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Indoor Radio Measurement and Planning for UMTS/HSPDA with Antennas

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INDOOR RADIO MEASUREMENT AND PLANNING FOR UMTS/HSDPA WITH ANTENNAS

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ABSTRACT

Over the last decade, mobile communication networks have evolved tremendously with a key focus on providing high speed data services in addition to voice. The third generation of mobile networks in the form of Universal Mobile Telecommunications System (UMTS) is already offering revolutionary mobile broadband experience to its users by deploying High Speed Downlink Packet Access (HSDPA) as its packet-data technology. With data speeds up to 14.4 Mbps and ubiquitous mobility, HSDPA is anticipated to become a preferred broadband access medium for end-users via mobile phones, laptops etc. While majority of these end-users are located indoors most of the time, approximately 70-80% of the HSDPA traffic is estimated to originate from inside buildings. Thus for network operators, indoor coverage has become a necessity for technical and business reasons.

Macro-cellular (outdoor) to indoor coverage is a natural inexpensive way of providing network coverage inside the buildings. However, it does not guarantee sufficient link quality required for optimal HSDPA operation. On the contrary, deploying a dedicated indoor system may be far too expensive from an operator's point of view. In this thesis, the concept is laid for the understanding of indoor radio wave propagation in a campus building environment which could be used to plan and improve outdoor-to-indoor UMTS/HSDPA radio propagation performance. It will be shown that indoor range performance depends not only on the transmit power of an indoor antenna, but also on the product's response to multipath and obstructions in the environment along the radio propagation path.

An extensive measurement campaign will be executed in different indoor environments analogous to easy, medium and hard radio conditions. The effects of walls, ceilings, doors and other obstacles on measurement results would be observed.

Chapter one gives a brief introduction to the evolution of UMTS and HSDPA. It goes on to talk about radio wave propagation and some important properties of antennas which must be considered when choosing an antenna for indoor radio propagation. The challenges of in-building network coverage and also the objectives of this thesis are also mentioned in this chapter.

The evolution and standardization, network architecture, radio features and most importantly, the radio resource management features of UMTS/HSDPA are given in **chapter two**. In this chapter, the reason why Wideband Code Division Multiple Access (WCDMA) was specified and selected for 3G (UMTS) systems would be seen. The architecture of the radio access network, interfaces with the radio access network between base stations and radio network controllers (RNC), and the interface between the radio access network and the core network are also described in this chapter. The main features of HSDPA are mentioned at the end of the chapter.

In **chapter three** the principles of the WCDMA air interface, including spreading, Rake reception, signal fading, power control and handovers are introduced. The different types and characteristics of the propagation environments and how they influence radio wave propagation are mentioned. UMTS transport, logical and physical channels are also mentioned, highlighting their significance and relationship in and with the network.

Radio network planning for UMTS is discussed in **chapter four**. The outdoor planning process which includes dimensioning, detailed planning, optimization and monitoring is outlined. Indoor radio planning with distributed antenna systems (DAS), which is the idea and motivation behind this thesis work, is also discussed.

The various antennas considered and the antenna that was selected for this thesis experiment was discussed in **chapter five**. The antenna radiation pattern, directivity, gain and input impedance were the properties of the antenna that were taken into consideration. The importance of the choice of the antenna for any particular type of indoor environment is also mentioned.

In **chapter six**, the design and fabrication of the monopole antennas used for the experimental measurement is mentioned. The procedure for measurement and the equipment used are also discussed. The results gotten from the experiment are finally analyzed and discussed. In this chapter the effect of walls, floors, doors, ceilings and other obstacles on radio wave propagation will be seen.

Finally, **chapter seven** concludes this thesis work and gives some directions for future work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

16-QAM	16-Quadrature Amplitude Modulation
64-QAM	64-Quadrature Amplitude Modulation
1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
AGC	Automatic Gain Control
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone Service
BCH	Broadcast Channel
BER	Bit Error Rate
BLER	Block Error Rate
CC	Chase Combining
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CN	Core Network
CPICH	Common Pilot Channel
CQI	Channel Quality Indicator
CS	Circuit Switched
DAS	Distributed Antenna Systems
DCH	Dedicated Channel (transport channel)
DL	Downlink
DPCCH	Dedicated Physical Control Channel
DPDCH	Dedicated Physical Data Channel

DS-CDMA	Direct Sequence CDMA
DSCH	Downlink Shared Channel
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
ETSI	European Telecommunications Standard Institute
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HHO	Hard Handover
HLR	Home Location Register
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HS-DPCCH	High Speed Downlink Physical Control Channel
HS-DSCH	High Speed Downlink Shared Channel
HSPA	High Speed Packet Access
HS-PDSCH	High Speed Physical Downlink Shared Channel
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
HTTP	Hyper Text Transfer Protocol
IM	Interference Margin
IMT-2000	International Mobile Telephony (name of 3G networks in ITU)
IR	Incremental Redundancy

ITU	International Telecommunications Union
KPI	Key Performance Indicator
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
ME	Mobile Equipment
MRC	Maximal Ration Combining
MSC	Mobile Switching Centre
NB	Narrowband
NF	Noise Figure
NLOS	Non-LOS
NMT	Nordic Mobile Telephony
OVSF	Orthogonal Variable Spreading Factor
PC	Power Control
PCH	Paging Channel
P-CPICH	Primary Common Pilot Channel
PCS	Personal Communication Systems
PDC	Personal Digital Cellular
PDP	Power Delay Profile
PG	Processing Gain
PLMN	Public Land Mobile Network
PS	Packet Switched
PSTN	Public Switched Telephone Network
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RC	Radiating Cable

RNC	Radio Network Controller
RNP	Radio Network Planning
RNS	Radio Network Subsystem
RRM	Radio Resource Management
RSCP	Received Signal Code Power
RSSI	Received Signal Strength Indicator
SA	Spectrum Analyzer
SAW	Stop and Wait
SfHO	Softer Handover
SGSN	Serving GPRS Support Node
SHO	Soft Handover
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TP	Throughput
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VNA	Vector Network Analyzer
WB	Wideband
WCDMA	Wideband Code Division Multiple Access

LIST OF SYMBOLS

α	Orthogonality factor
λ	Wavelength
S_Φ	Angular spread
Φ	Mean incident angle
$P(\Phi)$	Angular power distribution
S_τ	Delay spread
$\bar{\tau}$	Average delay
$P_\tau(\tau)$	Power delay profile
Δf_c	Coherence bandwidth
f_d	Doppler spread
f_c	Carrier frequency
E_b/N_o	Energy per bit to noise ratio
η_{UL}	Uplink Load
W	Chip rate
η_{UL}	Downlink load
k	Boltzmann constant
T	Noise temperature
EF_B	Effective noise at Node B
E_c/N_o	Energy per chip to noise ratio
i_{UL}	Uplink interference
G_p	Spreading factor
S_n	Narrowband signal
S_w	Wideband signal

CHAPTER ONE

INTRODUCTION

In the early 20^{th} century, technological revolutions in the electrical and telecommunications industry made wireless communication possible with the launch of first generation (1G) analogue cellular networks focusing on the real-time speech services. The concept of digital transmission was soon realized and in 1991, the second generation (2G) digital cellular network, called Global System for Mobile (GSM) communications was put into service. GSM was designed to support voice as well as data communication yet data transmission capabilities of GSM were rather limited. Improvements to enhance data transmission rates and reliability in GSM resulted in technologies like High Speed Circuit Switched Data (HSCSD), General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE) promising data rates up to 236 kbps [2].

During the past decade or more, the world of telecommunications changed drastically for various technical and political reasons. The widespread use of digital technology has brought radical changes in services and networks. In addition, a strong drive towards wireless internet access through mobile terminals has generated a need for a universal standard, which became known as the Universal Mobile Telecommunication System (UMTS) ([46]-[48]). These new third-generation (3G) networks are being developed by integrating the features of telecommunications- and Internet Protocol (IP)-based networks. Networks based on IP, initially designed to support data communication, have

begun to carry streaming traffic like voice/sound, though with limited voice quality and delays that are hard to control [8]. Commentaries and predictions regarding wireless broadband communications and wireless internet access are cultivating visions of unlimited services and applications that will be available to consumers ‘anywhere, anytime’. They (consumers) expect to surf the Web, check their emails, download files, make real time videoconference calls and perform a variety of other tasks through wireless communication links [8]. They expect a uniform user interface that will provide access to wireless links whether they are shopping at the mall, waiting at the airport, walking around town, working at the office or driving on the highway. The new generation of mobile communications is revolutionary not only in terms of radio access technology, and equally the drive for new technical solutions are not the only motivation for UMTS. Requirements also come from expanded customer demands, new business visions and new priorities in life [8].

Consequently, UMTS has met the challenge of continuously improving the end-user experience and service interaction by evolving its packet-data technology with high speed downlink packet access (HSDPA). Offering data speeds up to 14.4 Mbps; HSDPA is expected to become a preferred broadband access medium for end-users - from mobile phones to laptops [2].

In UMTS, coverage and capacity are interdependent. Transmit power in downlink (cell coverage) is shared among users whereas each user adds to the overall interference that decreases the cell capacity. Moreover, the performance of HSDPA link depends exclusively on the radio channel conditions surrounding the mobile device. The better the

channel conditions the higher the throughput. However, higher power levels needed to service indoor HSDPA users also draws out the capacity of outdoor cells [2].

UMTS radio network planning (RNP) aims to maximize network coverage and capacity and guarantee service quality despite the dynamic effects of radio channel. While the UMTS RNP processes are well proven in outdoor environments, they fail to address sufficient link quality required for HSDPA operation in typical urban indoor environments. For mobile network operators nowadays, indoor coverage has become a necessity both for technical and business reasons [1]. Since most of the end-users are located indoors most of the time, approximately 70-80% of the mobile traffic is expected to originate from inside the buildings [1]. With more and more of these users enjoying multimedia services via HSDPA, operators get a business opportunity they can profit from by improving their network's indoor performance and efficiency [2].

1.1 Radio and Microwave Communication Systems

The major role of a communication system is to transmit data from one side (transmitter) to another (receiver) by electromagnetic energy travelling between the two reference sides (Figure 1.1). Like any other communication system, a microwave communication system uses transmitters, receivers and antennas. The same modulation techniques used at lower frequencies are also used in the microwave range. However, the RF part of the equipment is physically different because of the special circuits and components that are used to implement the system [40].

The transmitted signal (electromagnetic wave) of a communication system is always followed by noise, which exists in free space as well as in the transmitter and receiver.

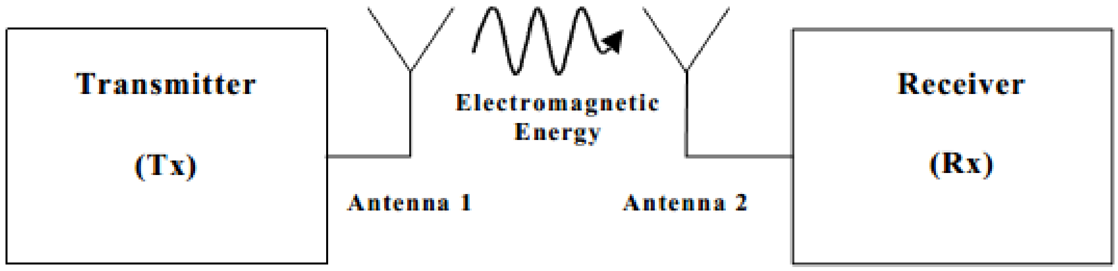

Figure 1.1: The concept of a wireless communication system [40]

Noise always reduces the efficiency of the system and determines the boundaries of the signal detection. The noise level of a communication system can be reduced by a careful design of the transmitter and receiver and by increasing the level of the signal in order to overcome equipment and background (free space) noise. Of course, the easiest solution to these problems is to increase the power at the source, but this method is expensive and limited. Therefore, the communication system must be designed as efficiently as possible and the most effective method is to make sure that all the components of the system (particular antenna and transmission lines) are "matched" in order to radiate (or receive) all the available energy from the generator [40].

1.2 The Antenna

One of the most important components of any communication system, which depends on the free space, such as the mobile telephone, is the antenna. Most antennas for radio communications consist of metal wires or rods connected to the transmitter or receiver [40].

In any communication system the roles of the antenna include; the radiation of the electromagnetic wave into the free space using the supplied energy of the source, the reception of the transmitted signal and the delivery of the signal to the receiver [40].

Typically an antenna consists of an arrangement of metallic conductors ("elements"), electrically connected (often through a transmission line) to the receiver or transmitter. An oscillating current of electrons forced through the antenna by a transmitter will create an oscillating magnetic field around the antenna elements, while the charge of the electrons also creates an oscillating electric field along the elements. These time-varying fields, when created in the proper proportions, radiate away from the antenna into space as a moving transverse electromagnetic field wave. Conversely, during reception, the oscillating electric and magnetic fields of an incoming radio wave exerts force on the electrons in the antenna elements, causing them to move back and forth, creating oscillating currents in the antenna. The dimensions of an antenna usually depend on the wavelength or frequency, of the radio wave for which the antenna is designed.

The general types of antennas according to their performance as a function of frequency include [41]:

- **Electrically small antennas**; the length of the antenna structure is less than a wavelength λ, in extent (where $\lambda = c/f$, c is the velocity of light and f is the frequency).
- **Resonant antennas**; operates well at a narrow bandwidth, specific examples include the λ/2 dipole and the λ/4 monopole antennas.
- **Aperture antennas**; have a physical aperture through which electromagnetic waves flow to the free space, specific examples are the horn and reflector antennas.

- **Broadband antennas**; the parameters of the antenna's properties are nearly constant over a wide frequency range. Specific examples are the spiral and yagi antennas.

The basic parameters of the properties of an antenna are [41]:

- **Input Impedance**; this is the impedance presented at its terminals or the ratio of the voltage to the current at the pair of terminals.
- **Radiation Pattern**; refers to the directional (angular) dependence of the strength of the radio waves from the antenna or other source. It is also a plot of the far-field radiation properties of an antenna as a function of the spatial co-ordinates.
- **Beamwidth**; is the angular separation of the half-power points of the radiated pattern.
- **Radiation Efficiency**; this is the ratio of the radiated power (P_{rad}) to the input power (P_{in}) of the antenna.
- **Directivity**; this is the ratio of the power flux density radiated by the actual antenna in a given direction to the flux density radiated by an isotropic antenna radiating the same total power.
- **Return Loss**; this indicates the amount of power that is "lost" to the load and does not return as a reflection. Hence the RL is a parameter to indicate how well the matching between the transmitter and antenna has taken place. Simply put it is the S11 of an antenna. A graph of S11 of an antenna vs frequency is called its return loss curve.

- **Antenna Gain**; this is the measure of the ability of the antenna to direct the input power into radiation in a particular direction and is measured at the peak radiation intensity.
- **Polarization**; which is the electric field vector of the radiated wave.

1.3 In-Building Network Coverage Challenges

Macrocellular radio signals attenuate as they pass through the fabric of a building, resulting in dead zones, where there is no coverage at all or only intermittent coverage, so the primary challenge is to provide consistent, robust signal strength throughout the building to maximize the performance of handsets and devices attached to the network.

To achieve this, there are several key considerations. It is necessary to determine exactly where the coverage is weak—it may be in several isolated areas or across the building or campus. Also, interference can be a significant problem, often caused by electronic instruments located within the building. Not all in-building wireless systems offer control over the amount of radio energy delivered at each internal antenna; however, some can control this energy, limiting interference and loss of signal strength [32].

The first step is to do a professional site survey, identifying coverage deficiencies, determining the impact of outside interference, and outlining the amount and type of equipment needed to establish a robust link budget (measurement of the quality of the network connection) throughout the building [32].

Technical choices for in-building systems range from a simple Band-Aid that will fix a coverage issue in a specific area, to a complete, campus-wide, multi-technology architecture. Aside from technical considerations, deployment of in-building wireless

coverage can be disruptive and expensive, depending on the choice of system. Systems vary in their scalability (a consideration if future expansion is planned) – some may not be flexible when it comes to being upgraded to enable future services to be delivered. Some only need upgrades to centralized electronics, and others require fundamental alterations to antennas [32].

While indoor coverage is a challenge for all cellular services, supporting pervasive 3G services indoors is even more challenging. Most 3G services, such as HSDPA and EV-DO, are currently being offered in higher frequencies, so operators can re-utilize the lower, cellular frequencies to support high-QAM W-CDMA based protocols. Also, newly available spectrum is mostly in higher frequencies, with the trend being a shift from 800/900Mhz to 1800/1900 to 2100Mhz. These higher frequencies are more easily attenuated by building materials. This can be a greater challenge for multi-level buildings, and it is not feasible – or sometimes legal – for operators to simply ratchet up the power to overcome signal dissipation [32].

Fundamentally, there is a need for a better link budget to support data applications. (The link budget represents the relationship between power transmitted and signal strength, and is reduced as the data rate goes up). HSDPA in particular suffers from poor in-building penetration, and brings an additional challenge for coverage, namely the reduction of the link budget.

Finally, it is increasingly important that improving cell phone coverage in an office complex is achieved with an appropriate commercial arrangement for the mobile operator and the user organization [32].

1.4 Research Objectives

The objectives of this thesis are to investigate and fabricate a narrow band monopole antenna with a circular ground plane for the optimization of UMTS and HSDPA in indoor environment.

The initial objective at the beginning of my research was to study the enhancement and optimization of HSDPA coverage, throughput and performance in typical indoor environments using indoor distributed antenna systems and a repeater as a deployment strategy. Since the most important part of any wireless communications network is the antenna, my final objective then, was to find out a very efficient and cost effective antenna that could be used to optimize and enhance indoor radio propagation around the UMTS frequency range. Measurements were then taken with this antenna to determine the channel characteristics of any indoor area(s) of interest.

The first antenna that was considered was the coaxial collinear antenna. This type of antenna is an omnidirectional antenna and is a popular array design for base stations. As the number of elements of the array is increased, the gain increases and the beamwidth decreases. Due to the cost of production, size, weight and feeding of this antenna, the dipole antenna (resonant $\lambda/2$ antenna) was then considered. Now, the cost of feeding the dipole antenna, together with other disadvantages which would be discussed later was also a problem, thus the monopole antenna was finally selected. The advantages of the monopole antenna over the dipole antenna and the coaxial collinear would be seen later in this thesis.

CHAPTER TWO

INTRODUCTION TO UMTS/HSPA

Universal Mobile Telecommunications System (UMTS) is a third generation mobile cellular technology for networks based on the GSM standard. From the first commercial launch of its services in 2001, UMTS has undoubtedly delivered its promise to provide a whole new mobile multimedia experience and services to its users [2]. Third generation systems are designed for multimedia communication: with them person-to-person communication can be enhanced with high quality images and video, and access to information and services on public and private networks will be enhanced by the higher data rates and new flexible communication capabilities [4]. UMTS employs Wideband Code Division Multiple Access (WCDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators. UMTS specifies a complete network system, covering the radio access network (UMTS Terrestrial Radio Access Network, or UTRAN), the core network (Mobile Application Part, or MAP) and the authentication of users via SIM cards (Subscriber Identity Module) [4].

In this chapter, I will be describing the development and standardization process of UMTS along with the system architecture and radio access technology. A brief account of High Speed Downlink Packet Access (HSDPA) will be discussed later in the chapter.

2.1 Evolution and Standardization

Prior to the development of the concept of cellular coverage by AT&T/Bell Laboratories, the mobile telephony systems were manual systems used only for mobile voice

telephony. Typically implemented with high masts that covered large areas, and with limited capacity per mast, they were only able to service few users at the same time [1]. These systems also lacked the ability to handover calls between masts, so mobility was limited to the specific coverage area from the servicing antenna, although in reality the coverage area was so large that only rarely would one move between coverage areas. Then, there were no portable mobile phones, only vehicle-installed terminals with roof-top antennas. Over time the use of mobile telephony became increasingly popular and the idea was born that the network needed to be divided into more and more smaller cells, accommodating more capacity for more users, implementing full mobility for the traffic and enabling the system to hand over traffic between these small cells [1].

Based on the above concept, several cellular systems have been developed over time and in different regions of the world. The first generation (1G) or analog cellular system, which focused on voice, was deployed in the early 1980s in Europe and was commonly known as NMT (Nordic Mobile Telephony) [2]. At the same time analog AMPS (Advanced Mobile Phone Service) was introduced in North America. With the advent of digital communication during the 1990s, the opportunity to develop a second generation (2G) of mobile communication standards and systems, based on digital technology, surfaced. Thus, analog systems were replaced by 2G digital cellular systems such as the GSM (Global System for Mobile Communication) developed in Europe, PCS (Personal Communications System) in USA and PDC (Personal Digital Cellular) in Japan. GSM was one of the first truly digital systems for mobile telephony [2, 3]. It was specified by the European Telecommunication Standards Institute (ETSI) and originally intended to be used only in the European countries. However GSM proved to be a very attractive

technology for mobile communications and, since the launce in Europe, GSM has evolved to more or less a global standard. The GSM is based on time division multiple access (TDMA) and frequency division multiple access (FDMA) schemes.

Now, due to the increased demand for higher data rates and mobility with internet based applications and data centric services, the third generation (3G) UMTS system was developed. UMTS was selected as the first 3G system for many reasons, mainly because it is a very efficient way to utilize the radio resources – the RF spectrum. WCDMA has a very good rejection of narrowband interference, is robust against frequency selective fading and offers good multipath resistance due to the use of rake receivers [1]. The handovers in WCDMA are imperceptible due to the use of soft handover, where the mobile is serviced by more cells at the same time, offering macro-diversity. Initially, UMTS offered high bit rates of up to 384 kbps but then enhancements to UMTS resulted in the High Speed Packet Access (HSPA) which offers data rates of 14.4 Mbps (in the downlink) [4]. These enhancements are often referred to as 3G evolution or 3.5G. The evolution path driven by the services demanding higher and higher data rates and bandwidth is presented in Figure 2.1 below.

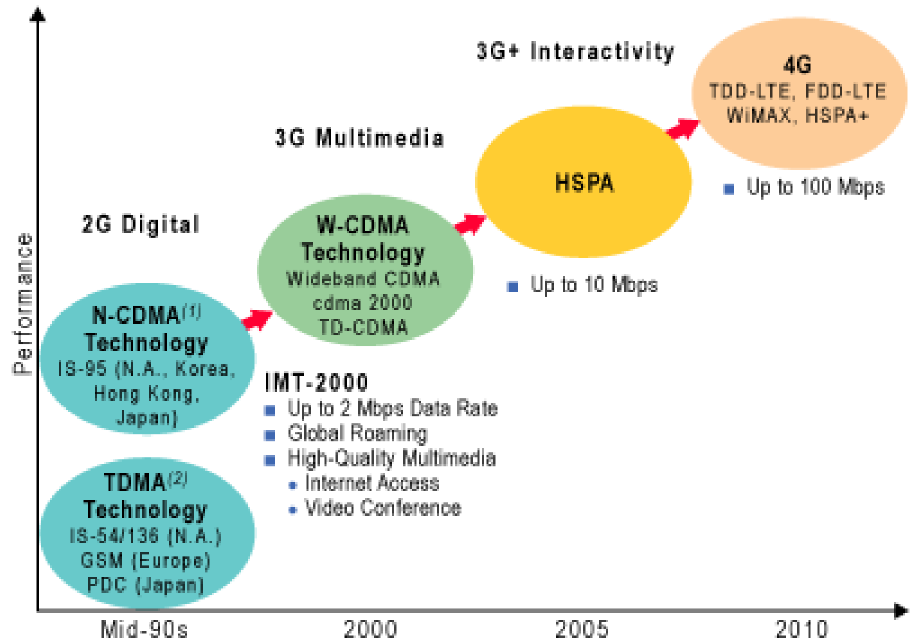

Figure 2.1: Evolution of mobile cellular communication systems [2]

The development and standardization of 3G systems is carried out by International Telecommunication Union (ITU). ITU specification suggested International Mobile Telephony 2000 (IMT-2000) as a common name for 3G systems and a 3rd Generation Partnership Project (3GPP) was formed to carry out the standardization. 3GPP is a collaboration between a number of telecommunication standards organizations, known as the Standards Development Organizations based in countries like Europe (ETSI), Japan (ARIB & TTC), Korea (TTA), USA (ATIS) and China (CCSA) [4]. In Europe, ETSI is involved in 3GPP for the development and standardization of 3G commonly known as UMTS. In 1998 ETSI decided upon WCDMA technology as UMTS air interface and since then it has appeared as the most widely adopted technology in Japan and Korea as well. 3GPP generates Technical Reports (TR) in addition to Technical Specification (TS). Within 3GPP, UMTS is referred to as UTRA (Universal Terrestrial Radio Access), FDD (Frequency Division Duplex) and TDD (Time Division Duplex), the name WCDMA

being used to cover both FDD and TDD operation [4]. The standardization process of UMTS continues as new techniques to enhance data rates and improve system performance are deployed. The set of 3GPP TS and TR have been and continue to be published using a series of releases. The first version of the UMTS specifications was release 99. The second, third and fourth versions of the specifications are release 4, release 5 (HSDPA), release 6 (HSUPA), release 7 and release 8 (Long Term Evolution - LTE) [2]. The 3GPP mobile network family is shown in

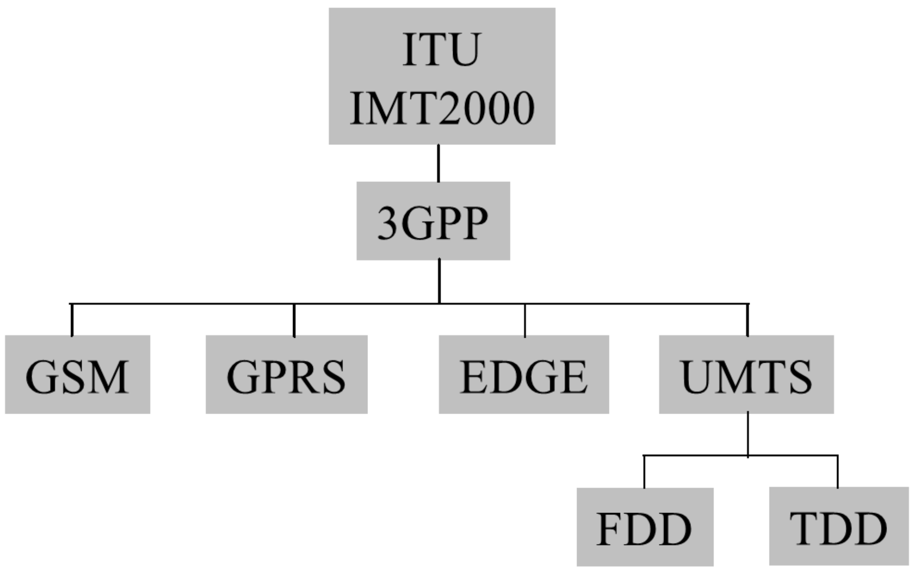

Figure 2.2: Evolution of mobile telephony [5]

The release 99 and release 4 versions of the specifications define the use of Dedicated Physical Channels (DPCH) in combination with soft, hard and inter-system handover. Operating bands I and II are specified at this stage [22]. Release 5 introduces IP Multimedia Subsystem (IMT) and HSDPA functionality whereas the Common Packet Channel (CPCH) and Downlink Shared Channel (DSCH) are removed. The CPCH and DSCH were removed because equipment manufacturers were not implementing them.

Release 6 of the specifications introduces HSUPA and Multimedia Broadcast Multicast Services (MBMS), enhancements to IMS such as Push to Talk over Cellular (PoC) whereas release 7 introduces operating band VIII. Release 7 focused on decreasing latency, improving Quality of Service (QoS) and real-time applications such as Voice over IP (VoIP). Table 2.1 presents an example subset of the functionality which appears in each 3GPP release [22]. It also shows the years and quarters they were released. The dots indicate the different properties of these releases listed in the table.

Table 2.1 Evolution of UMTS with 3GPP releases [22]

	Release 99 (2000 Q1)	**Release 4 (2001 Q4)**	**Release 5 (2002 Q2)**	**Release 6 (2004 Q4)**	**Release 7 (2007 Q4)**
DPCH	●	●	●	●	●
Soft handover	●	●	●	●	●
Hard handover	●	●	●	●	●
Inter-system handover	●	●	●	●	●
HSDPA			●	●	●
HSUPA				●	●
MBMS				●	●
CPCH	●	●			
DSCH	●	●			
Operating band I	●	●	●	●	●
Operating band II	●	●	●	●	●
Operating band III					●

2.2 UMTS Network Architecture

A UMTS network consists of three subsystems: User Equipment (UE), UMTS Terrestrial Radio Access Network (UTRAN), and the Core Network (CN) [2]. Each subsystem has several logical network elements with a defined functionality and all these elements interact with each other through different interfaces. The key elements of the UTRAN and the core network are shown in Fig. 2.3 below.

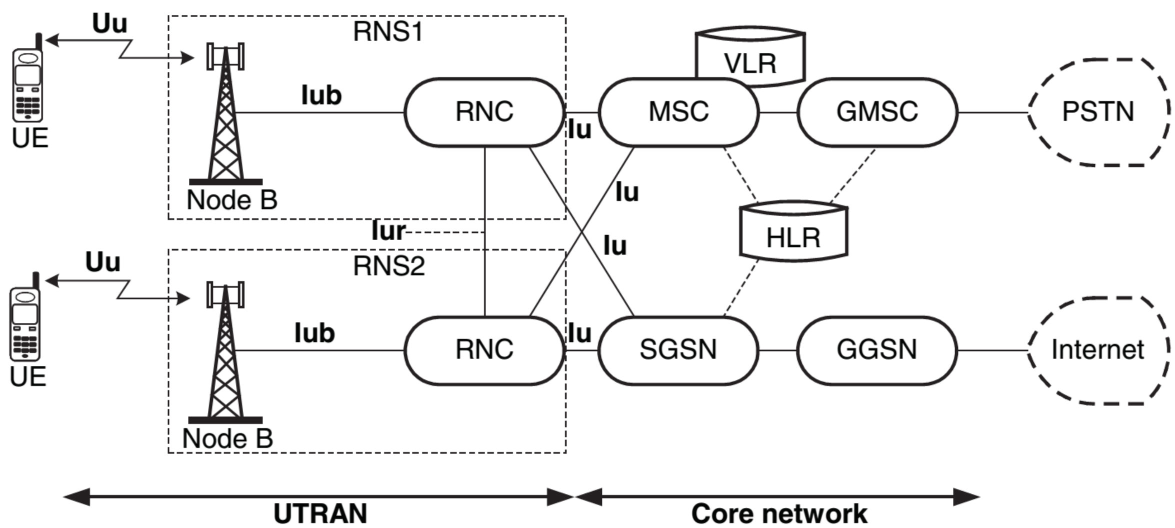

Figure 2.3: UMTS Network Architecture [1]

The mobile station is referred to as the user equipment (UE). The UE consists of Mobile Equipment (ME) and UMTS Subscriber Identity Module (USIM). ME is the terminal that contains the operating elements for the user interface e.g. keyboard, display, multimedia features etc. and radio equipment to communicate with UTRAN over Uu interface. USIM is a chip card that contains user specific information, network authentication and security keys for data encryption [4, 6].

