

ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER  
ENGINEERING

**Dimensioning and Radio Network Planning of Mobile WiMAX: The  
Case of Addis Ababa**

By

Benyam Getenet

Advisor

Dr.-Ing. Dereje Hailemariam

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Approval by Board of Examiners

\_\_\_\_\_  
Chairman, Dept. Graduate  
Committee

\_\_\_\_\_  
Signature

Dr.-Ing. Dereje Hailemariam

Advisor

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Internal Examiner

\_\_\_\_\_  
Signature

\_\_\_\_\_  
External Examiner

\_\_\_\_\_  
Signature

**Declaration**

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

Benyam Getenet

\_\_\_\_\_

Name

Signature

Place: Addis Ababa

Date of Submission: \_\_\_\_\_

This thesis has been submitted for examination with my approval as a university advisor.

Dr.-Ing. Dereje Hailemariam

\_\_\_\_\_

Advisor's Name

Signature

## ABSTRACT

Mobile Worldwide Interoperability for Microwave Access (WiMAX) is a broadband wireless technology based on the IEEE 802.16e standard. It is designed to provide voice, data and video services that require high data rates for fixed, nomadic and mobile users moving at vehicular speeds greater than 120 km/hr.

Growth trends of voice and data traffic in various African countries reflect a huge increment in recent years. Currently deployed second and third generation telecommunication technologies will eventually struggle to swallow this perpetual traffic growth. This signals an eminent need to ultimately resort to deploying fourth generation (4G) technologies such as WiMAX that offer better throughput and coverage. This presents an opportunity/market potential for WiMAX or other 4G technologies.

In order to deploy WiMAX in any given metropolitan area, it is imperative to perform dimensioning and radio network planning steps. The IEEE 802.16e standard offers several options/choices in its physical and medium access control layers. Within these choices, this thesis work focuses on carving out a mobile WiMAX package that fits a pre-defined coverage and capacity requirement of Addis Ababa city. The basic dimensioning steps for the access and core network are outlined and conducted using the geographic and demographic data of the aforementioned city.

Radio network planning tools such as EDX-PRO and ATTOL cost in the order of thousands of US dollars. Therefore, in this research, a Radio Network Planning (RNP) tool/MATLAB program that operates on a selected propagation model and a digital terrain model database is developed and used.

This thesis work, to the best of my knowledge, is the first research/case study to be conducted taking capacity and coverage requirements of developing nations. It is also the first research that is not constrained to capacity and coverage planning via theoretical analysis. Theoretical coverage estimations make use of empirical propagation models without any special consideration to the specific terrain type. The development of the RNP tool allows us to perform a more accurate coverage analysis based on actual terrain parameters that are extracted from a digital map. The RNP tool is used on five distinct metropolitan areas with different terrain type, namely, Bole Medhanialem, Gerji, Meskel Square, Piassa and Sidist Kilo. The average coverage per base station is computed from the results of these five areas. This process is useful in forecasting the total number of base stations required to offer the service on every corners of Addis Ababa or a selected portion of the city.

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## ABBREVIATIONS/ACKRONYMS

AAA	Authentication, Authorization and Accounting
AAS	Advanced Antenna System
AES	Advanced Encryption Standard
ARQ	Automatic Retransmission Request
ASN	Access Service Network
BE	Best Effort
BS	Base Station
CC	Convolutional Codes
CDMA	Code Division Multiple Access
CPE	Consumer Premises Equipment
CSN	Connectivity Service Network
CTC	Convolutional Turbo Codes
DHCP	Dynamic Host Control Protocol
DL	Downlink
EAP	Extensible Authentication Protocol
EIRP	Effective Isotropically Radiated Power
Ert-PS	Extended Real-Time Polling Service
FDD	Frequency-Division Duplex
FDM	Frequency-Division Multiplexing
FEC	Forward Error Correction
HA	Home Agent
IP	Internet Protocol
LDPC	Low Density Parity Check
MAC	Medium Access Control
MAPL	Maximum Allowable Pathloss
MIMO	Multiple Input Multiple Output

MS	Mobile Station
NRM	Network Reference Model
Nrt-PS	Non-Real-Time Polling Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
QoS	Quality of Service
Rt-PS	Real-Time Polling Service
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
SS	Subscriber Station
STC	Space-Time Coding
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
UGS	Unsolicited Grant Service
UL	Uplink
VoIP	Voice Over IP
WiMAX	Worldwide Interoperability for Microwave Access

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# Chapter 1: Introduction

## 1.1 Introduction

Worldwide Interoperability for Microwave Access (WiMAX) is a telecommunications protocol that provides fixed and mobile Internet access [2]. It is based on the IEEE 802.16 standard which is mainly aimed at providing broadband wireless access. It may be considered as an attractive alternative solution to wired broadband technologies like the digital subscriber line and cable modem access. One of its main advantages is fast deployment, which in turn results in cost savings. Such installation can be beneficial in very crowded geographical areas like cities and in rural areas where there is no wired infrastructure. It is also capable of covering a range of several kms with a data rate of 75 Mb/s. This is a useful long term solution for elevating capacity limitation problems that mobile operators may face as well as providing a distended range at a reasonable cost per bit per coverage. The frequency band supported by the standard covers 2 to 66 GHz [1]. This helps in elevating radio frequency spectrum scarcity problems that mobile operators could potentially face.

Many cable, wireless, and traditional telephone companies are closely examining it, in active trials or small scale deployments, for "last mile" connectivity at high data rates. This could result in lower pricing for both home and business customers as competition lowers prices. In areas without pre-existing physical cable or telephone networks, WiMAX will be a viable alternative for broadband access that has been unavailable before [2].

WiMAX will change telecommunications, as it is known throughout the world today [2]. It eradicates the capacity and coverage scarcity that has sustained incumbent service providers in the past. As this technology enables a lower barrier to entry given its scalable and fast deployment, it will allow true market based competition in all of the major telecommunication services; namely, voice (mobile and static), video, and data.

There are multiple physical-layer choices within IEEE 802-16 standard. Examples include frequency band of operation, antenna configuration, architecture and duplexing. Similarly, there are multiple choices for medium access control (MAC). In fact, we could say that IEEE 802.16 is a collection of standards, not one single interoperable standard [5]. This flexible nature of the standard allows various operators to carve out their own distinct

WiMAX package that fits their specific need/demand mainly in terms of capacity and coverage requirements.

This thesis work focuses on dimensioning the access and core network parameters of mobile WiMAX so as to make it suitable for deployment in the city of Addis Ababa. Dimensioning refers to the process of analyzing capacity and coverage requirements and accordingly deciding upon operating parameters in the radio access and core networks to sufficiently handle the aforementioned requirements. It is basically capacity and coverage planning rolled into one. This thesis work also analyses different wireless channel propagation models to determine the one which best suits (more accurately estimates pathloss) given the operating parameters chosen during the dimensioning phase. It should be noted that propagation models are developed for specific terrain types and frequency bands. It is therefore imperative that we identify which propagation model is the best fit for this particular case. This propagation model will then be used in a radio network planning tool that can operate on a digital terrain model database and can accurately plot coverage areas for different parts of Addis.

## 1.2 Statement of the Problem

The relatively lower disposable income that people in developing countries like ours have which put economic constraints on one's ability to spend, coupled with the limited usage of advanced technologies, suggest that the capacity requirements to support the voice and data traffic in these parts of the world is not as high as the other parts. However, the fast growing trend of voice and data traffic in different African countries is indicative of the eminent need to ultimately resort to fourth generation (4G) telecom technologies.

Mobile subscription penetration in Ethiopia has already reached 8.15% by the year 2010 [30]. This figure is expected to reach 50% by the year 2015 [30], which would mean a considerable rise in voice as well as mobile data traffic. This can be disconcerting when we take into consideration the fact that the second and third generation (2G and 3G) networks deployed in the city of Addis Ababa are already struggling to swallow the current voice and data traffic. Deploying capacity rich 4G technologies is one attractive alternative to circumvent this problem as persisting with older technologies would require much denser base station deployment.

If we take the case of Kenya, internet subscription has increased from 10% to 22% with 99% of this rise emanating from mobile internet subscribers [31]. This signals the need for a technology that supports mobility and can handle capacity congestions, a technology like Mobile WiMAX. Research done in Tanzania in the year 2010 shows that web page view on mobile handsets has grown by 335% in that year [32]. Data transfer has also increased by 288% in that period [32].

These traffic growth rates in Ethiopia and fellow African countries signal the eminent arrival of 4G technologies in these parts of the world. This thesis strives to conduct all the dimensioning and radio network planning steps for mobile WiMAX that ought to be performed prior to deployment.

## 1.3 Objectives

### 1.3.1 General Objectives

This thesis work has two main objectives. The first one is to dimension the access and core network parameters of mobile WiMAX in order to come up with a viable solution for deployment in the city of Addis Ababa, given the demographic and geographic data of the city. Secondly, it strives to develop a radio network planning tool that operates on a digital terrain model database and a suitable propagation model.

### 1.3.2 Specific Objectives

Specifically, the objectives of this thesis work can be outlined as,

- Dimensioning the radio access network parameters, e.g., radio link budgets, antenna configurations, frequency reuse schemes etc... and core network parameters which involve capacity estimation of the interfaces in the network architecture of mobile WiMAX.
- Studying different signal propagation models that can be used for estimating pathloss and/or range of our wireless network.
- Developing a radio network planning tool that operates on a digital terrain model database and can estimate (plot) our coverage area with a reasonable accuracy.

## 1.4 Methodology

The methods employed to achieve the objectives of the research are:

- Literature review: includes reading books, articles, white papers, simulation tools and other resources related to the topic.
- System Designing: involves dimensioning the access and core network components of IEEE 802.16e (mobile WiMAX), analysing various signal propagation models that are applicable in the frequency range of WiMAX and developing Radio Network Planning (RNP) tool.
- Simulation: involves developing a radio network planning tool and running computer simulations of our system using the programming tool, namely MATLAB.
- Analysis and Interpretation of the results: the performance characteristics results of the simulation will be analysed. We will use numerical simulations for performance comparison of signal propagation models. Also, we will make use of the output of our developed RNP tool for coverage analysis.

## 1.5 Related Works

This particular area of research is not an intensely explored one in the context of a thesis work or an academic research as this area is mostly dealt with by telecom companies prior to deployment. To the best of my knowledge, there is only one other thesis related to this research. This thesis, entitled “Dimensioning Mobile WIMAX in the Access and Core Network: A case Study”, was conducted by Mr. Mwesiga W. Barongo at the Helsinki University of Technology in Finland. It outlines the basic dimensioning steps for the access and core networks and performs a case study on the cities of Helsinki, Espoo and Kirkkonummi. This thesis is however confined to dimensioning and does not incorporate analysis of propagation models as well as radio network planning (which are included in this thesis along with developing an RNP tool.)

## 1.6 Contributions

As mentioned in prior sections, this thesis work conducts all the capacity coverage and radio network planning steps needed for deployment of Mobile WiMAX in the city of Addis Ababa. This research will serve as a good resource if/when Mobile WiMAX is deployed in Addis.

Furthermore radio network planning tools like ATOLL and EDX-PRO, that make use of digital terrain models and provide accurate coverage plots, cost in the order of thousands of US dollars. However, in this thesis, a radio network planning tool that operates on a digital terrain model database and can plot the corresponding coverage area is developed. This will also have further significance for future researches as well as actual deployments.

The other major contribution of this thesis work lies in the fact that it is, to the best of my knowledge, the first of its kind in the African context. One of the issues raised on the third international Information and Communication Technologies Conference on e-infrastructure and e-services, hosted in Tanzania, was the need for conducting researches on 4G technologies such as the Long Term Evolution (LTE) and WiMAX in the context of the African market [33]. I believe this research has duly addressed the call for papers in this area.

### **1.7 Scope/Limitations**

The performance analyses in this thesis work will be based on simulation of the proposed solutions using MATLAB. Thus, implementation details of the resulting systems will not be considered. The demographic and terrain data used on this paper is entirely that of the city of Addis Ababa. Therefore, the scope of this research is limited to capacity, coverage and radio network planning for the city of Addis using computer aided simulations.

### **1.8 Thesis Layout**

Chapter two of this thesis discusses the main features of the IEEE 802.16 standard. The main technologies incorporated in the standard such as orthogonal frequency division multiplexing (OFDM), adaptive modulation and coding, multiple antenna systems and so forth will be briefly discussed. Moreover, the WiMAX network architecture is presented. Chapter three of this thesis outlines the dimensioning steps of Mobile WiMAX in particular given a distinct demographic as well as geographic area. Chapter four analyses different signal propagation models and shows how a radio network planning tool is developed. Chapter five outlines the results of our computer simulations. The final chapter presents the conclusions and recommendations/future works.

## Chapter 2: Mobile WiMAX: An Overview

### 2.1 Introduction to Mobile WiMAX

WiMAX is a broadband wireless technology that provides wireless data access to fixed, nomadic and mobile users. It conforms to two standard technologies, namely, IEEE 802.16d and IEEE 802.16e [2]. IEEE 802.16d is a fixed wireless technology optimised for fixed and nomadic applications in line-of-sight (LOS) and non line-of-sight (NLOS) environments. It strives to provide a metropolitan area with a high bandwidth, for instance, we have a 390 MHz bandwidth available in the 2.5 GHz band and 500 MHz bandwidth available in the 3.5 GHz band. It also provides a larger coverage area, theoretically within a 2 km radius [3], than is currently available with the existing 2G and 3G technologies. Furthermore, theoretically, it is expected to provide each user with a data rate as high as 75 Mbps [1].

IEEE 802.16e or “**mobile WiMAX**” is a standard targeted for portable, mobile application as well as fixed and nomadic applications in NLOS environments. Mobile WiMAX extends the fixed WiMAX standard by giving users the ability to keep ongoing connections active while moving at vehicular speeds greater than 120km/hr [8].

It uses Orthogonal frequency division multiplexing (OFDM) physical layer technology and smart antenna techniques which make it strong and robust against the effects of multipath, i.e., frequency selective fading. The OFDM technique splits a radio signal into multiple small signals which are then transmitted simultaneously at different frequencies to the receiver. This combats frequency selective fading (see Section 2.4).

Also, in the context of multiple access techniques, the use of OFDM allows large amount of data to be transmitted over the spectrum with greater efficiency than existing techniques such as time division multiple access (TDMA) and code division multiple access (CDMA).

### 2.2 Wireless Channel Overview

As seen in Figure 2.1, the key steps in the digital domain are encoding and modulation. The encoder generally adds redundancy that will allow error correction at the receiver. The modulator prepares the digital signal for the wireless channel. The modulated digital signal is converted into a representative analog waveform by a digital-to-analog convertor (DAC) and then upconverted to one of the desired WiMAX radio frequency (RF)

bands. This RF signal is then radiated as electromagnetic waves by a suitable antenna. The receiver performs essentially the reverse of these operations [5].

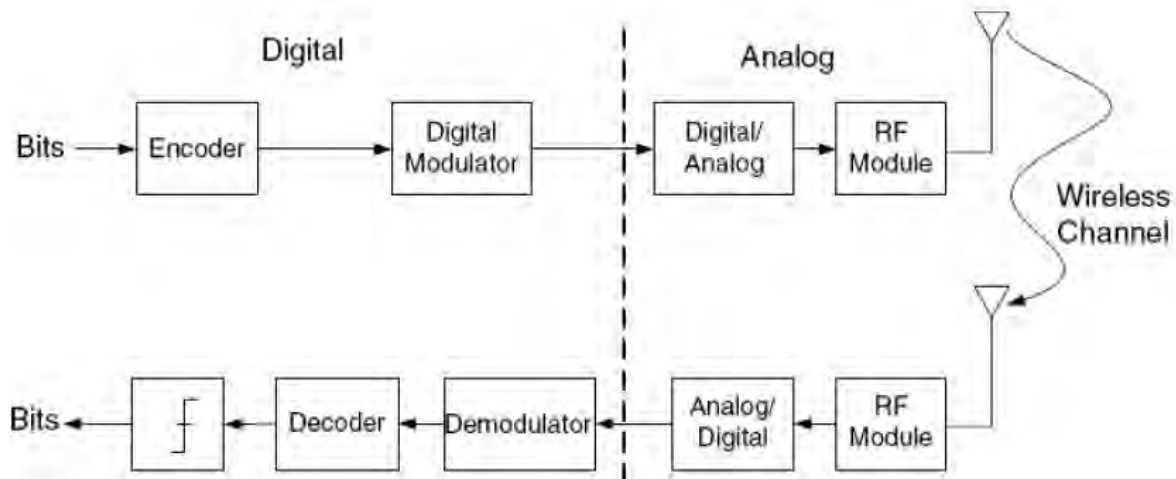


Figure 2.1: Basic digital communication system [5]

Wireless networks, as opposed to a wired network, can be grossly affected by pathloss, shadowing and fading. Pathloss refers to the reduction of the energy between transmitter and receiver that are located at a certain distance away from each other. Pathloss is dependent on the propagation environment. There are different formulas (propagation models) suggested for pathloss calculation in different urban, suburban and rural environments (see Chapter 4 for detailed explanations). Pathloss calculations are essential in determining the coverage area of a given wireless network.

