations with same frequency. As the frequencies are the same for the both base station than the frequency is reused at a distance D, the area is roughly $\pi\ (D/2)^2$ [m^2]. Then the area spectral efficiency can be approximated by, [25]

$$\eta_{area} = \frac{\sum_{k=1}^{N_s} C_k}{\pi W (D/2)^2} \tag{5.5}$$

where N_s is the total number of active serviced channels per cell, C_k. The average area is the maximum data of the k-th user and W [Hz] is the total assigned bandwidth per cell. The relation between the area spectral efficiency,$\bar{\eta}_{area}$and the cell spectral efficiency, η_{cell} can be illustrated as:

$$\bar{\eta}_{area}\left[\frac{bps}{Hz} per km^2\right] = \rho_{cell} \times \bar{\eta}_{cell} \tag{5.6}$$

where, ρ_{cell} = cell density for an area, $\bar{\eta}_{cell}$= average cell spectral efficiency and $\bar{\eta}_{cell}$ = $\langle \frac{C}{W} \rangle$.

5.1.4 Outdoor and Indoor receiver point distribution

In the simulation analysis, five different scenarios are simulated based on the relative distribution of outdoor and indoor points, as shown in Table 5.2. The reasons for this distribution are to analyze the impact of receiver point location on *SINR* distribution, and hence on the cell spectral efficiency. The receiver point locations were randomly selected for each scenario. This selection was done with 100 iterations to ensure statistically reliable results. Furthermore, the outdoor and indoor receiver points distribution was uniform. Looking at the table, we can see two extreme cases; *scenario-1*depicts a case where only the outdoor coverage is considered (i.e., no receiver points are located indoors), while *scenario-5*represents a case where users are located only indoors, across all floors.

Table 5.2 *Receiver point's distribution*

Scenario	Receiver point distribution
1	100 % outdoors and 0% indoors
2	80% outdoors and 20% indoors
3	50% outdoors and 50% indoors
4	20% outdoors and 80% indoors
5	0% outdoors and 100% indoors

5.2 Simulation Result and Analysis

The general target of any radio network planning process is to maximize the overall capacity of the network while providing sufficient level of coverage. The improvement in the cell edge performance is crucial as it has an effect on the overall cell level capacities. The border cell regions, due to being away from the serving base station, experience worse propagation and channel conditions. Hence, from the radio network planning perspective, it is imperative to get the cell capacities as high as possible by improving the capacity performance at the cell edge. This means that proper radio network deployment is required to improve the cell edge conditions, which eventually reduces the inter-cell interference that is caused by overlap between adjacent and neighboring cell. Hence, in the simulation analysis, the focus is on the lower 10^{th} percentile values, which refer to the cell edge performance values.

Figure 5.1 shows the statistical 10^{th} percentile values for the received signal power levels (coverage) for the outdoor and different indoor floor levels. The *x-axis* in the figure represents the cell density per km^2, while the *y-axis* represents the corresponding *received signal strength* [dBm]. In the considered analysis, three classes are created for the indoor floor levels. These classes have been named as *bottom floors*, *middle floor*s and *top floors*, as shown in Figure 5.1. The *bottom floors* class correspond to the average 10th percentile value on the 1st and 2nd floor (combined), the *middle floors* class represents the average 10th percentile values on the 3rd and 4th floor (combined), and the *top floor* class shows the average 10th percentile value on the 7th and 8th floor (combined). The received signal strength values, shown in the figure, are relative to the receiver noise floor level which is at -92 dBm (shown by the dotted black line). It is shown in the figure that the receiver signal levels are quite promising for the outdoor receiver points from the very beginning. On the other hand the indoor receiver points do not experience that much signal levels as compared to the outdoor receiver points. The receiver points in the bottom floors are always experiencing the low signal levels as compared to the other floors on the top. In the case of less densified configuration, the signal loss is shown to be very high for the bottom floors.