The base station in the UTRAN network is called node B. Node B consists of transceivers, processing modules that provide the ‘channel elements’ that service the users. The node B interfaces to the UE over the air interface, the Uu Interface. This interface currently supports rates up to 2 Mbps but higher rates of up to 14 Mbps are enabled by means of HSDPA protocol. Interfacing node B to the RNC is the Iub interface. Node B also performs important measurements on the Uu interface, and reports these measurement results (reports) to the RNC with regards to the quality of the link. These are BLER (block error rate) and BER (bit error rate). They are needed in order for the RNC to be able to evaluate the QoS (quality of service), and adjust the power control targets accordingly [1].

The radio network controller (RNC) is controlling the node Bs within its own system (RNS). For speech service, the RNC interfaces to the MSC (Mobile Switching Center). For packet-switched data service the RNC interfaces to the SGSN (Serving GPRS Support Node). The RNC is responsible for the load on the individual cells in the RNS, and handles admission (traffic) control, code allocation. Once a connection has been established between UE and node B, signaling to the elements higher up in the network is done by the RNC. This RNC is then referred to as the SRNC (serving RNC). The SRNC is responsible for handover evaluation, outer loop power control, as well as the signaling between the UE and the rest of the UTRAN. If the UE signal can be received (in soft handover) by other node Bs controlled by other RNCs, these RNCs are called DRNC (drift RNCs). The DRNC can process the uplink signal from the UE and provide macro diversity, transferring the data via the Iub/Iur interfaces to the SRNC [7].

One RNC with the entire connected node Bs is defined as a radio network sub-system (RNS). A UTRAN consists of several RNSs; each RNC within the RNS is interconnected with an Iur interface [1]. The Iu interface is the link between the UTRAN and the core network. The interface is standardized so that a UTRAN from one manufacturer will be compatible with a core network from another manufacturer [1]. The Iur interfaces data from soft handovers between different RNCs and the Iub interface is used between the node B and the RNC. It thus enables handling of RRM (Radio Resource Management) and eliminates the burden from the CN. It is also fully standardized so that different RNCs will support different vendors' node Bs [1].

The core network (CN) in UMTS has the similar characteristics as any other backbone network and it is responsible for the switching and control of the connections. Part of the mobility management is handled in the core network as well. Depending on the transport technology used, CN may either be circuit switched (CS) or packet switched (PS) [2]. In the packet switched domain, the serving GPRS support node (SGSN) and the gateway GPRS support node (GGSN), provide, amongst other things, support for packet switched services towards mobile stations, including mobility management, access control and control of packet data protocol contexts. In addition, the GGSN provides internetworking with external packet-switched networks such as the internet. The network entities that handle CS services are the MSC (Mobile Switching Center)/Visitor Location Register (VLR) and Gateway MSC (GMSC) [2]. MSC controls the circuit switched connections, speech and real-time data applications for an active UE in the network. The VLR (Visitor Location Register) is a database, with the location of all UEs attached to the network [6]. GMSC is the gateway node that connects UMTS PSTN (Public Switched Telephone

Network) to external CS networks. When a UE registers in the network, the VLR will retrieve relevant data about the user (SIM) from the HLR associated with the SIM (IMSI). The HLR (Home Location Register) is a central database at the CN and contains master copies of subscribers' service profiles, roaming areas, authorization information and current location information (MSC and/or SGSN level) [1].

2.3 UMTS Radio Features

In any mobile communication system, coverage and capacity are key parameters which are mainly dependent on the signal to interference ratio (SIR) and bandwidth of the access technology used to share the transmission medium (radio interface) [2]. There are several different access techniques in which multiple users could send information through the common channel to the receiver. 2G systems used TDMA and FDMA techniques for radio interface whereas CDMA (Code Division Multiple Access) technique was employed by 3G systems. In TDMA, all users transmit using the same frequency but the data is multiplexed in short consecutive time slots. In FDMA, the frequency spectrum is divided into small sub-frequency channels and user data is multiplexed on these channels at the same time [2].

In FDMA and TDMA the common channel is partitioned into orthogonal single-user sub-channels. A problem arises if the data from the users accessing the network is bursty in nature. A single user who has reserved a channel may transmit data irregularly so that silent periods are even longer than transmission periods. For example, a speech signal may contain long pauses [8]. In such cases TDMA or FDMA tend to be inefficient because a certain portion of the frequency – or of the timeslots – allocated to the user carries no information. An inefficiently designed multiple access system limits the

number of simultaneous users of the common communication channel. One way of overcoming this problem is to allow more than one user to share the channel or sub-channel by the use of spread spectrum signals [8]. In this method each user is assigned a unique code sequence or signature sequence that allows the user's signals to be spread on the common channel. Upon reception, the various users' signals are separated by cross-correlating each received signal with each of the possible user signature sequences [8]. By designing these code sequences with relatively little cross-correlation, the crosstalk inherent in the demodulation of the signals received from multiple transmitters is minimized. This multiple access method is called Code Division Multiple Access (CDMA) [9]. In CDMA technique, all users transmit simultaneously in the same frequency channel but are separated by different orthogonal codes. The multiple access schemes are presented in Figure 2.4.

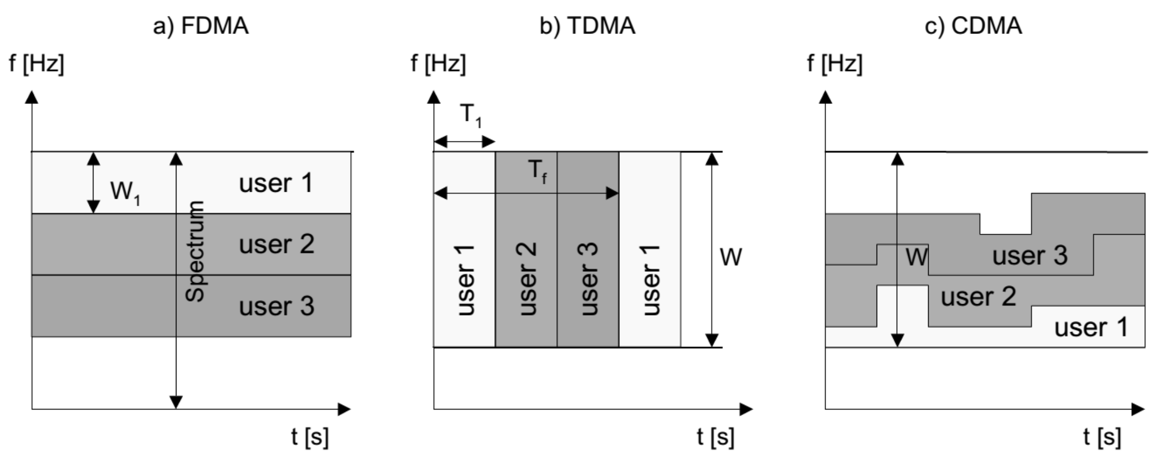

Figure 2.4: Multiple Access Schemes [8]

As part of 3GPP standardization, Wideband CDMA (WCDMA) was selected to be the radio interface for UMTS [2]. WCDMA is based on Direct Sequence CDMA (DS-CDMA) technology which has two modes of operation – WCDMA-TDD and WCDMA-

FDD [1]. Only the WCDMA-FDD mode is considered in this thesis. The WCDMA-FDD requires a paired set of bands, equal bandwidths separated with the 95 MHz duplex distance throughout the band. Frequency bands allocated for WCDMA-FDD are 1920-1980 MHz in uplink (UL) and 2110-2170 MHz in downlink (DL) direction (shown in Figure 2.5). The nominal carrier spectrum of a WCDMA signal is 5 MHz [1].

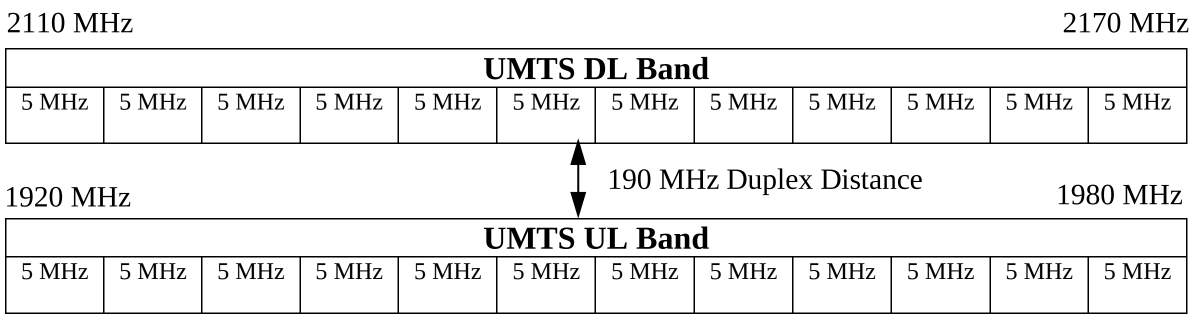

Figure 2.5: UMTS UL and DL frequency bands for the 12 FDD channels [1]

2.3.1 The WCDMA Radio Frequency Carrier

As mentioned above, the bandwidth of the UMTS carrier is about 5 MHz (4.75 MHz), and is divided into 3.84 Mcps (Figure 2.6). The chips are the raw information rate on the channel or carrier [1].

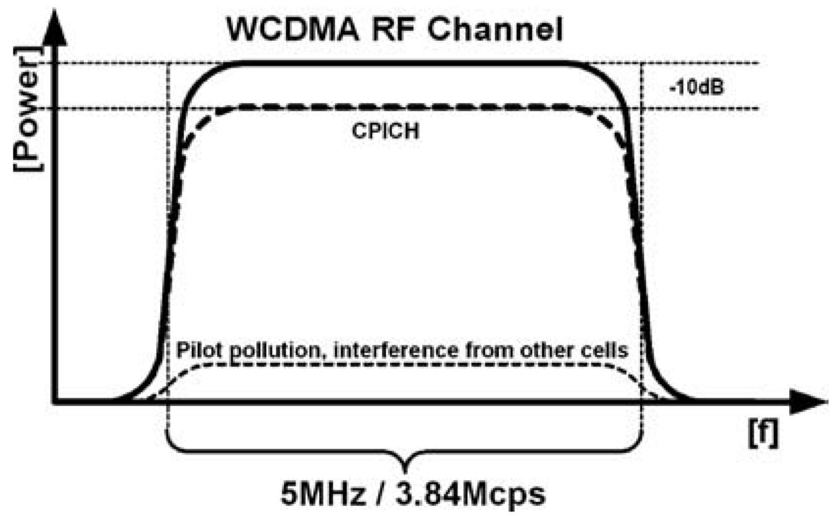

Figure 2.6: The WCDMA air channel, 5 MHz-wide modulated with 3.84 Mchips [1]

Each user is assigned a specific power according to the service requirement and path loss to that particular user. A large portion of the power is assigned to the important CPICH channel [1]. The more user traffic there is, the more power will be transmitted and the higher the amplitude of the UMTS carrier will be. Figure 2.7 shows how the spread WCDMA signal is transmitted in frames of 10 ms, enabling service on demand every 10 ms. One user in a voice session can get a higher data rate assigned in the next frame [1].

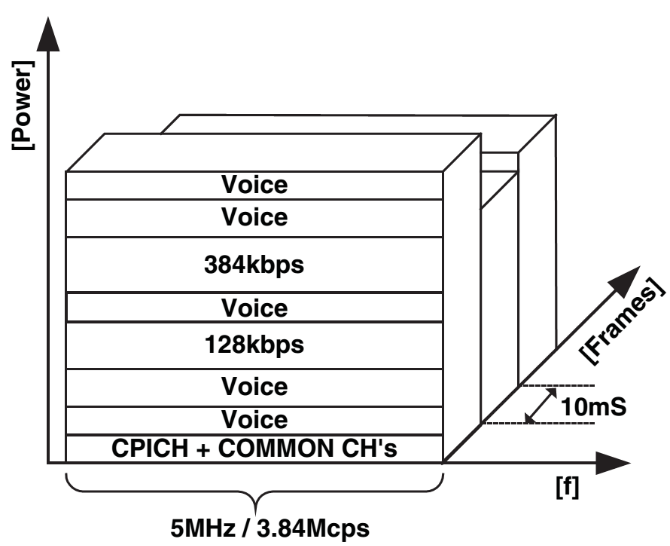

Figure 2.7: Spread WCDMA signal is transmitted in frames of 10ms [1]

2.3.2 Spread Spectrum Modulation

WCDMA is a spread spectrum signal. The narrow band information from the individual user is modulated, and spread throughout the spectrum. This distributes the energy of the user data over a wider bandwidth. Thus the signal becomes less sensitive to selective interference from narrow-band interference [1].

Formally, the operation of both transmitter and receiver can be partitioned into two steps. At the transmitter site, the first step is modulation in which the narrowband signal S_n, which occupies frequency band W_i, is formed [8]. In the modulation process, bit sequences of length n are mapped to 2^n different narrowband symbols constituting the narrowband signal S_n. In the second step, the signal spreading is carried out, in which the narrowband signal S_n is spread in a large frequency band W_c. The spread signal is denoted S_w, and the spreading function is expressed as $\varepsilon(\quad)$ as shown in Figure 2.8 [8].

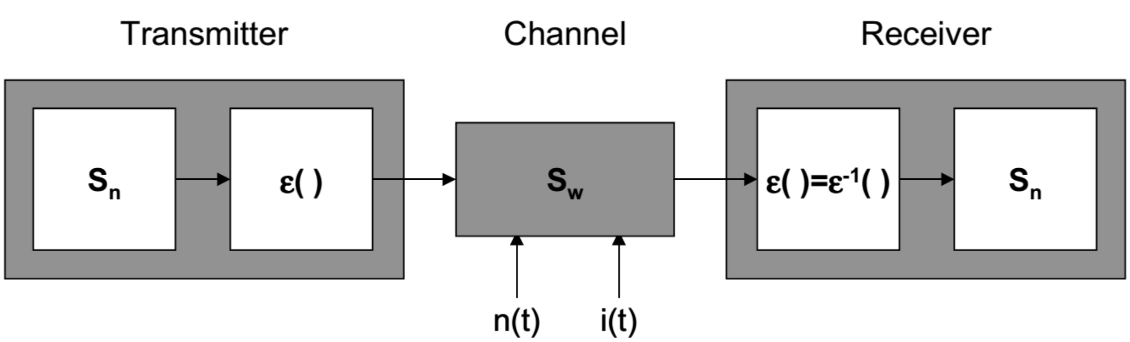

Figure 2.8: Spread spectrum system concept [8]

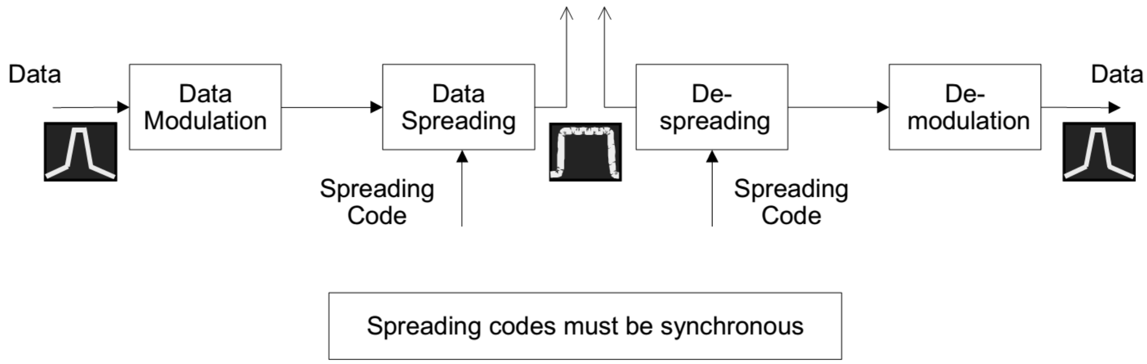

Figure 2.9: Direct Sequence Spread Spectrum concept with indicative bandwidth [8]

At the receiver site the first step is de-spreading, which can be formally presented by the inversion function $\varepsilon^{-1}(\quad) = \varepsilon(\quad)$. In dispreading, the wideband signal S_w is converted back to a narrowband signal S_n, which can then be demodulated using standard digital demodulation schemes [8]. Note that the nature of spreading and de-spreading operation is the same and could be performed by modulation of user data bits by spreading sequence bits. Such a basic concept is depicted in Figure 2.9.

Each mobile service is assigned an individual spreading code (as shown in Figure 2.8 and 2.9). All of the users transmit simultaneously using the same WCDMA frequency. The receiver is able to decode each individual user by applying the same specific spreading code assigned to each user [1].

The coded signal is orthogonal to other users in the cell. The principle is that the code is constructed in such a way that one coded signal will not 'spill' any energy to another coded user – if the orthogonality is maintained over the radio channel. Each individual user signal can only be retrieved by applying the same specific code, thereby limiting the interference between users [1]. Essentially all transmitted UMTS information is data;

each bit of this data is multiplied by a sequence of code bits, referred to as chips. The number of chips multiplied to each user bit is dependent on the service bit rate of the service assigned to each user. The principle is that the transmitted data is multiplied by the ‘raw’ channel code rate of a much higher frequency in UMTS 3.84Mcps (mega-chips per second) [1].

2.3.3 OVSF, Scrambling Codes and Common Pilot Channel (CPICH)

DSSS (Direct Sequence Spread Spectrum) technique is used in WCDMA technology to spread the information-bearing signal by use of code signals. In DSSS systems, signal spreading is achieved by modulating the data-modulated signal a second time by a wideband spreading signal [8]. The signal has to approximate closely to a random signal with uniform distribution of the symbols. Typical representatives of such signals in digital form are Pseudorandom noise (PN) sequences over a finite alphabet. Since a WCDMA system has to maximize system capacity during the spreading, the operation is done in two phases [8]. The user signal is first spread by the channelization code, which is a so-called Orthogonal Variable Spreading Factor (OVSF) code, its construction being based on the Hadamard matrix [10]. The code has the property that two different codes from the family are perfectly orthogonal if in phase. Thus, its use guarantees maximum capacity, measured by the number of active users. Now all the spread users’ signals are scrambled by the cell-specific scrambling sequence, which has the statistical properties of a random sequence.

The common pilot channel (CPICH) does not contain any signaling. It is a pure downlink channel that serves two purposes only: to broadcast the identity of the cell and to aid mobiles with cell evaluation and selection [1]. The CPICH is coded with the primary

scrambling code of the cell; it has a fixed channelization code with a spreading factor of 256. The mobiles in the network will measure the CPICH power from the different cells it is able to detect. It will access the cell with the most powerfully measured CPICH [1]. The mobile will also measure and evaluate the CPICH levels from other adjacent cells (defined in the neighbor list) for handover evaluation [1].

2.3.4 Tolerance of Narrowband Interference

A spread spectrum and hence WCDMA is tolerant to narrowband interference, as depicted in Figure 2.10 below.

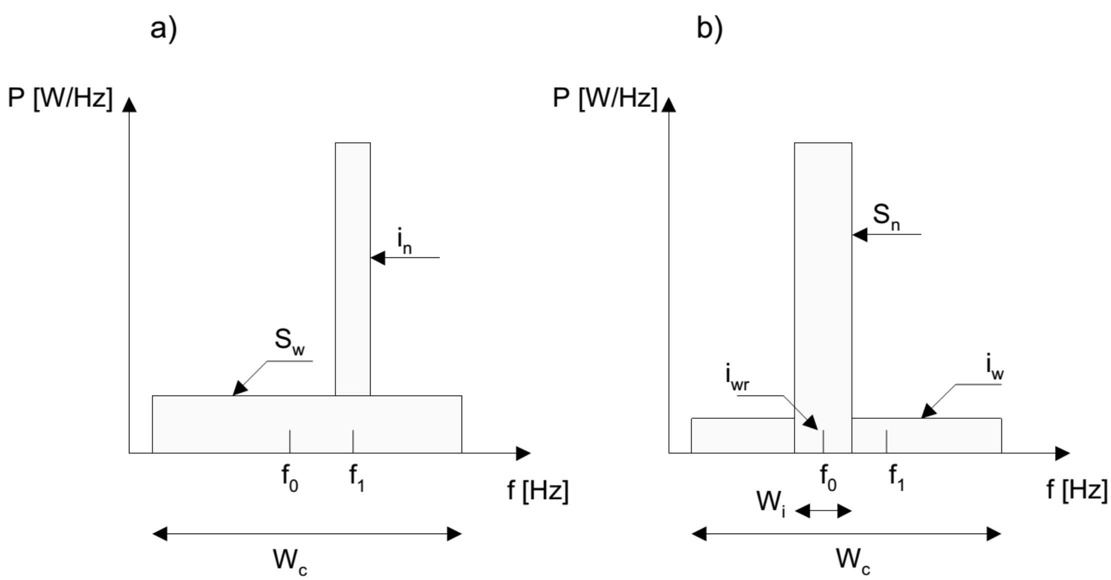

Figure 2.10: Direct Sequence Spread Spectrum concept with indicative bandwidth [8]

Now assuming that a wideband signal S_w is received in the presence of a narrowband interference signal i_n (Figures 2.4(a) and (b), the de-spreading process can be presented as follows [8]:

$$\varepsilon^{-1}(S_w + i_n) = \varepsilon^{-1}[\varepsilon(S_n)] + \varepsilon^{-1}(i_n) = S_n + i_w \tag{2.1}$$

The de-spreading operation converts the input signal into a sum of the useful narrowband signal and an interfering wideband signal. After the de-spreading operation narrowband filtering (operation $F(\quad)$) is applied with a bandpass filter of bandwidth B_n equal to the bandwidth W_i of S_n, resulting in [8]:

$$F(S_n + i_w) = S_n + F(i_w) = S_n + i_{wr} \tag{2.2}$$

2.3.5 Processing Gain (Spreading Factor)

From Figure 2.10(b), only a small proportion of the interfering signal energy passes the filter and remains as residual interference, because the bandwidth W_c of i_w is much larger than W_i. The ratio between the transmitted modulation bandwidth and the information signal bandwidth is called the processing gain or spreading factor, G_p:

$$G_p = \frac{W_c}{W_i} \tag{2.3}$$

The processing gain can also be said to be the gain obtained from using the spreading and de-spreading signal technique over a wideband carrier [8]. It is dependent on the relation between the carrier chip rate, and the user data bit (chip) rate, as shown in Table 2.2 below.

Table 2.2 UMTS data rate versus processing gain [1]

User Rate	Processing Gain
12.2 kbps	25 dB
64 kbps	18 dB
128 kbps	15 dB
384 kbps	10 dB

$$\text{Processing gain (spreading factor)} = \frac{\text{chip rate}}{\text{user data rate}}$$

$$\text{Processing gain} = \frac{3.84\ \text{M}}{\text{user rate [linear]}}$$

$$\text{Processing gain} = 10\log\left(\frac{3.84\ \text{M}}{\text{user rate}}\right)\ \text{[dB]} \tag{2.4}$$

Now equating W_c and W_i to the chip and user data rate, respectively, we prevent any filter- or modulation-specific properties.

The effect of processing gain can be clearly seen from Figure 2.10. The more processing gain the system has, the more the power of uncorrelated interfering signals is suppressed in the de-spreading process [8]. Thus, processing gain can be seen as improvement factor in the SIR (Signal to Interference Ratio) of the signal after de-spreading. There is a certain tradeoff in the value of the transmission bandwidth W_c. For a large processing gain to give greater interference suppression, a broad transmission bandwidth is needed. In the WCDMA system the value of W_c is 3.84Mcps which, owing to spectral side-lobes, results in a 5MHz carrier raster [8].

2.3.6 E_b/N_o and E_c/I_o

The signal quality of the user data on UMTS is defined as the E_b/N_o (signal-to-noise ratio). The E_b/N_o is defined as the ratio of energy per bit (E_b) to the spectral noise density (N_o). It is measured at the input to the receiver and is used as the basic measure of how strong the signal is over the noise [1]. The E_b/N_o defines the maximum data rate possible with a given noise different data rates have different E_b/N_o requirements: the higher the data speed, the stricter the E_b/N_o requirements.

The quality/signal strength of the pilot channel is measured as E_c/I_o, which is the energy per chip/interference density measured on the CPICH. It is effectively the CPICH signal strength. When the mobile detects two or more CPICH with similar levels, the mobile will enter soft handover. This is essential in order to secure the link. If the mobile did not enter soft handover, the link would break down due to interference between the two cells transmitting the same channel and received at the same power level [1].

The mobile continuously measures the E_c/I_o of the serving cell and adjacent cells (defined in the neighbor list/monitor set). The mobile compares the quality (E_c/I_o) of the serving CPICH against the quality of other measured CPICHs. The mobile uses trigger levels and thresholds to add or remove cells from the active set (the cell or cells the mobile is engaged with during traffic) [1].

2.4 Radio Resource Management Features

The Radio Resource Management (RRM) function consists of Power Control (PC), Handover Control (HC), congestion control – typically subdivided in to Admission Control (AC), Load Control (LC) and Packet data Scheduling (PS) – and the Resource Manager (RM) [8].

2.4.1 UMTS Power Control

In WCDMA technique, all the users have to share a common frequency, thus making interference control a crucial issue. This is particularly important for the uplink direction, since one mobile station located close to the base station and transmitting with excessive power can easily overshoot others that are at the cell edge (the near-far effect) or even block the whole cell. In the downlink the system capacity is directly determined by the

required code power for each connection [8]. Therefore, it is essential to keep the transmission powers at a minimum level while ensuring adequate signal quality at the receiving end.

The power control in UMTS has three different stages [1]:

(i) Open-loop power control (cell access)

(ii) Closed-loop power control (inner loop) - in dedicated (traffic) mode

(iii) Outer-loop power control.

(i) Open-Loop Power Control

Since the uplink and downlink frequencies of WCDMA are within the same frequency band, a significant correlation exists between the average path losses of the two links [8]. This makes it possible for each UE, before accessing the network, and for each BS, when the radio link is set up, to estimate the initial transmit powers needed in the uplink and downlink based on the path loss calculations in the downlink direction. The open loop PC is used when the mobile is in transition from idle mode (not engaged in traffic) to dedicated mode (setting up a call or responding to a paging signal) [1]. The mobile's initial power for the network attachment is estimated using the downlink pilot (CPICH) signal. The mobile will monitor the system information transmitted by the base station with regards to the reference for the transmitted CPICH power. This enables the mobile station to calculate the path loss back to the base station [1].

(ii) Closed-Loop Power Control (Inner Loop)

The closed loop PC allows the UE/Node B to adjust its transmitted power based on the received SIR (signal-to-interference ratio) level at the Node B/UE for compensating the fading of the radio channel [8]. The closed loop PC function in UMTS is used for the Dedicated Channels (DCHs) in both the uplink and downlink directions and for the Common Packet Channel (CPCH) in the uplink. Thus, the closed loop power control is active when the mobile station is in traffic mode (dedicated mode) [1]. On the downlink, power control on the base station preserves marginal power for mobiles on the edge of the cell. WCDMA has a fast power control of 1.5 kHz (666 μs) as compared to GSM with a power control rate of 16.7 Hz (60 ms) [1].

(iii) Outer-Loop Power Control

The aim of the outer-loop PC algorithm is to maintain the quality of the communication at the level defined by the quality requirements of the bearer service in question by producing an adequate target SIR for the closed loop PC [8]. This operation is done for each DCH belonging to the same Radio Resource Control (RRC) connection. The SIR target needs to be adjusted when the UE speed or the multi-path propagation environment changes. The higher the variation in the received power, the higher the SIR target needs to be [8].

2.4.2 UMTS Handover Control

The term handover refers to the process of transferring an ongoing call or data session from one channel connected to the core network to another. There are different handover scenarios that are supported by UTRAN [8]. The type of handover is dependent on

whether the handover is within the same node B, different node B, different UMTS frequencies or even handover between UMTS and GSM or DCS [8]. The handover control can be divided into the following handover types:

(i) **Intra-system Handover**: This occurs within a WCDMA system. It can be further subdivided into:

- **Intra-frequency Handover**, which is between cells belonging to the same WCDMA carrier.
- **Inter-frequency Handover**, which is between cells, operated on different WCDMA carriers.

(ii) **Inter-system Handover**: this takes place between cells belonging to two different Radio Access Technologies (RATs) or different Radio Access Modes (RAMs). This is very common between WCDMA and GSM/EDGE (Global System for Mobile communications/Enhanced Data rates for GSM Evolution) systems [8].

(iii) **Hard Handover**: Hard handover occurs when the radio links for a UE changes and there are no radio links that are common before the procedure is initiated and after the procedure is completed. It could be said to be a procedure in which all the old radio links of a UE are released before the new radio links are established [8].

(iv) **Soft Handover and Softer Handover**: These are handover procedures in which the UE always keeps at least one radio link to the UTRAN. In soft handover, the UE is simultaneously controlled by two or more cells belonging to different Node Bs of the same RNC or different RNCs. In softer handover the UE is controlled by a least two cells under one Node B [8].