Shadowing can be caused by obstacles that are located between transmitter and receiver that can affect the received power. In other words, any changes in the amount of received power in both decreasing or increasing way, for example absorption or diffraction caused by a building or a temporary LOS transmission path, is referred to as shadowing.[5]

Multipath fading is caused by the reception of multiple versions of the same signal at the receiver. These multiple versions are referred to as multipath and may arrive out of phase with one another. Moreover, the multipath components may arrive at different time instants at the receiver. If the delay is comparable to the symbol duration of the signal, it leads to inter symbol interference (ISI) among the different versions of the same signal. In such a case, the multipath channel becomes frequency selective.

In frequency selective fading channels the OFDM comes in handy, to mitigate the effects of multipath fading (frequency selective fading). OFDM uses several lower rate subcarriers instead of a single carrier that occupies the entire band. This technique allows the increase in symbol duration by splitting the available data rate among several subcarriers. Therefore the relative delay will no longer be comparable to the symbol duration of our signal and ISI is consequently mitigated.

### 2.3 Features of WiMAX

WiMAX is a wireless broadband solution that offers a variety of features with a lot of flexibility in terms of deployment options and potential service offerings. Some of the main features are highlighted as follows;

- **OFDM:** The WiMAX physical layer is based on OFDM, a scheme that offers good resistance to multipath. OFDM is now widely recognized as the method of choice for mitigating ISI for wireless technologies. WiMAX also uses OFDM as a multiple access technique and the resulting scheme is called *Orthogonal frequency division multiple access* (OFDMA). Using OFDMA, different users can be allocated different subsets of the OFDM subcarriers. OFDMA facilitates the use of frequency diversity and multiuser diversity to significantly improve the system capacity [1].
- **Operating frequency:** The frequency band supported by WiMAX covers 2 to 66 GHz [1]. The lower frequency bands are preferable because of reduced losses, cost and complexity of equipments. The most commonly used bands are the 2500 MHz band (2300 MHz up to 2690 MHz) and the 3500 MHz band (3300 MHz up to 3800 MHz).
- **Very high peak data rates:** WiMAX is capable of supporting very high peak data rates. As high as 74 Mbps in the downlink when operating using a 20MHz wide channel. More typically, using a 10MHz spectrum operating using TDD scheme with a 3:1 downlink-to-uplink ratio, the peak data rate is about 25Mbps and 6.7Mbps for the downlink and the uplink, respectively. These peak data rates are achieved when using 64-QAM modulation with code rate 5/6 error-correction coding. Under very good signal conditions, even higher peak rates may be achieved using multiple antennas and spatial multiplexing [1].
- **Scalable bandwidth and data rate support:** WiMAX has a scalable physical-layer architecture that allows for the data rate to change easily with the available channel

bandwidth. This scalability is supported in the OFDMA mode, where the fast fourier transform (FFT) size may be scaled based on the available channel bandwidth. For example, a WiMAX system may use 128, 512, or 1,048-bit FFTs based on whether the channel bandwidth is 1.25 MHz, 5 MHz, or 10 MHz, respectively [1].

- **Adaptive modulation and coding (AMC):** WiMAX supports a number of modulation and forward error correction (FEC) coding schemes and allows the schemes to be changed on a per user and per frame basis, based on channel conditions [1]. AMC is an effective mechanism to maximize throughput in a time-varying channel. The adaptation algorithm typically calls for the use of the highest modulation and coding scheme that can be supported by the signal-to-noise and interference ratio (SNIR) at the receiver such that each user is provided with the highest possible data rate that can be supported in their respective links.
- **Link-layer retransmissions:** For connections that require enhanced reliability, WiMAX supports automatic retransmission requests (ARQ) at the link layer [1]. ARQ-enabled connections require each transmitted packet to be acknowledged by the receiver. Unacknowledged packets are assumed to be lost and are retransmitted. WiMAX also optionally supports hybrid-ARQ, which is an effective hybrid between FEC and ARQ.
- **Support for TDD and FDD:** IEEE 802.16-2004 and IEEE 802.16e-2005 support both time division duplexing (TDD) and frequency division duplexing (FDD), as well as a half-duplex FDD, which allows for a low-cost system implementation [1]. TDD is favoured by a majority of implementations because of its advantages that include; (i) flexibility in choosing uplink-to-downlink data rate ratios, (ii) ability to exploit channel reciprocity, (iii) ability to implement in non-paired spectrum, and (iv) less complex transceiver design (see Section 3.6 for details).
- **Flexible and dynamic per user resource allocation:** Both uplink and downlink resource/capacity allocation are controlled by a scheduler in the base station. Capacity is shared among multiple users on a demand basis, using a burst TDM scheme. Multiplexing is additionally done in the frequency domain, by allocating different subsets of OFDM subcarriers to different users. Resources may be allocated in the spatial domain as well when using the optional advanced antenna systems

(AAS). The standard allows for bandwidth resources to be allocated in time, frequency, and space [1].

- **Support for advanced antenna techniques:** The WiMAX solution allows for the use of multiple-antenna techniques, such as beamforming, space-time coding, and spatial multiplexing. These schemes can be used to improve the overall system capacity and spectral efficiency by deploying multiple antennas at the transmitter and/or the receiver.
- **Quality-of-service (QoS):** The WiMAX medium access control (MAC) layer has a connection-oriented architecture that is designed to support a variety of applications, including voice and multimedia services [1]. The system offers support for constant bit rate, variable bit rate, real-time, and non-real-time traffic flows, in addition to best-effort data traffic.
- **Robust security:** WiMAX supports strong encryption, using Advanced Encryption Standard (AES) and has a robust privacy and key-management protocol. The system also offers a very flexible authentication architecture based on Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including username, password, digital certificates, and smart cards [1].
- **Support for mobility:** The mobile WiMAX variant of the system (which is of most concern in this thesis work) has mechanisms to support and secure seamless handovers for applications such as Voice over IP (VoIP). The system also has built-in support for power-saving mechanisms that extend the battery life of handheld subscriber devices. Physical-layer enhancements, such as more frequent channel estimation, uplink sub-channelization and power control are also useful in support of mobile applications.
- **IP-based architecture:** The WiMAX Forum has defined a reference network architecture that is based on an all-IP platform. All end-to-end services are delivered over an IP architecture relying on IP-based protocols for end-to-end transport, QoS, session management, security, and mobility. Reliance on IP allows WiMAX the declining cost of IP processing, facilitate easy convergence with other networks, and use the application development that exists for IP [1].

## 2.4 Orthogonal Frequency Division Multiplexing

OFDM is a modulation technique where a single data stream is transmitted over a number of lower rate subcarriers [9]. It is a prominent modulation scheme with diverse applications in current as well as future wireless communication technologies.

The word ‘orthogonal’ indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. It implies they are completely uncorrelated. In a normal FDM system, many carriers are spaced apart in such a way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands are introduced between the different carriers and in the frequency domain, which results in a lowering of spectrum efficiency.

It is possible, however, to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals are still received without adjacent carrier interference. To enable this, the carriers must be mathematically orthogonal. This allows us to use baseband processing (as opposed to passband filtering) to separate the overlapped carriers at the receiver.

OFDM provides robustness to the transmitted signal by mitigating the effects of frequency selective fading. This fading occurs when the signal bandwidth exceeds the coherence bandwidth (spectral range for which the channel properties remain more or less the same) of the wireless channel. In an OFDM system, we use several lower rate subcarriers as opposed to a single carrier that occupies the entire available bandwidth. As long as we maintain the bandwidth of each individual subcarrier below the coherence bandwidth, the effects of frequency selective fading will be greatly diminished.

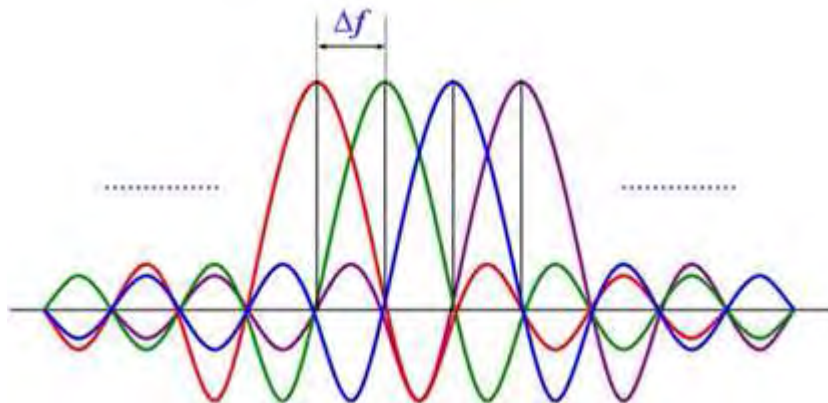


Figure 2.2 : Subcarrier spacing in OFDM systems

OFDM also serves the added purpose of saving bandwidth as there is no need for guard intervals and the subcarriers are allowed to overlap as long as they remain mathematically orthogonal to one another. The synergetic nature of OFDM also allows us to use it in conjunction with other technologies such as multiple antenna system, CDMA and the like [9].

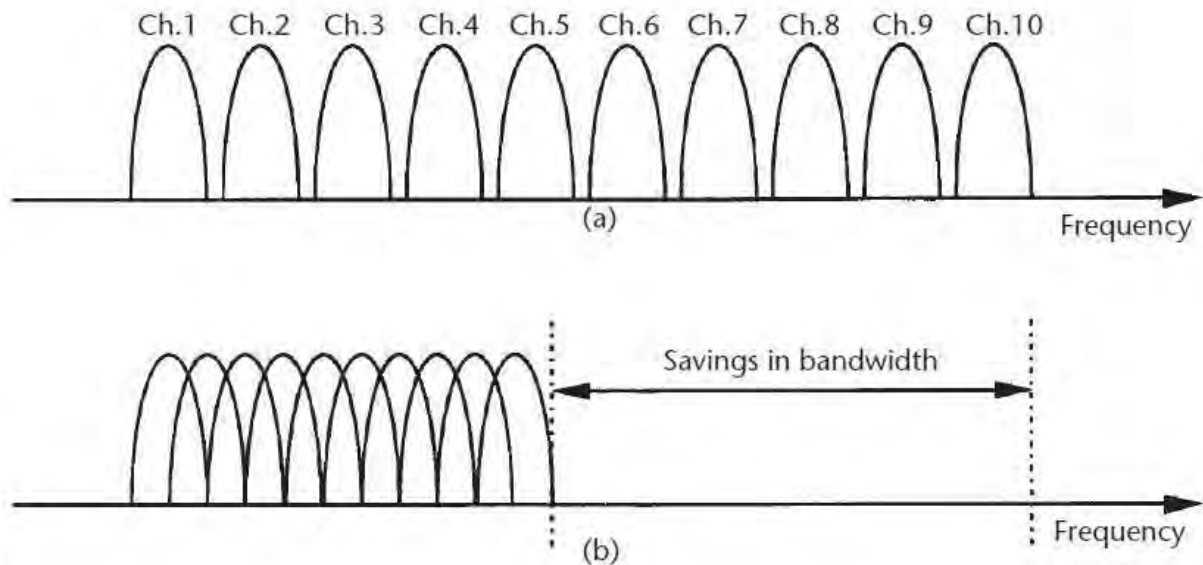


Figure 2.3: a) Classical FDM carrier spacing b) OFDM subcarrier spacing [9]

## 2.5 Adaptive Modulation and Coding

WiMAX supports a variety of modulation and coding schemes and allows for the schemes to change on a burst-by-burst basis per link, depending on channel conditions. Using the channel quality feedback indicator, for the uplink case, the mobile can provide the base station with feedback on the downlink channel quality. The base station accordingly assigns the highest modulation order that can be supported in the aforementioned channel quality.

The base station can estimate the channel quality, based on the received signal quality. The base station scheduler can take into account the channel quality of each user's uplink and downlink and assign a modulation and coding scheme that maximizes the throughput for the available signal-to-noise ratio (SNR) that indicates the channel quality. For a specific coding or modulation scheme, the SNR determines the corresponding bit error rate (BER), AMC allows for the selection of the highest order modulation and coding without exceeding the maximum allowable BER needed to maintain a pre-defined quality of service.

Adaptive modulation and coding significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link. As we increase our throughput via a higher order modulation, the robustness of the signal decreases due to increased bit error rate (BER). AMC strives to achieve the highest supportable coding and modulation order while maintaining the minimum acceptable link quality in terms of BER. In the downlink, QPSK, 16-QAM, and 64-QAM are mandatory for both fixed and mobile WiMAX. 64-QAM is optional in the uplink [2].

Forward error correction (FEC) coding using convolutional codes is mandatory. The standard optionally supports turbo codes and low-density parity check (LDPC) codes at a variety of code rates as well. A total of 52 combinations of modulation and coding schemes are defined in WiMAX as profiles [1].

## 2.6 Multiple Antenna Systems

Mobile WiMAX technology incorporates the use of multiple-input multiple-output (MIMO) systems and smart antenna technologies to enhance both coverage and throughput. A (2x2) MIMO configuration offers the possibility for improved performance with Space-Time Coding (STC), spatial multiplexing (SM) and dual polarization [3,8].

In STC, downlink data streams are sent from each transmit antenna providing space and time diversity. In an environment with multipath, STC enhances the SNR of the received signal at the mobile station to enable support of higher modulation efficiency or enhance the range.

With spatial multiplexing each of the base station transmit antennas send a different downlink data stream. This technique, theoretically, has the potential to double the downlink capacity.

## 2.7 WiMAX Network Architecture

WiMAX Forum has developed a standard network reference model (NRM) which is shown in Figure 2.4. The NRM consists of the entities Mobile Station (MS)/Subscriber Station(SS), Base station (BS), Access service network (ASN) and Connectivity Service Network (CSN).

The ASN defines the logical boundary for functional interoperability with WiMAX clients, connectivity service functions and aggregation of functions embodied by different vendors. ASN deals with the message flows associated with the access services. ASN also

provides an IP packet delivery service between WiMAX subscribers and the CSN. The ASN connects base stations to the WiMAX ASN gateway using transport networks such as microwave, copper or fibre links. The WiMAX ASN gateway also provides connectivity to the Internet through Home agent (HA) or a routing device [3].

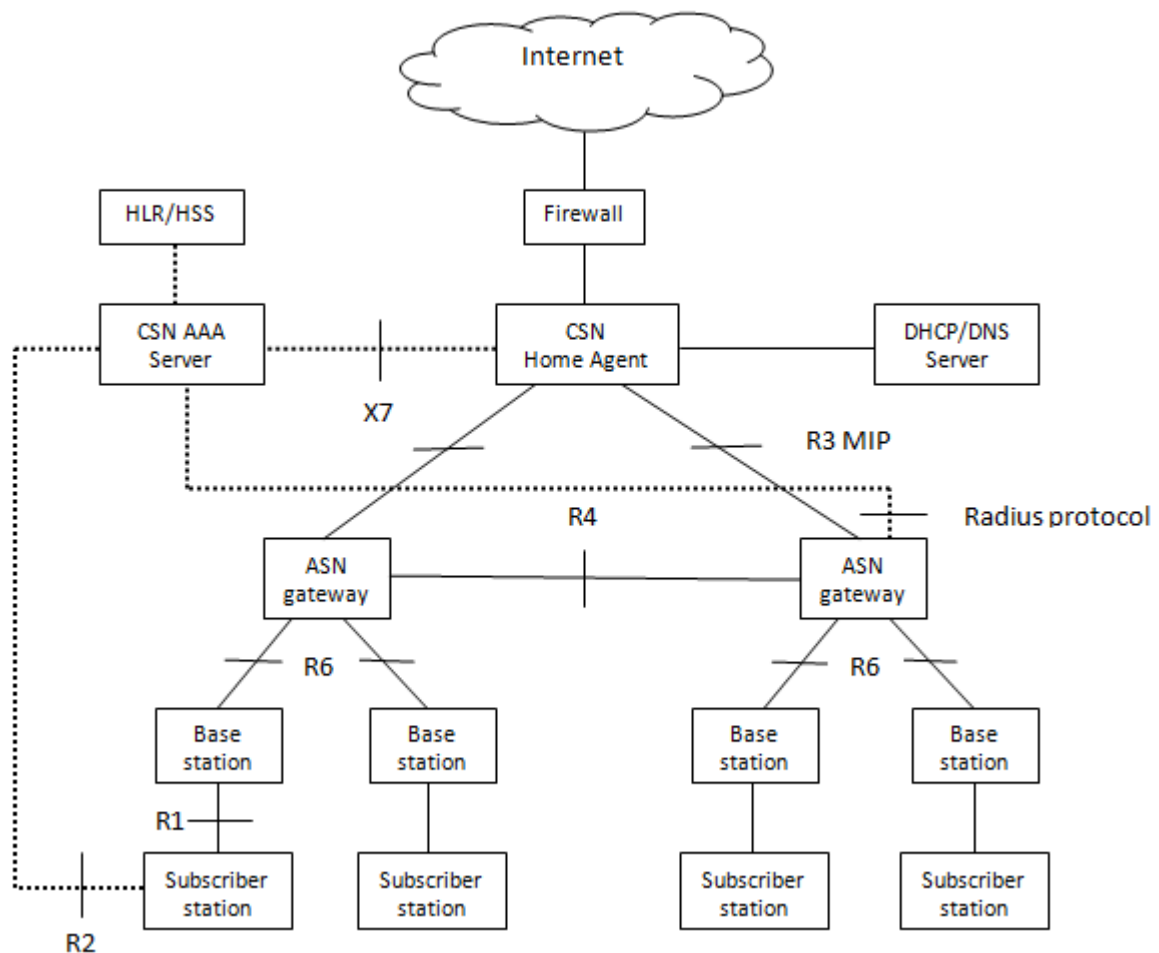


Figure 2.4 : WiMAX network architecture (Network Reference Model) [3]

The CSN provides a set of networking functions that enable IP connectivity services to WiMAX subscribers. The CSN is also responsible for the switching and routing of calls and data connections to external networks. It comprises of network elements such as routers, Authentication, Authorisation and Accounting (AAA) servers, user databases and Interworking gateway devices [3].