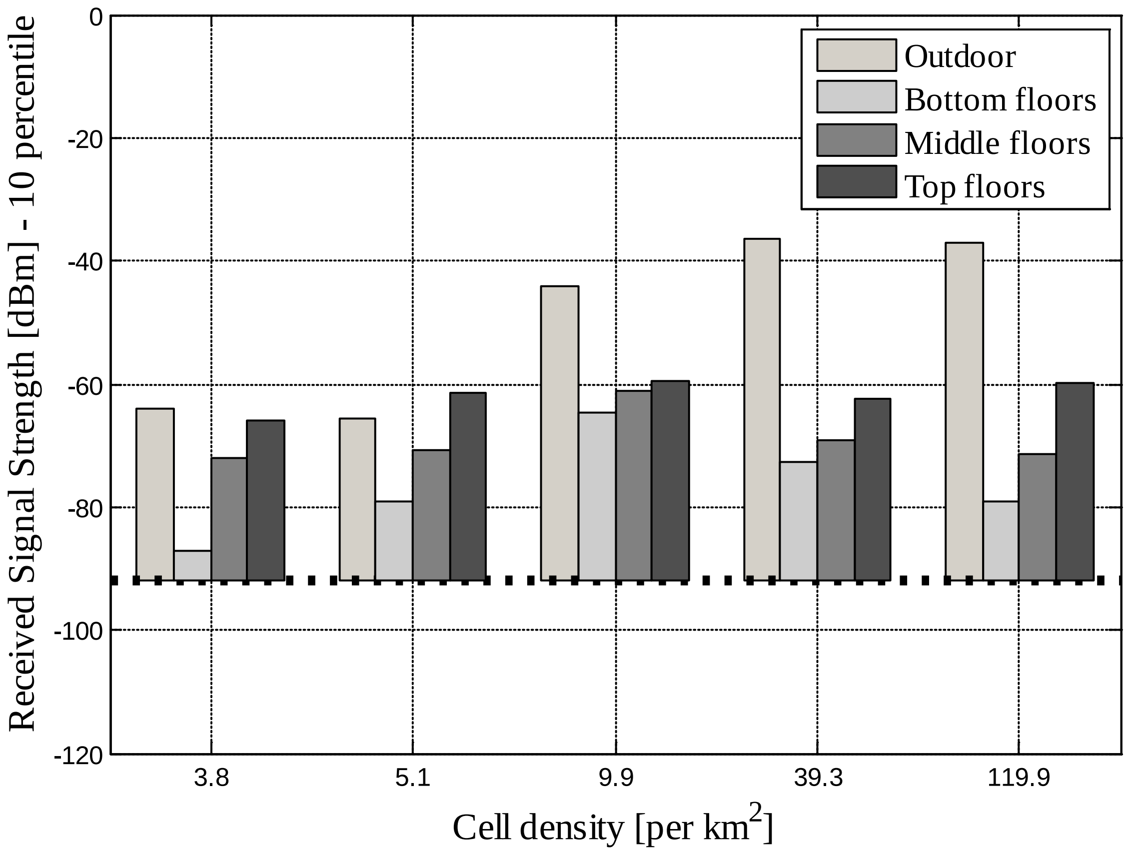

Figure 5.1 *Cell edge values (the 10th percentile statistics) for received signal strength.*

However, the overall coverage levels tend to improve, as a result of densification of the network. This improvement in the coverage level is because of the deployment of the more base stations together with antenna down tilt. Furthermore, as a result of the densification, the cell size is reduced which in turn reduces the path loss. On the other hand, subsequent densification of network does not bring improvement in the indoor coverage. On the contrary, the outdoor receiver points experience a moderate improvement in the average signal levels. In the case of 120 cells/km^2 (or average ISD of 170 m), which shows the densest configuration, the signal levels for receivers in the *middle* and *bottom floors* start to experience coverage degradation, but the average signal levels for receivers in outdoor and *top floors* is saturated. This is because the high antenna tilt angles result in extensive attenuation of signal in the lower floors.