2.4.3 Congestion Control

It is of paramount importance to keep the air interface load in WCDMA systems under predefined thresholds. This is because excessive loading prevents the network from guaranteeing the needed requirements. This could lead to the planned area of coverage not being provided, lower capacity than is required, degraded quality of service and an unstable network condition [8]. Congestion control functions are divided into three:

(i) **Admission Control**: This handles all new incoming traffic and checks whether a new packet or circuit switched RAB (Radio Access Bearer) can be admitted to the system [8]. Admission control consists basically of two parts. For RT (Real Time) traffic, i.e., the delay-sensitive conversational and streaming classes, it must be decided whether a UE is allowed to enter the network. If the new radio bearer would cause excessive interference to the system, access is denied. For NRT traffic (less delay-sensitive interactive and background classes) the optimum scheduling of the packets (time and bit rate) must be determined after the RAB has been admitted. This is done in close cooperation with the packet scheduler [8].

(ii) **Load Control**: This manages the situation when the system load has exceeded the threshold(s) and some countermeasures have to be taken to get the system back to a feasible load [8].

(iii) **Packet Scheduling**: This handles all the NRT (Non-Real Time) traffic – i.e., packet data users. In general, it decides when a packet transmission is initiated and the bit rate to be used [8].

2.5 HSDPA (High Speed Downlink Packet Access)

One of the significant improvements in the development of 3G systems was the support of high speed packet data throughput to improve the end-user experience of multimedia and data centric services on mobile [2]. Release 99 WCDMA was already able to provide peak data rate of 384 kbps with a latency of 100-200 ms which is quite close to a low end digital Internet connection [12]. Release 99 was primitive because it dedicated channel resources to each data user, and power control mechanisms were the same between real-time applications such as voice and non-real-time data. Dedicating channel resources for each data user is inefficient.

With the introduction of the High Speed Downlink Shared Channel (HS-DSCH), fast HSDPA scheduler, adaptive modulation and coding and fast retransmission (HARQ). HSDPA technology, which is a result of continued WCDMA evolution, is able to deliver even higher data throughput up to 14.4 Mbps, lower latency and improved downlink capacity for packet data services. HSDPA was standardized as part of 3GPP Release 5 specification. This section provides necessary background information about HSDPA technology along with the physical layer structure as well as few key performance indicators (KPI) which are important in understanding this thesis work.

2.5.1 Main HSDPA Features

The key idea of the HSDPA concept is to increase packet data throughput with methods known already from Global System for Mobile Communications (GSM)/Enhanced Data rates for Global Evolution (EDGE) standards, including link adaptation and fast physical layer (L1) retransmission combining [4, 12]. The key modifications introduced were [14]:

(i) A shared data channel, multiplexed in time (TDM);

(ii) New modulation (16QAM) and coding schemes, with the possibility to transmit with up to 15 parallel channelization codes;

(iii) Modification of the MAC protocol architecture to enable faster response to changes in user demands and radio conditions;

(iv) Adaptive Modulation and Coding (AMC) and new error correction mechanisms in the MAC layer (HARQ) [14].

2.5.1.1 New Modulation and Coding Schemes

Release 99 only supported one type of modulation (QPSK), while HSDPA supports three different modulation schemes, namely, QPSK, 16QAM and 64QAM. Typical devices today support QPSK and 16QAM, and at least five parallel codes [14]. With five codes allocated to HSDPA, QPSK can provide 1.8Mbps peak rate and 16QAM can reach 3.6Mbps [14]. 16QAM and 64QAM schemes are a very efficient use of the channel bandwidth, but it demands a really good ‘clean’ radio channel in order to perform 64QAM. This increased demand to the quality of the radio channel, is owing to the fact that the channel needs to be more ‘accurate’ in order for the receiver to decode the many statuses in the constellation of the phases/amplitude of the signal. The radio channel will need to have a high signal to noise ratio and high phase accuracy – a good EVM (Error Vector Magnitude). At this point in time 64QAM is the highest order modulation scheme used in HSPA+ and LTE [42].

2.5.1.2 High Speed Downlink Shared Channel (HS-DSCH)

To increase the channel utilization efficiency, HSDPA introduces a new physical channel called high speed downlink shared channel (HS-DSCH) [14]. This channel is shared

among all data users and uses a 2ms frame or TTI (Transmission Time Interval), as compared to the 10ms radio frame used by Release 99 channels. HS-DSCH enables the UTRAN to rapidly allocate a significant portion of downlink resources for bursty packet data transmission to a specific user for a short period of time [2]. A big shared data pipe provides the benefit of statistical multiplexing among all data users and thus improves the overall system efficiency. The Transmission Time Interval (TTI) or interleaving period has been defined to be 2 ms (three slots) to achieve a short round-trip delay for the operation between the terminal and Node B for retransmissions. Adding a higher-order modulation scheme, 16 QAM, and lower encoding redundancy has increased the instantaneous peak data rate. In the code domain perspective, the SF (Spreading Factor) is fixed; it is always 16, and multi-code transmission as well as code multiplexing of different users can take place [4]. The maximum number of codes that can be allocated is 15, but depending on the terminal (UE) capability, individual terminals may receive a maximum of 5, 10 or 15 codes [4]. The total number of channelization codes with SF 16 is respectively 16 (under the same scrambling code), but as there is need to have code space available for common channels, HS-SCCHs (High Speed Shared Control Channel) and for the associated DCH, the maximum usable number of codes is thus set to be 15. An illustration is shown in Figure 2.11 below, where two users are using the same HS-DSCH [4]. Both users check the information from the HS-SCCHs to determine which HS-DSCH codes to dispread, as well as other parameters necessary for correct detection.

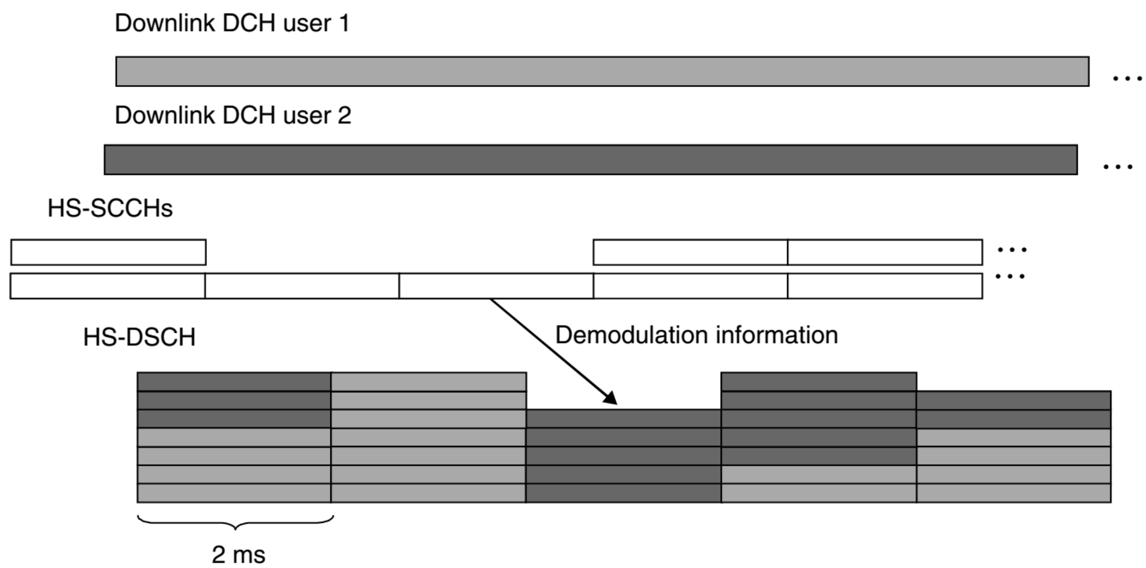

Figure 2.11: Code multiplexing example with two active users [4]

The time and code sharing transmission is illustrated in Figure 2.12.

In addition to code sharing, a part of total transmission power also needs to be allocated for HS-DSCH transmission. In WCDMA, this is typically achieved by power control [2]. However, the concept of power control is not applied in HSDPA. Therefore to efficiently utilize the Node B power, either a fixed part of total available power is allocated for HS-DSCH transmission or after allocating power to common control and dedicated channels, remaining power is used for HS-DSCH transmission [2]. On the other hand, modulation, coding and number of codes are dynamically and rapidly changed to adapt to the variations in radio conditions [12, 13].

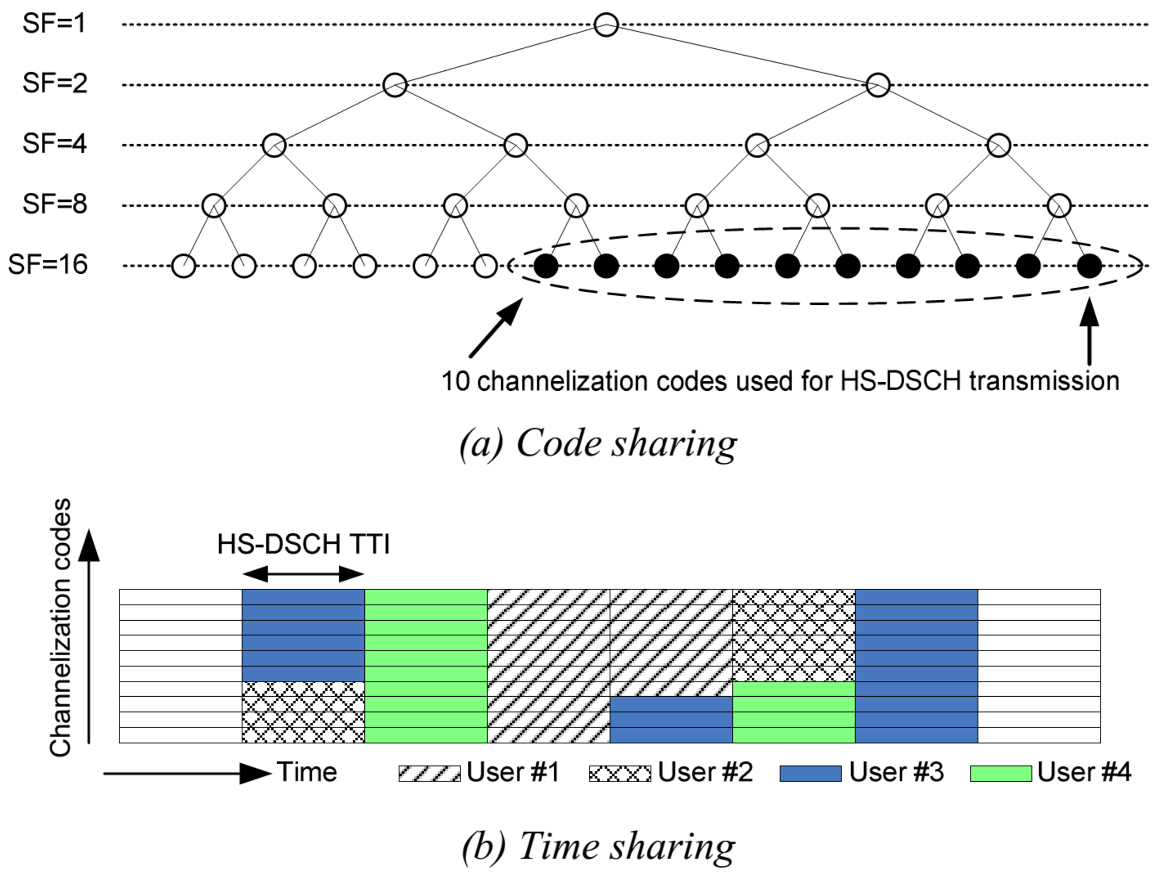

Figure 2.12: (a) Code and (b) Time domain structure of HS-DSCH [13]

2.5.1.3 Adaptive Modulation and Coding (AMC)

Adaptive modulation and coding (AMC) provides an alternative to the conventional CDMA fast power control for link adaptation [14]. With AMC, the coding rate and modulation scheme for each user is dynamically adjusted based on the average channel condition of the radio link. In general, the channel power is constant over an interval defined by the system [14]. The link adaptation is achieved by assigning a different modulation scheme or coding rate to each user based on the channel condition reported by the UE. Thus this process involves dynamically adjusting the coding rate, modulation scheme and number of codes used for HS-DSCH according to the varying channel

conditions of HSDPA users, leading to a higher data rate for users with favorable radio conditions [2]. This link adaptation, also known as adaptive modulation and coding, is applied by Node B in every 2 ms TTI based on physical layer CQI (Channel Quality Index) reported by the UE [2].

2.5.1.4 HARQ (Hybrid Automatic Repeat ReQuest) with Soft Combining

HARQ improves throughput by combining failed transmission attempts with the re-transmissions, effectively creating a more powerful error correction scheme [14]. Hybrid ARQ can be combined with Adaptive Modulation and Coding (AMC), making the initial selection of modulation and code rate more tolerant to errors. The HARQ retransmission mechanism is based on Stop and Wait (SAW) protocol [14]. Also in order to support fast HSDPA operation, HARQ is implemented in MAC-hs and physical layer which enables Node B to quickly respond to multiple retransmission requests of UE without involving higher layers, thus resulting in lower retransmission roundtrip delay - as low as 12 ms [15].

In a typical SAW, Node B keeps the current transmitted block in its buffer and holds off further transmission until it receives a successful acknowledgement (ACK) from the UE. However, to utilize the radio link during this waiting time, HSDPA configures up to N (max. 8) parallel SAW transmissions for the same UE in separate TTIs [2].

The probability of successfully decoding the transport block is increased by combining the retransmission(s) with the original transmission at UE. This is known as soft combining. HSDPA defines two different HARQ methods: Chase Combining (CC) and Incremental Redundancy (IR) retransmission strategies which are used for the purpose of soft combining [2]. With Chase Combining, the re-transmitted data is identical to the

original transmission, whereas with Incremental Redundancy, each retransmission provides new code bits from the original code to build a lower rate code [14]. There are pros and cons on both algorithms. Chase Combining is sufficient to make AMC robust and consumes less buffer memory while IR offers the potential for better performance with high initial code rates at the cost of additional memory and decoding complexity in the UE.

Figure 2.13 below shows a typical response time for the HARQ process, which illustrates the dependency between the number of simultaneous processes (buffers) and the delay of the network [14]. It shows that the more the users on the Node B, the slower the response time. T_{Prop} is the propagation time over the air, T_{UEP} is the UE processing time, T_{ACK} is the period when the acknowledgment is sent, T_{NBP} is the Node B processing time and T_{CTRL} is the time for sending the UE the control information which is related to the data sent on the shared channel [14].

The total processing time for each UE and the network is the time when the system is dealing with other sub-channels and the UE is not receiving information or sending acknowledgment to the network.

$$T_{Processing} = T_{UEP} + T_{NBP} + T_{CTRL} \tag{2.5}$$

It can be observed that both the TTI length and number of sub-channels have an impact on the latency [14]. Shorter TTI provides short latency but leaves less processing time for UE and the network. More sub-channels means longer latency but provides more processing time. So there is a balance between the performance and the system capability.

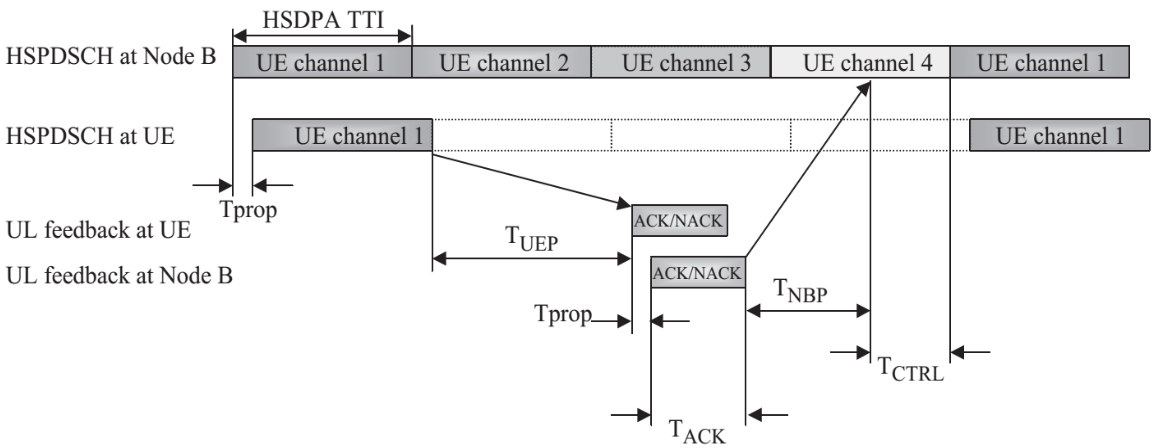

Figure 2.13: Four-Channel SAW HARQ © 2008 3GPP [14]

CHAPTER THREE

RADIO PROPAGATION IN UMTS

Radio propagation in cellular communications is the behavior of radio waves when they are transmitted, or propagated from one point on the earth to another, or into various parts of the atmosphere [43]. As a form of electromagnetic radiation, like light waves, radio waves are affected by the phenomena of reflection, refraction, diffraction, absorption, polarization and scattering [44]. Radio propagation is affected by the daily changes of water vapor in the troposphere and ionization in the upper atmosphere, due to the Sun. This chapter describes some basic radio propagation phenomenon, channel characteristics and different propagation environments that affect the behavior of the UMTS system.

The simplest case of signal propagation is free space propagation where the radio wave is not obstructed by any obstacles and signal attenuation depends only on the frequency and distance travelled. Mathematically, Friis's transmission equation (3.1) defines free space propagation as:

$$L_{FS} = \frac{P_{RX}}{P_{TX}} = G_{TX} G_{RX} \left(\frac{\lambda}{4\pi d}\right)^2 \quad , \qquad (3.1)$$

where G_{TX} is the transmitter antenna gain, G_{RX} is the receiver antenna gain, λ is the wavelength of the signal and d is the distance between transmitter and receiver [21].

3.1 Propagation Environments

In mobile communication systems, the propagation environment is defined as a space, where radio waves travel towards the target receiver antenna. Different types of

propagation environments are defined to correspond to certain types of terrain and network infrastructure [16]. The propagation environment can simply be divided into outdoor and indoor classes [2]. On cellular network level, these are further classified as illustrated in Figure 3.1.

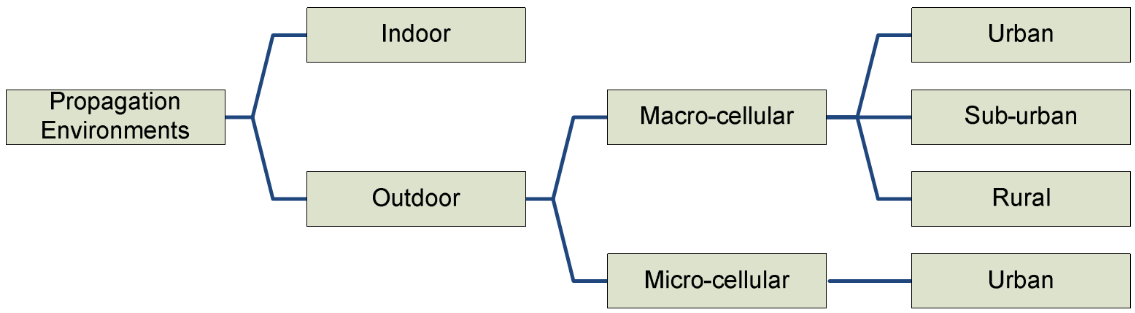

Figure 3.1: Classification of propagation environments [2]

3.1.1 Outdoor (Macro- and Micro-cell)

Outdoor environment is typically classified into macro-cellular and micro-cellular environments. Generally, macro-cellular corresponds to the environment where the base station (Node B) antenna height is above the average rooftop level [2]. Accordingly microcellular corresponds to the environment where the antenna height is below the average rooftop level [2]. Macro-cellular environment can be divided into urban, suburban and rural area types based on varying characteristics of obstacles and terrain structure (buildings, trees, mountains etc.) surrounding the Node B and UE. In urban areas, building dimensions and density obstructs the propagation path significantly therefore microcellular environment is typically built in such areas to avoid shadowing and improve coverage.

3.1.2 Indoor (Pico-cell)

Pico-cellular environment corresponds to the indoor scenario when the Node B antenna is located inside a building. Since most of the users are located indoors for most of the time therefore, pico-cells are usually created to serve such high traffic areas e.g. inside office buildings, shopping malls, airports etc [2]. Alternatively, a radio signal from macro-cellular and micro-cellular systems penetrating into the building also contributes towards indoor propagation; acting either as interference or as means of providing extended coverage without capacity [17].

3.2 Multipath Radio Channels and Rake Reception

As mentioned earlier, radio propagation in the land mobile channel is characterized by multiple reflections, diffractions and attenuation of the signal energy [45]. These are caused by natural obstacles such as buildings, hills, and so on, resulting in so-called multipath propagation [45]. There are two effects resulting from multipath propagation that we are concerned with in this section:

1. The signal energy (pertaining, for example, to a single chip of a CDMA waveform) may arrive at the receiver across clearly distinguishable time instants [45]. The arriving energy is 'smeared' into a certain multipath delay profile: see Figure 3.2, for example. The delay profile extends typically from 1 to 2μs in urban and suburban areas, although in some cases delays as long as 20 μs or more with significant signal energy have been observed in hilly areas [45]. The chip duration at 3.84 Mcps is 0.26 μs. If the time difference of the multipath components is at least 0.26 μs, the WCDMA receiver (rake receiver) can separate those multipath components and combine them coherently to obtain multipath diversity. The 0.26 μs delay can be

obtained if the difference in path lengths is at least 78 m ($= \text{speed of light} \div \text{chip rate} = 3.0 \times 10^8\ \text{ms}^{-1} \div 3.84\ \text{Mcps}$) [45].

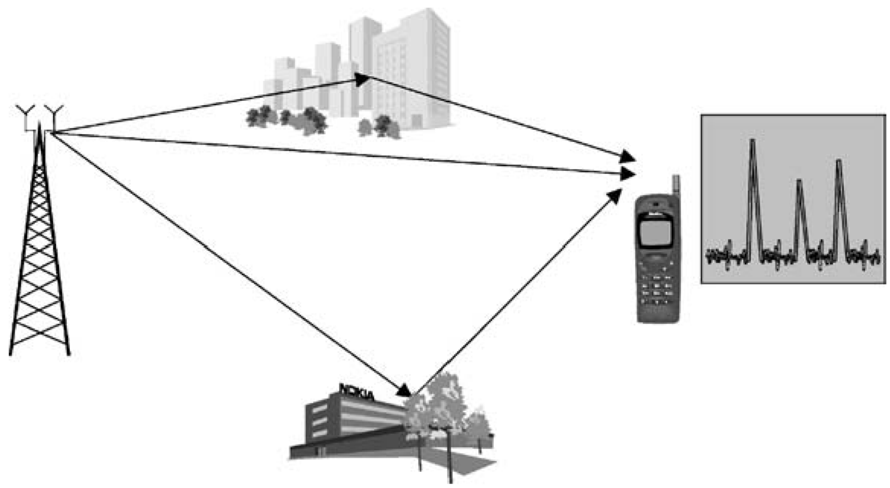

Figure 3.2: Multipath propagation leads to a multipath delay profile [45]

2. Also, for a certain time delay position there are usually many paths nearly equal in length along which the radio signal travels [45]. For example, paths with a length difference of half a wavelength (at 2 GHz this is approximately 7 cm) arrive at virtually the same instant when compared to the duration of a single chip, which is 78m at 3.84Mcps [45]. As a result, signal cancellation, called fast fading, takes place as the receiver moves across even short distances. Signal cancellation is best understood as a summation of several weighted phasors that describe the phase shift (usually modulo radio wavelength) and attenuation along a certain path at a certain time instant [45].

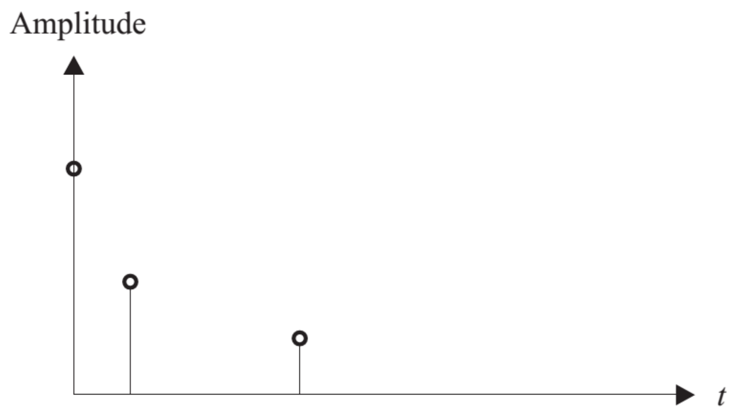

Figure 3.3: An example impulse response in multipath environment [16]

Some parameters are used to define the properties of a propagation environment. Angular spread describes the deviation of the received signal incident angle. It can be calculated using equation:

$$S_{\Phi} = \sqrt{\int_{\bar{\Phi}-180}^{\bar{\Phi}+180} (\Phi - \bar{\Phi})^2 \frac{P(\Phi)}{P_{\Phi\_TOT}} d\Phi} \ , \tag{3.2}$$

where $\bar{\Phi}$ is the mean incident angle, $P(\Phi)$ is the angular power distribution, and P_{Φ_TOT} is the total power [18]. Delay spread describes the signal power as a function of delay. It can be calculated using equation:

$$S_{\tau} = \sqrt{\frac{\int_0^{\infty} (\tau - \bar{\tau})^2 P_{\tau}(\tau) d\tau}{P_{\tau\_TOT}}} \ , \tag{3.3}$$

where $P_{\tau}(\tau)$ is the delay profile, $\bar{\tau}$ is the mean delay and P_{τ_TOT} is the total power [18].

When observed in frequency domain, different frequencies attenuate differently. This is known as *frequency selective fading*. The bandwidth over which two frequencies of a

signal experience the same fading is called *coherence bandwidth* (Δf_c). In order to have uncorrelated fading between two multipath components, the frequency separation needs to be equal or higher than the coherence bandwidth. It is represented as a function of delay spread in equation (3.4):

$$\Delta f_c = \frac{1}{2\pi S_\tau} \ . \tag{3.4}$$

Moreover, in multipath propagation, the motion of transmitter or receiver typically causes frequency dispersion of the received signal. This is known as *Doppler spread* (f_d) and is expressed by equation (3.5):

$$f_d = f_c \frac{v}{c} \cos\theta \ , \tag{3.5}$$

where f_c is the carrier frequency, v is the velocity of motion, c is the speed of light and θ is the angle between direction of motion and direction of incident signal.

It is important to mention here that a cellular system is considered wideband when the signal bandwidth is much larger than the coherence bandwidth of the channel. On the contrary the system is narrowband if the signal bandwidth is less than the coherence bandwidth.

Radio propagation in indoor environment differs from the outdoor mainly due to close proximity of reflecting structures (walls, floors etc.), mobility of UE, usage of different construction materials, density of people and furniture; all resulting in random behavior and strong fluctuations in average received signal level (higher slow fading). Large reflective surfaces surrounding the Node B antenna causes wide angular spread thus

compromising antenna diversity reception techniques. Delay spread is very critical because WCDMA uses a special receiver (RAKE) whose performance depends on the multipath propagation and channel characteristics. A RAKE receiver is a receiver, which gathers and combines information from signal components arriving at least one chip duration apart using *Maximal Ratio Combining* (MRC). It could be compared with three or more parallel receivers, each receiving a different offset signal from the same RF channel. Therefore, the larger the number of multipath components that can be separated the better is the performance of RAKE receiver [18]. Figure 3.4 shows the block diagram of the RAKE receiver [19].

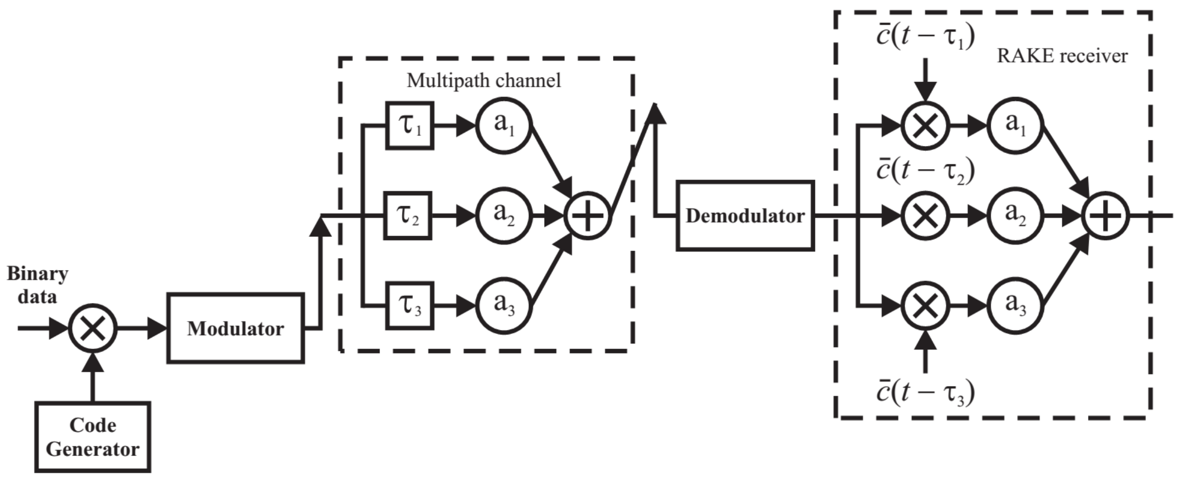

Figure 3.4: Principle of a RAKE receiver [19]

In the radio transmission path of UMTS, the signal enters the multipath channel after spreading and modulation. In RAKE receiver architecture, multipath channel is modeled by using tapped delay lines with delays τ and attenuations a. Each signal component travels through a propagation path with its own delay and attenuation value. Received sum of multipath components is then demodulated and taken to a rake receiver. The

receiver consists of fixed number of fingers. In each finger, the signal is de-spread in a correlator with corrected attenuation ($\bar{c}$) and delay factors (τ) estimated from the measured tapped line delay profile. Finally, the de-spread signal components are combined by using a certain algorithm, e.g. MRC (maximum ratio combining). Due to changes in multipath environment, RAKE fingers must be continuously reallocated to synchronize to new delay and attenuation profile for successful receiver operation [19]. As mentioned above, 0.26 μs is the smallest delay between multipath components to enable separation [23].