The reference points R1-R6 connect the aforementioned entities. R1 is the interface between the MS and ASN. It implements air interface (IEEE 802.16e) specifications. Whereas R2 is the interface between the MS and CSN. It is a logical interface that is used for the

authentication, authorisation, IP host configuration management, and mobility management. R3 is the interface between the ASN and CSN. It is responsible for methods to transfer IP data between ASN and CSN. R4 is a set of control and bearer plane protocols originating or terminating in various entities within the ASN that coordinates MS mobility between the ASNs. R5 is also a set of control and bearer plane protocols for interworking between the home and visited network [3].

## 2.8 Quality of Service (QoS)

WiMAX provides five QoS classes which are described as follows, [3]

- Unsolicited Grant Service (UGS): This is designed to support real-time data streams that consist of fixed sized packets issued at periodic intervals, such as backhaul and voice over IP (VoIP) without silence suppression.
- Extended Real-Time Polling Service (Ert-PS): This is designed for the extended real-time services of variable rates such as VoIP with silence suppression, interactive gaming and video telephony.
- Real-Time Polling Service (Rt-PS): This is designed to support real-time data streams of variable rates that are issued at periodic intervals, such as MPEG video, audio and video streaming, and interactive gaming.
- Non Real-Time Polling Service (Nrt-PS): This is designed to support delay-tolerant data streams consisting of variable-sized data packets such as file transfer protocol (FTP), browsing, video download, and video on demand.
- Best Effort (BE): This is designed to support data streams for which there is no minimum service requirements, and no guarantee of timely delivery of packets such as E-mail and Internet browsing.

## Chapter 3 : Dimensioning Mobile WiMAX: The case of Addis Ababa

Planning of a wireless network usually involves a number of steps that are essential for a successful deployment. The first step is to define the geographic area where the service is expected to be offered. Key metrics used to specify the geographic area are population density, number of households, and number of small and medium businesses. The terrain type also needs to be specified [3].

The next step is to determine the spectrum and bandwidth to be used. From the available frequency bands specified by the standard (2.5GHz and 3.5GHz), the selection of either of the frequency band determines the total bandwidth achievable. Depending upon the frequency band chosen, we can decide whether to use channel bandwidth of 1.25MHz, 1.75MHz, 3.5MHz, 5MHz, 8.75MHz, 10MHz, 14MHz or 20MHz.

The steps that will follow involve determining the parameters to calculate range and capacity. These Parameters include link budget, spectral efficiency, antenna configurations (SIMO, MIMO), frequency reuse factor which altogether control the coverage area per cell site and the total number of cell sites or base stations needed to cover the desired geographic area.

In order to achieve end-to-end connectivity, the next step is to dimension and plan the elements that form the core service network. This involves estimating the capacity requirements of the reference points of our core network (see figure 2.4).

### 3.1 Coverage Planning

The target for the coverage planning is to find optimal locations for the base stations to build a continuous coverage according to the planning requirements. Coverage planning is performed with a planning tool, in this thesis work we will develop a radio network planning tool that includes a digital map with terrain information of Addis Ababa and uses a selected propagation model that aids in determining the coverage area. The choice of propagation model depends on the suitability of that model for the specific terrain type and operating parameters (frequency, base station antenna height and so on) chosen on this chapter (see Chapter 4 for details). The overall coverage prediction is then determined based upon the combination of the digital map information and the selected propagation model.

During coverage planning the link budget analysis is performed that defines the maximum allowed pathloss (MAPL) with certain configurations. The maximum allowed pathloss is the link margin that we get when we subtract all our losses from the sum of our gain parameters. In order to have reception at a given point, the pathloss at that point has to be less than or equal to the link margin (MAPL). Different parameters that constitute the link budget lead to the determination of the theoretical maximum cell size. The cell size or range leads to the determination of the coverage area (see Section 3.9 for details).

- The first step in coverage planning is to create a preliminary plan based upon the calculated number of base stations. In this step, the theoretical locations of the base stations are determined and the decision on whether to use omni cells or sectorised cells is made. Omni cells are better suited for rural areas or sparsely populated areas where the need for a high capacity is limited. Sectorised cells are better suited in areas where there is a need for coverage in precise locations [3].
- The next step is to find the actual locations of the base stations. The choice of locations should make maximum use of current second and third generation (2G and 3G) telecom towers to minimize the cost of tower constructions and site leasing.
- After the actual locations have been determined, the plan based on the preliminary location is updated and cell coverage areas are calculated again using the terrain parameters. During this step, the coverage and capacity requirements are determined with the actual base station locations.

In achieving coverage in a region, several factors have to be taken into consideration such as buildings heights, terrain, building densities and so on. Mobile WiMAX can be deployed for coverage without regard to capacity requirements. This means at first, the minimum number of base stations are deployed to provide enough coverage in a particular area. Capacity is only increased whenever the need arises, and this can be done by adding more channels to the existing base stations assuming there is available spectrum or by decreasing cell size for better frequency re-use. This kind of technique is useful in situations where there are uncertainties about market penetration rates as is the case with Addis Ababa.

### 3.2 Capacity Planning

Capacity planning is based on the coverage maps and traffic estimates. Capacity planning involves anticipating how users will use the system and the demand they place on the system.

Data density is the metric that is used in determining the capacity planning and is expressed as Mbps/km<sup>2</sup>. Given a certain demographics region, determining the required data density involves classifying users of the systems on different categories. User categories depend on the load they place on the system in terms of usage. Various demands that are placed by the users on the system include browsing the web, e-mailing, VoIP, download or upload of video content, etc...

Data density is used for matching the base station capacity to the market requirements. Projected market requirements determine the base station capacity requirements. Expected market penetration is the other factor that an operator has to take into account when analysing capacity requirements. In this case, the operator has to forecast how the market will evolve after several years (10 years is usually assumed) of operation, and consequently address its capacity needs [3].

### 3.3 Estimation of Capacity Density

In this section, an approach for estimating the data density requirements to meet specific customer needs is discussed. Arriving at an accurate estimate of capacity requirements for new broadband services is not a simple task. We must anticipate how users will make use of the new services being offered and how often users will use the network. Since we don't have an existing data to base our estimate on (as the service is new to that specific area), we must make use of demographic data as is the general technique used for first time deployment.

Data density is useful for describing capacity requirements. First, let us start by stating the different kinds of metropolitan areas (classification is based on terrain type and expected traffic of the area in question) [8].

- **Dense Urban:** This is the city centre where many of the businesses are located as well as high density of buildings and residential units are found. These areas represent a challenging propagation environment due to the multipath caused by the buildings.

- **Urban:** Immediately surrounding the city centre where there would be more businesses and moderate to high density multiple dwelling units. Average building heights may be lower but the propagation environment will be equally challenging.
- **Suburban:** This describes areas with lower density housing and fewer businesses. Average building heights are also lower in comparison with urban areas and, on average, structures are more spread out, thus creating a more favourable propagation environment.
- **Rural:** Moving further from the city centre, homes are further apart resulting in significantly lower population density with scattered small businesses.
- **Open Space:** Throughout the entire metropolitan area there will generally be areas of open space. This includes parks, greenbelts, lakes, golf courses, etc. Although there are few full time residents, these are still areas that require consideration for wireless deployment since at any given time these regions can be visited by a large number of people.

As stated in previous sections, this thesis work focuses on conducting the dimensioning and radio network planning steps of mobile WiMAX for deployment in the city of Addis Ababa. Based on the aforementioned classification, the city of Addis Ababa falls in the “urban” category and such will be the assumption of this paper from here onwards.

Population density and population growth rates are easily obtained for any metropolitan area by referring to the census data. We then take these figures and use them to calculate the number of expected customers (assuming we have estimated our market penetration rate). When considering mobile services the addressable market can be assumed to be any individual within a certain age group. For wireless broadband services such as WiMAX, it is assumed to be anyone between 15 and 70 years old [8].

The expected market penetration, or take-up rate, is dependent on a number of factors including the competitive situation and the services offered that distinguish one service provider from another. The service provider’s penetration may also vary within the metropolitan area since urban and dense urban residents will usually offer more customers. Current trend of market penetration rate or take up rate at maturity (10<sup>th</sup> year of operation) is between 10 to 12% averaging at 10.4% [8]. We will assume the lowest take-up rate (10%)

for the city of Addis Ababa because the low disposable income of its inhabitants hinder their ability to subscribe the service as well as purchase the necessary consumer electronics.

Now, let us proceed by identifying or defining the different types of customers that may subscribe these broadband services for various reasons [3].

- **Professional User:** This describes the customer that requires mobile broadband access for business purposes and would also use the service for personal use. E-mail, video conferencing, file downloads, etc... would be key applications for this type of users.
- **High-end Consumer:** This is a high usage customer whose primary interest is for personal rather than business use. Web browsing, gaming, music downloads, etc... may be dominant applications for this type of users.
- **Casual User:** These are consumers who desire periodic access for web browsing and other data oriented services, but may only be actively connected to the network a few hours per day.

Assumptions made in our capacity density estimation are outlined in the following table. These assumptions were arbitrarily chosen in this case, and can be altered for the case of an actual deployment as the operator sees fit.

Description	Assumptions
Addressable Market	Aged between 15 to 70 years old
Market penetration	10%
Customer mix	<ul style="list-style-type: none"> <li>• 50% professional user</li> <li>• 20% high end user</li> <li>• 30% casual user</li> </ul>

Table 3.1 : Assumptions made for capacity density estimation

The demographic data for the city of Addis Ababa is given in Table (3.2). The data is taken from the census conducted in the year 2007 but the estimated population growth rate quoted in the document allows us to make sensible estimate of what the current demography might resemble.

<b>Demographics of the City of Addis Ababa</b>	
Population of the year 2007	2,738,248
Growth rate of the year 2007	2.1 %
Expected population of 2012	3,038,097
Composition of the people in the age group 15-70 (our addressable market)	1,597,188 (52.57 %)
Expected market penetration (by the 10 <sup>th</sup> year of operation)	159,719 (10 %)
Geographic area of the city of Addis Ababa	530.14 KM <sup>2</sup>

Table 3.2 : Demographic data of Addis Ababa [28]

The data rate requirement of any given customer depends on the type of customer and the services he/she intends to use. WiMAX offers various services that require their own share of data rate to perform at a reasonable quality of service. These services are listed below.

<b>Class description</b>	<b>Application type</b>	<b>Bandwidth</b>
Interactive gaming	Interactive gaming	50 - 85 kbps
VoIP, Video conferencing	VoIP	4 - 64 kbps
	Video phone	32 - 384 kbps
Streaming media	Music/Speech	5 - 128 kbps
	Video clips	20 - 384 kbps
	Movies streaming	>2 Mbps
Information technology	Instant messaging	<250 bps
	Web browsing	>500 kbps
	Email(with attachment)	>500 kbps
Media content download (store and forward)	Bulk data, movie download	>1 Mbps
	peer-to-peer	>500 kbps

Table 3.3 : Services offered by WiMAX and the corresponding BW requirements

Prior to calculating the data density requirement, the operator needs to decide the data rate assigned to individual customers (of all types) during the busiest hour of the day. The numbers chosen for this thesis work are shown in Table 3.4. Note that, for instance, the

400 kbps assigned to the professional user at the busiest hour of the day will allow him/her to download a 1Mb document within a reasonable time of 20 seconds. The customer will also be able to enjoy most of the services (apart from movie streaming and bulky data download) at a reasonable quality of service. It's also worth noting that these figures come into play only during the peak/busy hours of a day and the data rate for the remainder of the time is much higher. The operator may choose to change these figures as per the need but that would also mean a change in data density requirement.

Type of Customer	Customer Mix	Assigned PBH data rate (minimum)
Professional users	50 %	400 Kbps
High end users	20 %	320 Kbps
Casual users	30 %	200 Kbps
Assumed traffic load at PBH		15 %
Aggregate (per user)		324 Kbps
Aggregate (for all users)		51748.956Mbps
<b>Data density requirement</b>		<b>14.64 Mbps/km<sup>2</sup></b>

Table 3.4 : Data density requirement

### 3.4 Frequency Band Choice

The WiMAX Forum supports several profiles for Mobile WiMAX. Release-1 profiles include various channel bandwidths from 5 MHz to 10 MHz in frequency bands ranging from 2300 MHz to 2690 MHz and 3300 MHz to 3800 MHz. The 2300 to 2690 MHz band is referred to as the 2500 MHz band and the 3300 to 3800 MHz band is referred to as the 3500 MHz band [1].

In discussing the relative performance between frequency bands, range difference is generally the parameter of greatest interest and this, of course, is a function of the link budget. It is important to understand the link budget characteristics that are common to the frequency bands in the 2500 and 3500 MHz range.

In comparing 2500 MHz performance with 3500 MHz, there are some important frequency dependent differences that must be considered. For example, building/vehicle penetration loss must be taken into account. Penetration losses will be higher at higher

frequencies. However, studies show that the penetration losses vary very little in the range from 1 to 6 GHz [8]. Therefore, for the purposes of comparing 2500 MHz with 3500 MHz we will assume, in this thesis work, that no difference in the penetration loss exists.

For a fixed antenna size and type, the antenna gain is directly proportional to the square of the operating frequency, thereby, achieving higher antenna gains at the higher frequencies. To compare 3500 MHz with 2500 MHz the same aperture is assumed for both bands. At 3500 MHz we will have an added antenna gain of 2 dB [8].

WiMAX forum recommends that the Modified COST 231 Hata model is a suitable propagation model for mobile WiMAX applications [3]. It is assumed to be acceptable for 2500 and 3500 MHz. Calculations of the Range for the two distinct frequency bands using the cost 231 Hata model (with a 2dB increase in maximum allowable pathloss for the 3500 MHz band due to the added antenna gain) shows that we can acquire approximately 20 % more range using the 2500 MHz band [8]. See Figure 3.1.

The spectrum licensing fee is generally slightly higher for the lower frequency bands. However, for a city like Addis Ababa, where there are not any wide area networks deployed at these high frequencies, and where subscribers are sparsely populated and few in number, the priority should be given to the range of the wireless communication system. Therefore, for reasons outlined in this section, the 2500 MHz band is chosen to be the operating band. Figure 3.1 provides a view of the relative ranges for the 2500 MHz and 3500 MHz frequency bands.