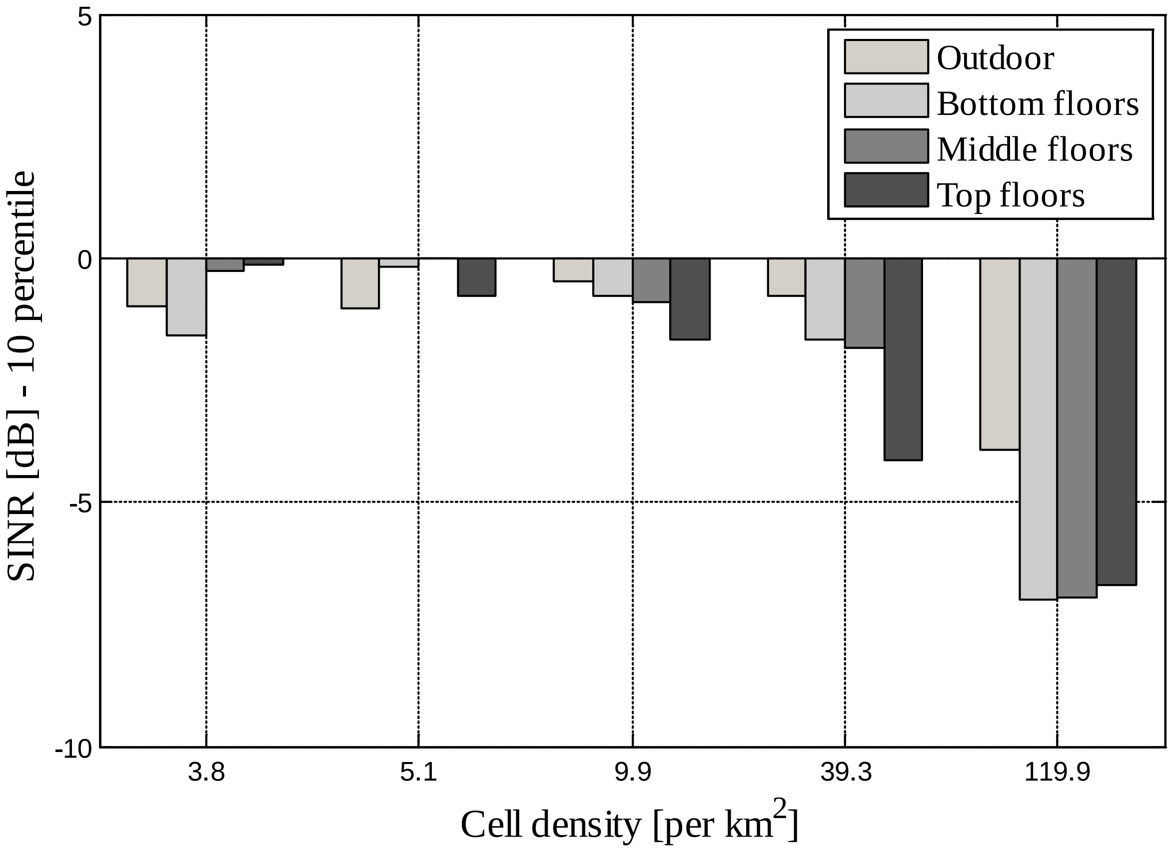

Figure 5.2 *cell edge values (the 10th percentile statistics) for SINR [dB]*

Figure 5.2 presents the 10th percentile values, obtained from the statistics from the cell edge, for SINR in outdoor and indoor environment for different cell densities. In this figure *x-axis* shows cell density per km^2 and *y-axis* represents the *SINR* [dB] levels. It shows in the figure that the *SINR* performance degrades abruptly on top floors as the cell density increases. However, from Figure 5.1, it is observed that coverage conditions in top floors are better than the middle and bottom floors. The reason for that situation is the rising interference conditions as the network is densified. This interference condition is more prominent on the top floors then the other floors. When the network is densified to the level of 5 cells/km^2(average ISD of 828m), the radio conditions in the lower and middle floor improve slightly as a result of coverage improvement. However, upon further densification, the *lower* and *middle floors* start to experience more interference and the coverage are becomes more.