In an *indoor channel*, the propagation distance between transmitter and receiver is usually short which results in small delay spreads (<< 0.26 μs). Consequently, all or most of the multipath components lie within the same chip interval, thus the RAKE receiver is unable to separate them and use them for efficient combining. Power delay profile of an indoor channel is presented in Figure 3.5.

Table 3.1: Delay spread, coherence bandwidth and propagation channel types [5]

	Delay Spread	Coherence bandwidth (MHz)	WCDMA
Bandwidth			3.84 MHz
Macro-cell (Urban)	0.5	0.32	WB
Macro-cell (Rural)	0.1	1.6	NB/WB
Macro-cell (Hilly)	3	0.053	WB
Micro-cell	< 0.1	> 1.6	NB/WB
Indoor	< 0.01	> 16	NB

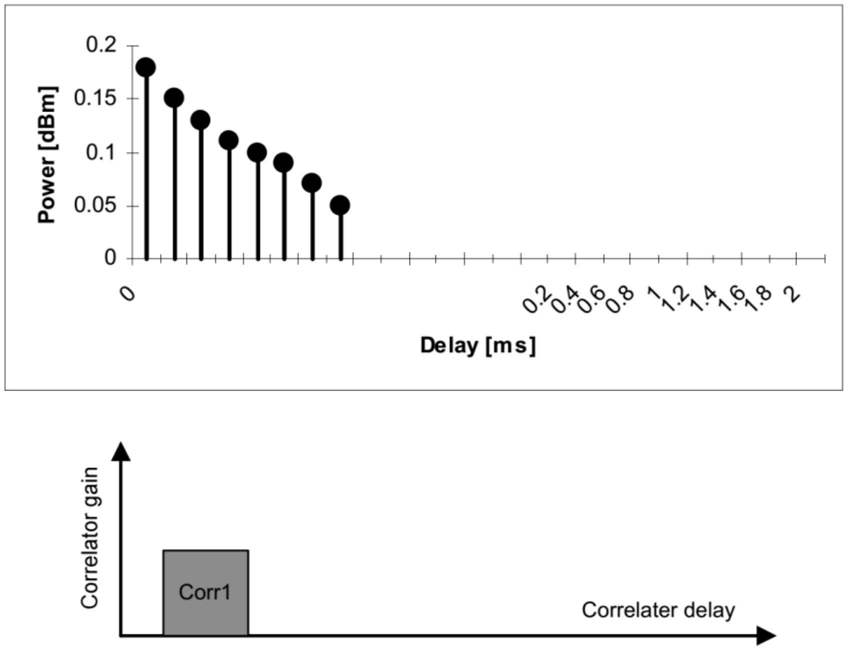

Figure 3.5: An example of indoor channel and RAKE receiver finger delay [2]

Moreover, coherence bandwidth (frequency domain property) of a channel is inversely dependent on delay spread; therefore a smaller delay spread would result in higher coherence bandwidth. As mentioned previously, the system is considered narrowband if the channel coherence bandwidth is greater than the system bandwidth which establishes the fact that WCDMA behaves as a narrowband system in indoor environment. This behavior is also presented in Table 3.1 which lists the coherence bandwidth of indoor channel as high as 16 MHz as compared to 3.84 MHz WCDMA system bandwidth. A narrowband system results in frequency non-selective or flat fading behavior with no means to exploit multipath diversity [18, 22].

3.3 Signal Fading

In wireless communications, fading is the deviation of the attenuation affecting a signal over certain propagation channels. Fading may either be due to multipath propagation,

referred to as *multipath induced fading,* or due to shadowing from obstacles affecting the wave propagation, sometimes referred to as *shadow fading*.

The terms *slow* and *fast fading* refer to the rate at which the magnitude and phase change imposed by the channel on the signal changes. The *coherence time* may be defined as the maximum time for which the magnitude change of the channel is correlated to its previous value. *Slow fading* arises when the coherence time of the channel is large relative to the delay constraint of the channel. In this regime, the amplitude and phase change imposed by the channel can be considered roughly constant over the period of use. Slow fading can be caused by events such as shadowing, where a large obstruction such as a hill or large building obscures the main signal path between the transmitter and the receiver. Slow fading is the variation of the local mean value of fast fading signal over a wider area and has a log-normal distribution, therefore, it also known as *log-normal fading*. *Fast fading* occurs when the coherence time of the channel is small relative to the delay constraint of the channel. In this regime, the amplitude and phase change imposed by the channel varies considerably over the period of use.

In a NLOS (Non-Line of sight) situation, when there is no direct signal path component, the amplitude variations are quite large and the phases of the components have random uniform distribution. In such a fading channel, amplitude is modeled by Rayleigh distribution and, therefore, is also referred to as *Rayleigh fading*. However, in a LOS situation, the amplitude has Ricean distribution due to the presence of a direct strong component and such a fading is known as *Ricean fading* [18]. Typically, in UMTS, a slow fading margin of 8-9 dB is taken into account for path loss calculations [5]. Figure 3.6 makes the distinction between fast and slow fading [20].

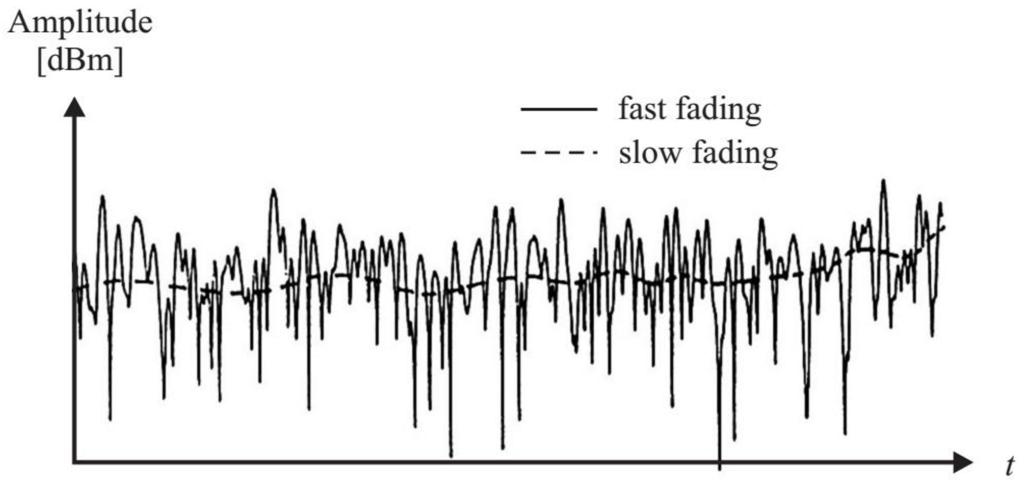

Figure 3.6: Fast Fading and Slow Fading [20].

3.4 UMTS Signaling

Signaling refers to the mechanism for exchanging information. In telecommunication networks, signaling plays an integral part in providing services and operating the network. In the case of UMTS, signaling is used to exchange information among various components in the UMTS system. Signaling is not related to service processing itself but provides the information necessary for service processing.

3.4.1 UMTS Transport Channels

The UMTS radio interface has logical channels that are mapped to transport channels. The data generated at higher layers is carried over the air with transport channels, which are mapped in the physical layer to different physical channels. The physical layer is required to support variable bit rate transport channels to offer bandwidth-on-demand services, and to be able to multiplex several services to one connection. There are two types of transport channels: common and dedicated channels.

3.4.1.1 Dedicated Transport Channel

The dedicated transport channel or DCH (dedicated channel) carries all the information intended for the given user coming from layers above the physical layer, including data for the actual service as well as higher layer control information. The content of the information carried on the DCH is not visible to the physical layer, thus higher layer control information and user data are treated in the same way. Naturally the physical layer parameters set by UTRAN may vary between control and data. The dedicated transport channel carries both the service data, such as speech frames, and higher layer control information, such as handover commands or measurement reports from the terminal. In WCDMA a separate transport channel is not needed because of the support of variable bit rate and service multiplexing [4]. The dedicated transport channel is characterized by features such as fast power control, fast data rate change on a frame-by-frame basis, and supports soft handover.

3.4.1.2 Common Transport Channels

Common channels do not have soft handover but some of them can have fast power control. There are six common transport channels:

1. **Broadcast Channel (BCH):** BCH is a transport channel that is used to transmit identification information specific to the UTRA network or for a given cell, such as access codes, access slots, etc. the BCH is sent with a low fixed data rate. The BCH must be decoded by all the mobiles in the cell, therefore relative high power is allocated to broadcast the BCH. The BCH is mapped into the PCCPCH (primary common control physical channel).

2. **Forward Access Channel (FACH):** FACH is a downlink transport channel that carries control information to terminals known to be located in the given cell. The FACH can also carry packet data. The FACH is mapped into the SCCPCH (secondary control physical channel).
3. **Paging Channel (PCH):** PCH is a downlink transport channel that carries paging signals within the location area, which alerts mobiles about incoming calls, SMS and data connections. The PCH is mapped into the SCCPCH.
4. **Random Access Channel (RACH):** RACH is an uplink transport channel intended to be used to carry control information from the terminal, such as requests to set up a connection. It can also be used to send small amounts of packet data from the terminal to the network. The RACH is mapped into PRACH (physical random access channel).
5. **Uplink Common Packet Channel (CPCH):** CPCH is an extension to the RACH channel that is intended to carry packet-based user data in the uplink direction. It is used for fast power control, and also provides additional capacity beyond the capacity of the RACH. The CPCH is mapped into the PCPCH (physical common packet channel) [1].
6. **Downlink Shared Channel (DSCH):** DSCH is a transport channel intended to carry dedicated user data and/or control information; it can be shared by several users. In many respects it is similar to the forward access channel, although the shared channel supports the use of fast power control as well as variable bit rate on a frame-by-frame basis. The DSCH is mapped to the PDSCH (physical

downlink shared channel). Table 3.2 shows the set of physical channels available to each transport channel.

Table 3.2 Transport channels for UMTS [22]

Transport channel	Type	Uplink	Downlink
Broadcast Channel (BCH)	Common		●
Paging Channel (PCH)	Common		●
Random Access Channel (RACH)	Common	●	
Forward Access Channel (FACH)	Common		●
High Speed Downlink Shared Channel (HS-DSCH)	Common		●
Dedicated Channel (DCH)	Dedicated	●	●
Enhanced Dedicated Channel (E-DCH)	Dedicated	●	

Table 3.3 Transport channels mapped onto physical channels [22]

Transport channel	Physical channel
RACH	Physical Random Access Channel (PRACH)
FACH	Secondary Common Control Physical Channel (S-CCPCH)
BCH	Primary Common Control Physical Channel (P-CCPCH)
PCH	Secondary Common Control Physical Channel (S-CCPCH)
HS-DSCH	High Speed Physical Downlink Shared Channel (HS-PDSCH)
DCH	Dedicated Physical Data Channel (DPDCH)
E-DCH	Enhanced Dedicated Physical Data Channel (E-DPDCH)

3.4.2 UMTS Logical Channels

Logical channels are used to transfer data between the RLC and MAC layers. The MAC layer provides the mapping between logical channels and transport channels. They define the type of information being transferred. They are categorized as either *control* or *traffic*.

Control channels include the BCCH, PCCH, CCCH, DCCH, MCCH and MSCH. These logical channels are responsible for transferring RRC signaling messages. Traffic channels include the CTCH, DTCH and MTCH. These logical channels are responsible for transferring application data. The DTCH is the only logical channel able to transfer application data in both the uplink and downlink directions.

3.4.2.1 Control Channels

1. **Broadcast Control Channel (BCCH):** This channel broadcasts information to the mobiles for system control, system information about the serving cell and the monitored set (neighbor list). The BCCH is carried by the BCH or FACH.
2. **Paging Control Channel (PCCH):** This is a downlink channel that transfers paging information. The PCCH is carried by the PCH.
3. **Dedicated Control Channel (DCCH):** A point-to-point bidirectional channel that transmits dedicated control information between a UE and the RNC. This channel is established during the RRC connection establishment procedure.
4. **Common Control Channel (CCCH):** A bidirectional channel for transmitting control information between the network and UEs. This logical channel is always mapped onto RACH/FACH transport channels. A long UTRAN UE identity is required (U-RNTI, which includes SRNC address), so that the uplink messages can be routed to the correct serving RNC even if the RNC receiving the message is not the serving RNC of this UE.
5. **MBMS Control Channel (MCCH) and MBMS Scheduling Channel (MSCH):** MCCH and MSCH are point-to-multi-point logical channels used by UE that support the Multimedia Broadcast/Multicast Service (MBMS). The majority of

MBMS control plane information is sent on the MCCH. The MSCH is used to send scheduling information to indicate when specific MBMS services are transmitted. System information on the BCCH informs UE of the information necessary to read the MCCH and MSCH. Both logical channels can be read from either RRC Idle mode or RRC Connected mode. MBMS procedures can also make use of other logical channels and more general RRC messages, e.g. the MBMS counting procedure which allows the network to estimate the number of MBMS UE within a cell can use the Cell Update message and the CCCH or DCCH logical channels [22].

3.4.2.2 Traffic Channels

1. **Dedicated Traffic Channel (DTCH):** This is a point-to-point channel, dedicated to one UE, for the transfer of user information. A DTCH can exist in both uplink and downlink [4].
2. **Common Traffic Channel (CTCH):** This is a downlink-only channel, used to transmit dedicated user information to a single mobile or a whole group of mobiles [4].

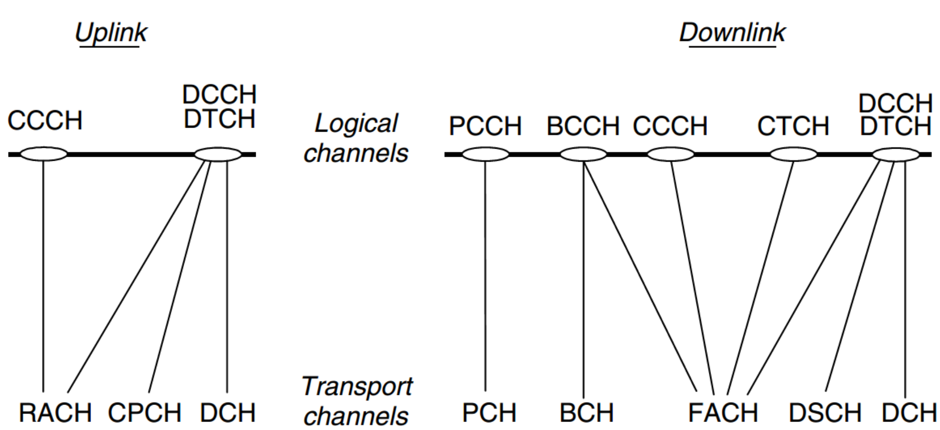

Figure 3.7: Mapping between logical and transport channels, UL and DL directions [4]

3.4.2.3 Mapping Between Logical Channels and Transport Channels

The mapping between logical channels and transport channels is shown in Figure 3.7. The following connections between logical channels and transport channels exist [4]:

- PCCH is connected to PCH
- BCCH is connected to BCH and may also be connected to FACH
- DCCH and DTCH can be connected to either RACH and FACH, to CPCH and FACH, to RACH and DSCH, to DCH and DSCH, or to a DCH and DCH.
- CCCH is connected to RACH and FACH
- CTCH is connected to FACH.

3.4.3 UMTS Physical Channels

Physical channels are used to transfer data across the air-interface. They are categorized as either *common* or *dedicated*. Common channels can be used by more than a single UE, whereas dedicated channels can be used by only a single UE. Common channels include the SCH, CPICH, P-CCPCH, S-CCPCH, PICH, AICH, PRACH, HS-PDSCH, HS-SCCH, E-AGCH and MICH. Dedicated channels include the DPDCH, DPCCH, F-DPCH, HS-DPCCH, E-DPDCH, E-DPCCH, E-RGCH and E-HICH. The transport channels are mapped into physical channels. Table 3.3 presents the set of physical channels.

1. **Common Pilot Channel (CPICH):** This was discussed briefly in chapter two. It is an unmodulated code channel, which is scrambled with the cell-specific primary scrambling code. The function of the CPICH is to aid the channel estimation at the terminal for the dedicated channel and to provide the channel estimation reference

for the common channels when they are not associated with the dedicated channels or not involved in the adaptive antenna techniques.

UTRA has two types of common pilot channel, *primary* and *secondary*. The difference is that the Primary CPICH is always under the primary scrambling code with a fixed channelization code allocation and there is only one such channel for a cell or sector. The Secondary CPICH may have any channelization code of length 256 and may be under a secondary scrambling code as well. The typical area of Secondary CPICH usage would be operations with narrow antenna beams intended for service provision at specific ‘hot spots’ or places with high traffic density.

2. **Synchronization Channel (SCH):** This is needed for cell search and consists of two channels, the *primary* and *secondary* synchronization channels. The Primary SCH uses a 256-chip spreading sequence identical in every cell. The Secondary SCH uses sequences with different code word combination possibilities representing different code groups. Once the terminal has identified the secondary synchronization channel, it has obtained frame and slot synchronization as well as information on the group the cell belongs to. There are 64 different code groups in use, pointed out by the 256 chip sequences sent on the secondary SCHs.

3. **Common Control Physical Channel (CCPCH):** There are two types of CCPCHs, the *primary* and the *secondary*. The PCCPCH continuously broadcasts the system identification (the BCH) and access control information. The SCCPCH transmits the FACH (forward access channel), and provides control information, as well as the PACH (paging channel).

4. **Random Access Channel (RACH):** This is typically used for signaling purposes, to register the terminal, after power-on to the network or to perform location update after moving from one location area to another or to initiate a call. The RACH that can be used for initial access has a relatively low payload size, since it needs to be usable by all terminals. The ability to support 16 kbps data rate on RACH is a mandatory requirement for all terminals regardless of what kind of services they provide.

5. **Acquisition Indicator Channel (AICH):** This is used to indicate the reception of the random access channel signature sequence from the base station. The AICH uses an identical signature sequence as the RACH on one of the downlink channelization codes of the base station to which the RACH belongs. Once the base station has detected the preamble with the random access attempt, then the same signature sequence that has been used on the preamble will be echoed back on AICH. As the structure of AICH is the same as with the RACH preamble, it also uses a spreading factor of 256 and 16 symbols as the signature sequence [4].

6. **Paging Indicator Channel (PICH):** PICH provides terminals with efficient sleep mode operation. The paging indicators use a channelization code of length 256. The paging indicators occur once per slot on the corresponding physical channel, the Paging Indicator Channel (PICH). Each PICH frame carries 288 bits to be used by the paging indicator bit, and 12 bits are left idle. PICH indicates the paging group the mobile belongs to. This enables the mobiles to be able to monitor the PCH (paging channel) when its group is paged, and in the meantime the mobile can ‘sleep’ and preserve its battery.

7. **MBMS Indicator Channel (MICH):** This is used to broadcast MBMS Notification Indicators (NI) across the entire coverage area of a cell. A positive NI is used to trigger UE which have activated a specific MBMS service to decode control information on the MCCH. The MCCH logical channel is always transferred using the FACH transport channel and the S-CCPCH physical channel. This means that the MICH is always associated with a S-CCPCH which includes at least one FACH transport channel. This is in contrast to the PICH which is always associated with a S-CCPCH which includes one PCH transport channel. A single cell can have a maximum of one FACH transport channel carrying MCCH information and so there is a maximum of one MICH per cell.

8. **Dedicated Physical Channel (DPCH):** This can be used to transfer user plane data and control plane signaling in both the uplink and downlink directions. The DTCH and DCCH logical channels are mapped onto the DCH transport channel when using the DPCH physical channel. The uplink DPCH includes the Dedicated Physical Control Channel (DPCCH) and the Dedicated Physical Data Channel (DPDCH). It may also include the High Speed Dedicated Physical Control Channel (HS-DPCCH), the Enhanced Dedicated Physical Control Channel (E-DPCCH) and the Enhanced Dedicated Physical Data Channel (E-DPDCH). The HS-DPCCH is used for HSDPA connections whereas the E-DPCCH and E-DPDCH are used for HSUPA connections. The downlink DPCH uses Fractional Dedicated Physical Channel (F-DPCH) to replace DPCCH and DPDCH when both the user and control plane signaling are transferred using one or more HS-PDSCH. The F-DPCH reduces the

requirement for downlink resources in terms of both transmit power and channelization codes [22].

Table 3.4 Physical Channels of the UMTS Network [22]

Physical channel	**Type**	**Uplink**	**Downlink**
Synchronous Channel (SCH)	Common		●
Common Pilot Channel (CPICH)	Common		●
Primary Common Control Physical Channel (P-CCPCH)	Common		●
Secondary Common Control Physical Channel (S-CCPCH)	Common		●
Paging Indication Channel (PICH)	Common		●
Access Indication Channel (AICH)	Common		●
High Speed Physical Downlink Shared Channel (HS-PDSCH)	Common		●
E-DCH Absolute Grant Channel (E-AGCH)	Common		●
MBMS Indicator Channel (MICH)	Common		●
Physical Random Access Channel (PRACH)	Common	●	
High Speed Shared Control Channel (HS-SCCH)	Common	●	
Dedicated Physical Data Channel (DPDCH)	Dedicated	●	●
Dedicated Physical Control Channel (DPCCH)	Dedicated	●	●
Fractional Dedicated Physical Channel (F-DPCH)	Dedicated		●
E-DCH Relative Grant Channel (E-RGCH)	Dedicated		●
E-DCH Hybrid ARQ Indicator Channel (E-HICH)	Dedicated		●
High Speed Dedicated Physical Control Channel (HS-DPCCH)	Dedicated	●	
E-DCH Dedicated Physical Data Channel (E-DPDCH)	Dedicated	●	
E-DCH Dedicated Physical Control Channel (E-DPCCH)	Dedicated	●	

3.5 Propagation Models

The performance of a cellular network depends on the careful prediction of parameters that define the behavior of radio wave propagation in a certain environment. These

predictions later become an input to the network planning process. *Path loss* is one such critical parameter that is necessary to predict for all possible paths between a transmitter and a receiver in different environments. Propagation models are usually used to make such predictions. There are several models available but generally they are classified into Empirical, Physical or Semi-empirical and Deterministic models.

Empirical models are based on equations typically derived from extensive field measurements. *Physical* models rely on the analytical approach towards certain propagation mechanism e.g. diffraction while *semi-empirical* models provide empirical corrections to the analytical approach. Deterministic models use ray optical methods and numerical solutions of electromagnetic wave equations to make predictions. Since all of these models consider different phenomena and approach therefore their accuracy and complexity differs and they are not effective to predict all environments.

There are features common to 2G and third-generation (3G) coverage prediction. In both systems uplink (UL) as well as downlink (DL) have to be analyzed. In current 2G systems the links tend to be in balance whereas in 3G systems one of the links can be loaded higher than the other, so that either link could be limiting the cell capacity or coverage. The propagation calculation is basically the same for all radio access technologies, with the exception that different propagation models could be used.

3.5.1 The Okumura-Hata Propagation Model

This is the most extensively used fully empirical prediction propagation model for mobile communications and is based on Mr. Okumura’s field measurements in Japan in 1968 [24]. These measurements were later fitted into a mathematical form by Mr. Hata in 1980

[25]. A COST-231 program was later launched by European Union to study the radio propagation for 3G systems [26]. One result from this program was the extension for the original Okumura-Hata propagation model to support frequencies up to 2000MHz. This COST-231 expansion gives the possibility to use the Okumura-Hata model also for UMTS operating frequencies at adequate accuracy. The results originated from Mr. Okumura's measurements in Tokyo are widely used in radio network planning tools to model radio wave propagation. The basic path loss model equation made by Hata from Okumura's measurements is of the following form:

$$\begin{aligned} L_P = 69.55 + 26.16 \log_{10} f_c \\ - 13.82 \log_{10} h_b - a(h_m) \\ + (44.9 - 6.55 \log_{10} h_b) \log_{10} d_{km}, \end{aligned} \qquad (3.6)$$

where the term $a(h_m)$ is a correction factor for mobile antenna height [25].

The following equation is tuned Okumura-Hata propagation model from the COST-231 program:

$$\begin{aligned} L_P = A + B \log_{10} f_c - 13.82 \log_{10} h_b - a(h_m) \\ + (44.9 - 6.55 \log_{10} h_b) \log_{10} d_{km} + C_m, \end{aligned} \qquad (3.7)$$

which demonstrates the changes from the original model (Equation (3.6)). The definitions for common parameter values for Equations (3.6) and (3.7) are listed in Tables 3.4 and 3.5. [18].

Table 3.5: COST-231 propagation model parameter description [18]

Parameter	**Description**
C_m	Area correction factor, $C_m < 0$ for rural, $C_m > 0$ for urban
d_{km}	Distance
$f_{carrier}$	Carrier frequency
h_b	Node B antenna height
h_m	Mobile station antenna height

Table 3.6: Frequency dependent constant value definitions for COST-231 equation [18]

$\boldsymbol{f_{carrier}}$	**150-1000 MHz**	**1500-2000 MHz**
A	69.55	46.3
B	26.16	33.9

CHAPTER FOUR

RADIO NETWORK PLANNING FOR UMTS

Achieving maximum capacity, while maintaining an acceptable grade of service and good speech quality, is the main issue for the network planning. Planning an immature network with a limited number of subscribers is not the real problem. The difficulty is to plan a network that allows future growth and expansion. Wise re-use of site location in the future network structure will save money for the operator.

UMTS is a multi-service and multi-rate system that relies on a completely different air interface approach (WCDMA) based on single frequency use in the network thus making it highly vulnerable to interference as compared to GSM system. Moreover unlike GSM, capacity and coverage in UMTS are tightly coupled with each other. Therefore UMTS deployment must be preceded with careful radio network planning.

This chapter presents WCDMA radio network planning, including dimensioning, detailed capacity and coverage planning, and network optimization. In the dimensioning phase, an approximate number of base station sites, base stations and their configurations and other network elements are estimated based on the operator’s requirements for coverage, capacity and quality of service. Capacity and coverage are closely related in WCDMA networks, and therefore both must be considered simultaneously in the dimensioning of such networks.

4.1 The Planning Process

The overall radio network planning goal is to maximize the coverage and capacity while meeting the key performance indicators (KPIs) and quality of service (QoS) [18]. Basic WCDMA planning process is similar to GSM but detailed planning phases need modifications.

Figure 4.1 shows the overall UMTS planning process. This process is divided into three: dimensioning (pre-planning), detailed planning, optimization & monitoring (post-planning).

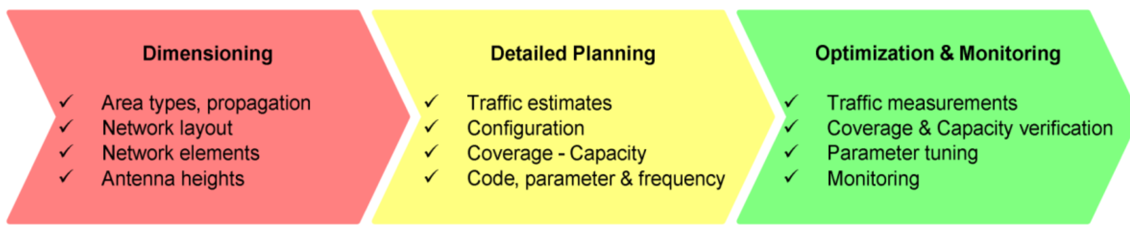

Figure 4.1: UMTS radio network planning process [5]

So far it has been adequate to specify the speech coverage and blocking probability only, but it is increasingly necessary to consider the indoor and in-car coverage probabilities. In the case of UMTS the problem is slightly more multi-dimensional. For each service the QoS targets have to be set and naturally also met. In practice this means that the tightest requirement shall determine the site density. In addition to the coverage probability, the packet data QoS criteria are related to the acceptable delays and throughput. Estimation of the delays in the planning phase requires good knowledge of user behavior and understanding of the functions of the packet scheduler.

4.1.1 Dimensioning

The purpose of the dimensioning phase is to estimate the approximate number of sites required, the Base Station (BS) configurations and the number of network elements, in order to forecast the projected costs and associated investments. It provides the first and most rapid evaluation of the network element count as well as the associated capacity of those elements. This includes both the Radio Access Network (RAN) as well as the Core Network (CN). The target of the initial planning phase is to estimate the required site density and site configurations for the area of interest. Initial planning activities include radio link budget and coverage analysis, capacity evaluation and lastly estimation of the amount of BS hardware and sites, Radio Network Controllers (RNCs), equipment at different interfaces and CN elements. The service distribution, traffic density, traffic growth estimates and QoS requirements are already essential elements in the initial planning phase.

4.1.2 Detailed Planning

In detailed planning phase, more realistic values for individual sites are calculated based on the estimates from dimensioning. This phase can be further classified into configuration planning, topology planning, and code and parameter planning.

4.1.2.1 Configuration Planning

Here, the base and base station antenna line equipment are defined, and the maximum loss allowed between the base station antenna and mobile station antenna is calculated in the uplink and downlink directions. The configuration planning of an indoor base station, a micro cell, and a repeater are special cases due to the special propagation environment type, site characteristics, or equipment configuration.

In UMTS, power budget calculations, gains (antenna, amplifier, etc.), losses (cable, filters, etc.), and margins (slow fading, etc.) are added to transmit and receiving power levels, as in GSM. In UMTS, the transmission requirements of common control channels and the pilot channel must be included in the power budget. In addition, the impact of intra-cell and inter-cell interference (interference margin, IM) and new WCDMA margins (for example, fast fading margin also called power control headroom) must be added to the power budget. The UMTS power budget is uplink-limited when maximum coverage is targeted and the load of the network is low. Moreover, the UMTS power budget is downlink-limited when the load of the network is increased to the maximum.

4.1.2.2 Topology Planning

Topology planning is made up of coverage and capacity planning. UMTS coverage planning can be done as in GSM by using path loss information and prediction models such as Okumura-Hata, if there is no other traffic (only one mobile terminal) and thus no interference in the radio network. When traffic is included, *cell-breathing* occurs and cell range, as well as coverage area, is dynamic, based on the load of the network. Thus, coverage areas are linked to each other as a function of mobile terminal locations. Moreover, the maximum load or capacity of the UMTS radio network depends on the coverage areas (cell overlapping, depth of propagation slope, etc.), base station locations, and base station antenna line configurations (antenna height, direction, beam width, tilting, etc.). Therefore in UMTS radio network planning, both coverage and capacity have to be analyzed simultaneously and together [5]. Coverage and capacity are typically linked together via link budget calculations and load equations respectively. Network

must be planned so that adequate coverage is available for users at cell edges and indoors in high load situations while keeping the interference low.