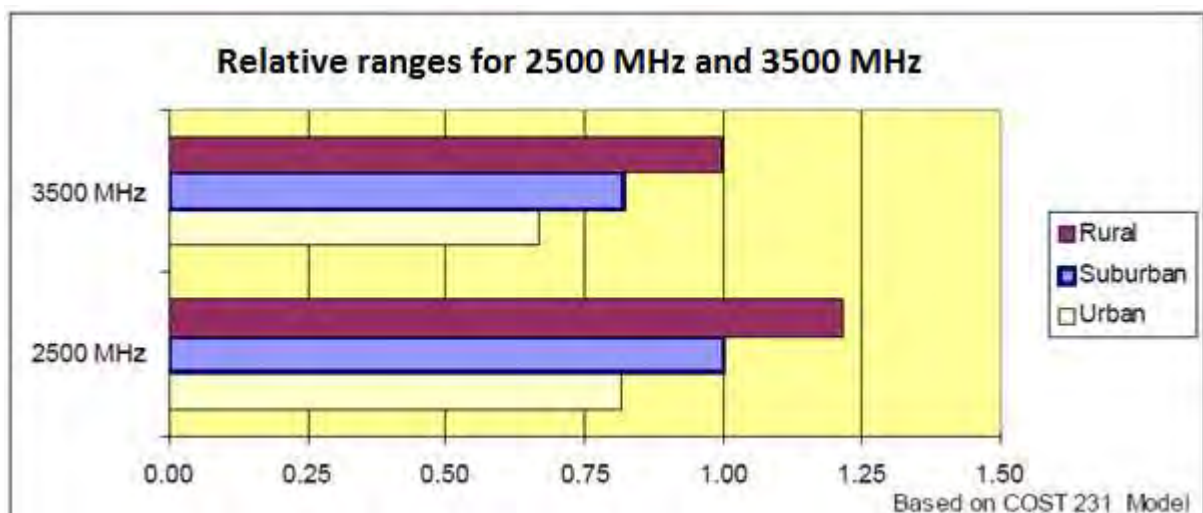


Figure 3.1: Relative ranges for 2500 MHz and 3500 MHz frequency bands [8]

## 3.5 Antenna Configurations

In addition to SIMO and MIMO antenna configurations, mobile WiMAX technology supports smart antenna technologies to enhance both coverage and throughput. The advanced antenna features supported in the Release-1 profiles include Adaptive Beamforming, Space-Time Coding (STC) and Spatial Multiplexing (SM).

Although many of these base station advanced antenna features are optional, the mobile station is required to support all of the base station options that might be deployed to ensure inter-vendor interoperability.

### 3.5.1 1x2 SIMO

A typical WiMAX base station antenna configuration is (1x2) SIMO. Even with only a single transmit antenna at each end of the link this configuration takes advantage of multipath to improve both the downlink and uplink received signal strength as compared to a single input single output (SISO) configuration. With dual receive antennas at both the base station and the mobile station the received signal is enhanced through the use of spatial diversity and the use of maximal ratio combining techniques.

### 3.5.2 2x2 MIMO

Adding a second transmitting antenna for both uplink and downlink provides a (2x2) MIMO configuration. This offers the possibility for Space-Time Coding (STC). Downlink data streams are sent from each transmit antenna providing space and time diversity. In an environment with rapid fading and multipath, STC enhances the signal-to-noise ratio of the received signal at the mobile station to enable support of higher modulation efficiency bursts and thus enhance DL range.

With Spatial Multiplexing (SM), each of the base station transmit antennas send a different downlink data stream. This technique uses multipath to distinguish between the different data streams and theoretically has the potential to double the DL capacity. To take best advantage of STC and SM, Mobile WiMAX also supports adaptive MIMO Switching. This enables dynamic switching between STC and SM depending on existing channel conditions at any given time.

Dual polarization diversity can also be supported with MIMO 2x2 to provide improved performance when there is not sufficient multipath.

### 3.5.3 Adaptive Beamforming

Beamforming is another advanced antenna option supported by WiMAX technology. This antenna technology, also commonly referred to as Smart or Adaptive antenna system, can be implemented in a variety of ways.

The simplest approach, known as switched beam, provides the ability to switch between several narrow beam antennas or between different beams in an antenna array. Switched beam systems have several available fixed beam patterns. A decision is made as to which beam to access, at any given point in time, based upon the requirements of the system. Adaptive arrays allow the antenna to steer the beam to any direction of interest while simultaneously nulling interfering signals. Beam direction can be estimated using the direction-of-arrival (DOA) estimation methods.

A second approach, known as dynamically phased array, dynamically phased array antennas form a beam to a device digitally. The array forms a beam by activating certain omni-directional elements in the array which have a multiplying effect to form a beam. This beam can then be steered or pointed in the direction of a device by phasing the transmission of the signal in the elements and adjusting the gain on each antenna element. A dynamically phased array steers the created beam at the desired device. As the beams are formed digitally the same array of elements can target beams at multiple devices on multiple frequencies. Both of the above approaches enhance the received signal strength and therefore can provide range and/or channel capacity improvement but are also subject to angle spread due to scattering and multipath.

A third approach to beamforming is known as adaptive array or adaptive beamforming. With this approach the beamforming parameters are adaptively determined based on both channel and interference conditions. This can also enable the array to not only maximize signal strength to the desired user but also provides a mechanism to null out interference.

The 2x2 MIMO and beamforming techniques are quite essential in increasing the channel throughput as well as improving the SNR of the link. But they also require a relatively higher capital expenditure for deployment. The **1x2 SIMO** is most commonly used

for first-time deployment and seems the outstanding choice for deployment in cities like Addis. There is always the possibility to upgrade the system to a MIMO (2x2), beamforming or even a combination of these two. But as things stand, it would not be sensible to invest in such costly systems (2x2 MIMO and Beamforming) as the added throughput that they provide (which is their biggest asset) would be surplus to requirements in the context of Addis since we can't expect capacity crunch at first time deployment due to the economic and technical constraints on its inhabitants that hinder their ability to subscribe the service or purchase the necessary consumer electronics.

### 3.6 Duplexing Scheme

Time Division Duplex (TDD) is called for in all of the current performance profiles for Mobile WiMAX [1]. TDD has several advantages over Frequency Division Duplex (FDD) and generally will be the preferred duplexing approach. One key advantage of TDD is that it assures channel reciprocity between the uplink and downlink.

With FDD there would be some performance degradation due to the varied link conditions between the DL and UL channels because they may be separated by 100 MHz or more. Another important advantage is the ability of TDD to adapt to asymmetric traffic conditions. In TDD mode, mobile WiMAX supports downlink to uplink ratios 1:1 and 3:1. This provides a significant throughput advantage for data-centric traffic that is expected to be more dominant in the downlink direction. This is shown in Figure 3.2, which shows the downlink channel capacity for both a 1:1 and 3:1 downlink to uplink ratio and for different antenna configurations.

We can see in Figure 3.2 that this represents a 50% increase in the downlink data throughput for a 3:1 downlink to uplink traffic ratio as compared to 1:1 for the same channel bandwidth for all the antenna configurations. If this was an FDD system, the downlink channel capacity would be limited to the 1:1 values regardless of the traffic asymmetry and the uplink channel would be underutilized.

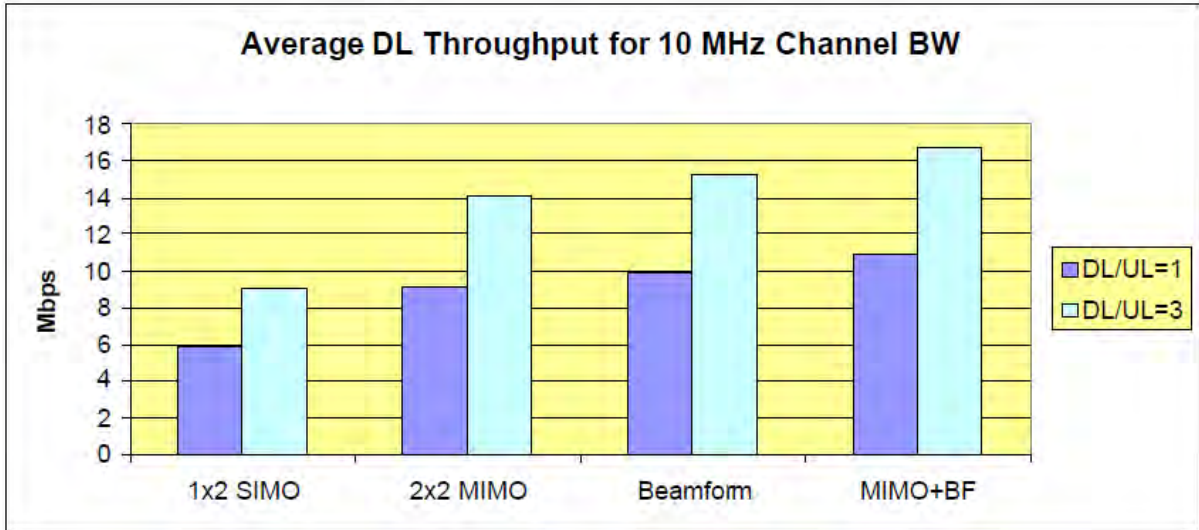


Figure 3.2: Relative DL data rates for 1:1 and 3:1 TDD schemes for different antenna configurations [8]

### 3.7 Channel Bandwidth

The approved WiMAX Forum profiles for Mobile WiMAX currently support channel bandwidths of 5, 7, 8.75, and 10 MHz. The IEEE 802.16e-2005 standard, on which Mobile WiMAX technology is based, supports channel bandwidths from 1.25 to 20 MHz with all channel bandwidths in between being integral multiples of 1.25 and 1.75. The standard opens the possibility for additional WiMAX channel profiles in the future [1]. From an equipment-complexity and cost point of view, there will be little difference in selecting a 5 MHz or a 10 MHz channel bandwidth [8]. Since the wider channel bandwidth will have greater capacity it will be more cost-effective to deploy because it provides us with improved throughput for nearly the same complexity and cost. The 10 MHz channel bandwidth is chosen for the purposes of this thesis work.

### 3.8 Frequency Reuse Scheme

The nomenclature for naming the frequency reuse patterns is  $(c,n,s)$  where  $c$  stands for the number of base stations,  $n$  the number of channels and  $s$  the number of sectors per base station site [3]. Two common frequency reuse configurations for a multi-cellular deployment with 3-sector base stations are a sector reuse of 3  $(c, 3, 3)$  and a sector reuse of 1  $(c, 1, 3)$  also referred to as universal frequency reuse. With a frequency reuse of 1 the same channel is deployed in each of the three base station sectors. This approach has the advantage of using the least amount of spectrum. With Reuse 1, a pseudorandom subcarrier permutation scheme is employed where with a segmentation mechanism users are given

subchannels that are only a small part of the whole bandwidth. With this fractional frequency reuse, the mobile station uses part of the subchannel set, partially used subcarriers (PUSC), when approaching the borders of the cell. When it is close to the middle of the cell, it uses all the subchannels, fully used sub-carrier (FUSC) to mitigate co-channel interference at the sector boundaries and at the cell-edge. As a result some downlink channel capacity is sacrificed since some subcarriers will not be fully utilized throughout the entire cell. Nevertheless, the downlink spectral efficiency for WiMAX with universal reuse is still quite high and generally preferred over reuse 3 [3,8].

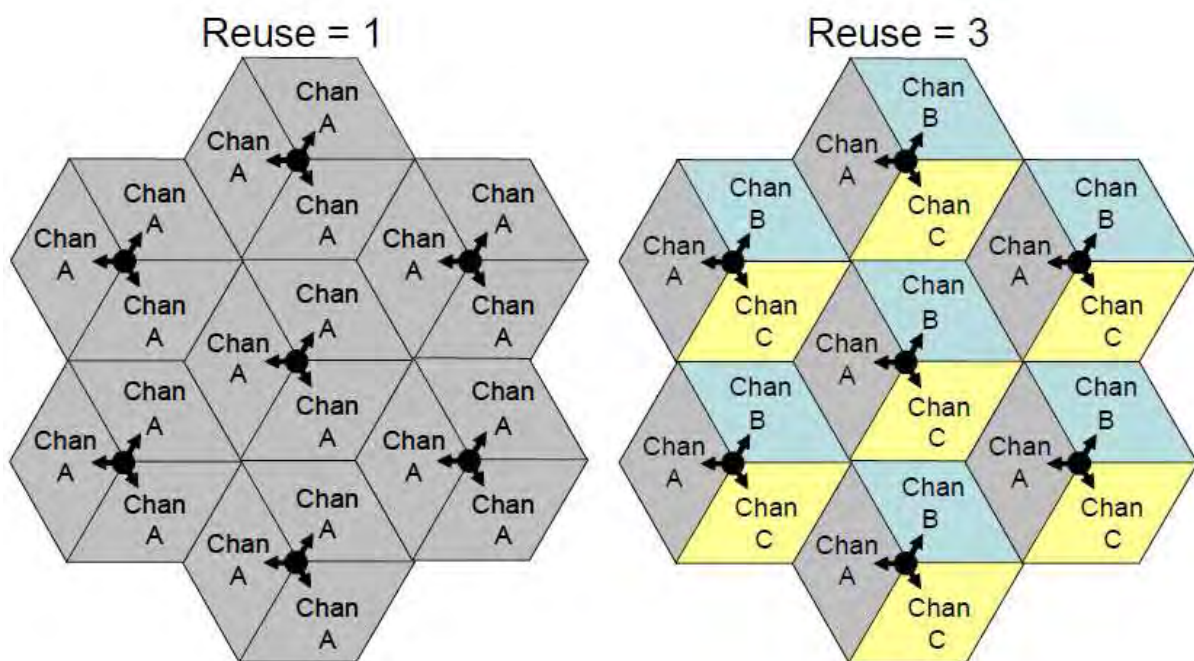


Figure 3.3 : Frequency reuse schemes [3]

### 3.9 Link Budget Analysis

A link budget is the accounting of all of the gains and losses from the transmitter, through the medium, to the receiver in a telecommunication system. It accounts for all the gains including antenna gains, diversity gain, sub-channelization gain and the like. All loss parameters including attenuation of the transmitted signal due to propagation as well as the feed line and other losses are also considered. Randomly varying channel parameters such as fading are taken into account by adding some margin depending on the anticipated severity of its effects. The amount of margin required can be reduced by the use of mitigating techniques such as antenna diversity [12]. Equation (3.1) gives a generic

representation of all gains and losses which will be further discussed in the forthcoming sections.

$$P_{tx} + G_{tx} - A_{pl} + G_{rx} - A_m = P_{rx} \dots \dots \dots (3.1)$$

Where

- $P_{tx}$  is the transmitter output power in (dBm),
- $G_{tx}$  is the transmitter antenna gain in (dBi),
- $A_{pl}$  is Pathloss in (dB),
- $G_{rx}$  is receiver antenna gain in (dBi),
- $A_m$  is miscellaneous losses such as connector loss, diffraction loss, link margin etc... (dB).

$A_{pl}$  includes the entire pathloss between the transmission and reception locations.  $A_{pl}$  and  $A_m$  are quite generic/gross terms. We will break them down and cover all the individual parameters that contribute to these gross expressions in the following sections. We will also enumerate transmission power and gain figures.

### 3.9.1 Base Station Transmission Power and Antenna Gains

We will consider three types of base station configurations, namely; 1x2 SIMO, 2x2 MIMO and 2x2 MIMO with beamforming. Details on these profiles have been discussed in Section 3.5. On Table 3.5, we see the implications these three profiles have on parameters such as transmitter/receiver power, antenna gain and noise figure in the link budget calculations for both UL and DL cases.

	<b>1x2 SIMO</b>	<b>2x2 MIMO</b>	<b>2x2 MIMO with Beamforming</b>
DL TX Power	35 dBm	35 dBm	35 dBm
DL TX antenna gain	16 dBi	16 dBi	16 dBi
Other DL TX antenna gain	0 dB	9 dB	15 dB
UL RX antenna gain	16 dBi	16 dBi	16 dBi
Other UL RX antenna gain	3 dB	3 dB	6 dB
UL RX noise figure	5 dB	5 dB	5 dB

Table 3.5 UL and DL gain/power parameters for different antenna configurations [12]

In this thesis work, we will take DL and UL antenna gain and receiver noise figure parameters from the 1x2 SIMO column as that is our chosen antenna configuration. See Section 3.5.

### 3.9.2 Customer Premises Equipment

With regard to the customer premises equipment (CPE), we can choose from two profiles, namely, portable CPE and mobile CPE. The first type includes devices such as cable modem. They are installed indoors, have their own power supply and are usually connected via an Ethernet cable to the computer. They do not guarantee any form of mobility. The second type consists of mobile devices such as cell phones and laptops that have a built-in modem and batteries to ensure mobility.