Table 5.3 provides the average *cell* and *area spectral efficiency* for different ISDs. The table shows that the average *cell spectral efficiency* is reduced with the cell densification. For the outdoor scenario, the average *cell spectral efficiency* is approximately 2.7 bps/Hz, during the initial stage of densification i.e. 3.8 cells/km^2 (ISD 960 m). This cell spectral efficiency reduces to the level of 1.65 bps/Hz when network is densified to the level of 120 cells/km^2 (ISD 170 m). The same situation is also for the indoor scenario. For the indoor scenario, the average cell spectral efficiency is at the level of 2.67 bps/Hz, at ISD is 960 m configuration, and it is reduces to the level of 0.88 cells/Hz when the network is densified to 120 cells/km^2 i.e. higher densified network. On the other hand the average *area spectral efficiency* increases with the higher network density due to tight frequency reuse. From Table IV, we observe that the average area spectral efficiency is quite marginal for the both outdoor and indoor scenarios. It shows that for the average ISD of 969 m and 828 m, the average area spectral efficiencies in outdoor are 15.1 bps/Hz and 22.42 bps/Hz respectively, and in indoor they are 14.96 bps/Hz and 22.06 bps/Hz and 28.74 bps/Hz respectively. The effect of the area spectral efficiency is getting more acknowledged when the network densified is over the level of 5cells/km^2 (or average ISD of 828m). These situations characterize the rising interference level in indoor scenario, particularly on the top floors as shown in the Figure 5.2.

Table 5.3 *Average cell and area spectral efficiency for different ISDs.*

ISD $\bar{d}_{site}$ **[km^2]**	**Cell density** ρ_{cell} **[Cells per km^2]**	**Average cell spectral efficiency,** $\bar{\eta}_{cell}$ **[bps/Hz]**		**Average area spectral efficiency,** $\bar{\eta}_{area}$ **[bps/Hz]**	
		Outdoor	***Indoor***	***Outdoor***	***Indoor***
969 m	3.8	2.7	2.67	15.1	14.96
828 m	5.1	2.65	2.61	22.42	22.06
593 m	9.9	2.57	2.05	36.05	28.74
297 m	39.3	2.09	1.99	92.81	88.06
170 m	119.9	1.65	0.88	289.2	153.9

The results shows that the macrocellular network configuration in urban Manhattan environment does not provide sufficient outcome for the indoors receivers. Mobile communication industries contemplate that approximately 70 % of the overall mobile data traffic is originated by indoor users. Hence, it is important for a mobile operator to design their network from the indoor user demand perspective. From the results it can be observed that if the network planning target is limited to coverage, only for the outdoor users then densification efficiency is higher as shown in the Figure 5.1. On the contrary, if network is planned for the coverage for indoor users then the densification configuration gives clearly lower efficiency. Considering the indoor/outdoor user distribution, as shown in Table III, scenario 4 pertains to the practical case where in 80 % of the users and located indoors and the remaining 20 % are located outdoors. The receiver points were randomly selected in order to get statically reliable results.