Figure 4.2 shows how topology planning in UMTS begins with coverage predictions, in order to estimate coverage overlapping and dominance areas. Coverage thresholds are used at this point for estimating coverage and dominance areas, as in GSM planning. Figure 4.3 shows the link between the UMTS coverage and capacity planning process.

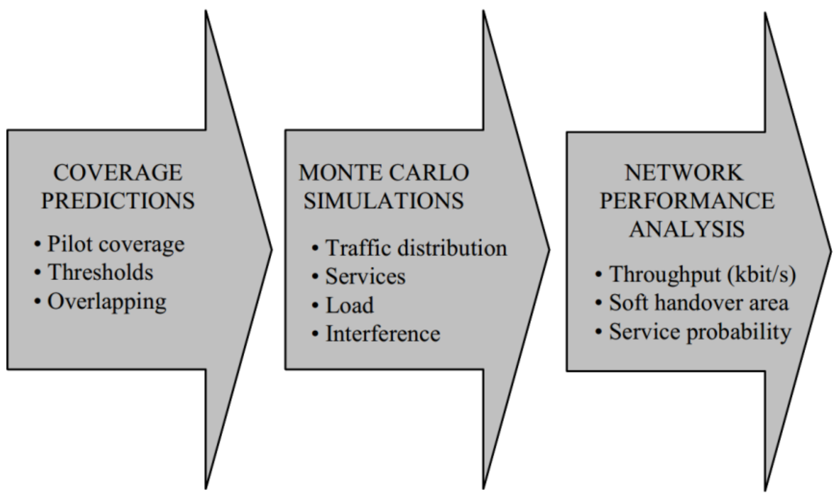

Figure 4.2: UMTS topology planning process [5]

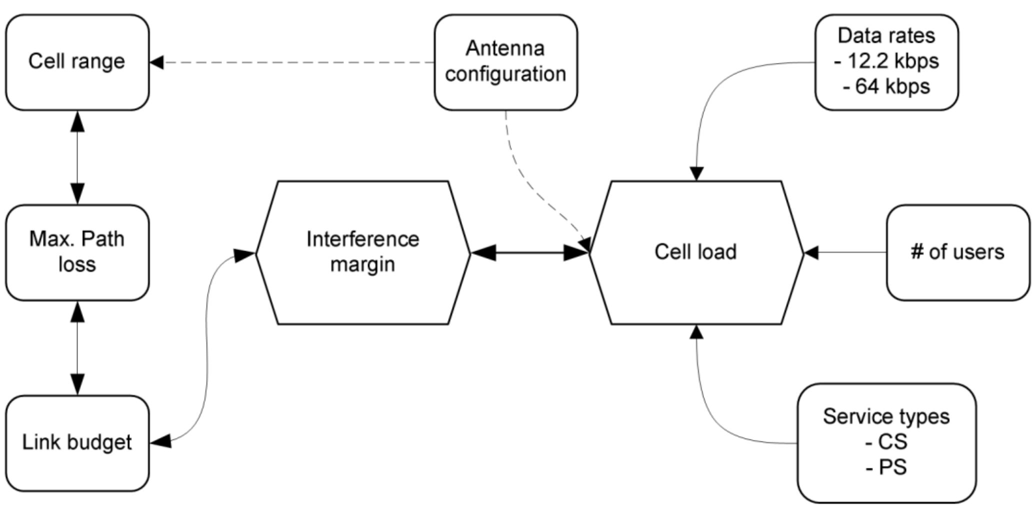

Figure 4.3: Link between coverage and capacity of a UMTS network [5]

In coverage prediction, the pilot channel coverage (P-CPICH) is first estimated. In UMTS, maximum transmit power is limited and in the downlink this power is shared among user traffic (e.g. DCH) as well as signaling channels (e.g. CPICH). Adequate power allocation to CPICH is an important task since its received level is used for cell selection, channel estimation and handover measurements. Too high power allocation increases the coverage area of the pilot channel but at the same time there is less power available for DCH, which in fact, reduces the system capacity. On the contrary too low power allocation for CPICH results in reduction of cell dominance area. Therefore balance between CPICH and DCH power allocation is critical if coverage and capacity needs to be maximized. Typically, 5-10% of the total base station power is reserved for CPICH [5].

System level simulations are based, for example, on *Monte Carlo* type of simulations, where a certain number of mobile terminals are located over a coverage area and distributed homogenously or non-homogenously (with greater weight for indoor locations, for example). The results of Monte Carlo simulation include coverage, capacity, and interference-related information such as transmit powers of base stations, maximum number of users in each cell, and own-cell-to-other-cell interference. These results finally give an estimate on whether base station sites are located correctly (throughput, service probability) and the total capacity of the radio network for a particular area.

1. **Coverage Planning – Link Budget**: In UMTS coverage planning, accurate cell ranges are calculated using link budget from configuration planning and by applying propagation prediction models like Okumura-Hata (macro-cell) or COST 231 multi-

wall (indoor). Base station and antenna line equipment play an important role in cell coverage. Moreover, cell coverage is significantly affected by the propagation environment, location probability targets defined for indoor and outdoor and services offered by the network. Different services have different propagation losses and therefore cell ranges are typically limited by the most sensitive service. The main objective of coverage planning is to balance the link budget in order to achieve stable communication in both link directions.

Table 4.1 shows an example of UMTS link budget for asymmetric speech service (12.2 kbps) and for asymmetric data service (384 kbps) both uplink and downlink. The link budget takes into account the base station equipment and the base station antenna line configuration. In this example, the maximum allowable propagation loss is calculated for speech service of 50% load in the uplink and 75% load in the downlink. Allowed propagation loss is higher in the DL direction for speech service and for data service. Thus, in both cases, the UL direction would limit the coverage.

Table 4.1: An example of UMTS 2100 link budget for different service types [2]

General Information	**Unit**	**UPLINK**		**DOWNLINK**	
Services		Speech	Data	Speech	Data
Frequency	MHz	2100	2100	2100	2100
Bit Rate	Kbps	12.2	64	12.2	384
Chip Rate	Mbps	3.84	3.84	3.84	3.84
Load	%	50	50	50	75
Transmitting End					
Maximum Power per Connection	W dBm	0.125 21	0.125 21	2 33	2 33

TX Gain	dBi	0	0	17	17
Cable Loss	dB	0	0	3	3
Peak EIRP	dBm	21	21	47	47

Receiving End

Thermal Noise Density	dBm/Hz	-173.93	-173.93	-173.93	-173.93
Receiver Noise Figure	dB	4	4	8	8
Receiver Noise Density	dBm/Hz	-169.93	-169.93	-169.93	-169.93
Noise Bandwidth	MHz	3.84	3.84	3.84	3.84
Receiver Noise Power	dBm	-104.09	-104.09	-100.09	-100.09
Interference Margin	dB	3.01	3.01	3.01	6.01
Total Interference Level	dBm	-101.08	-101.08	-97.08	-94.08
Processing Gain	dB	24.98	17.78	24.98	10
Required E_b/N_o	dB	5	2.5	8	5
Receiver Sensitivity	dBm	-121.06	-116.36	-114.06	-99.08
RX Antenna Gain	dBi	17	17	0	0
Cable Loss	dB	3	3	0	0
Power Control Headroom	dB	3	3	0	0
Soft Handover Diversity Gain	dB	2	2	3	3
Required Signal Level	dBm	-134.06	-129.36	-117.06	-102.08

Planning Thresholds

Soft Handover Gain	dB	3	3	3	3
Body Loss	dB	3	3	3	3
Outdoor Coverage Probability	%	95	95	95	95
Outdoor Slow Fading STD	dB	7	7	7	7
Outdoor Slow Fading Margin	dB	7.3	7.3	7.3	7.3
Outdoor Planning Threshold	dBm	-123.76	-119.06	-106.76	-91.78
Indoor Coverage Probability	%	90	90	90	90
Indoor Slow Fading STD	dB	9	9	9	9
Indoor Slow Fading Margin	dB	6.5	6.5	6.5	6.5
Building Penetration Loss	dB	15	15	15	15

Indoor Planning Threshold	dBm	-112.56	-107.86	-95.56	-80.58
Outdoor Isotropic Path Loss	dB	144.76	140.06	153.76	138.78
Indoor Isotropic Path Loss	dB	133.56	128.86	142.56	127.58

2. **Capacity Planning – Load Equations:** An increase in cell interference decreases the capacity and causes cell breathing and call blocking. A WCDMA network is known to be soft blocked (due to interference) as opposed to hard blocked TDMA/FDMA network (lack of traffic channels). Because of the soft blocking and dynamic nature, conventional Erlang B formula cannot be used for calculating UMTS soft capacity as it produces too pessimistic results.

   The load equation is commonly used to make a semi-analytical prediction of the average capacity of a WCDMA cell, without going into system level capacity simulations [27]. These equations are calculated separately for uplink and downlink directions. There are a number of parameters that influence the load on a UMTS network, which on the contrary defines the maximum number of users per cell, such as the number of users and their bit rates, the activity factor in speech and data services and finally, the E_b/N_o value. The most important contributor to the load is the required E_b/N_o value, which depends on the service type, data rate of the service, propagation conditions, and receiver performance. If a very good quality (i.e. high E_b/N_o) connection is required, air interface load is increased due to more error correction bits and consequently capacity for traffic channels is decreased [5].

Now, depending on the maximum allowed load in a cell, the number of users can be calculated by using the load equation. The *uplink load equation* can be expressed by Equation (4.1)

$$\eta_{UL} = \sum_{j=1}^{N} \frac{1}{1 + \frac{W}{(E_b/N_o)_j \cdot R_j \cdot v_j}}(1+i) \quad (4.1)$$

where N is the number of active users in the cell, W is the system bit rate (chip rate), R_j is a bit rate of the jth user, $(E_b/N_o)_j$ is energy per bit over the noise spectral density requirement for the jth user, v_j is the activity factor of the jth user and it indicates the activity of speech when discontinuous transmission is used, and i is the other-to-own-cell interference, which informs the noise power received from the neighbor cells. Maximum capacity which a cell can handle (*pole capacity*) is achieved when η_{UL} approaches 1 but in practice load must be kept clearly below 1 to ensure network stability [5].

The noise rise (interference margin) tells how much noise is required to be added to the noise floor of the receiver to facilitate the exact amount of interference. It takes into account the noise from own cell as well as the noise from other cells. The uplink load factor defines the required interference margin (IM) in a power budget, given in Equation (4.2), in order to take into account the effect of cell-breathing.

$$IM_{UL} = -10\log_{10}(1-\eta_{UL}) \quad (4.2)$$

Figure 4.4 shows an example of uplink interference margin (noise rise) for data service, assuming an E_b/N_o requirement of 1.5 dB and $i = 0.65$. The noise rise of 3.0 dB

corresponds to a 50% load factor, and the noise rise of 6.0 dB to a 75% load factor. The more users there are in the network, the more interference there will be, both for own cell and from surrounding (other) cells.

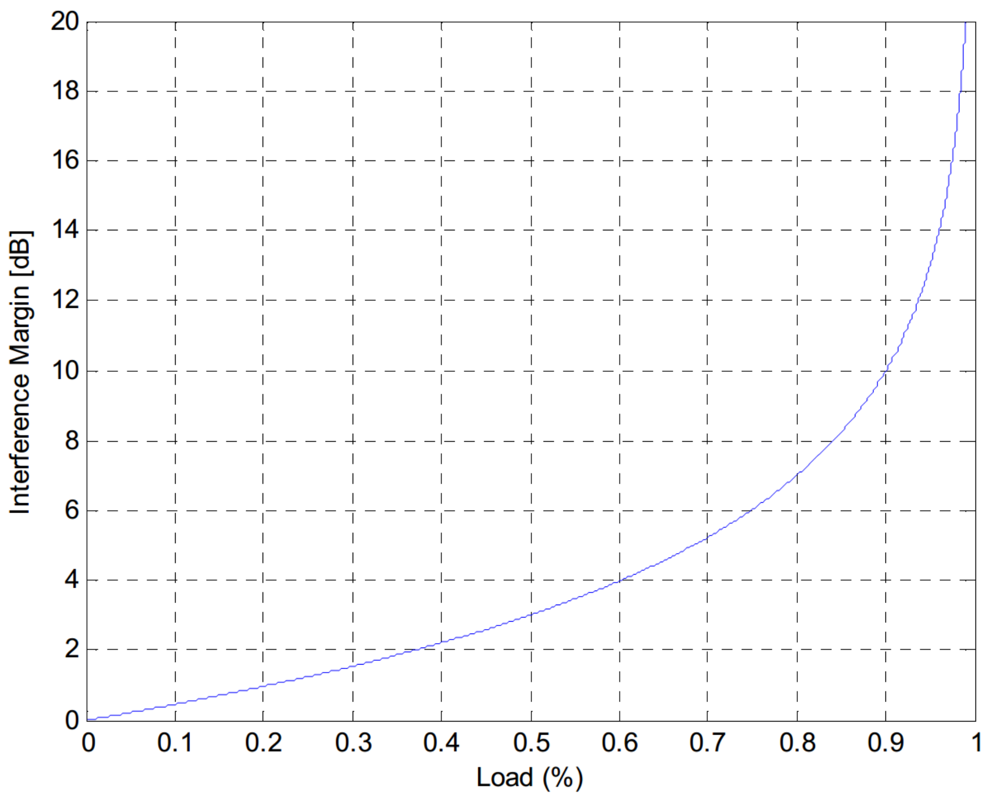

Figure 4.4: Interference margin as a function of load [5].

Typically, cells are designed to be loaded to a maximum of 50-60%, and the graph in Figure 4.4 shows that a 60% load rate corresponds to a load factor of 0.6 and causes an interference margin (noise rise) of 4dB. When the load rate exceeds 80%, the noise simply rises abruptly and can cause the cell to collapse.

In UMTS networks, the downlink behaves a little differently from uplink because multiple connections share the same base station transmit power. Moreover, every mobile experiences different interference levels depending on its location within the

cell. Thus, the downlink load equation, given by Equation (4.3), includes an orthogonality factor α_j.

$$\eta_{DL} = \sum_{j=1}^{N} v_j \frac{(E_b/N_o)_j}{W/R_j} \left[\left(1 - \alpha_j\right) + i_j\right] \tag{4.3}$$

The value of the orthogonality factor depends on the orthogonality of the codes used in the network. Basically, codes are fully orthogonal when $\alpha_j = 1$. However, multipath propagation destroys this orthogonality and causes interference and increases the load [5].

Node B transmit power is typically limited by specifications and therefore it may limit the coverage and capacity in highly loaded networks. From Equations 4.1 and 4.3, it could be seen that decreasing the other-to-own-cell interference, decreases the load of the network significantly. Consequently, this lowers the noise rise in the uplink and reduces the required Node B transmit power in the downlink.

4.1.2.3 Code and Parameter Planning

In code planning, scrambling codes are allocated for different cells in order to separate cells in the downlink direction. Code planning is straightforward because there are enough codes in the 3GPP specification (altogether 512 primary codes); therefore, code limitations should not occur.

In parameter planning, the functionality of the radio interface is optimized; this basically includes signaling and radio resource management tasks. Parameters can be divided into signaling, identifier, RRM, measurement, handover and power control groups, which are

all related to idle, connection establishment and connected modes. In the parameter planning phase, all parameters are grouped to these different categories, and default values are given when the network or a cell is launched. Later on, separate parameter values (such as active set parameters for handovers) can be changed, based on the needs of the radio propagation environment.

4.1.3 Monitoring and Optimization

A UMTS network may be launched after detailed planning phase however constant monitoring of network is needed. This is due to the fact that user location and traffic behavior vary constantly which directly affects radio network quality. Monitoring contains Key Performance Indicator (KPI) values that are related to call success (or call establishment failures prevented by load or admission control) rates and drop call (soft, softer, or hard handover failures, cell-breathing and lack of coverage, overload, etc.) rates. More detailed monitoring is based on signaling messages between Node Bs and mobile stations measured by a radio interface field measurement tool or by a Quality-of-Service (QoS) analyzing tool, for example, from the Iub interface. The radio interface field measurement tool is based on information gathered by a UE and thus location information is also available.

Optimization contains different kinds of planning-related actions to solve problems found in the verification and monitoring phases. Optimization entails continuous problem solving; it could also be called *re-planning* because all planning phases and their results must be checked before any modifications can be done to the actual plan. The optimization process includes radio interface field measurements and QoS measurements to understand network bottlenecks at the cell, site, and RNC levels.

4.2 Indoor Radio Planning for UMTS

In 3G (UMTS) networks, the need to offload the existing macro network is an especially important parameter. Also the need for higher-speed data rates inside buildings plays an important factor. Thus, a dedicated in-building (IB) solution is needed to provide high-speed data services on UMTS, especially when HSDPA/HSUPA services are deployed.

It is important to note that when designing IB solutions, the main driver for any mobile network operator is to increase the revenue factor, i.e., maximizing the revenue of the network and lowering the production cost of the traffic. In many countries, 80% of mobile users are inside buildings, and providing high-performance indoor coverage, especially with higher data rates, is quite challenging.

In this thesis, I do not intend to go into a detailed account of UMTS indoor planning. However, there are three very common strategies that are employed for UMTS indoor coverage.

4.2.1 Macro/Micro-cell Indoor Coverage

This is the primary method for covering the indoors in use today and has been the tradition since the beginning of cellular telephone networks. This is possible provided that the serving macro base stations are within few hundred meters of the building, and have direct line-of-sight. The outdoor signal propagates inside the buildings despite high building penetration loss. However, complete or homogeneous coverage throughout the building cannot be guaranteed since the building penetration loss can be as high as 20 dB while indoor propagation losses are often in tens of dBs [29]. With such losses, coverage may be adequate for residential areas but it is not ideal for high rise buildings since

ground floors may have little or no coverage as compared to top floors. Moreover, indoor coverage at cell edges could be improved by high overlapping of outdoor cell areas but at the same time too much overlapping may degrade the macro-cell performance due to pilot pollution.

In UMTS, the power load per user (PLPU) is an important factor, owing to the fact that the DL power on the Node B is directly related to the capacity. The higher the PLPU, the higher the capacity drain from the base station per mobile user. This increases the production costs for indoor traffic on UMTS when trying to service the users inside buildings from the outdoor Macro network. Therefore, when using dedicated indoor coverage solutions, the PLPU will be much lower due to the fact that with an indoor system, the Node B will not have to overcome the high penetration loss of the building (20-50 dB). In addition, when servicing indoor UMTS users from the macro base station, the signal will rely mostly on reflections in order to service the users, degrading the orthogonality [1]. Thus implementing indoor coverage solutions could reduce the production cost per call minute or MB, and also reduce the overall noise rise in the network.

4.2.2 Indoor Antenna Systems

A UMTS indoor system typically employed to serve indoor users with high data rate requirements and usually includes a base station or repeater connected to an antenna system specially designed for the building. They provide macro-cell independent coverage and capacity for indoor traffic hot spots. The base station configuration is planned mostly as in an outdoor base station as described earlier in this chapter, but the antenna system configuration deviates from outdoor sites. There are three main

configurations used for indoor antenna systems, they include: Distributed Antenna System (DAS), Radiating Cable System and Optical solutions [5]. DAS consists of network of (omni-)directional antennas connected to a base station with coaxial cables, splitters, tappers etc; providing coverage throughout the building. Optical fiber cables are used in optical solution to form an indoor network similar to DAS, whereas leaky radiating cables are used instead of antennas to provide smooth coverage in long indoor areas such as tunnels [2]. This thesis is based on the concept of the Distributed Antenna System (DAS) and is discussed below.

4.2.3 Distributed Antenna Systems (DAS)

A significant number of high data rate users will be located at indoor locations. Therefore, providing good indoor coverage and capacity also for indoor users is an important topic for network operators. High density of indoor users without dedicated solution for in-building coverage easily deteriorates the performance of the entire network. This phenomenon is caused by high required transmission power due to significant indoor propagation losses. Distributed antenna system is the most common and effective approach for providing in-building coverage. Antennas used in DAS are small discrete antenna elements designed specifically for indoor use. Typically they are either omnidirectional or directional 65-90^{o} antennas. In DAS implementation, signal is transferred from base station by network of feeder cables, connected by splitters and tappers. Advantages of DAS are easy planning and good coverage, while drawbacks include high installation costs compared to, e.g., indoor pico-cells or outdoor to indoor repeaters [30]. There are many different approaches to designing an indoor coverage system with uniformly distributed coverage level; passive distribution, active distribution,

hybrid solutions, repeaters or even distributed Pico-cells in the building. Each of these approaches have their advantages and disadvantages, depending on the project at hand. One design approach could be perfect for one project, but a very bad choice for the next project – it all depends on the building, and the design requirements for the current project, and the future needs in the building [1]. Figure 4.5 shows a typical DAS design.

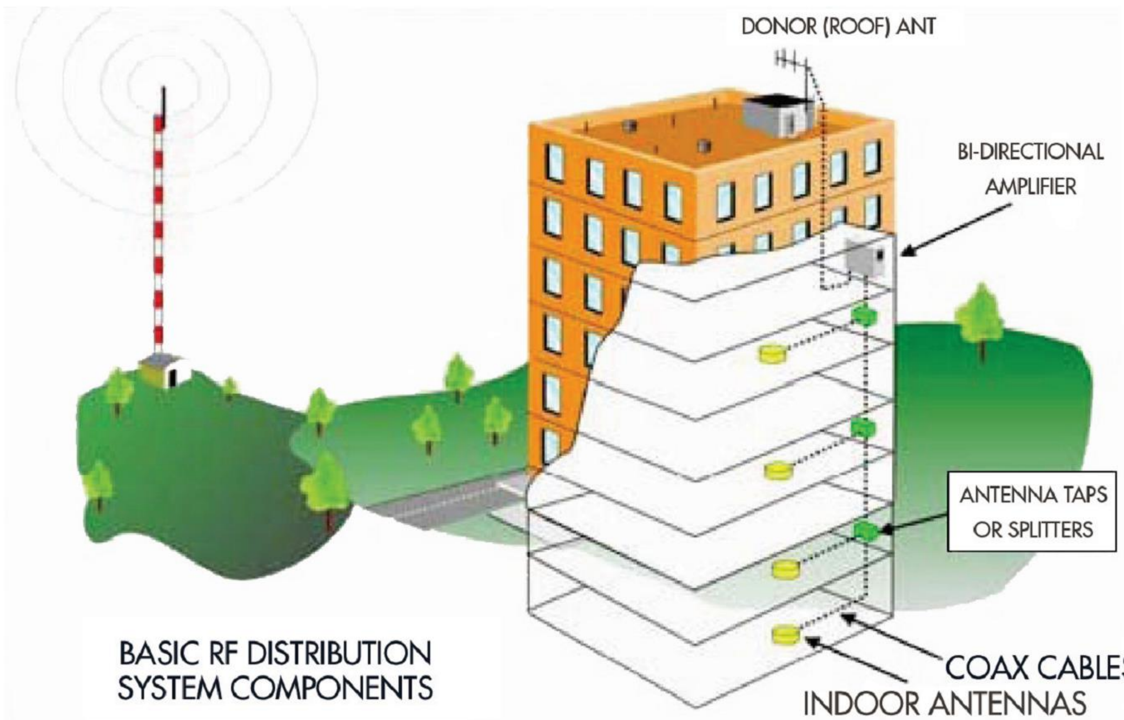

Figure 4.5: A typical distributed antenna system [33].

4.2.3.1 Passive and Active DAS

A DAS could either be *active* or *passive*. A Passive DAS consists of distributed feeder lines, i.e., coaxial feeder cables connected by tappers, power splitters etc., or single point antennas. They could be installed in large office buildings where they provide efficient coverage throughout the building. The signal distribution may even take place along the (feeding) coaxial cable without any definable single point antennas. This solution is

commonly known as the *radiating coax* (leaky feeder), where controlled slots, or a loosely woven shield in the coax, leaks part of the radio frequency (RF) energy propagating within the wire [31].

Traditional passive DAS systems based on coax cables will in many cases have too high an attenuation to provide sufficient HSPA data service inside buildings. Passive DAS can perform on HSPA provided that the attenuation between the Node B and the indoor antenna is less than 20 dB. In practice, however, using passive DAS for indoor HSPA solutions is only possible for smaller buildings that can be covered by six to eight indoor antennas. Each antenna's coverage area will vary depending on the length of coax to which it is attached, which could mean that the whole system will need re-engineering if more capacity or coverage areas are added. In addition, passive DAS is often expensive and time-consuming to install because of the specialist requirements of installing heavy coaxial cable. Figure 4.6 shows a typical passive DAS design.

The basic function of active DAS is same as that of the passive however the fundamental difference is the digital distribution of signals as well as low feeder losses. The RF signals are converted to and from digital signals for distribution via fiber optic or copper cables (Cat-5/CATV). The active DAS combines electronic hubs, fiber optics, and active radio access units to distribute the signal from a single, centrally located radio source as shown in Figure 4.7. For UMTS and especially HSPA, active DAS will often give the best radio link performance and higher data rates.

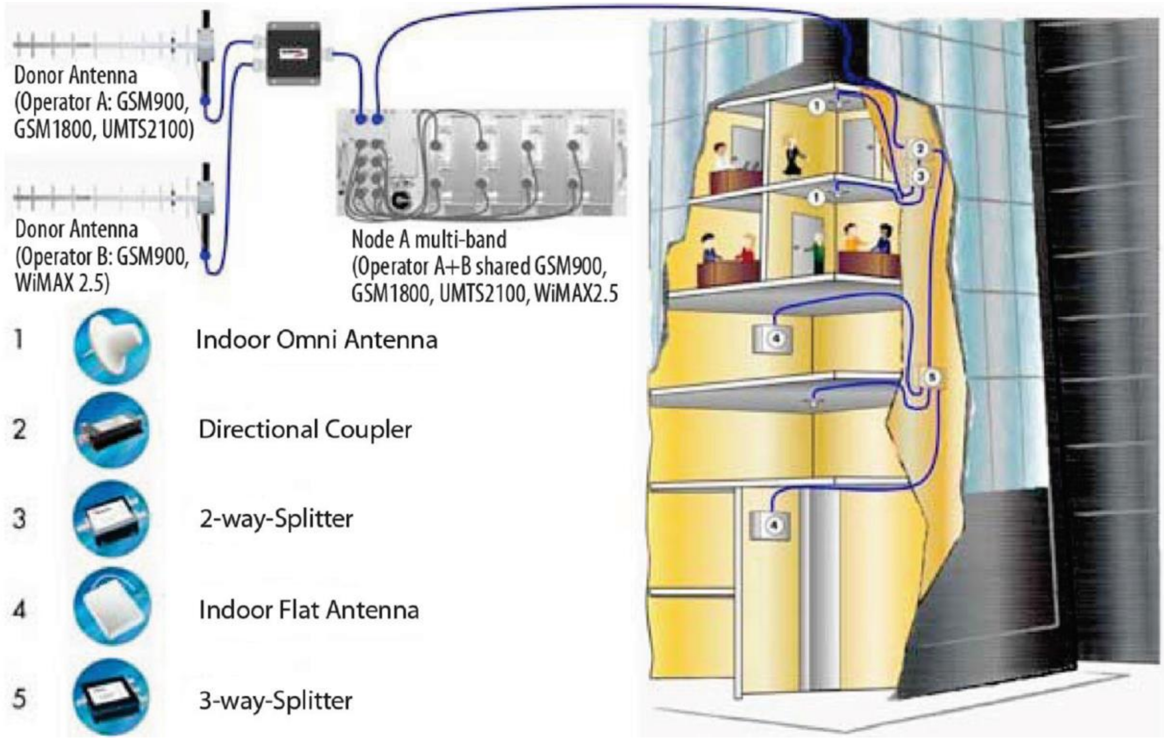

Figure 4.6: A typical passive design for a distributed antenna system [33].

Because the signal does not degrade, it has the same strength at every antenna point, regardless of the distance from the central radio. Since every antenna is simply an extension of the centralized radio source, there is no interference among antennas and no limit on the number of antennas that can be deployed within a building, or where they can be located. The signal consistency means there is no need to traffic engineer the system at the individual antenna level to deliver pervasive coverage for high user-density areas.

Some active DAS systems support optimum signal strength throughout the interiors of buildings that span hundreds of thousands of square feet. To increase capacity, additional radios can be added to the macro base station.