	<b>Portable CPE</b>	<b>Mobile CPE</b>
UL TX power	27 dBm	27 dBm
UL TX antenna gain	6 dBi	2 dBi
Other UL TX gain	0 dB	0 dB
DL RX antenna gain	6 dBi	2 dBi
Other DL RX gain	0 dB	0 dB
DL RX noise figure	6 dB	6 dB

Table 3.6 : UL and DL parameters for different customer premises equipments [12]

The mobile CPE gain and loss parameters were taken for the purposes of this thesis work as the service is expected to support mobile data traffic. In addition, the portable devices, as can be seen in Table 3.6, have lower gain parameters due to their smaller size which constraints the antenna size. Therefore, as long as one is able to connect to the network using a mobile CPE, there's no reason he/she would not be able to do so using a portable CPE (but not vice versa). It is necessary that we take into account worst case scenarios in the planning phase.

### 3.9.3 Equivalent isotropic radiated power

From the above six parameters (in Table 3.5 and 3.6) for BS and CPE, we can calculate the equivalent isotropic radiated power (EIRP). EIRP is the amount of power that a theoretical isotropic antenna (that evenly distributes power in all directions) would emit to produce the peak power density observed in the direction of maximum antenna gain. EIRP

can take into account the losses in transmission line and connectors and includes the gain of the antenna.

$$EIRP(dB) = TX\ power(dBm) - cable\ \&\ connector\ losses\ (dB) + antenna\ gain(dBi) \dots \dots \dots (3.2)$$

For DL communication ,BS is the transmitter and its EIRP can be calculated as:

$$EIRP(dB) = (DL\ TX\ power) - (feeder\ loss + connector\ loss + jumper\ losses) + (DL\ TX\ antenna\ gain + other\ DL\ TX\ antenna\ gain) \dots \dots \dots (3.3)$$

For UL communication ,CPE is the transmitter and its EIRP can be calculated as:

$$EIRP = (UL\ TX\ power) - (Head\ or\ body\ loss) + (UL\ TX\ antenna\ gain + other\ UL\ TX\ antenna\ gain\ or\ Diversity\ gain) \dots \dots \dots (3.4)$$

Where,

- DL TX power is the downlink transmission power in [dB]
- DL TX antenna gain is the downlink transmission antenna gain in [dBi]
- Feeder, connector and jumper losses are induced by the cables and connectors that connect the transmitter with the transmitting antenna.
- UL TX power is the uplink transmission power in [dB]
- UL TX antenna gain is the uplink transmission antenna gain in [dBi]
- Head/body loss, which vary based on the whether the devise is worn at the hip or held at head level. When calculating the effective receiver sensitivity of portable devises, the antenna de-coupling to the body changes the gain from the value specified and must be modified in the link budget.

### 3.9.4 Receiver Sensitivity

Receiver sensitivity is a function of the thermal noise, receiver SNR, the noise figure and implementation losses. Receiver sensitivity is normally taken as the minimum input signal required to produce a specified output signal having a specified SNR and is defined as the minimum signal-to-noise ratio times the mean noise power.

$$\text{Sensitivity} = \text{thermal noise} + \text{RX SNR} + \text{RX Noise figure} + \text{implementation loss} \dots \dots \dots (3.5)$$

The parameters in Equation 3.5 are discussed in subsequent paragraphs.

The thermal noise is dependent on the channel bandwidth and can be estimated as (in dBm):

$$\text{Thermal noise} = -174 + 10\log_{10}(\Delta f) \dots \dots \dots (3.6)$$

Where  $\Delta f$  is the bandwidth in Hz over which the noise is measured. For the calculation of the thermal noise, the bandwidth  $\Delta f$  has to be scaled to the effectively used bandwidth, meaning the value of BW has to be multiplied by the ratio between the number of used subcarriers  $N_{Used}$  and the total number of OFDM subcarriers or FFT size  $N_{FFT}$ , and the sampling factor ( $n$ ). For each bandwidth, the model contains different values for  $N_{FFT}$  and  $N_{Used}$ .

$N_{Used}$  is equal to the sum of the number of data subcarriers ( $N_{Data}$ ) and pilot subcarriers ( $N_{Pilot}$ ), together with the DC carrier. The following table shows the values of these different parameters for the aforementioned channel bandwidths.

	$N_{FFT}$	$N_{Used}$	$N_{Data}$ (DL)	$N_{Data}$ (UL)	$N_{SubCh}$ (DL)	$N_{SubCh}$ (UL)
1.25 MHz	128	85	72	56	3	4
5 MHz	512	421	360	280	15	17
10 MHz	1024	841	720	560	30	35
20 MHz	2048	1681	1440	1120	60	70

Table 3.7 : FFT size and usage of subcarriers for different channel BWs [1]

The number of sub-channels ( $N_{SubCh}$ ) is not required for calculating receiver sensitivity but will be used in following sections to calculate sub-channelization gain.

The sampling factor  $n$  is set to 28/25 for channel bandwidths that are a multiple of any of 1.25, 1.5, 2 or 2.75 MHz (which is applicable in our case).

The receiver SNR depends on the modulation scheme and the corresponding values are shown in the table below, for two different forward error correction (FEC) methods (convolution code (CC) and convolution turbo code (CTC)) in an additive white Gaussian noise (AWGN) channel at a bit error rate (BER) of  $10^{-6}$ . As WiMAX adaptively selects the

modulation scheme per user, the appropriate SNR value used in the link budget calculation is dynamically adapted [12].

Modulation Scheme	SNR CC (AWGN, BER $10^{-6}$ )	SNR CTC (AWGN, BER $10^{-6}$ )	Data bit per symbol
QPSK 1/2	5 dB	2.5 dB	1
QPSK 3/4	8 dB	6.3 dB	1.5
16-QAM 1/2	10.5 dB	8.6 dB	2
16-QAM 3/4	14 dB	12.7 dB	3
64-QAM 1/2	16 dB	13.8 dB	3
64-QAM 2/3	18 dB	16.9 dB	4
64-QAM 3/4	20 dB	18 dB	4.5

Table 3.8 : required SNR level for the various supported modulation schemes [12]

The noise figure is the ratio of the output noise power of a device to the portion attributable to thermal noise in the input termination at standard noise temperature  $T_0$  (290 K) [12]. The noise figure is thus the ratio of actual output noise to that which would remain if the device itself did not introduce noise.

$$NF = \frac{SNR_{in}}{SNR_{out}} \dots \dots \dots (3.7)$$

The implementation loss includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. The assumed value is 2 dB [12].

### 3.9.5 Uplink Subchanneling Gain

In the uplink direction, it will hardly occur that data is sent over all subcarriers simultaneously. An uplink subchanneling gain is taken into account, based on the number of used subchannels per user and is defined as,

$$Uplink\ Subchanneling\ gain = -10 \log_{10} \frac{N_{usedsubchul}}{N_{subchul}} \dots \dots \dots (3.8)$$

Where,

- $N_{usedsubchul}$  is the number of used subchannels in the uplink.
- $N_{subchul}$  Total number of subchannels in the uplink (see Table 3.7).

### 3.9.6 Link Budget Calculation

Link budget calculation is used to determine the maximum allowable pathloss (MAPL). MAPL is the link margin we get when we subtract all the loss parameters from the sum of our gain parameters. The pathloss at any given point in our intended coverage area needs to be less than or equal to this link margin. With the data discussed in the previous sections, it is possible to calculate the link budget.

For the downlink communication MAPL is defined as,

$$\begin{aligned}
 \text{MAPL} = & \text{EIRP} + \text{CPE DL RX antenna gain} + \text{other CPE DL RX antenna gain} - \\
 & \text{Head or Body loss} - \text{RX sensitivity} - \text{lognormal fading margin} - \\
 & \text{fast fading margin} - \text{interference margin} - \\
 & \text{building penetration loss} \dots \dots \dots (3.9)
 \end{aligned}$$

For the uplink communication MAPL is defined as,

$$\begin{aligned}
 \text{MAPL} = & \text{EIRP} + \text{BS UL RX antenna gain} + \text{other BS UL RX antenna gain} - \\
 & -\text{RX sensitivity} - \text{lognormal fading margin} - \\
 & \text{fast fading margin} - \text{interference margin} - \\
 & \text{building penetration loss} + \\
 & \text{UL Subchanneling gain} \dots \dots \dots (3.10)
 \end{aligned}$$

Where,

- Lognormal fading margin is the slow fading margin expressed as a lognormal ratio.
- Interference margin is the loss margin attributed to various sources of interference.
- Fast fading margin is fading margin due to fast fading (Coherence time of the channel is small relative to the delay constraint of the channel).
- Building penetration loss is the loss in signal power while penetrating walls for indoor reception.
- Other parameters have been discussed in previous discussions.

The building penetration loss figure is assumed to be 10 dB for urban areas such as Addis Ababa. Similarly, the interference margin is mostly taken as 2 dB for downlink and 3

dB for uplink communications, respectively. The assumed value for fast fading margin is 3 dB [12].

Using equations enlisted in Section 3.9, and taking into consideration choices made regarding operating frequency band (2.5 GHz), antenna configuration (SIMO) and channel bandwidth (10 MHz), we can now proceed with the calculation for MAPL. For the purposes of calculating MAPL, we will assume the lowest modulation order, QPSK  $\frac{1}{2}$  which requires only 0.8dB [1] SNR at the receiver.

The resulting MAPL for a mobile handheld device would equate to **145.2 dB** in the uplink and **146.2 dB** in the downlink.

From the value of the MAPL for the UL cases (since range is limited by the uplink transmission rather than the downlink due to constraints on power and antenna gain of CPEs) it is possible to predict the coverage range using the COST-231 Hata propagation model (see Section 4.1.3). Assuming a base station antenna height of 30 meters and a mobile station height of 1.5 meters, our coverage range will equate to **1.06 km**.

We can now predict the coverage per base station as follows, the area of a tri-sectored base station can be computed as  $1.95 R^2$  where R is the cell radius shown in Figure 3.3. We have already computed R to be 1.06 Km. Therefore, the area of one cell would equate to,  $1.95 (1.06 \text{ km})^2 = \mathbf{2.19 \text{ km}^2}$ . Hence, from the dimensioning perspective, we would need **243** base stations to provide the service throughout the entire district of Addis.

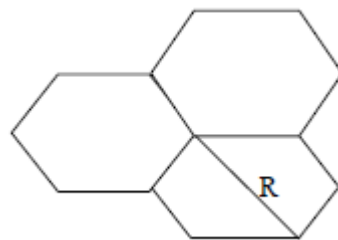


Figure 3.4: Tri-Sectored base station

### 3.10 Dimensioning the Core Network

In order to achieve end-to-end connectivity, the next step is to dimension and plan the elements that form the core service network. In this step, we will estimate the traffic load on the reference points R3, R4 and R6. (see Section 2.7 and Figure 2.4 for details)

We will assume the following traffic model for the purposes of this calculation. Of our total number of subscribers, powered on subscribers are once that have switched on their CPE. These subscribers are further classified into active or idle depending on whether or not they are using the network at the time.

Type	Quantity
Total number of subscribers	159,719
Powered on subscribers (90%)	143,747
Sleeping subscribers (10%)	5,972
Active subscribers (50% of powered on)	71,874
Idle subscribers (50% of powered on)	71,874
mobility	4%

Table 3.9 : End to end traffic model

The next step is to estimate the total number of calls during the busiest hour of the day using the Erlang C formula assuming a delay probability of 0.1 % and a traffic per user of 30 mErl which are common values used in WiMAX dimensioning [3].

$$P_c = \frac{(T^C C / [C! (C - T)])}{\sum_{i=0}^{C-1} (T^i / i! + T^C C / [C! (C - T)])} \dots \dots \dots (3.11)$$

Where

- T is the total traffic
- C is the number of servers
- Pc is the probability of delay

The consequent number of calls at peak busy hour (PBH) will be **2713**. Assuming the G.729 package, which states that we have 40 Kbps bit rate for voice calls. Therefore, 2713 calls would require a data rate of **108.52 Mbps**. We already have a data density requirement of **14.64 Mbps/km<sup>2</sup>** (see section 3.3). This equates to **7.761 Gbps** overall datarate requirement given the 530.14 km<sup>2</sup> area of Addis.

Therefore, the expected traffic on the R6 interface will be **108.52 Mbps** for VoIP services and **7.761 Gbps** for data services.

Since we have assumed 4% mobility, we would expect 4% of the active users on the R4 interface, i.e., crossing over from one ASN gateway to another. Therefore, the expected

traffic on the R4 interface will be **4.34 Mbps** for VoIP services and **310.44 Mbps** for data services.

The remaining 96 % of the users will make up the load on the R3 interface ultimately resulting in a capacity requirement of **104.18 Mbps** for VoIP services and **7.451 Gbps** for data services.

## Chapter 4: Radio Network Planning

### 4.1 Analysis of Propagation Models

In the analysis of propagation models, it is necessary to estimate a system's propagation characteristic through a medium so that the signal parameters can be more accurate in a communication system. In wireless communication systems, the interaction between the electromagnetic waves and the environment reduces the signal strength sent from the transmitter to the receiver, that causes pathloss. Different models are used to calculate the pathloss. These models make use of the laws governing electromagnetic wave propagation in order to determine the received signal power in a particular location.

Propagation analysis is very important in evaluating the signal characteristics. For wireless communication system, the system should have the ability to predict the accurateness of the radio propagation behaviour [6].

In this chapter, we analyze different propagation models at 2.5 GHz to determine as to which model best suits or more accurately predicts the range of our wireless network given the maximum allowable path loss calculated in the previous chapter. After running a numerical simulation of these different propagation models, we will analyze the results and base our choice of propagation model on the findings (Further explanation will be given in section 4.2).

#### 4.1.1 Free Space Path Loss

Path loss in free space denoted as  $PL_{FSPL}$  in dB, defines how much strength of the signal is lost during propagation from transmitter to receiver. This model does not take into account the losses due to interference and other environmental factors such as shadowing, diffraction, scattering and the like. It is included in this chapter to comparatively show the losses due to environmental factors that are predicted by the forthcoming propagation models in comparison with free space pathloss. The calculation is done by using the following equation.

$$PL_{FSPL} = 32.45 + 20 \log_{10}(d) + 20 \log_{10}(f) \dots \dots \dots (4.1)$$

Where

- f: Frequency in (MHz)

- d: Distance between transmitter and receiver in (m)

This model does not take terrain parameters into consideration, the subsequent propagation models give a much more accurate pathloss estimation in that regard.

#### 4.1.2 Okumura Model

This model was built by the data collected in Tokyo, Japan. This model is good for using in the cities having dense and tall structures, like Tokyo. By using Okumura model we can predict path loss in urban, suburban and rural area up to 3 GHz [14].

$$PL(dB) = L_f + A_{mn}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA} \dots \dots \dots (4.2)$$

Where

- PL: Median path loss in [dB]
- L<sub>f</sub>: Free space path loss in [dB]
- A<sub>mn</sub> (f,d): Median attenuation relative to free space in [dB]
- G (h<sub>te</sub>): Base station antenna height gain factor in [dB]
- G (h<sub>re</sub>): Mobile station antenna height gain factor in [dB]
- G<sub>AREA</sub>: Gain due to the type of environment in [dB]
- f: Frequency in [MHz]
- h<sub>te</sub>: Transmitter antenna height in [m]
- h<sub>re</sub>: Receiver antenna height in [m]
- d: Distance between transmitter and receiver antenna in [km]

G(h<sub>te</sub>) can be calculated by using the following equation.

$$G(h_{te}) = \begin{cases} 20 \log_{10} \left( \frac{h_{te}}{200} \right) & \text{for } 1000m > h_{re} > 10m \\ 10 \log_{10} \left( \frac{h_{re}}{3} \right) & \text{for } h_{re} \leq 3m \dots \dots \dots (4.3) \\ 20 \log_{10} \left( \frac{h_{re}}{3} \right) & \text{for } 10m > h_{re} > 3m \end{cases}$$

Although this model is ideally suited for urban areas with high building density, it can also be used for sub-urban and rural areas. The gain due the type of environment (G<sub>AREA</sub>) and the median attenuation relative to free space (A<sub>mn</sub> (f,d)) , are different for the various types of metropolitan areas and can be extracted from figure 4.1. This model was the basis for the Okumura-

Hata propagation model. The Okumura-Hata model was derived as a numerical fit to the propagation curves published by Okumura. As such, the model is somewhat specific to Japan's propagation environment [29]. But a more generic and widely used model was further developed from the Okumura-Hata model which will be discussed in the next section.