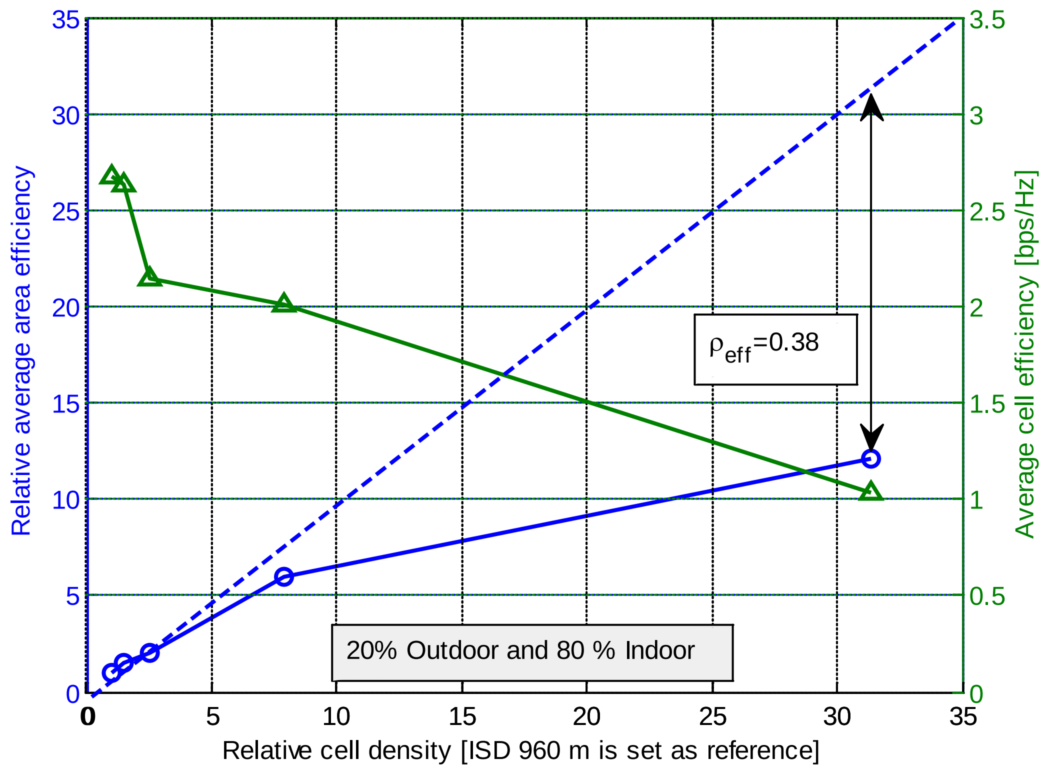

Figure 5.3 *Relative area efficiency and cell efficiency vs. relative cell count.*

Figure 5.3 shows the *relative area spectral efficiency* and *cell spectral efficiency* with respect to the relative cell count, for scenario 4. In the figure, ISD 960 m i.e. 3.8 cells/km^2 is taken as reference. The dashed line represent 100 % densification efficiency (ρ_{eff}) line. The blue solid line represents *relative average area efficiency* and the green solid line represents *average cell efficiency*. The blue solid line shows the improvement of the area spectral efficiency for the scenario 4. The figure reveals that there is a linearly increasing trend in the area spectral efficiency with respect to cell density, for the less dense configuration. It is shown that the densification efficiency is approximately 0.8 for average ISD of 597 m (i.e. 9.9 cells/km^2). After that point the efficiency fall down significantly. It drops down to 0.38 for 119.9 cells/km^2 scenerio. The decreased efficiency with respect to 100% densification efficiency is observed due to increase of inter-cell interference resulting in form of network densification. Analysis of these results reveals that the macrocellular network densification with a more practical user distribution is not sufficient.

6. CONCLUSION

The objective of this thesis work is to study and analyse the densification of classical macrocellular network. In the research 3D radio signal propagation model is used to illustrate how implementing macrocellular network densification can reduce the cell spectral efficiency under full load conditions and varying receiver point distributions namely in both indoor and outdoor conditions. The reduction in the *cell spectral efficiency* have resulted the saturation of the *area spectral efficiency* and reduction in the efficiency of the network densification. Nevertheless, if the situation is implemented in outdoor coverage with macrocellular network it should be sufficient to tackle the required capacity demands through densification. However, it is observed from the results that in indoor coverage and capacity provisioning perspective, the macrocellular network densification is evidently less efficient, since the densification efficiency is 0.38 and the outdoor/indoor receiver point distribution is 20/80% respectively. Moreover, in urban environment where there are high raised buildings, the macrocellular network is unable to provide the desired coverage inside the building floors. In order to combat the situation that is to further enhance the network capacity alternate deployment strategies such as introduction of small cells (Pico) or indoor (Pico, Femto) would require to be adopted. On the other hand in macrocellular network the finding of the research reveals that alternate mechanisms as interference mitigation techniques such as smart antenna systems or base station transmission coordination or interference cancellation mechanisms are evidently necessary to increase the densification efficiency.

In future the research can be extended in the fields of analyzing the coverage, capacity, costs and energy consumption in small or microcell networks and the parameters could be compared with macrocellular networks. In addition, the effect of macrocellular network densification with base station coordination in perspective of capacity, costs, and energy-efficiency requires to be evaluated. Therefore, it can be safely stated that the findings of the research opens doors towards valuable findings that would require to be shared with the scientific world.

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