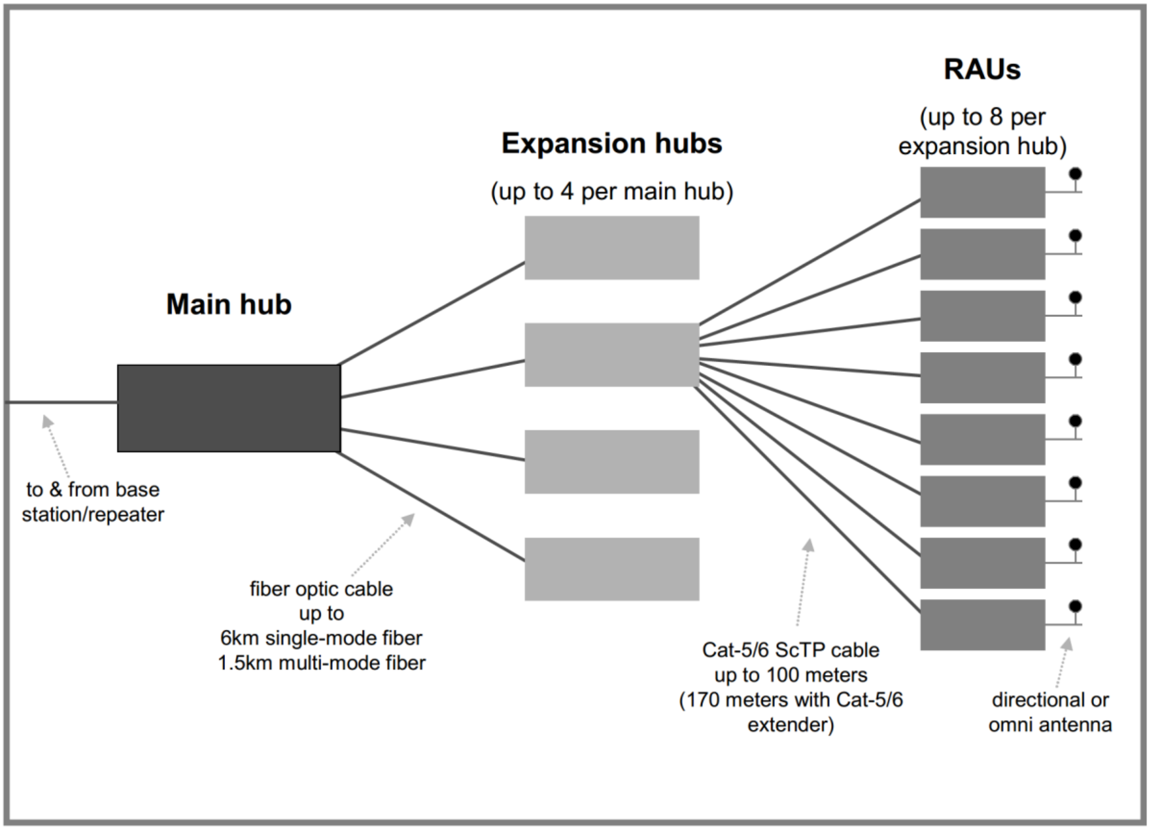

Figure 4.7: Active Distributed Antenna System [32].

DAS antennas themselves are relatively small and inexpensive, and can deliver maximum output power to support voice and high speed data. Also, active DAS uses standard cabling to connect hubs to RAUs and remote antennas, reducing deployment costs and time when compared with passive DAS - unlike passive systems that require specialized cable installation, regular IT staff can easily roll out the infrastructure with commonly used wiring [32].

4.2.3.2 Passive DAS Components

When exploring the design of indoor passive distributed antenna systems, a good understanding of the functions and usage of the common types of passive components is

necessary. These components are passive, which means they do not need external power supply. Below are some of these components and their functions.

1. Coaxial Cable

Coaxial cables are used to split the signal and form the link between the different elements of the DAS. Their main disadvantage is high signal loss depending on the distance. Thus engineers, in order to ensure they have the right radiated power at each antenna, must take into account the length of the cables to compute the global loss. The most common types of coaxial cable and their associated losses are listed in Table 4.2. With this listing, the total loss of a passive coaxial cable at a given frequency can be easily calculated by Equation (4.4):

$$loss = distance\ (m) \times attenuation\ per\ meter\ (dB/m) \tag{4.4}$$

Table 4.2: Typical Attenuation of coaxial cable [1].

	Frequency / typical loss per 100 m (dB)		
Cable type	**900 MHz**	**1800 MHz**	**2100 MHz**
$^1/_4$ inch	13	19	20
$^1/_2$ inch	7	10	11
$^7/_8$ inch	4	6	6.5
$1^1/_4$ inch	3	4.4	4.6
$1^5/_8$ inch	2.4	3.7	3.8

The biggest challenge in selecting the cable is not its price but rather a tradeoff between its installation cost and performance i.e. heavy rigid cables with lower attenuation are harder to install in buildings than the thinner ones with higher attenuation.

2. Power Splitters or Power Dividers

Splitters are commonly used components in passive DAS. Splitters are used for dividing one coax line signal into two or more lines or vice versa. It is used as an interconnection to split the signal between the different antennas. Typical splitter types are shown in Figure 4.8. The signal splitting is done so that the input power is divided among the output ports. If 1-to-2 port splitter is used, only half-power minus the insertion loss is available at the output ports. Splitter also introduces loss in the antenna line which can be calculated by Equation (4.5):

$$splitter\ loss = 10\log(number\ of\ ports) + insertion\ loss \tag{4.5}$$

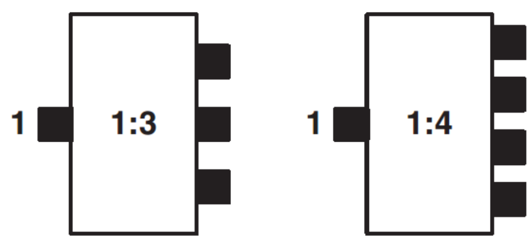

Figure 4.8: Power splitters [1].

3. Taps

Taps are similar to splitters, but are able to divide the input signal into two output signals with different ratios. They are very useful in passive DAS deployment in high-rise buildings where one heavy main cable is installed through the building and a portion of signal power is tapped to feed signal to splitters and discrete antennas installed at individual floors. This can avoid the installation of many parallel heavy cables while keeping the loss low. They come in various types and have a low loss port (1-2) and a high-loss port (3) as shown in Figure 4.9.

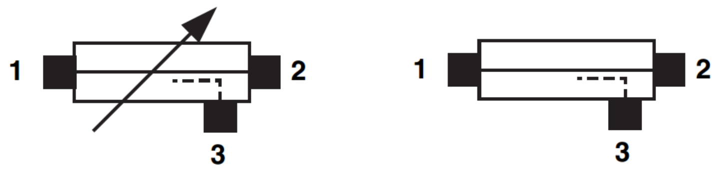

Figure 4.9: Taps, adjustable and fixed [1].

4. Attenuators

They are used to attenuate the signal with the value of the attenuator. Attenuators are used to bring higher power signals down to a desired range of operation, typical to avoid overdriving an amplifier, or to limit the impact of noise power from an active distributed antenna system. Note that, when attenuating high power signals for many carriers, typically for multi-operator applications you should use a special type of attenuator, a 'cable absorber', to avoid passive intermodulation problems.

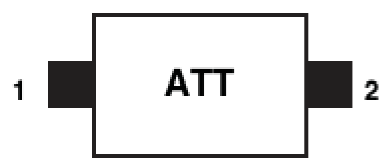

Figure 4.10: RF attenuator [1].

4.2.3.3 Active DAS Components

The active DAS requires the use of electronic components (active elements) unlike the passive systems. Below is the description of some of these active elements.

The Master Unit

The master unit (MU) can be connected to the base station or the repeater. It distributes the signal via the optical fiber to the different expansion units. The master unit is the

intelligent part of the distributed antenna system that controls all the signals to deliver and adjust the signal levels thanks to internal amplifiers and converters.

Expansion Unit

The EUs are typically distributed throughout the building or campus and are placed in central cable raisers or IT X-connect rooms.

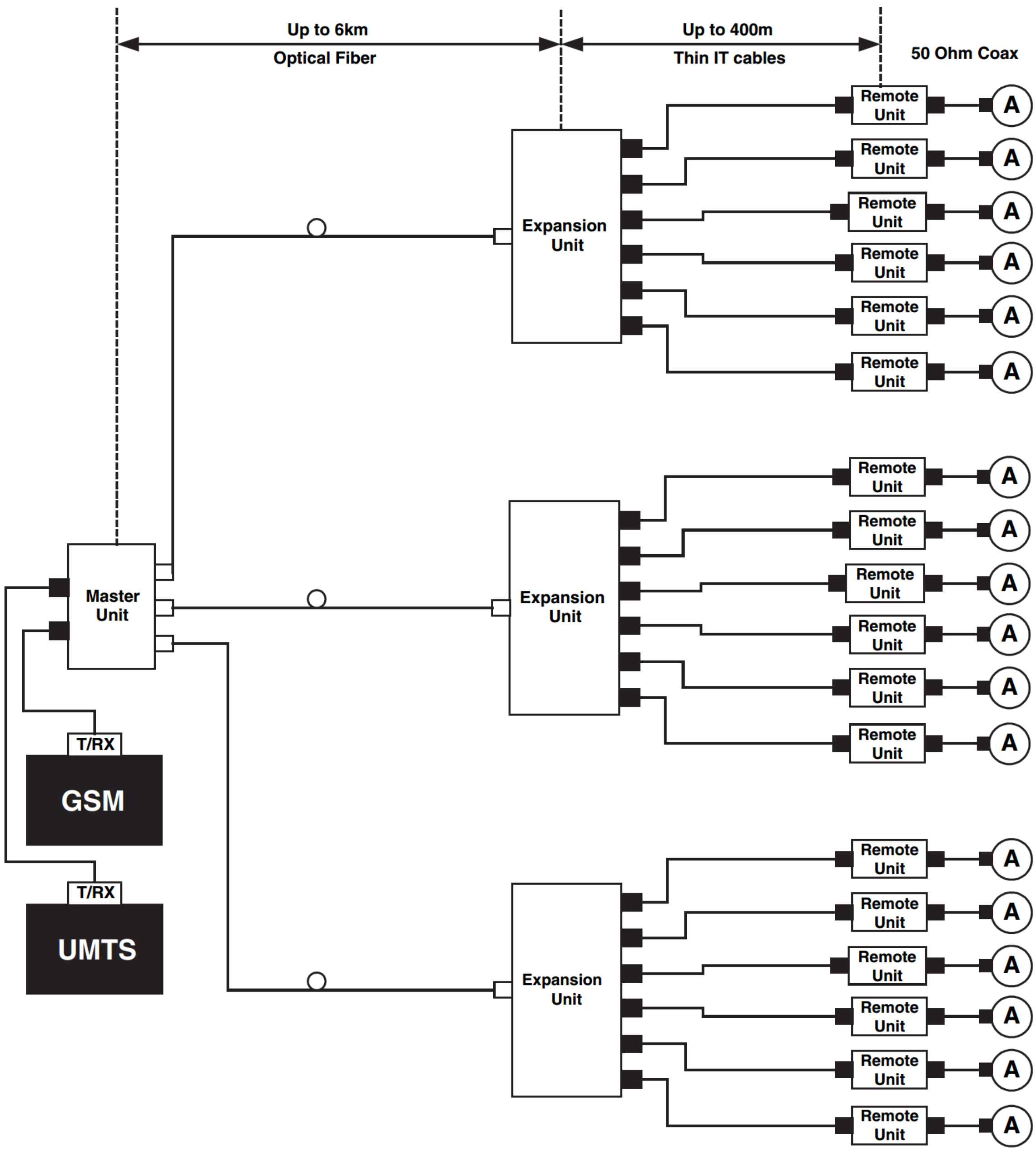

Figure 4.11: Example of a pure active dual band DAS for large buildings [1].

fibers, typically separate fibers for the UL and the DL. The EU converts the optical signal from the MU to an electrical signal and distributes this to the RU.

Remote Unit

The RU is installed near the antenna to minimize the losses and is connected to the antenna. The RU converts the signal from the RU into downlink radio signal, and converts the uplink radio signal into signal to the EU.

Cable

First active systems where deployed using standard connections like coaxial. In this case the problem of the losses between cables is still important. However, the installation is made easier because the active remote unit can compensate for the loss depending on the distance. Later, with the development of cheap optical fiber, some systems using such a technology have been proposed in order to transport the signal over longer distances.

4.2.3.4 Active Fiber DAS

Active fiber DAS is the most efficient in terms of performance. Optical fibers are used to make the link between the MU and the RU. They can cover very long distances (up to 6 km) and support multiple radio services. With such a system the RU directly converts the optical signal into radio signal and vice versa. The other advantage is that optical fiber is very cheap and easy to install. Radio over fiber is now the most common technique used for indoor radio coverage [34, 35].

4.2.3.5 Hybrid DAS

Some other solutions combining passive DAS and active DAS have been installed. The idea is to connect the remote units via fiber optic, but to use passive coaxial cabling to

link these remote units to the antennas. The combined method has the advantages of covering a long distance thanks to the fiber optic connection, and a cheaper price due to the passive components. Hybrid DAS can also combine different systems with different frequency bands. Due to the simplicity of radio over fiber installation, there are many possible solutions, such as combining the distributed antenna system with repeaters for example.

In terms of buying costs, passive systems are cheaper but suffer from high installation price due to the coaxial cabling. Active systems offer better performance and easier installation but are more expensive. With passive systems, no electronic systems have to be installed or power supplied. Hybrid DAS is sometimes a good compromise but still requires installation of coaxial cables. Active systems are easier to manage because automatic diagnostics and alarms are integrated into the remote units, making the problems of system failures easier to solve. Table 4.3, shows the comparison between passive and active DAS.

Table 4.3: Comparison between the different DAS technologies [36]

	Passive DAS	**Basic active DAS**	**Active fiber DAS**
Covered distance	Up to 400 m	Up to 400 m	Up to 6 km
Equipment price	Cheap	Standard	Standard
Installation	Difficult	Easy	Very easy
Multi-standard	No	No	Yes
Input (base station or repeater)	High power	Low power	Low power

CHAPTER FIVE

THE ANTENNAS USED FOR THE EXPERIMENT

5.1 Introduction

In this chapter, the three antennas that were considered for this experiment will be discussed briefly, and then the monopole antenna, which was the antenna that was finally used for the experiment, will be talked about in more detail. The other antennas considered were the half-wavelength dipole and the coaxial collinear antenna.

Monopole antennas are commonly employed in airborne and ground-based communication systems at a wide range of frequencies. The electrical properties of such antennas are dependent upon the geometry of both the monopole element and the ground plane. Typically, the monopole element may be electrically short (length is much less than a quarter-wavelength) or near-resonant (length approximately a quarter-wavelength), and it may be thin (length-to-radius ratio is much greater than 10^4) or relatively thick (length-to-radius ratio of 10^1 to 10^4). In addition, the ground-plane dimensions may vary from a fraction of a wavelength to many wavelengths. Therefore, it is desirable to know how the input impedance and radiation pattern of the antenna change as the dimensions of the monopole element and the ground plane vary. The directivity on or near the radio horizon (the ground plane is assumed to be horizontal) is of particular interest because the maximum operational range of a communication system often depends on the directivity on the radio horizon.

This thesis is going to concentrate on the monopole geometry consisting of a vertical cylindrical element at the center of a perfectly conducting, infinitely thin, circular ground plane in an indoor environment. This geometry is of interest because its radiation pattern is uniform in the azimuthal direction and because its electrical characteristics are primarily a function of only three parameters, namely, the *element length*, *the element radius*, and *the ground-plane radius*, when each is normalized to the excitation wavelength.

A typical feed for the monopole antenna is a coaxial line with its inner conductor connected through a hole in the ground plane to the vertical monopole element and its outer conductor connected by means of a soldering lead to the ground plane. Typically, the inner conductor's diameter is equal to the monopole element's diameter [37].

5.2 Effect of a Ground Plane on Monopole Antenna Characteristics

The monopole antenna may be modeled by the method of images as a dipole with one-half the input impedance and double the peak directivity of the dipole, when considered as having a ground plane of infinite extent and infinite conductivity. The infinite ground plane prevents monopole radiation into the hemisphere below the ground plane, but allows a radiation pattern identical to that of the dipole in the upper hemisphere. However, for a monopole element mounted on a ground plane of finite extent, the outer edge of the ground plane diffracts incident radiation in all directions, and consequently modifies the currents on the ground plane and the vertical element from those of an infinite ground plane. The limited size of the ground plane causes radiated power to leak to the lower half of the space, which means that the radiation pattern is changed. There may be side or even back lobes. At the outer edge of the ground plane, the currents on its

top and bottom faces are equal in magnitude but opposite in direction because the net current must be zero at the edge. Outer-edge diffraction becomes increasingly significant with decreasing size of the ground plane because of the increasing magnitude of the currents on the ground-plane faces at the outer edge. Edge diffraction can alter the input impedance by more than 3dB and directivity in the plane of the ground plane by more than 6dB from the values for a ground plane of infinite extent. The maximum angle is also changed (tilted towards the sky) and the directivity is reduced [38].

5.3 The Relationship between the Monopole and the Dipole Antenna

The currents (I_m) and charges on a monopole are the same as on the upper half of a dipole (I_{dip}). The voltage of the monopole (V_m) is half the voltage of the dipole (V_{dip}), because the electric field is the same but the length of the antenna is half, hence the same electric field over the half distance gives the voltage. Therefore, the impedance of the monopole (Z_m) antenna is half that of the dipole (Z_{dip}):

$$Z_m = \frac{\frac{1}{2}V_{dip}}{I_{dip}}$$

$$\therefore Z_m = \frac{1}{2}Z_{dip} \tag{5.1}$$

The radiation resistance $\left(R_{r,m}\right)$ of the monopole is half that of the dipole $\left(R_{r,dip}\right)$, due to the monopole radiation power $\left(P_{r,m}\right)$, which emits only over the upper hemisphere. Hence, it is half of the radiation power of the dipole $\left(P_{r,dip}\right)$ that radiates over a full sphere [51].

$$R_{r,m} = \frac{1}{2} R_{r,dip} \tag{5.2}$$

The directivity (D_m) of the monopole antenna is double the directivity of the dipole (D_{dip}). The reason for this is that the radiated power of the monopole is half that of the dipole for the same current levels. The radiation intensity in the free space for the monopole (Φ_m) is the same with the dipole (Φ_{dip}), due to the unchanged current. Since there are 4π steradians in the total solid angle, the monopole directivity is

$$D_m = \frac{\Phi_m}{P_m/_{4\pi}} = \frac{\Phi_m}{\frac{1}{2} P_{dip}/4\pi} = 2D_{dip} \tag{5.3}$$

Accordingly, from the above equations, the impedance of a quarter-wavelength (λ/4) monopole antenna $\left(Z_{m,\lambda/4}\right)$ is half the impedance of the half-wavelength (λ/2) dipole antenna $\left(Z_{m,\lambda/2}\right)$ [51]. Thus

$$Z_{m,\lambda/4} = \frac{1}{2} Z_{m,\lambda/2}$$

$$\therefore Z_{m,\lambda/4} = \frac{1}{2}(72 + j42.5)$$

$$\therefore Z_{m,\lambda/4} = 36 + j21.3\Omega \tag{5.4}$$

Similarly, the directivity of a quarter-wavelength (λ/4) monopole antenna $\left(D_{m,\lambda/4}\right)$ is double the directivity of the half-wavelength (λ/2) dipole antenna $\left(D_{m,\lambda/2}\right)$ [51].

$$D_{m,\lambda/4} = 2D_{m,\lambda/2}$$

$$\therefore D_{m,\lambda/4} = 2 \times 1.64$$

$$D_{m,\lambda/4} = 3.28 = 5.16\ dB \tag{5.5}$$

Thus from the above equations, it can be seen that the quarter-wavelength monopole antenna with a ground plane has more gain than the half-wavelength dipole antenna. The quarter-wavelength monopole is also half the size of the half-wavelength dipole [51].

5.4 Radiation Pattern of the Monopole and Dipole

Just like the dipole, the monopole antenna has an omnidirectional radiation pattern. Below are the matlab radiation pattern plots for the monopole without a ground plane and dipole. Thus when the ground plan is added to the monopole, the principle of image theory makes the radiation pattern to look exactly like that of the dipole but with a higher directivity. The matlab codes for these plots are in the Appendix.

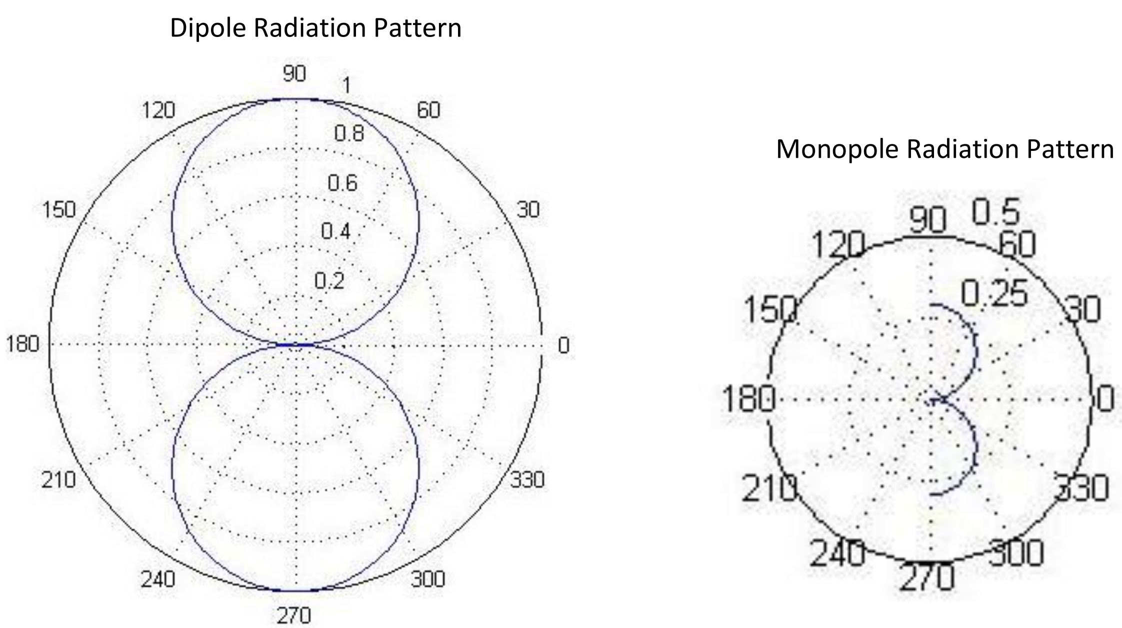

Figure 5.1: Matlab plots for Radiation Pattern of Dipole and Monopole

5.5 Matching and Feeding Techniques

An antenna feed refers to the components of an antenna which feed the radio waves to the rest of the antenna structure, or in receiving antennas collect the incoming radio waves, convert them to electric currents and transmit them to the receiver. There are two major issues when constructing the feed circuit: impedance matching and balanced-unbalanced matching.

5.5.1 Impedance Matching

The basic idea of impedance matching is illustrated in Figure 5.1, which shows an impedance matching network placed between a load impedance and a transmission line. The matching network is ideally lossless, to avoid unnecessary loss of power, and is usually designed so that the impedance seen looking into the matching network is Z_0. Then reflections will be eliminated on the transmission line to the left of the matching network, although there will usually be multiple reflections between the matching network and the load. Impedance matching is important for the following reasons:

- Maximum power is delivered when the load is matched to the line (assuming the generator is matched), and power loss in the feed line is minimized.
- Impedance matching sensitive receiver components (antenna, low-noise amplifier, etc.) may improve the signal-to-noise ratio of the system.
- Impedance matching in a power distribution network (such as an antenna array feed network) may reduce amplitude and phase errors.

As long as the load impedance, Z_L, has a positive real part, a matching network can always be found.

Figure 5.2: Impedance Matching Concept

Impedance mismatch is undesirable not only because of the inefficient power transfer. In high-power transmitting systems, high VSWR leads to maxima of the standing wave which can cause arcing. Sometimes, the frequency of the transmitter can be affected by severe impedance mismatch (frequency pulling). Excessive reflections can damage the amplifier stages in the transmitter.

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{5.6}$$

Reflected power in terms of VSWR:

$$|\Gamma|^2 = \left(\frac{VSWR - 1}{VSWR + 1}\right)^2 \tag{5.7}$$

Transmitted power:

$$|T|^2 = 1 - |\Gamma|^2 \tag{5.8}$$

Matching Networks have disadvantages. They add cost, weight, and power loss to a system and can decrease the bandwidth of the antenna system.

All the equipment used to perform the experiments for this thesis had an input impedance of 50 Ω. The input resistance of the half-wavelength dipole is approximately 73 Ω and so a standard coaxial feed-line of 75 Ω would be well suited for this antenna. On the other

hand, the quarter-wavelength monopole has an input resistance of approximately 37 Ω and so could be used with a standard 50 Ω coaxial line. Thus a matching network would be very necessary to use with the measuring equipment, if a half-wavelength dipole was used.

5.4.2 Challenges of Feeding the Dipole Antenna

At UHF and low microwave frequencies, distributed tuning devices such as stubs are introduced to transform the real part of the impedance to that of the transmission line as well as tuning out the reactive components. Now two different types of cables could be used to feed a dipole, namely; the open-wire line and the coaxial cable. Open-wire lines are balanced transmission lines and have high-power handling capability and low loss. Now at ultra-high frequencies (UHF), parallel wire lines are seldom used because the spacing between the conductors becomes electrically large enough to disturb the transmission line behavior of the line, i.e., radiation by the transmission line may occur [51]. On the other hand coaxial cables are unbalanced transmission lines and so a *balun* (balanced to unbalanced transformer) is used. The *balun* transforms the balanced input impedance of the dipole to the unbalanced impedance of the coaxial line such that there is no net current on the outer conductor of the coaxial cable. Now the use of *baluns* adds cost, weight, and power loss to a system and can also decrease the bandwidth of the antenna system [51].

5.5 The Coaxial Collinear Antenna

A cophased collinear array is a type of broadside array. Collinear is to mean that the elements lie on the same line, and phased, to mean that the currents in all elements are

substantially in-phase, so that all elements reinforce the field strength broadside to the array.

Broadside arrays can be made up of collinear or parallel elements or combinations of the two. Collinear arrays are always operated with the elements in-phase. (If alternate elements in such an array are out-of-phase, the system simply becomes a harmonic type of antenna). A collinear array is a broadside radiator, the direction of maximum radiation being at right angles to the line of the antenna [50].

It must be noted that the basic building block of this type of antenna consist of several series connected resonant half-wave radiators and make each radiator to launch the RF wave in Phase. Since the dipole has two poles (the positive pole and the negative pole), we need something to reverse the poles (Phase) of the succeeding dipole so that wave cancellation will not occur. To accomplish this phase reversal, a phase reversal line (called phasing harness or phasing stub) must be used to connect between each dipole. One such line is the shorted ¼ wave stub. When several dipoles are connected in this manner, the antenna assembly is called a **collinear (or co-linear) antenna array.** This array of dipole antennas is mounted in such a manner that every element is an extension, with respect to its long axis. The primary purpose is to increase the overall gain and directivity [49].

In the VHF and UHF region, a collinear array is usually mounted vertically. When stacks of ½ λ elements are added one on top of the other, the gain and directivity is increased in the horizontal direction. The shorted phasing stub separates the ½ λ elements and reverses the phase angle of the RF wave developed in the next stack. This will make all

the elements radiate in the same phase as the first below it, all in unison, hence the apparent gain. If another half-wave pair of elements are added, this will increase the horizontal gain by as much as 3dBi (see Figure 5.3 below).

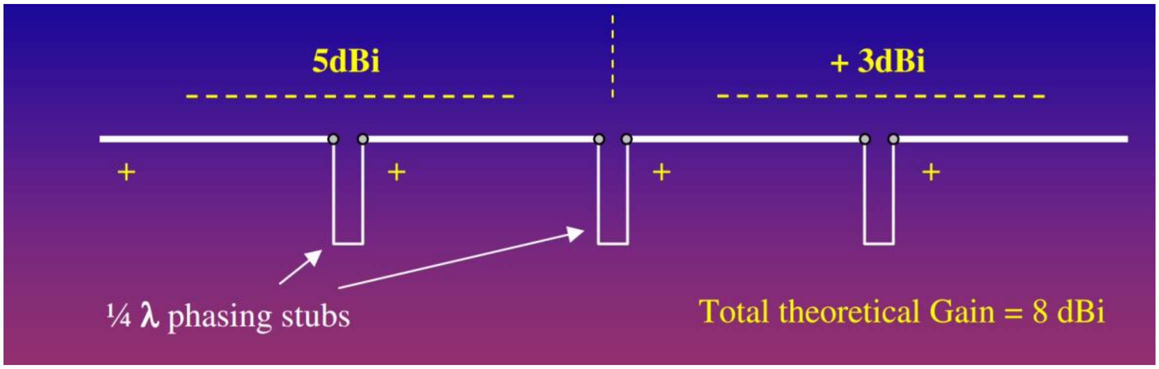

Figure 5.3: A 4-element collinear antenna array [49].

Any number of dipoles may be added as desired. This however will depend on available space and height limitation. In the UHF region, about eight or more can be stacked. Doubling the number of dipoles to that shown in Fig. 5.3 will give an additional gain and directivity of 3dBi [49].

Figure 5.4 shows a coaxial collinear antenna construction which requires the transposition of the feed system to make the dipoles radiate in phase. Here, a coaxial transmission line is cut to half-wavelength dipoles and then connected end to end by transposing the inner leads and coax shield alternately from one dipole stack to the next to radiate RF energy in phase. At the end of the last dipole, a quarter-wave radiator is connected to the center lead. The construction details are shown in Figure 5.4 A, B and C. In this design, toroids were used in place of a *balun* [49].

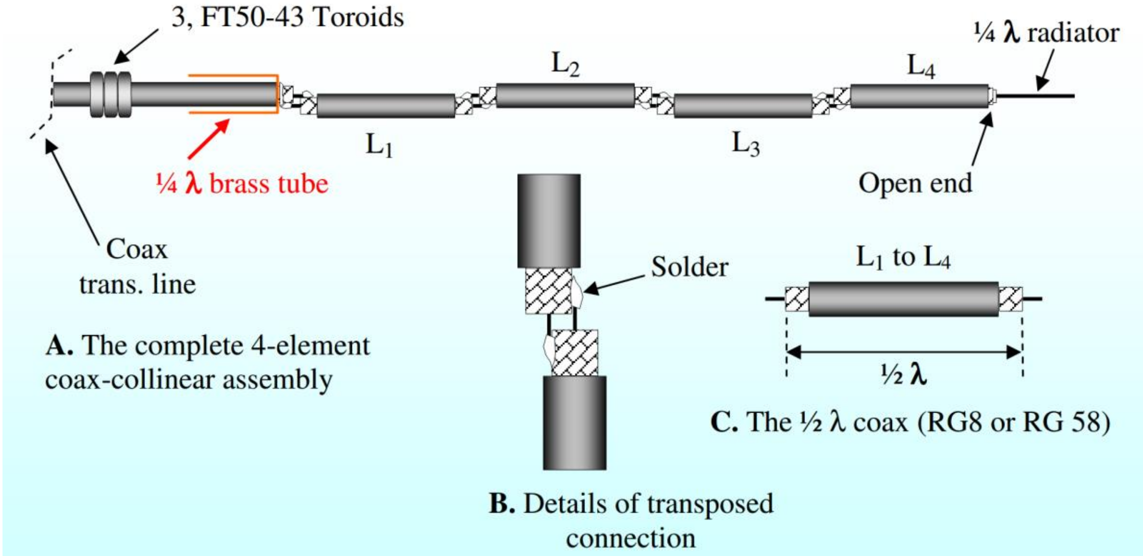

Figure 5.4: A 4-element collinear antenna using coaxial transmission line. Gains of 5-6 dBi (4 elements) and 8-9 dBi (8 elements) can be achieved [49]

The length of the quarter-wave radiator at the top and the brass tubing is calculated as true ¼ λ in free space (no velocity factor). The whole assembly can be hanged inside a blue PVC tubing for weather protection and mounted vertically [49].