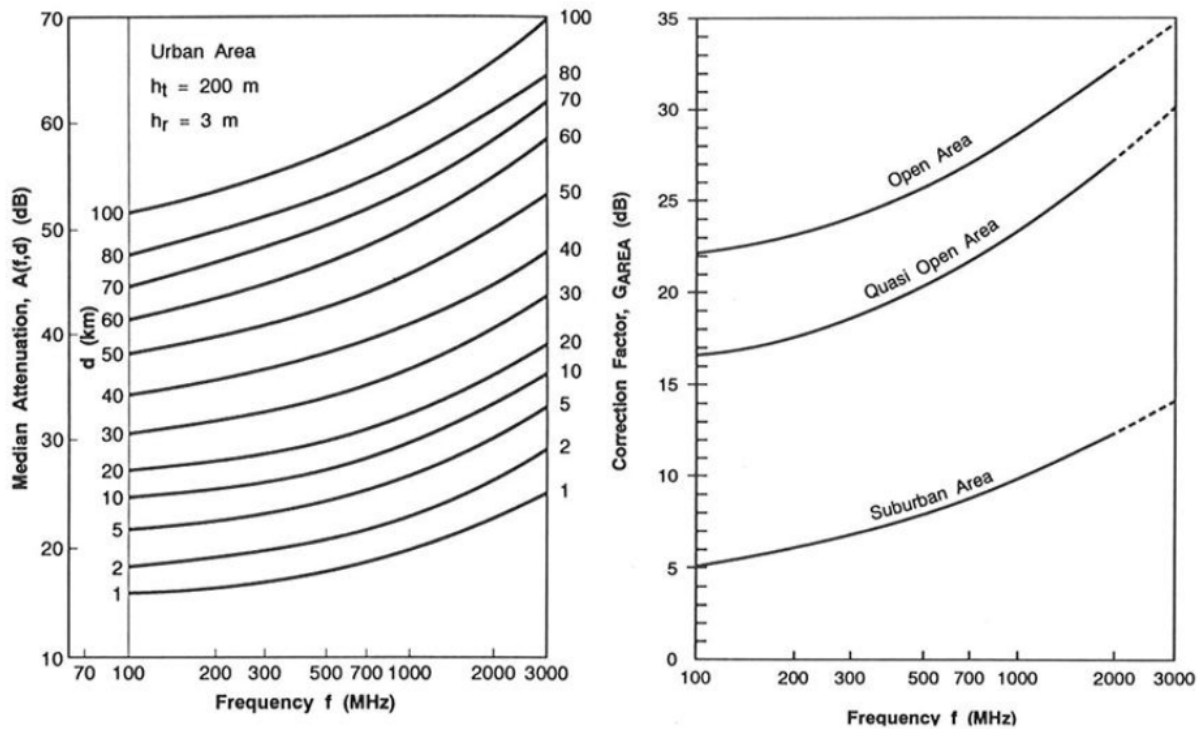


Figure 4.1 : Curves for extracting  $A_{mn}(f,d)$  and  $G_{AREA}$  [14]

#### 4.1.3 COST 231 Hata Model

COST 231 Hata model is an extension of the Okumura-Hata model. It is used to calculate pathloss in three different environments like urban, suburban and rural (flat). This model provides simple and easy ways to calculate the path loss. Although our chosen frequency, which is, 2.5 GHz is outside of its measurement range, its simplicity and correction factors still allowed to predict the pathloss in this higher frequency range. On reference [3], this model was used to estimate pathloss in the cities of Helsinki and Espoo at operating frequencies of 3.5 GHz. In fact, this model is recommended by the WiMAX forum to calculate pathloss in urban and sub-urban areas at operating frequencies of 2.5 GHz and 3.5 GHz [1,3], which is given as:

$$PL = 46.3 + 33.9 \log_{10}(f) - 13.82 \log_{10}(h_b) - ah_m + (44.9 - 6.55 \log_{10}(h_b)) \log_{10} d + C_m \dots \dots \dots (4.4)$$

Where

- d: Distance between transmitter and receiver antenna in [km]
- f: Frequency in [MHz]
- hb: Transmitter antenna height in [m]
- ah<sub>m</sub>: Mobile station antenna height correction factor in [dB]
- C<sub>m</sub>: Metropolitan area correction factor in [dB]

The parameter C<sub>m</sub> has different values for different environments like 0 dB for suburban and 3 dB for urban areas. ah<sub>m</sub> is defined in urban areas as,

$$ah_m = 3.20(\log_{10}(11.75h_r))^2 - 4.79 \dots \dots \dots (4.5)$$

The value for ah<sub>m</sub> in suburban and rural (flat) areas is given as,

$$ah_m = (1.11 \log_{10} f - 0.7)h_r - (1.5 \log_{10} f - 0.8) \dots \dots \dots (4.6)$$

Where the h<sub>r</sub> is the receiver antenna height in meter.

#### 4.1.4 Stanford University Interim (SUI) Model

The IEEE 802.16 Broadband Wireless Access working group proposed the standard for the frequency band below 11 GHz. This model developed by Stanford University and is named the SUI model [6].

The base station antenna height of SUI model can range from 10 m to 80 m. Receiver antenna height is from 2 m to 10 m. The cell radius is from 0.1 km to 8 km. The SUI model describes three types of terrain, they are terrain A, terrain B and terrain C.

Terrain A can be used for hilly areas with moderate or very dense vegetation. This terrain presents the highest pathloss. Terrain A can be taken as a dense populated urban area. Terrain B is characterized for the hilly terrains with rare vegetation, or flat terrains with moderate or heavy tree densities. This is the intermediate pathloss scheme. We consider this model for suburban environment. Terrain C is suitable for flat terrains or rural with light vegetation, here path loss is minimum [6]. The basic pathloss expression of the SUI model is given as;

$$PL(dB) = A + 10\gamma \log_{10}\left(\frac{d}{d_o}\right) + X_f + X_h + S \text{ for } d > d_o \dots \dots \dots (4.7)$$

Where

- d: Distance between BS and receiving antenna in [m]
- $d_0$ : 100 in [m]
- $\lambda$ : Wavelength in [m]
- $X_f$ : Correction for frequency above 2 GHz [MHz]
- $X_h$ : Correction for receiving antenna height [m]
- S: Correction for shadowing [dB]
- $\gamma$ : Path loss exponent

The log normally distributed factor S, is for shadow fading because of trees and other clutter on a propagations path and its value is between 8.2 dB and 10.6 dB [6].

The parameter A is defined as,

$$A = 20 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right) \dots \dots \dots 4.8$$

And the path loss exponent  $\gamma$  is given by,

$$\gamma = a - b h_b + \left( \frac{c}{h_b} \right) \dots \dots \dots 4.9$$

Where, the parameter  $h_b$  is the base station antenna height in meters. This is between 10 m and 80 m. The constants a, b, and c depend upon the types of terrain, that are given in the table below. The value of parameter  $\gamma = 2$  for free space propagation in an urban area,  $3 < \gamma < 5$  for urban NLOS environment, and  $\gamma > 5$  for indoor propagation [6].

Model Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b ( $m^{-1}$ )	0.0075	0.0065	0.005
C (m)	12.6	17.1	20

Table 4.1 : Values of model parameters for all three terrain models [6].

The frequency correction factor  $X_f$  and the correction for receiver antenna height  $X_h$  for the model are expressed by,

$$X_f = 6.0 \log_{10} \left( \frac{f}{2000} \right) \dots \dots \dots (4.10 a)$$

$$X_h = \begin{cases} -10.8 \log_{10} \left( \frac{h_r}{2000} \right) & \text{for terrain type A and B} \\ -20 \log_{10} \left( \frac{h_r}{2000} \right) & \text{for terrain type C} \end{cases} \dots \dots \dots (4.10 b)$$

Where,  $f$  is the operating frequency in MHz, and  $h_r$  is the receiver antenna height in meter.

#### 4.1.5 Hata-Okumura extended model or ECC-33 Model

This model was developed based on the Okumura model. The original Okumura model doesn't provide any data greater than 3 GHz. This method is applied to predict the model for higher frequency greater than 3 GHz. In this model path loss is given by the following equation.

$$PL(dB) = A_{fs} + A_{bm} - G_b - G_r \dots \dots \dots (4.11)$$

Where

- $A_{fs}$ : Free space attenuation in [dB] given in equation (4.12 a)
- $A_{bm}$ : Basic median path loss in [dB] given in equation (4.12 b)
- $G_b$ : Transmitter antenna height gain factor given in equation (4.12 c)
- $G_r$ : Receiver antenna height gain factor given in equation (4.12 d)

The gain and loss parameters can be calculated as,

$$A_{fs} = 92.4 + 20 \log_{10}(d) + 20 \log_{10}(f) \dots \dots \dots (4.12 a)$$

$$A_{bm} = 20.41 + 9.83 \log_{10}(d) + 7.894 \log_{10}(f) + 9.56(\log_{10}(f))^2 \dots \dots \dots (4.12 b)$$

$$G_b = \log_{10} \left( \frac{h_b}{200} \right) \{13.958 + 5.8[\log_{10} d]^2\} \dots \dots \dots (4.12 c)$$

$$G_r = [42.57 + 13.7 \log_{10}(f)][\log_{10}(h_r) - 0.585] \dots \dots \dots (4.12 d)$$

Where

- $d$ : Distance between transmitter and receiver antenna in [km]
- $f$ : Frequency in [GHz]
- $h_b$ : Transmitter antenna height in [m]
- $h_r$ : Receiver antenna height in [m]

#### 4.1.6 COST 231 Walfish-Ikegami (W-I) model

This model is a combination of the J. Walfish and F. Ikegami models [6]. The COST 231 project further developed this model. Now it is known as a COST 231 Walfish-Ikegami (W-I) model. The equations are expressed as,

For LOS condition,

$$PL_{LOS} = 42.6 + 26 \log_{10}(d) + 20 \log_{10}(f) \dots \dots \dots (4.13)$$

And for NLOS condition,

$$PL_{NLOS} = \begin{cases} L_{FSL} + L_{rts} + L_{msd} & \text{for urban and suburban} \\ L_{FS} & \text{if } L_{rts} + L_{msd} > 0 \end{cases} \dots \dots \dots (4.14)$$

Where

- $L_{FSL}$ = Free space loss
- $L_{rts}$ = Roof top to street diffraction
- $L_{msd}$ = Multi-screen diffraction loss

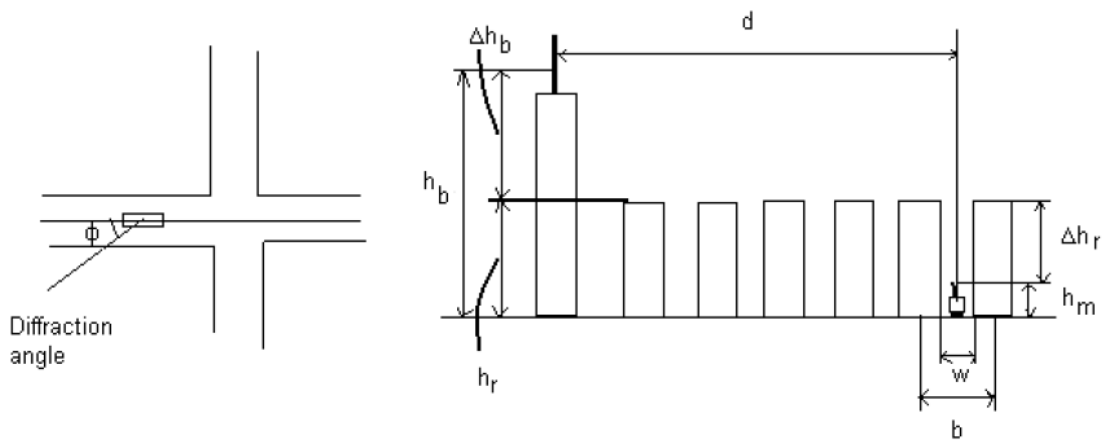


Figure 4.2: Illustration of terrain parameters for COST 231 Walfish-Ikegami model

Where,

$$\Delta h_{mobile} = h_{roof} - h_{mobile}$$

$$\Delta h_{base} = h_{base} - h_{roof}$$

The expression for  $L_{FSL}$  is given on Equation (4.1)

The expression for roof top to street diffraction is,

$$L_{rts} = \begin{cases} -16.9 - 10 \log_{10}(w) + 10 \log_{10}(f) + 20 \log_{10} h_m + L_{ori} & \text{if } h_{roof} > h_m \\ 0 & \text{otherwise} \end{cases} \dots\dots (4.15)$$

$$L_{ori} = \begin{cases} -10 + 0.354\varphi & \text{for } 0 \leq \varphi < 35 \\ 2.5 + 0.075(\varphi - 35) & \text{for } 35 \leq \varphi \leq 55 \\ 4 - 0.114(\varphi - 55) & \text{for } 55 \leq \varphi \leq 90 \end{cases} \dots\dots\dots (4.16)$$

The multi-screen diffraction loss is,

$$L_{msd} = \begin{cases} L_{bsh} + K_a + K_d \log_{10}(d) + (K_f - 9) \log_{10}(f) - 9 \log_{10}(B) & \text{if } L_{msd} > 0 \\ 0 & \text{otherwise} \end{cases} \dots\dots (4.17)$$

Where

$$L_{bsh} = \begin{cases} -18 \log_{10}(1 + \Delta h_{base}) & \text{for } h_b > h_{roof} \\ 0 & \text{otherwise} \end{cases} \dots\dots\dots (4.18)$$

$$K_a = \begin{cases} 54 & \text{for } h_b > h_{roof} \\ 54 - 0.8 \Delta h_{base} & \text{for } d \geq 0.5 \text{ km and } h_b \leq h_{roof} \\ 54 - 0.8 \Delta h_{base} \left(\frac{d}{0.5}\right) & \text{for } d < 0.5 \text{ km and } h_b \leq h_{roof} \end{cases} \dots\dots\dots (4.19)$$

$$K_d = \begin{cases} 18 & \text{for } h_b > h_{roof} \\ 18 - 15 \left(\frac{\Delta h_{base}}{h_{roof}}\right) & \text{for } h_b \leq h_{roof} \end{cases} \dots\dots\dots (4.20)$$

$$K_f = \begin{cases} -4 + 0.7 \left(\frac{f}{925} - 1\right) & \text{for suburban} \\ -4 + 1.5 \left(\frac{f}{925} - 1\right) & \text{for urban} \end{cases} \dots\dots\dots (4.21)$$

Where

- d: Distance between transmitter and receiver antenna [m]
- f: Frequency [GHz]
- B: Building to building distance [m]
- w: Street width [m]
- $\varphi$ : Street orientation angel with respect to direct radio path [degree]

## 4.2 Numerical Results and Analysis

For the purposes of this numerical simulation (and others that follow), we will assume Addis Ababa as an urban metropolitan area for reasons discussed in Section 3.3. Other assumptions include an average building-to-building distance of 50 m, street width 25 m (width of most two-way streets), street orientation angle 30 degree. Average building height is assumed as 15 m (most buildings in Addis are 3 to 4 storeys high), base station height 30 m. The operating frequency is set at 2500 MHz.

Note that the above assumed values are subject to change and were selected based on a reasonable estimate.

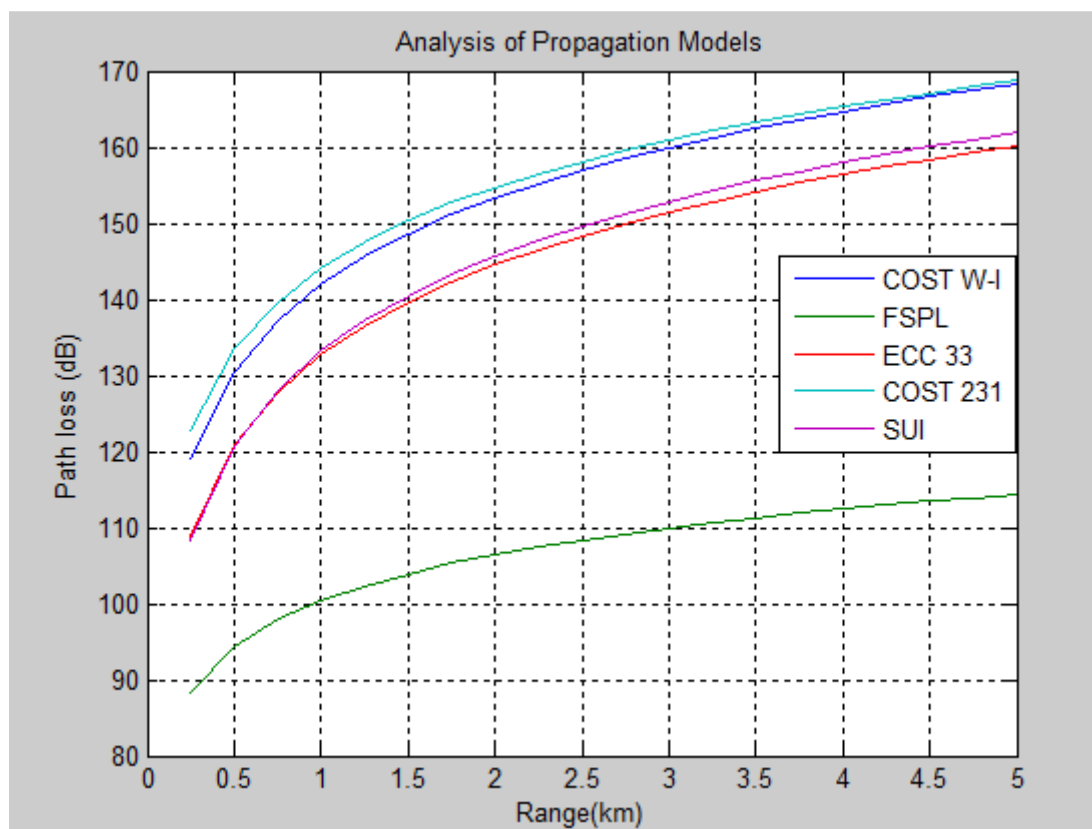


Figure 4.3 : Numerical result for the four propagation models

As mentioned in prior sections, the WiMAX forum recommends the COST-231 Hata model for pathloss/range calculations in urban and suburban areas. This model is expected to perform better (yield more accurate pathloss estimates) than the other propagation models in the aforementioned metropolitan areas according to the WiMAX forum. However, the COST-231 Hata model is an empirical model that can only be used to calculate

the average range or more specifically, cell radius. It does not take into account the terrain data (such as particular building heights, street width etc...) for each nominal direction as the average values for these parameters have already been incorporated into the formula.

We can also see in Figure 4.3 that the propagation model that yields the closest result to the COST-231 Hata model given the particular scenario we assumed is the COST 231 Walfish-Ikegami (W-I) model. In fact, the pathloss versus range curves almost overlap for the two models. However, the latter allows us to manually enter terrain parameters and calculate the range for each nominal direction and consequently come up with the actual coverage area, i.e. we will be able to see what our actual coverage area might resemble because we are calculating our range in every direction. The COST-231 Hata model only yields the average cell radius.

It is also worth noting that COST-231 and COST W-I models yield the highest pathloss. From a planning perspective, it is better to assume worst case scenarios so as to avoid risking an inadequate coverage. As the saying goes, “better safe than sorry”.

### **4.3 Radio Network Planning (RNP)**

For reasons mentioned in the above paragraphs, the COST 231 Walfish-Ikegami (W-I) model has been chosen in this thesis work to develop the radio network planning tool. The RNP tool extracts terrain parameters such as building height, building-to-building distance, street width and geographical co-ordinates from a digital terrain map for each nominal direction with a 1 degree sampling interval. It extracts the aforementioned parameters within a 2 km radius (theoretical coverage radius of the standard) from the base station site.

The RNP tool, set up with the COST W-I model, then performs pathloss versus range calculations for each direction. The pathloss value, as per our link budget calculation, is 145.2 dB. The corresponding range for this value of pathloss is then determined for all 360 directions and the coverage area, that resembles what our realistic cell coverage might look like, is plotted. Results, derived by the aforementioned methods, are presented in the next chapter.

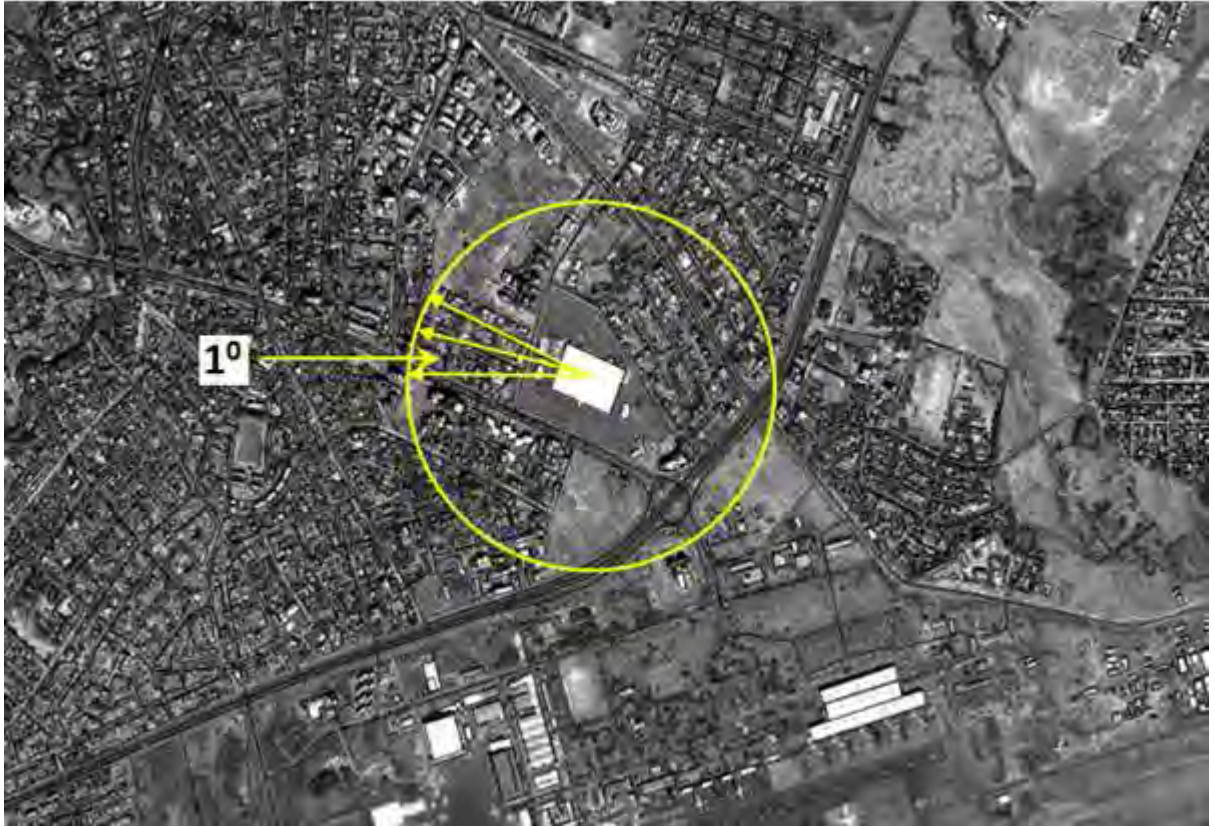


Figure 4.4: Map of Addis Ababa, Millennium Hall region

## Chapter 5: Results

The radio network planning was conducted for five distinct metropolitan areas in the district of Addis, namely; Bole Medhanialem, Gerji, Meskel Square, Piassa (Arada Mobile) and Sidist Kilo. The former three have a high building density, the piassa region has a moderate building density whereas a large portion of the Sidist kilo area comprises of a campus compound with relatively lower building density. We will take the average cell radius of these five regions to get a reasonable estimate of our expected coverage per cell.

The site location geographical co-ordinates were taken at the exact same locations where GSM telecommunication towers currently exist. A significant portion of the capital expenditure in wireless network deployment is the cost of building towers and site leasing. However, mounting the transmitting antennas on existing towers will spare this cost.

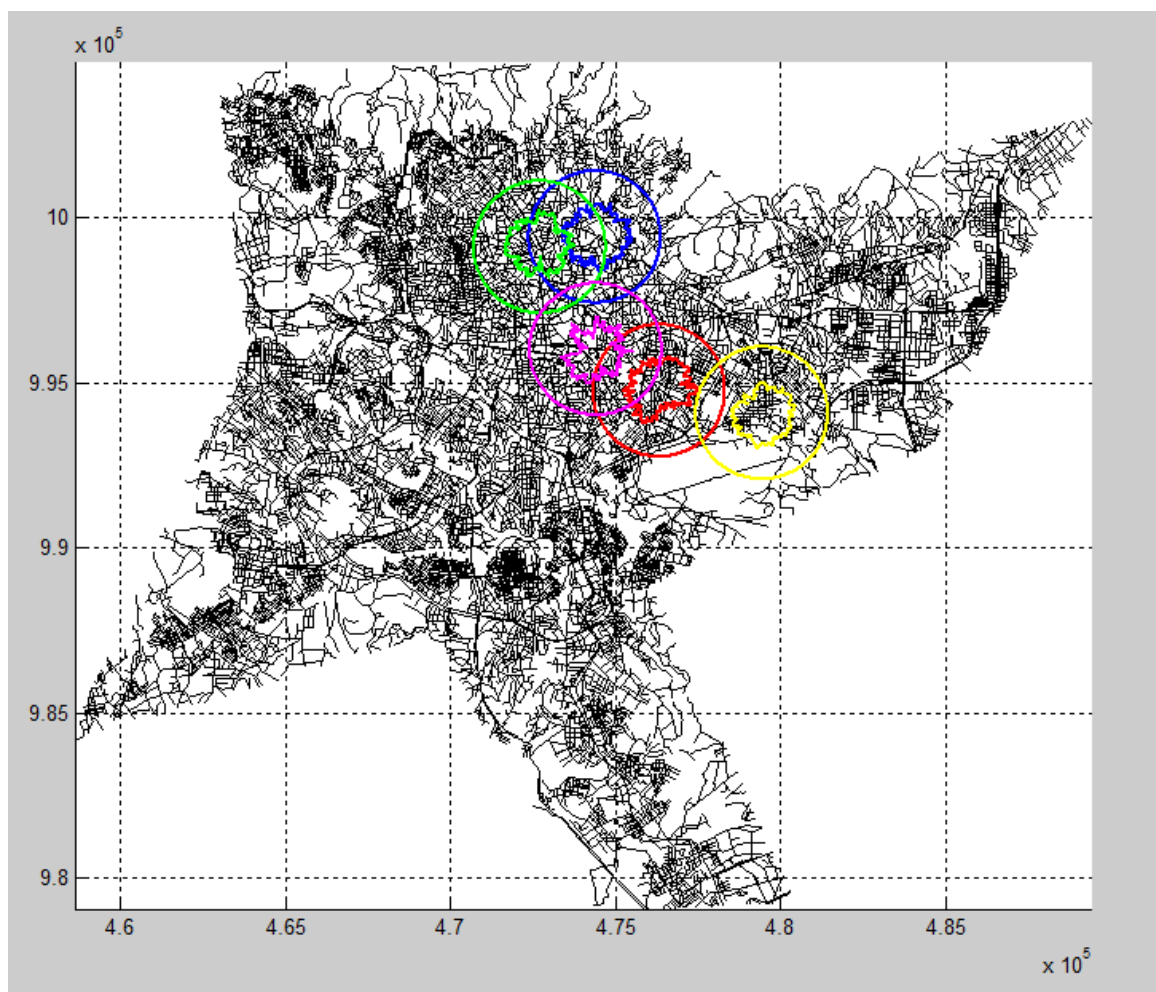


Figure 5.1 : Coverage areas of the selected 5 regions

The outer circles on Figure 5.1 represent our theoretical coverage area (2 km radius) where terrain parameters were sampled. The inner shapes are the expected coverage area plotted with the RNP tool. The green, blue, purple, red and yellow shapes represent the coverage areas of Piassa, Sidist Kilo, Meskel Square, Bole Medhanialelem and Gerji respectively. A close up view of the coverage areas is provided in the next figures.

### 1) Bole Medhanialelem

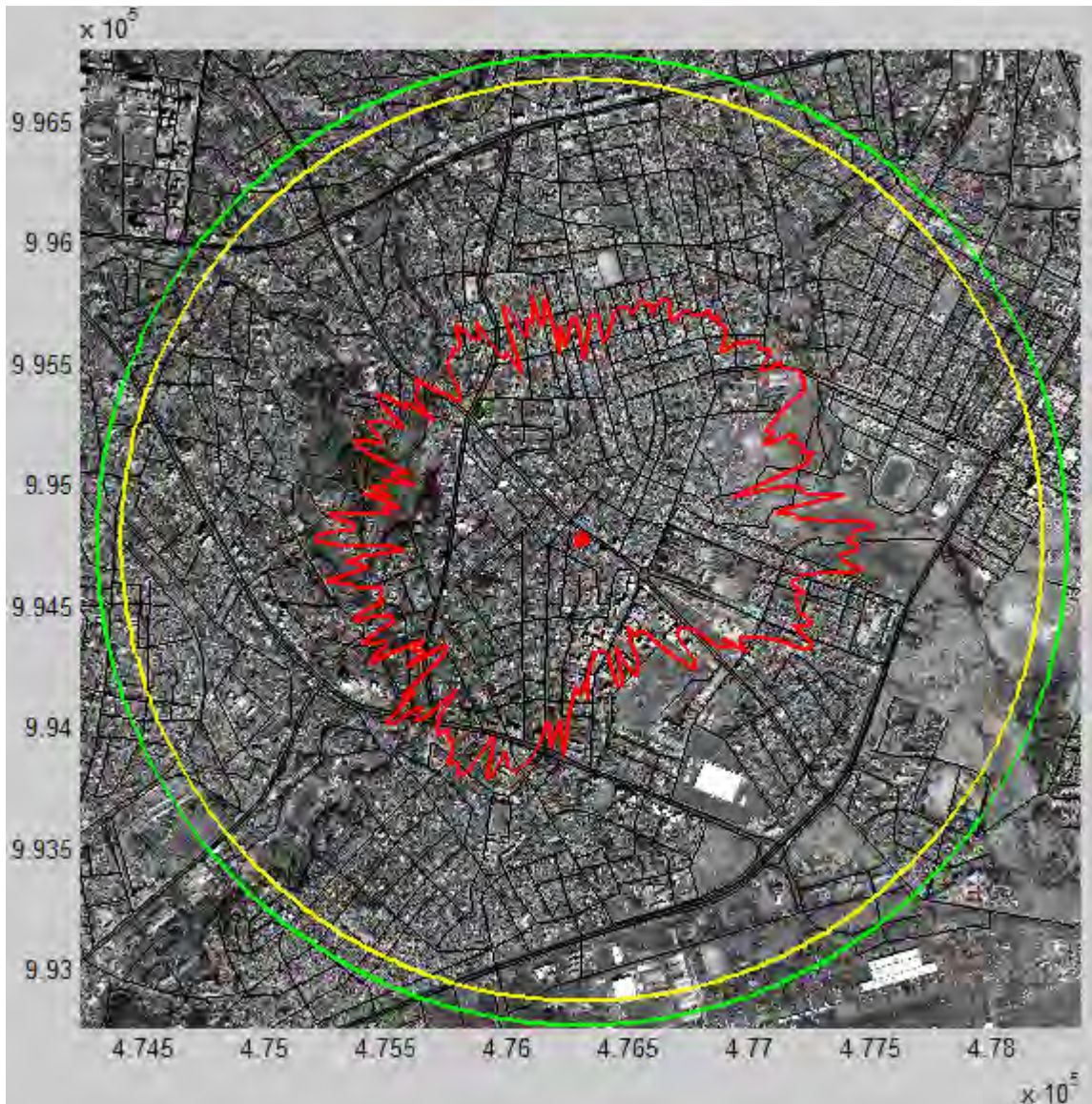


Figure 5.2 : The Bole Medhanialelem coverage area using different propagation models

The outer green circle is the coverage area we can expect if we had used the ECC-33 propagation model. It has a radius of 2 km. Similarly the middle yellow circle shows the coverage computed by the SUI propagation model, the radius in this case is 1.9 km. Figure 5.2 gives a good illustration of what was meant by ‘preparing for the worst’ in Section 4.2.2 as we can see in forthcoming figures that the coverage computed using the COST W-I model

(inner irregular shape) is roughly five times less than the coverage of the other two models, i.e., ECC-33 and SUI. Our actual coverage area using the COST W-I model is the one shown by the **red** inner shape. We can see that there is larger pathloss towards the bottom right owing to the presence of a dense cluster of buildings. This can be seen more clearly in Figure 5.3.