5.5.1 Radiation Pattern of the Coaxial Collinear

The radiation pattern of the coaxial collinear antenna is similar to that of the dipole but is dependent on the number of elements or stacks of series connected resonant half-wave radiators and also the distance between each of these dipole radiators. Figure 5.5 shows the matlab plots for the radiation pattern of collinear antennas. The matlab codes for these plots are in the Appendix. From Figure 5.5 it can be seen that the directivity of a collinear array, in a plane containing the axis of the array, increases with its length. Small secondary lobes appear in the pattern when more than two elements are used.

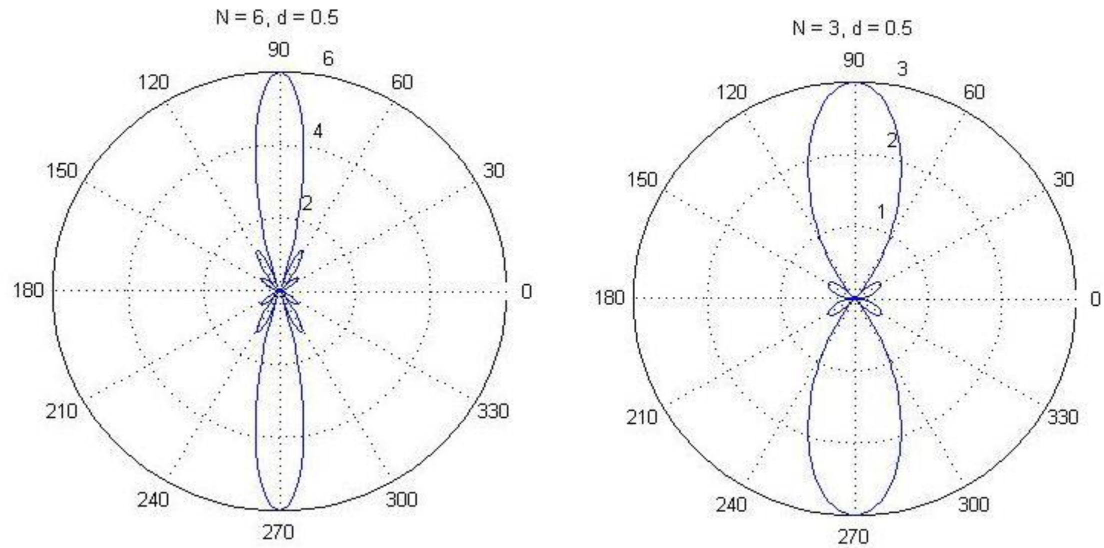

Figure 5.5: A 3- and 6-element collinear antenna radiation pattern.

5.5.2 Mutual Impedance and Gain of the Coaxial Collinear

When power is applied to one of two λ/2 elements that are fairly close to each other, causing current to flow, an electromagnetic field is created. This electromagnetic field induces a voltage in the second element and causes current to flow in it as well. The current flowing in element 2 will in turn induce a voltage in element 1, causing additional current to flow there. The total current in 1 is then the sum (taking phase into account) of the original current and the induced current [50].

With element 2 present, the amplitude and phase of the resulting current in element 1 will be different than if element 2 were not there. This indicates that the presence of the second element has changed the impedance of the first. This effect is called mutual coupling. Mutual coupling results in mutual impedance between the two elements. The mutual impedance has both resistive and reactive components. The actual impedance of

an antenna element is the sum of its self-impedance (the impedance with no other antennas present) and its mutual impedances with all other antennas in the vicinity.

The magnitude and nature of the feed-point impedance of the first antenna depends on the amplitude of the current induced in it by the second, and on the phase relationship between the original and induced currents. The amplitude and phase of the induced current depend on the spacing between the antennas and whether or not the second antenna is tuned to resonance [50].

The induced current can range all the way from being completely in-phase with the original current to being completely out-of-phase with it. If the currents are in-phase, the total current is larger than the original current and the antenna feed-point impedance is reduced. If the currents are out-of-phase, the total current is smaller and the impedance is increased.

The coupling between collinear antennas is comparatively small, and so the mutual impedance between such antennas is likewise small. It is not negligible, however.

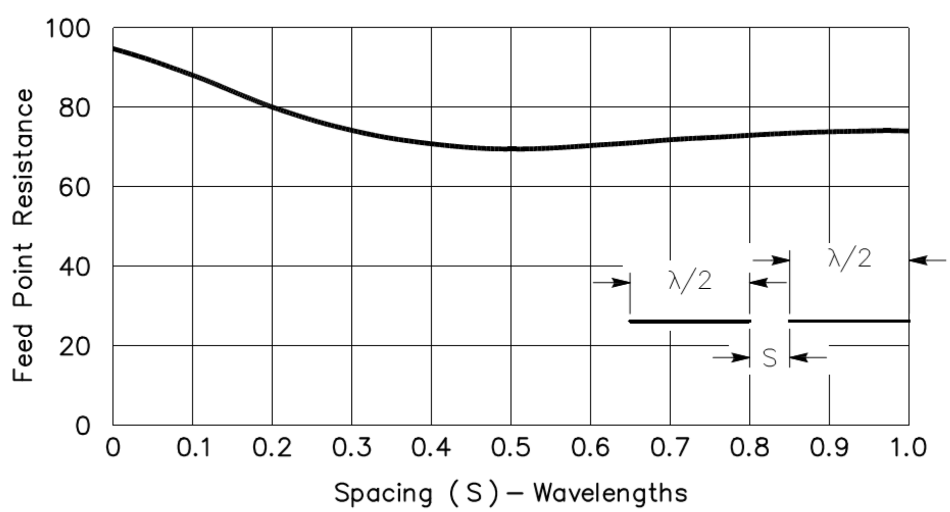

Figure 5.6: Feed-point resistance of two collinear λ/2 elements as a function of spacing between the adjacent ends [50].

Figure 5.6 above shows the feed-point resistance measured at the center of one element as a function of the spacing between the ends of two collinear self-resonant ½ λ antenna elements operated in phase. Figure 5.6 shows that the feed-point resistance decreases and goes through a broad minimum in the region of 0.4 to 0.6-λspacing between the adjacent ends of the antennas. As the minimum is not significantly less than the feed-point resistance of an isolated antenna, the gain will not exceed the gain calculated on the basis of uncoupled antennas. That is, the best that two collinear elements will give, even with optimum spacing, is a power gain of about 2 (3 dB) [50]. When the separation between the ends is very small—the usual method of operation—the gain is reduced.

Because of the nature of the mutual impedance between collinear elements, the feed-point resistance (compared to a single element, which is $\approx 73\Omega$) is increased as shown in the Figure 5.6 above. For this reason the power gain does not increase in direct proportion to the number of elements. The gain with two elements, as the spacing between them is varied, is shown in the Figure 5.7 below. Although the gain is greatest when the end-to-end spacing is in the region of 0.4 to 0.6 λ, the use of spacing of this order is inconvenient during construction and introduces problems in feeding the two elements [50]. As a result, collinear elements are almost always operated with their ends quite close together – in wire antennas, usually with just a strain insulator between.

With very small spacing between the ends of adjacent elements, the theoretical power gain of collinear arrays, assuming the use of #12 copper wire, is approximately as follows over a dipole in free space:

2 collinear elements – 1.6 dB

3 collinear elements – 3.1 dB

4 collinear elements – 3.9 dB

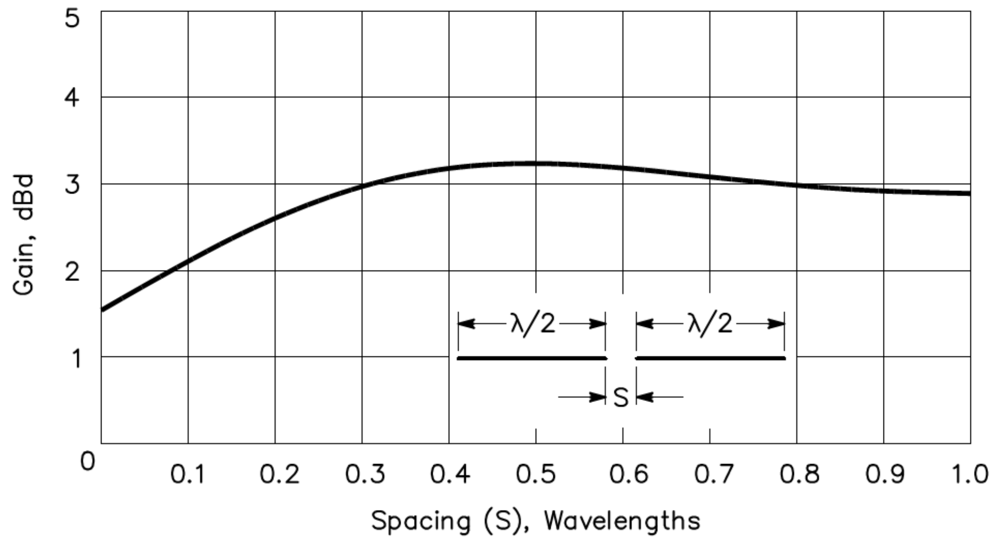

Figure 5.7: Gain of two collinear ½ λ elements as a function of spacing between the adjacent ends [50].

5.5.3 Challenges of Matching and Feeding the Coaxial Collinear

Let us consider a 2-element collinear dipole with the phasing quarter-wave stub connected as shown in Figure 5.8A. Now the shorted end of the stub has zero (or neutral) impedance. Thus the same stub can be used to inject RF energy into this quarter-wave line. The shorted ¼ λ stub is useful when loading the feed point of antenna systems with unknown high feed impedance [49]. It is a balanced line and must be loaded also with balanced transmission lines (twin-lead 300 Ω, 600 Ω or any other open-wire line). Now as mentioned earlier in this chapter, at UHF, parallel wire lines are seldom used because the spacing between the conductors becomes electrically large enough to disturb the transmission line behavior of the line. Also they are usually not readily available. Using

an unbalanced coaxial line (RG58 or RG8 cable) to feed the stub requires a Balance to Unbalance contraption, called “BALUN”, which we discussed above.

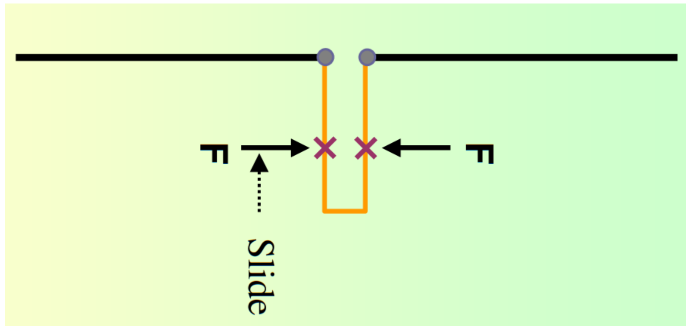

Figure 5.8: Matching and feeding RF energy in collinear antennas using a stub [49].

To match the line, say 300 Ω, to the 300 Ω point in the stub, you have to slide the connection point from zero (shorted end) to a distance equal to 300 Ω impedance. An antenna analyzer or SWR meter can then be used to find the correct match. This is when the Voltage Standing Wave Ratio (VSWR) reading is lowest. If the dipoles are equally resonant, VSWR readings at the correct matching point and frequency will be 1:1 ratio or close to that value [49].

From the discussions of the quarter-wave monopole, the half-wave dipole and the coaxial collinear antenna, it can be seen that despite the fact that the coaxial collinear antenna had better directivity and thus gain, it had the disadvantages of feeding, cost, weight and size characteristics. These disadvantages which are attributed the coaxial collinear are also similar to those of the dipole when compared to the monopole. The monopole on the other hand had a suitable gain, directivity, and radiation pattern necessary for the experimental measurements. These measurements will be discussed in the next chapter.

CHAPTER SIX

EXPERIMENTAL MEASUREMENTS

6.1 The Monopole Antenna Construction

Two quarter-wavelength monopole antennas were constructed with a semi-rigid coaxial cable and a circular copper sheet to act as the ground plane. The solid outer conductor and the dielectric were stripped from the rigid coaxial cable up to a length a little longer than the required quarter-wavelength needed for the monopole antenna. The radius of the circular ground plane was made to be a quarter-wavelength.

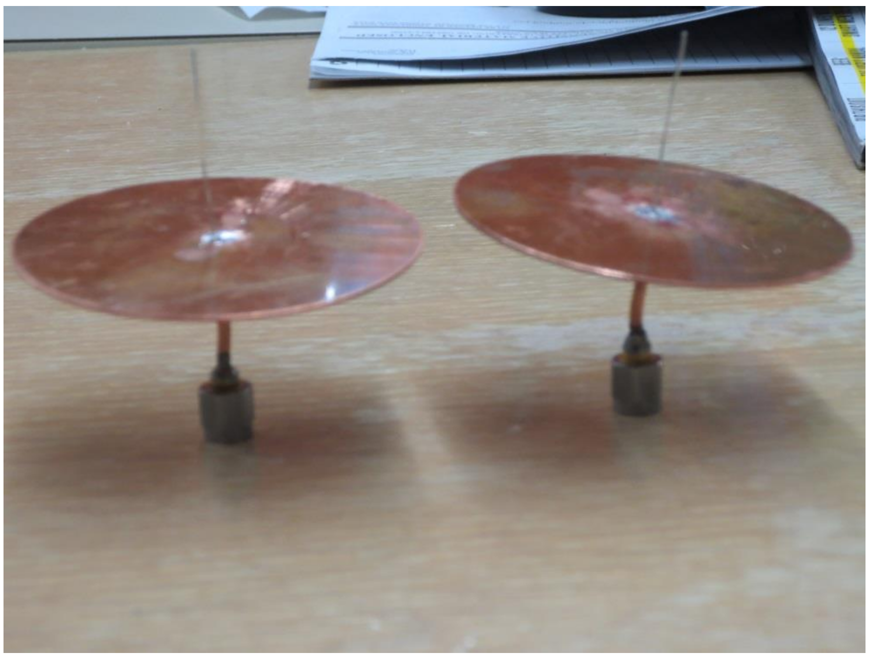

Figure 6.1: The Monopole Antennas used for the experiment

The ground plane was then soldered to the outer conductor of the semi-rigid coaxial cable exactly at the end of the exposed center conductor (the point where the cable was stripped

up to). A male SMA connector was then attached to the other end of the semi-rigid coaxial cable to be able to connect the antenna to a network analyzer or spectrum analyzer.

After constructing both monopole antennas, it was discovered that they were not exactly identical. One of the monopole antennas was resonant at 2.436 GHz while the other monopole antenna was resonant at 2.416 GHz. Thus a middle frequency of 2.425 GHz was chosen for the transmitting signal.

6.2 Experimental Measurement Setup

The measurement setup consists of the transmitting unit and the receiving unit. The transmitter hardware was located on a wheeled trolley at a height of approximately 3 ft to avoid body effect, and consisted of an Agilent 8753ES Vector Network Analyzer (VNA) supplying a 0 dBm narrowband signal at a frequency of 2.425 GHz and an omnidirectional quarter-wavelength monopole antenna attached to one of the ports of the VNA. Data was collected from the VNA with a diskette drive.

The receiver hardware located on a cart, consists of a HP 8593E Spectrum Analyzer (SA) set to receive at a frequency of 2.425 GHz with a span of 1M Hz. The second monopole antenna is attached to the input port of the SA. Data was collected from the SA with a digital camera.

The length and type of coaxial cables used to connect the VNA to one antenna and also the SA to the other antenna were also considered so as to further reduce the transmission loss. Also the use of SMA adapters was also avoided since they also introduce connector losses to the measurement system. The cables used for this experiment were Ultra Low-

loss Double Shielded MILSPEC LMR195 Coaxial Cables and they were 6 ft long. The connectors at both ends of the cables were gold plated which was suitable for the experiment, since the VNA and SA female connector terminals were also gold plated.

Figure 6.2: Measurement Setup

6.3 Measurement Campaign

In order to study the effects of an indoor environment on transmitted and received electromagnetic waves and also identify those areas in the building where coverage could be weak, a measurement campaign was carried out in a typical multi-storied campus building in the Department of Engineering and Mathematical Sciences (EMS), University of Wisconsin Milwaukee.

Before the measurements were taken, the VNA was set to the frequency range of interest (2.425 GHz) and was calibrated with a HP 85033D Calibration Kit so as to improve measurement accuracy. The VNA was used to measure the complex one port reflection coefficient S11 or simply Γ. This was done in order to reduce the return loss or reflection

of the antennas. The dimensions and some properties of the two monopole antennas, measured from the VNA, are listed in Table 6.1.

Figure 6.3: VNA Calibration Kit

Table 6.1: Some properties of the Monopole Antennas

	Resonant Frequency	Input Impedance	SWR	Log Magnitude
Antenna 1	2.436 GHz	42 + j26 Ω	1:1.79	-10.7 dB
Antenna 2	2.416 GHz	42 + j30 Ω	1:1.90	-9.82 dB

At 2.425 GHz, Antenna 1 had an SWR of 1.83 and an input impedance of 32.6 + j17.18 Ω while Antenna 2 had an SWR of 1.91 and an input impedance of 50.1 + j34 Ω. Now for most antenna experiments, one of the major goals is to match the antenna impedance with that of the VNA (50 Ω) so as to reduce return losses and thus increase antenna gain. On the other hand, in this experiment matching the antenna impedance is not of paramount importance, since we are mainly interested in studying the extent of wave propagation losses of the typical indoor environments of interest in the aforementioned

building. Thus the above properties of the constructed antennas were very suitable for this experiment.

The different typical indoor scenarios that were considered include: a semi-open area (1^{st} floor), a long narrow corridor (5^{th} floor), two wide corridors (On 2^{nd} floor), three engineering labs (two electronics labs and one power engineering lab), and a computer lab. Also measurements were taken between different floors of the EMS building. These environments were analogous to easy, medium and hard propagation environments and so were selected for the measurement campaign.

The semi-open area chosen for this experiment was the 1^{st} floor of the EMS building which is composed of mostly classrooms and wide corridors to the east and to the west of the floor. The semi-open area had a room height of approximately 10 ft 8" and is 18 ft wide. The transmitter and receiver were placed at a distance of 44 ft apart and at a height of approximately 3 ft above the floor. Therefore, LOS and wall reflected NLOS propagation paths were present between both antennas.

Measurements were taken in two corridors on the 2^{nd} floor. One corridor was 10 ft wide, 8 ft high and 70 ft long. Where the transmitter was located on this corridor had a width of 20 ft for a distance of 20 ft. This corridor was in a classroom environment. The other corridor was 8 ft high and 8 ft wide and 85 ft long. This corridor was in a lab and office environment. In both cases, measurements were taken at 10 ft intervals. Measurements were also taken in a narrow closed corridor on the fifth floor at 3ft intervals. The 5^{th} floor was 5 ft 7" wide, 80 ft long, and 8 ft 10" high. This corridor was in an office environment. Now since the objective of this experiment is to determine the effect of

location to the channel fading, the received power measurements were made by fixing the transmitter in a suitable place and moving the receiver to different locations.

In order to see the effect of lab environments on the received power from a transmitter, measurements were taken in a Computer Lab on the second floor. The transmitter was placed at one corner of the Lab while the receiver location was changed to the remaining three corners of the lab. This Lab was 13 ft high, 30 ft long and 28 ft 11” wide. Measurements were taken in two electronics labs and one power engineering lab all on the second floor. For one of the electronics labs, the receiver was placed in three corners of the lab while the transmitter was left fixed, at the fourth corner. The lab was 13 ft high, 30 ft long and 21 ft 5” wide. Measurements in the second electronics and power engineering labs were taken at 6 ft intervals and with the door closed. Both labs were 13 ft high, 29 ft 7” long and 19 ft 5” wide. Now for the last three labs mentioned, measurements were also taken with the receiver in front of the door outside the lab, and with the door open and closed in all cases. This was done in order to see the effect of an open door and a closed door on received signal power.

In order to see the effect of concrete walls and floors on signal propagation and received signal power, measurements were taken between the last three labs (the two electronics and the power engineering labs) mentioned above. The transmitter was placed in the Power electronics lab while the receiver position was changed between the two electronics labs. The first electronics lab had an office between it and the transmitter location, thus it had two walls and other obstacles separating it from the transmitter. The second electronics lab was next to the transmitter location and so having just one wall separating the antennas. Measurements were also taken between the 12^{th} and 11^{th} floor

and between the 12th and 10th floor with the transmitter on the 12th floor and the receiver on the other floors. The 10th to 12th floors were made up of narrow corridors with offices on one side and labs on the other. The receiver was placed in the middle of the corridor on the 12th floor while the receiver was placed at approximately the same location, just below the transmitter on the corridor of the 10th and 11th floors. These corridors had the same dimensions as that of the 5th floor. Measurements were taken between the 3rd and 2nd floor and between the 3rd and 1st floor. The transmitter was placed in a narrow corridor on the 3rd floor. The narrow corridor had a height of 7 ft and a width of 15 ft. Finally, Measurements were taken between the 5th and the 3rd floor, with the transmitter on the 5th floor and the receiver on the 3rd floor.

These measurements were taken during weekends and late in the evenings to reduce the noise created by human body movement on received signals.

6.4 Measurement Results and Analysis

The results of this experiment are a basic and general guide to understanding the effects of walls, windows, doors, floors and many other obstacles on indoor radio propagation and thus assist an indoor radio planner in planning the antenna locations.

In all measurement cases, the total received power (in dBm) and the occupied bandwidth (OBW) (which is 99% of the power bandwidth) were measured. The power spectral density was also measured in all cases. To ensure that the VNA was transmitting a 0 dBm signal, the VNA and the SA were connected together with a coaxial cable, and the received signal power was measured.

Figure 6.4 shows a sample of the measurement obtained from the spectrum analyzer. Here the channel power was measured, and signal of interest can be seen in the middle of the display close to the top of the screen. The received total power from this display is -61.02 dBm and the power spectral density is -121.02 dBm/Hz.

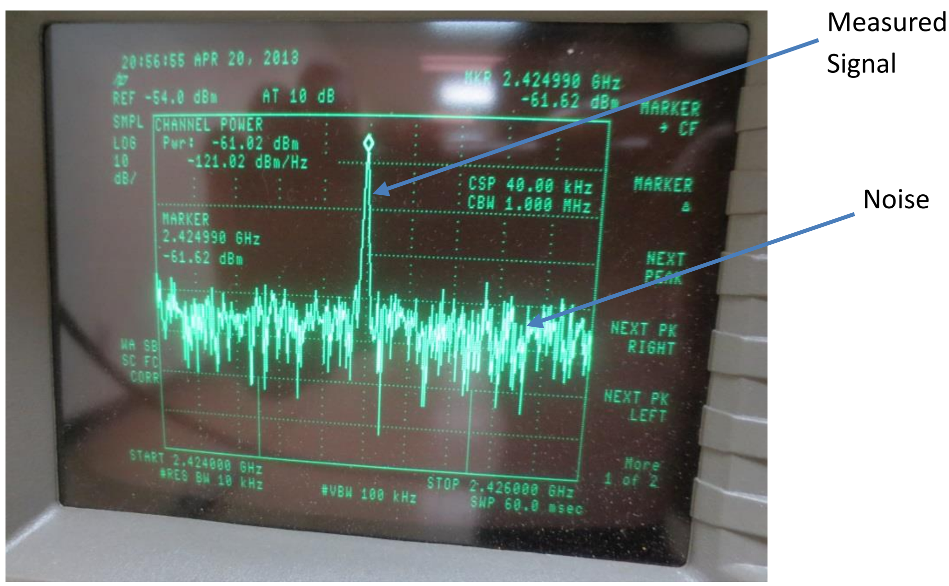

Figure 6.4: Channel Power Measurement Display from Spectrum

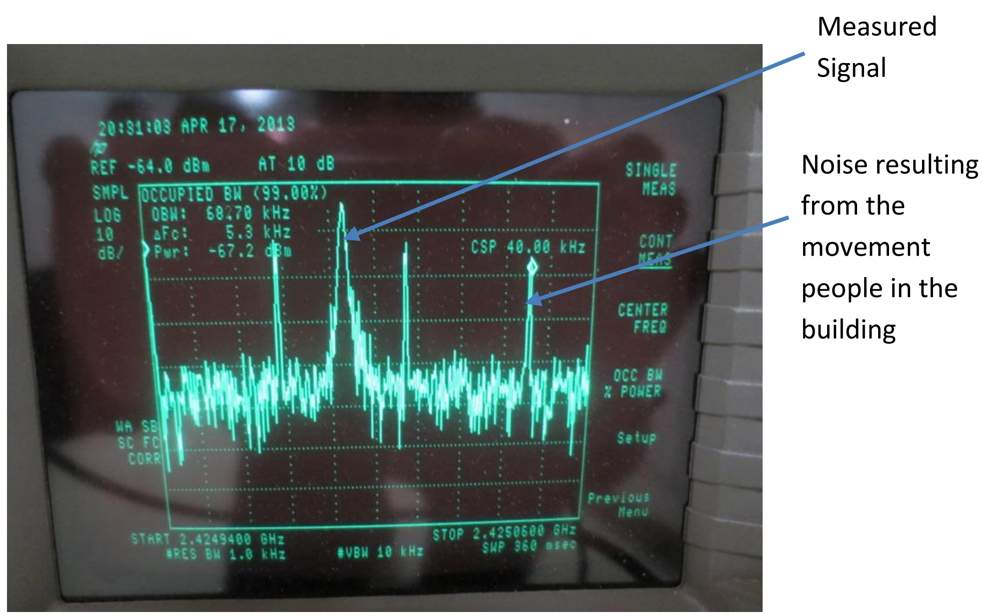

Figure 6.5: Occupied Bandwidth Measurement display from Spectrum

Figure 6.5 shows a sample measurement of occupied bandwidth from the SA display. The measured signal can be seen in the middle of the display. The other signal spikes are as a result of the noise produced by the movement of people in the EMS building during measurement rounds. This is one of the reasons why measurements were taken late in the evenings on weekends with little or no one present.

Table 6.2 below shows the results obtained from the semi-open area and corridor measurements taken on the 1st floor, the two corridor measurements taken on the 2nd floor, and the narrow corridor measurement taken on the 5th floor. These measurements were taken in LOS propagation paths. It can be observed that as the distance between the transmitter and receiver increased, the total received power reduced. Also in the case of the open area, as the distance increased, the occupied bandwidth of the channel increased due to signal reflection and noise from the environment.

Table 6.2: Semi-Open Area and Corridor Measurements

Location	Power Spectral Density	Distance between Tx and Rx	Total Received Power	Occupied Bandwidth
Semi-Open Area on 1st floor	-105.62 dBm/Hz	8 ft	-44.70 dBm	6.80 kHz
	-114.34 dBm/Hz	20 ft	-50.60 dBm	8.60 kHz
	-127.94 dBm/Hz	42 ft	-63.65 dBm	58.80 kHz
2nd Floor Corridor (class room area)	-120.05 dBm/Hz	10 ft	-50.32 dBm	6.00 kHz
	-122.43 dBm/Hz	20 ft	-54.41 dBm	6.10 kHz
	-124.52 dBm/Hz	30 ft	-57.36 dBm	6.00 kHz
	-126.02 dBm/Hz	40 ft	-67.70 dBm	6.00 kHz
2nd Floor Corridor (Lab and Offices	-124.32 dBm/Hz	10 ft	-45.70 dBm	4.50 kHz
	-125.51 dBm/Hz	20 ft	-48.30 dBm	4.50 kHz
	-127.23 dBm/Hz	30 ft	-50.60 dBm	4.60 kHz

area)	-128.35 dBm/Hz	40 ft	-58.05 dBm	5.40 kHz
5th Floor Corridor (Offices area)	-100.85 dBm/Hz	20 ft	-57.70 dBm	4.80 kHz
	-108.34 dBm/Hz	40 ft	-68.20 dBm	4.50 kHz

The power spectral density, which is the ratio of total average power to bandwidth, can be seen to be increasing with increasing distance. Figure 6.6 shows an extract from the floor plan of the 1st floor. The red marker (x) indicates the position of the transmitter while the blue marker (x) shows the different positions of the receiver. The corridors to the right and left of the semi-open area, together with other obstacles (which are not shown in the floor plan), can further explain the increase in occupied bandwidth of the channel.

Also comparing the data of the two 2nd floor corridors, it can be observed that the classroom area corridor had more power losses mainly because the transmitter was located in the wider area of the corridor. Figure 6.7 shows an extract from the floor plan of the 2nd floor. The red marker (x) is the transmitter location while the blue markers (x) are the different receiver locations.

When the received power measurements of the 20 ft and 40 ft transmitter and receiver distances of the 2nd floor corridor (lab and offices area) and the 5th floor corridor are compared, it can be seen that there is reduction in power in the 5th floor. This is because the 5th floor has a narrower corridor and so there is increased amount of reflections from the walls. Figure 6.6 shows an extract from the 5th floor plan. These measurements were taken with all office doors closed.

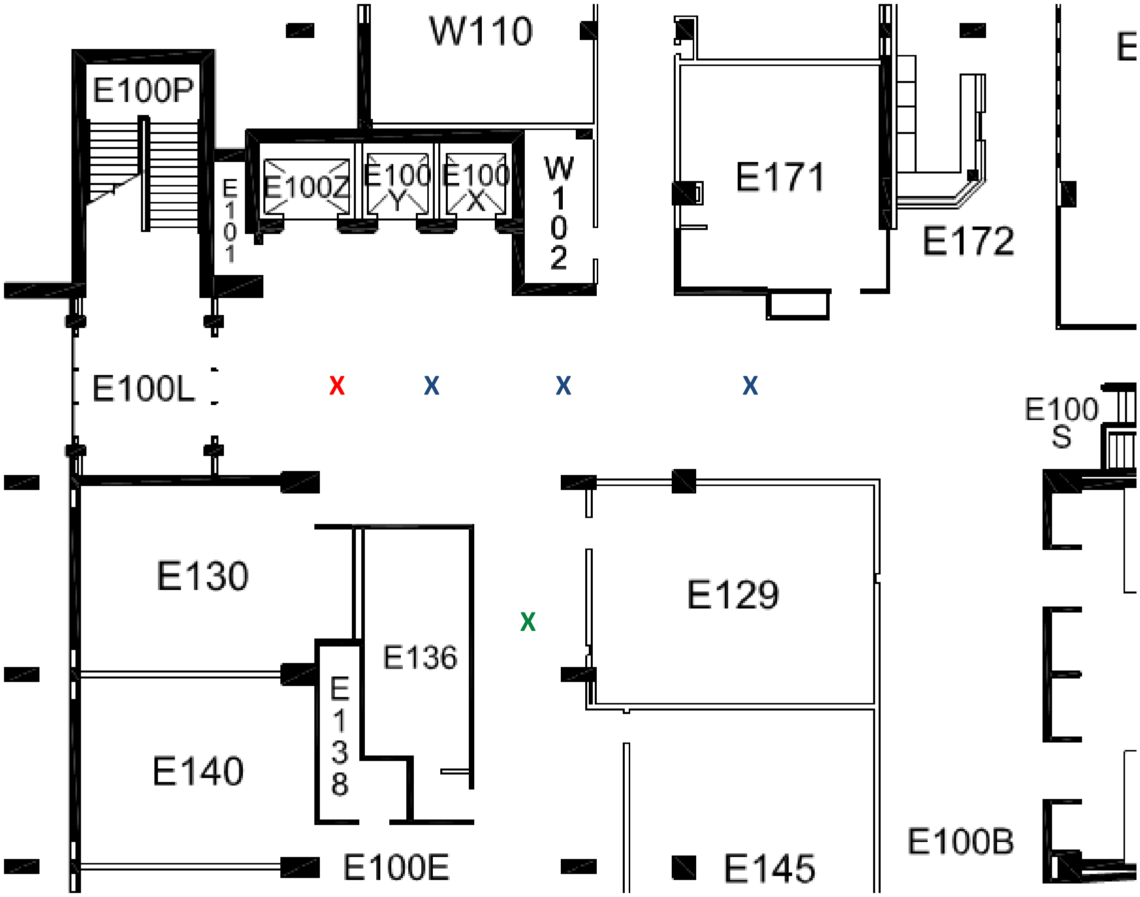

Figure 6.6: Extract from the floor plan of 1st floor

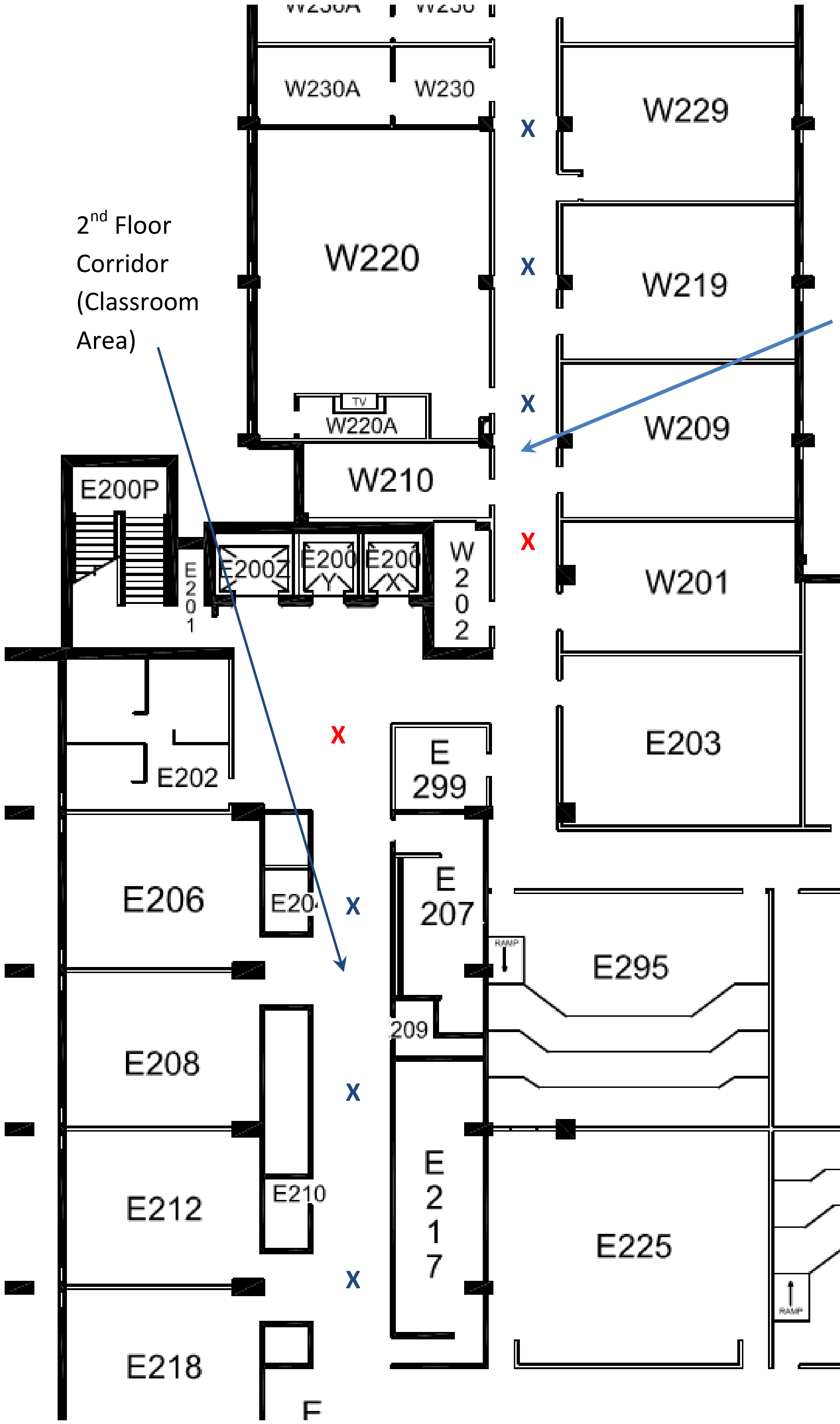

Figure 6.7: Extract from the floor plan of 2nd floor

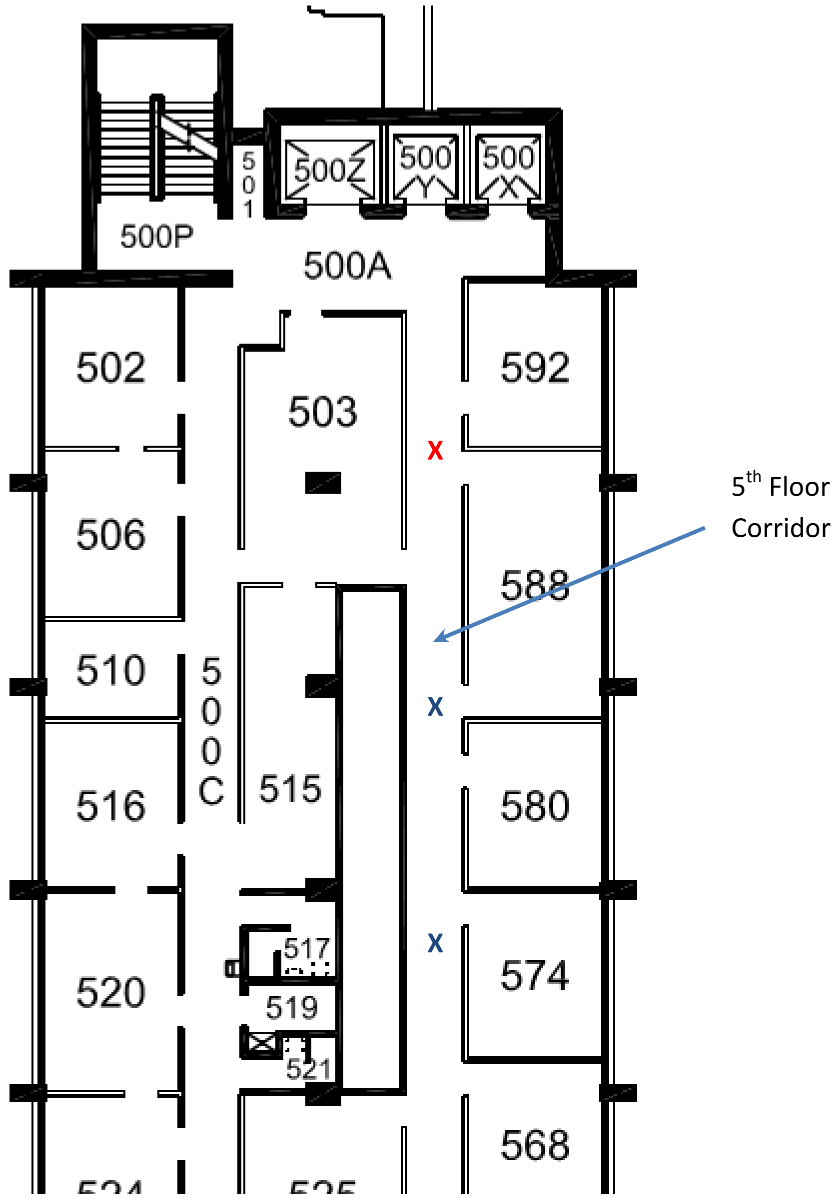

Figure 6.8: Extract from floor plan of 5th floor

It can be observed from table 6.3 that the occupied bandwidth measured in the computer lab on 2nd floor is higher when the transmitter and receiver are placed diagonally across the room. Also the received total power is much higher in the same case. This is because the computers, tables and chairs in the room reduce the LOS propagation path and thus these surfaces cause signal reflection and multipath fading. The same phenomenon

happens in the Electronics Lab (E203) on 2nd floor. The received total power for all the measurement scenarios in the former, are less than that of the later because the Computer Lab is larger than the Electronics Lab (E203) and thus has more obstacles in its propagation path than the Electronics Lab (E203) does.

Also from Table 6.3, the difference can be noticed between the 24 ft (Open Door) and 24 ft (Closed Door) measurements in Electronics Lab (W219) and Power Engineering Lab (W209) both on the 2nd floor. The occupied bandwidth for the closed door scenario is higher than that of the open door scenario. The received total power for the closed door scenario is less than that of the open door scenario. Both labs have the same dimensions but because of the huge difference in the equipment and arrangement of each lab, the open and closed door received total power of the Electronics lab (W219) are larger than those of the open and closed door scenarios of the Power Engineering Lab (W209).

Table 6.3: Laboratory Room Measurements on the 2nd floor of the EMS Building

Location	Power Spectral Density	Distance between Tx and Rx	Total Received Power	Occupied Bandwidth
Computer Lab on 2nd Floor	-105.43 dBm/Hz	1st corner	-53.70 dBm	6.80 kHz
	-124.26 dBm/Hz	2nd corner (diagonal)	-70.60 dBm	87.60 kHz
	-113.35 dBm/Hz	3rd corner	-59.32 dBm	6.00 kHz
Electronics Lab (E203) on 2nd Floor	-108.67 dBm/Hz	1st corner	-34.0 dBm	6.90 kHz
	-122.23 dBm/Hz	2nd corner (diagonal)	-51.10 dBm	115.80 kHz
	-114.46 dBm/Hz	3rd corner	-49.62 dBm	24.00 kHz
Electronics Lab (W219) on 2nd Floor	-102.53 dBm/Hz	6 ft	-42.0 dBm	4.80 kHz
	-109.64 dBm/Hz	13 ft	-45.50 dBm	3.90 kHz
	-120.65 dBm/Hz	18 ft	-53.70 dBm	4.80 kHz
	-124.35 dBm/Hz	24 ft (Open Door)	-58.4 dBm	4.80 kHz

	-128.61 dBm/Hz	24 ft (Closed Door)	-69.5 dBm	78.90 kHz
Power Engineering Lab (W209) on 2nd Floor	-100.85 dBm/Hz	6 ft	-40.85 dBm	4.80 kHz
	-108.34 dBm/Hz	13 ft	-46.00 dBm	4.50 kHz
	-115.14 dBm/Hz	20 ft	-51.10 dBm	4.50 kHz
	-118.68 dBm/Hz	24 ft (Open Door)	-62.0 dBm	6.60 kHz
	-125.45 dBm/Hz	24 ft (Closed Door)	-66.4 dBm	24.00 kHz

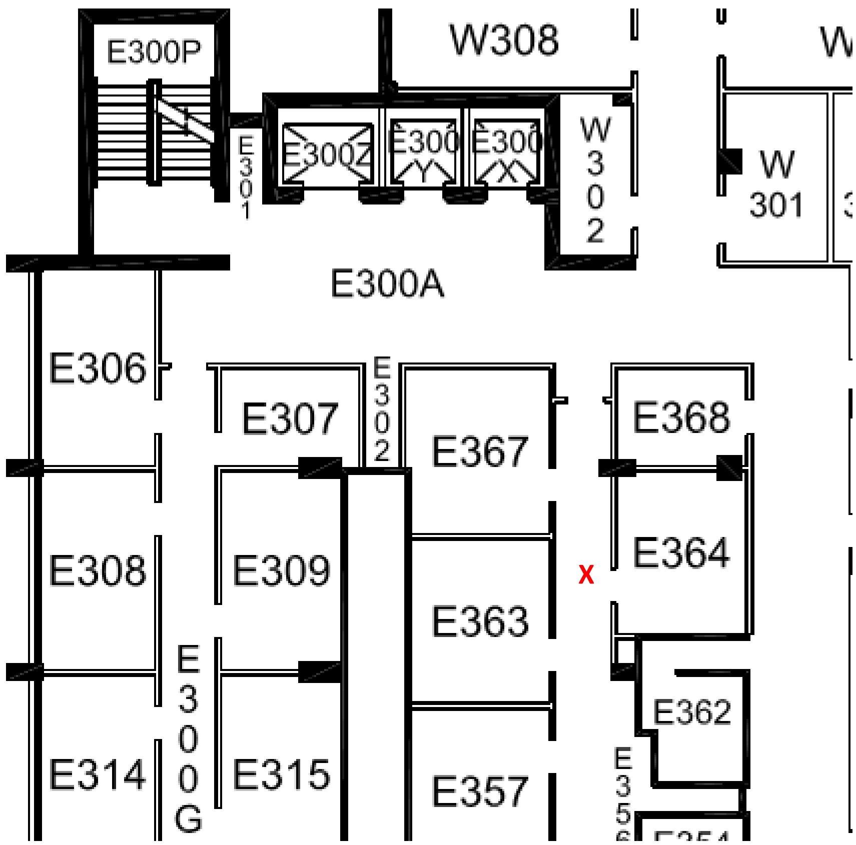

Figure 6.9: Extract from 3rd floor plan

Table 6.4 shows the data recorded from the measurements taken between the W209 and E203, and also between W209 and W219. Figure 6.7 shows the locations of these labs with W201 between W209 and E203. The reduction in received total power and increase

in occupied bandwidth can be seen between W209 and W219 when compared to that between W209 and E203.

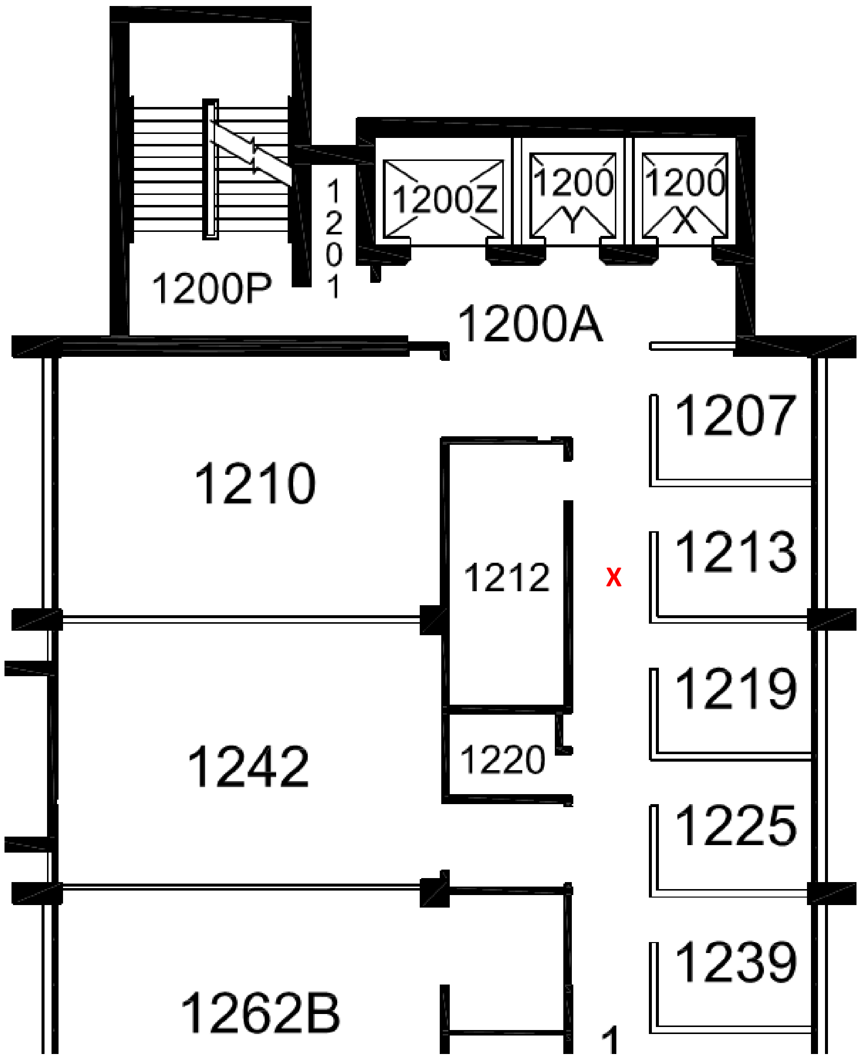

Figure 6.10: Extract from floor plan of 12th floor (similar to 10th and 11th floor plans)

Measurements were also taken between different floors of the EMS building. Figure 6.8 is an extract form the 3rd floor plan and shows the location of the transmitter (the position marked **x**). For measurements taken between the 3rd and 2nd floors, the receiver was placed on the position marked **x** in the 2nd floor corridor (classroom area) shown in Figure 6.7 above. Now it can be observed from the data in Table 6.4, that there is a lot of power

loss between the 2nd and 3rd floor and also a relatively high occupied bandwidth. There is also much more loss (reduction in received total power) when the receiver is placed in the green marker (x) position on the 1st floor shown in Figure 6.6. The same procedure was used for measurements between the 12th and 11th floors, 12th and 10th floors and also the 5th and 3rd floor. These measurement results also show how the received total power decreases and occupied bandwidth increases with increase vertical distance from the transmitter.

It can be seen from Table 6.4 that the lowest received total power occurs between the 5th and the 3rd floors. This is because the measured waves pass through more propagation paths (between both floors, above the 5th floor and below the 3rd floor) and undergo much more reflection and multipath fading from walls, floors and other obstacles than those measured between the 12th and 10th floor or between the 3rd and 1st floor.

Table 6.4: Measurement between Rooms and Floors

Transmitter Location	Receiver Location	Distance between Tx and Rx	Occupied Bandwidth	Total Received Power
Power Engineering Lab (W209)	Electronics Lab (E203)	40 ft (two walls in-between)	115.80 kHz	-70.10 dBm
	Electronics Lab (W219)	20 ft (one wall in-between)	6.90 kHz	-62.50 dBm
3rd Floor Corridor	1st Floor corridor		113.40 kHz	-84.64 dBm
	2nd Floor Corridor		95.40 kHz	-75.00 dBm
12th Floor	10th Floor		118.50 kHz	-82.40 dBm

Corridor	Corridor			
	11th Floor Corridor		98.40 kHz	-64.90 dBm
5th Floor Corridor	3rd Floor Corridor		118.90 kHz	-92.79 dBm

6.5 The Corridor Effect and Network Planning

One effect that is very important to know and utilize when placing antennas inside a building is the ‘corridor effect’. This is the distribution of coverage when placing an antenna in one of the most typical locations, the corridor. Now corridors mask out most of the antenna gain or directivity due to the reflections caused by the walls. Thus on narrow corridors, such as those on the 12th, 11th , 10th , 5th and 3rd floors, it makes more sense to install directional antennas at the end of these corridors. The advantages of locating an antenna or antennas in the corridor are the reason why most of the measurements above were taken either on corridors or between different floor corridors. These advantages include:

- Easy installation access to cable conduits in the corridors of the building, which will save implementation costs.
- Corridors are often ‘static’ when buildings are being refurbished, so the antennas are left in place with no impact of service degradation caused by refurbishment of the internal structure of the building.
- The users of the building are less concerned about radiation when they do not have antennas installed in the ceiling above their office desks.

- One can use the corridor to distribute the signal from the antenna since there is usually LOS throughout the corridor. This basically is what is known as the 'corridor effect'.

When planning indoor radio propagation using distributed antenna systems, antennas are chosen to match the environment.

6.6 Obstructed Path Loss in the EMS Building

Obstructed path loss is much more difficult to predict, especially for the myriad of different indoor scenarios and materials. Therefore, different path loss models exist to describe unique dominant indoor characteristics. Based on free space loss and the three propagation phenomenon, the path loss models also account for the effects of different in-building floor scenarios of the EMS building.

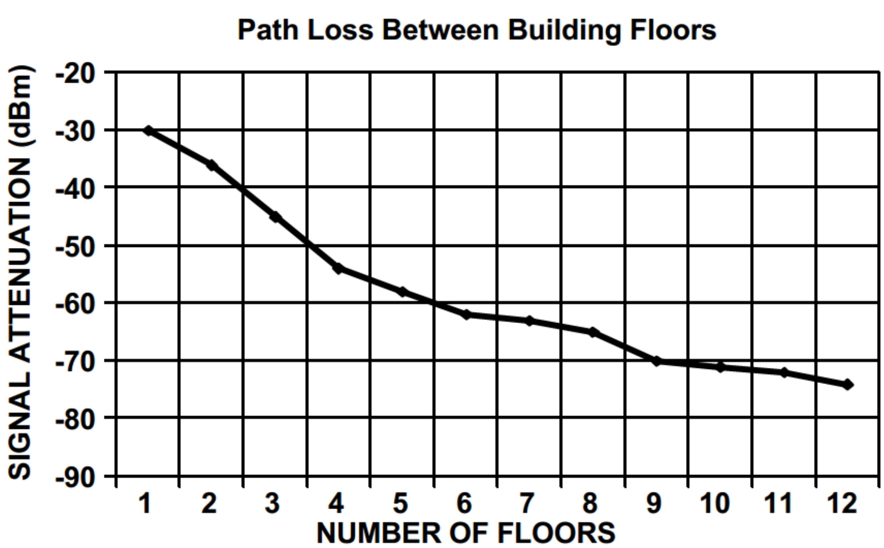

Figure 6.11: Multiple EMS building floors indoor path loss

From Figure 6.11, it has been shown that the propagation loss between floors begin to diminish with increasing separation of floors non-linearly. The attenuation becomes less per floor as the number of floors increases. This phenomenon is thought to be caused by diffraction of the radio waves alongside of a building as the radio waves penetrate the building's windows. Also, a variety of different indoor configurations can be categorized for buildings with enclosed offices like on the 5^{th} to 12^{th} floors of the EMS building and, or office spaces consisting of a mix of cubicles and enclosed rooms.

6.7 Sources of Error

There are errors in my measurement process which will be mentioned below. They include:

- Errors resulting from receiver and antenna noise. There were also errors due to the movement of people in the building.
- There are also errors resulting from the measurement of building dimensions, and the transmitter and receiver location coordinates.

CHAPTER SEVEN

CONCLUSION

The number of mobile broadband users are increasing at an accelerated pace and in the current competitive cellular market, extensive coverage, capacity and quality of service have become key factors in increasing end-user base. Earlier on, the focus on indoor network planning was rather limited. Nevertheless, with more and more users enjoying multimedia services via UMTS/HSDPA, typically inside buildings, operators get a business opportunity they can profit from by improving their network's indoor performance.

The main purpose of this thesis was to attempt to study the effect of location on channel fading in an indoor environment for the purpose of planning for UMTS/HSDPA indoor network coverage. The study was based on an extensive indoor signal measurement campaign carried out in the EMS building with a transmitter (comprising a VNA and a quarter-wave monopole antenna) and a receiver (comprising an SA and a monopole antenna). Different typical indoor environments were measured to evaluate the extent of signal losses due to noise and reflection during propagation.

The measurement results show that the amount of reflection and thus losses during wave propagation in corridors increases with increasing distance between the transmitter and receiver. It was also observed that measurements taken in narrower corridors had a lower received total power than those on wider corridors, as a result of increased reflection from walls. Furthermore, it was found that the amount of reflections and fading increased with the increase in vertical distance between the transmitter and receiver on different

floors. These loses between floors where seen to be much greater than those between walls or rooms. Thus radio wave obstacles in an indoor environment do have tremendous impact on the UMTS/HSDPA network. From the experimental measurements analysis above, it would be better to use more DAS resources on lower floors than on higher floors of the EMS building when planning the in-building network coverage.

Finally, the characteristics of the antenna can make a dramatic difference in range performance. This is also true regarding the sensitivity to propagation and fading. The biggest impact to range performance in in-building network propagation environments therefore is the choice of the antennas for the different building environments. With a properly selected antenna, the effects of multipath can be reduced and the range improved.

7.1 Future Work

In this thesis work, one of the things that was not put into consideration when analyzing the amount of received power loss during measurements is the construction materials of the walls, floors, doors and ceilings in the EMS building. It is very important to put building construction materials into consideration when analyzing path loss and fading in any indoor building.

Future measurement would have to be carried out from outdoor-to-indoor so as to measure the Received Signal Strength Indicator (RSSI) inside the building. Also it will be very necessary to measure the outdoor-to-indoor quality of the signal, i.e. the signal-to-noise ratio (E_c/I_o).

A distributed antenna system (DAS) will also need to be used for the experiment. Since the EMS building is a large building with 12 floors, the active DAS will have to be used.

Also from [2], the results indicated how significant increase in HSDPA throughput could be achieved if outdoor-to-indoor signal strength was raised to an adequate level via a repeater. An analog WCDMA repeater will be used to amplify or repeat the outdoor signal to indoor distributed antenna systems. Additionally, using a DAS with an increased the antenna density can further improve the network performance. These would be considered for future work when studying HSDPA performance improvement in the EMS building.

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APPENDIX

Matlab Codes for the Plots in Chapter 5

Code for the dipole radiation pattern

```
clear all;

% element numbers
N = 1;

% element spacing
d = 0.5;

% theta zero direction
% 90 degree for broadside, 0 degree for endfire.
theta_zero=0;

An=1;
beta = 2*pi;
j=sqrt(-1);
f = zeros(1,360);

for theta = 1:1:360

    % change degree to radian
    deg2rad(theta) = (theta*pi)/180;

    if theta == 180 || theta == 360
    % g = 0 if theta = 180 or 360
    g(theta) = 0;
    else

    % element pattern of dipole antenna
    g(theta) = abs(sin(deg2rad(theta)));

    end

    %array factor calculation
    for n=0:N-1
        f(theta) = f(theta)+
An*exp(j*n*(beta*d*cos(deg2rad(theta))+(theta_zero*pi/180))) ;
    end
    f(theta) = abs(f(theta));

    % pattern multiplication
    F(theta) = abs(g(theta)*f(theta));

end

figure(1)
```

```
polar(deg2rad,g)
title('Element Pattern of Dipole');

figure(2)
polar(deg2rad,f)
title('Array Factor');

figure(3)
polar(deg2rad,F)
title('Total Pattern of Dipole');
```

Code for the monopole radiation pattern

```
%This program print pattern for Short and any monopole Antenna by
giving the length of your Dipole
%and the wavelength you work with

lamda=input('enter the value of wave length= ');
l=input('enter your monopole length l= ');
ratio=l/lamda;
B=(2*pi/lamda);
theta= -pi/2:pi/100:pi/2;
if ratio<= 0.1             %check if Short Dipole
    E=sin(theta);
    En=abs(E);
    subplot(2,3,4)
    polar(theta,En)      %This plot polar pattern in plane which dipole
appear as line
else                     %check if not short dipole
    f1=cos(B*l/2.*cos(theta));
    f2=cos(B*l/2);
    f3=sin(theta);
    E=(f1-f2)./f3;
    En=abs(E);
    subplot(2,3,6)
    polar(theta,En)        %This plot polar pattern in plane which
dipole appear as line
end
```

Code for the coaxial collinear radiation pattern

```
clear all;

% element numbers
N = 6;

% element spacing
d = 0.5;
```

```
% theta zero direction
% 90 degree for broadside, 0 degree for endfire.
theta_zero=0;

An=1;
beta = 2*pi;
j=sqrt(-1);
f = zeros(1,360);

for theta = 1:1:360

    % change degree to radian
    deg2rad(theta) = (theta*pi)/180;

    if theta == 180 || theta == 360
    % g = 0 if theta = 180 or 360
    g(theta) = 0;
    else

    % element pattern of dipole antenna
    g(theta) = abs(sin(deg2rad(theta)));

    end

    %array factor calculation
    for n=0:N-1
        f(theta) = f(theta)+
An*exp(j*n*(beta*d*cos(deg2rad(theta))+(theta_zero*pi/180))) ;
    end
    f(theta) = abs(f(theta));

    % pattern multiplication
    F(theta) = abs(g(theta)*f(theta));

end

figure(1)
polar(deg2rad,g)
title('Element Pattern of Dipole');

figure(2)
polar(deg2rad,f)
title('Array Factor');

figure(3)
polar(deg2rad,F)
title('Total Pattern of Dipole');
```