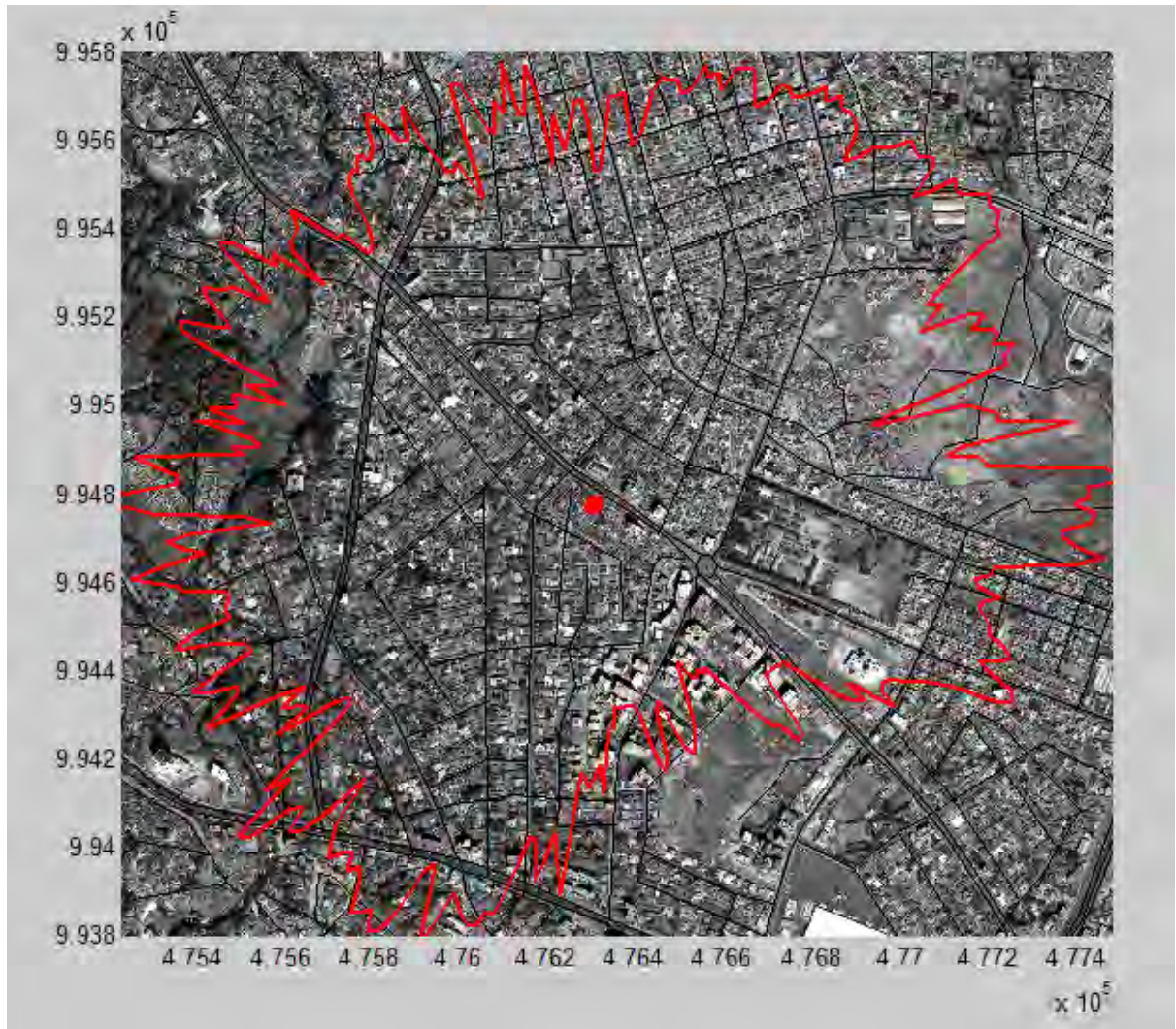


Figure 5.3: A close up view of the Bole Medhanialem coverage area

A bar plot of the radius in all 360 nominal directions is shown on figure 5.4. The average cell radius/coverage range, shown by the red horizontal line, is **0.879** km. This figure is considerably less than the theoretical cell radius which is 2 km but close to our dimensioning result, 1.06 km. In the dimensioning phase we used the COST-231 Hata model which showed similar performance characteristic to the COST W-I model during the numerical simulation in Chapter 4. This similarity is further reflected in the closeness of the two results, i.e., 0.879 km and 1.06 km. The corresponding coverage area of the Bole

Medhaniale region, according to the results of our RNP tool, will be (assuming tri-sector configuration) **1.51 km<sup>2</sup>**. It is also worth noting that our expected cell coverage would have been 7.8 km<sup>2</sup> had we used the ECC-33 model and 7.03 for that of the SUI model.

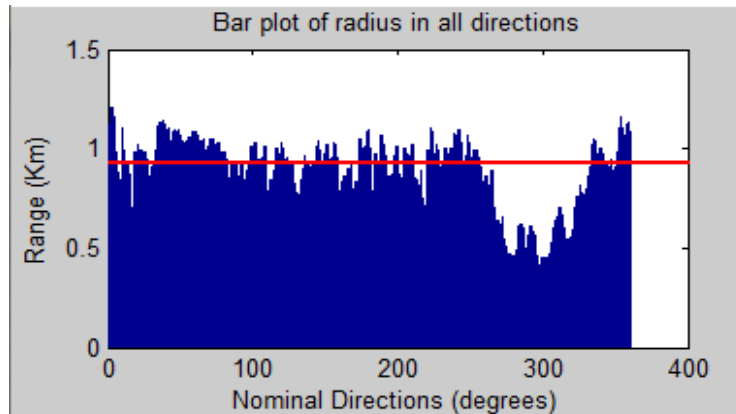


Figure 5.4 : The calculated range for each direction (Bole Medhaniale)

## 2) Gerji

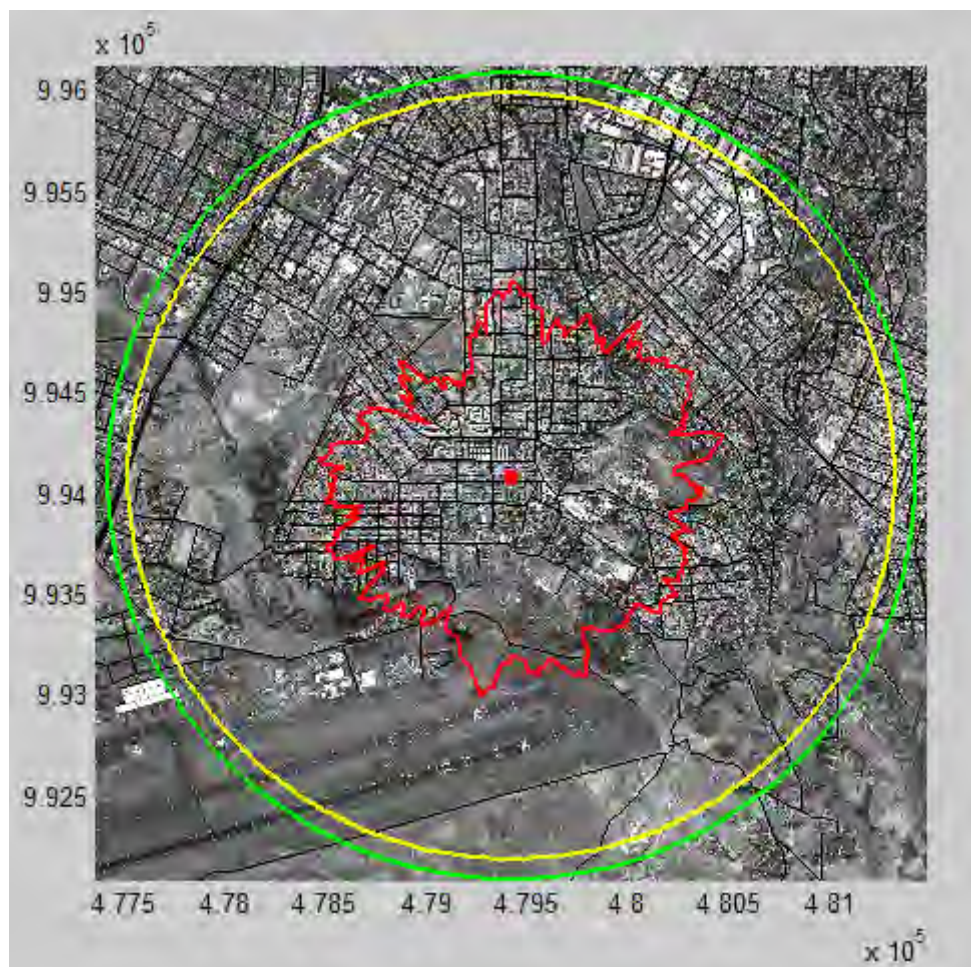


Figure 5.5 : The Gerji coverage area using different propagation models

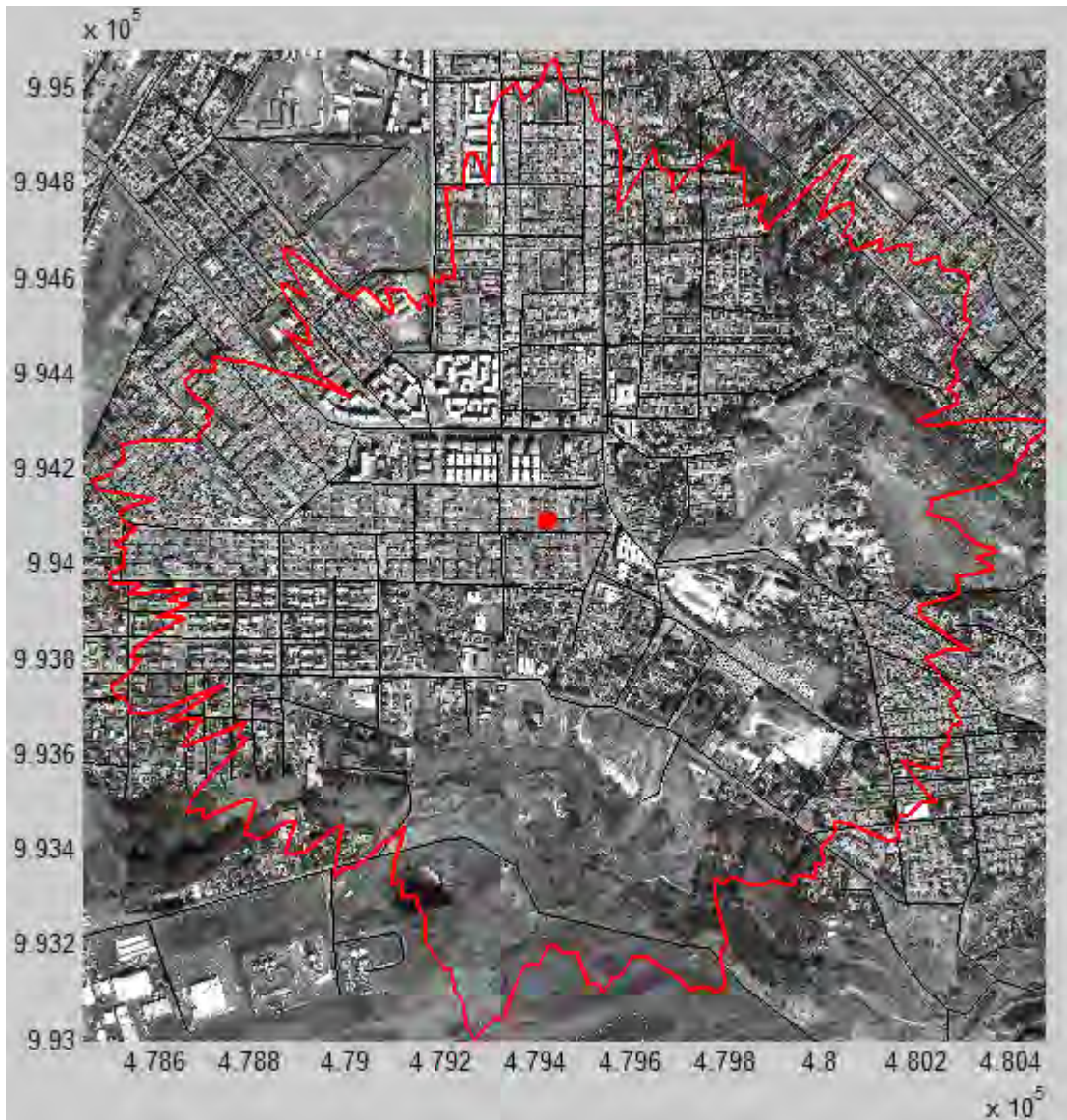


Figure 5.6: A close up view of the Gerji coverage area

Similar to Figure 5.2, the green and yellow outer circles of Figure 5.5 represent the expected coverage area using the ECC-33 and SUI propagation models respectively. This is presented here for the sake of comparison. A close up view of the Gerji coverage area is provided in Figure 5.6, the radius is fairly uniform except for small protrusions in the bottom since that particular area, as can be seen, is an open space. We can also observe a higher pathloss towards the upper left region, fittingly, right after the small cluster of buildings. Figure 5.7 shows a bar plot of the radius in all 360 nominal directions. The average cell radius is **0.855 km** and the corresponding coverage area is **1.43 km<sup>2</sup>**. The Gerji coverage area is nearly the same as but slightly less than the Bole Medhanialem coverage. This could be indicative of denser and/or taller building presence in this area.

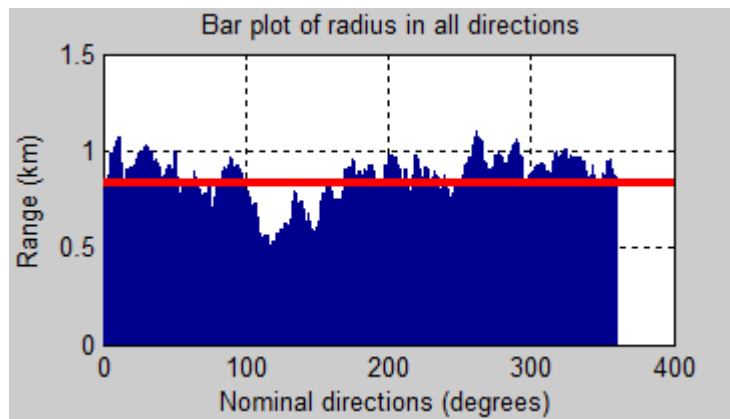


Figure 5.7: The calculated range for each direction (Gerji)

### 3) Meskel Square

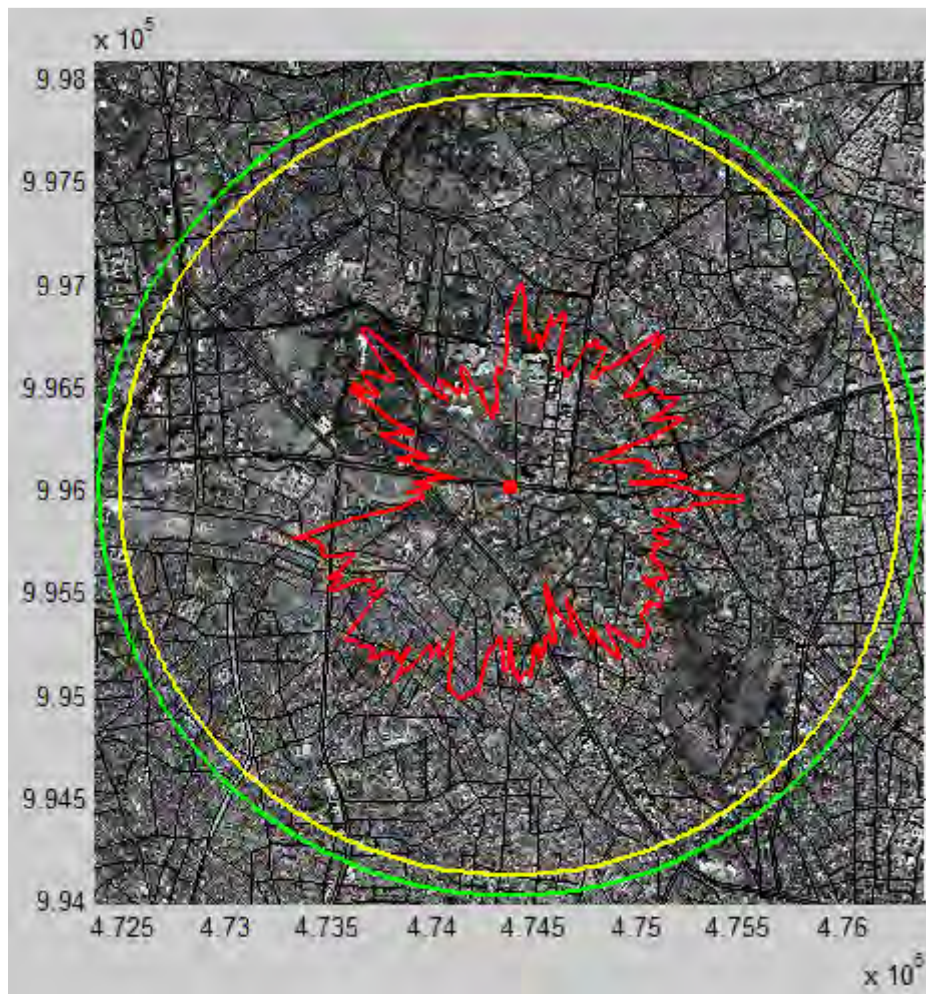


Figure 5.8: The Meskel Square coverage area using different propagation models

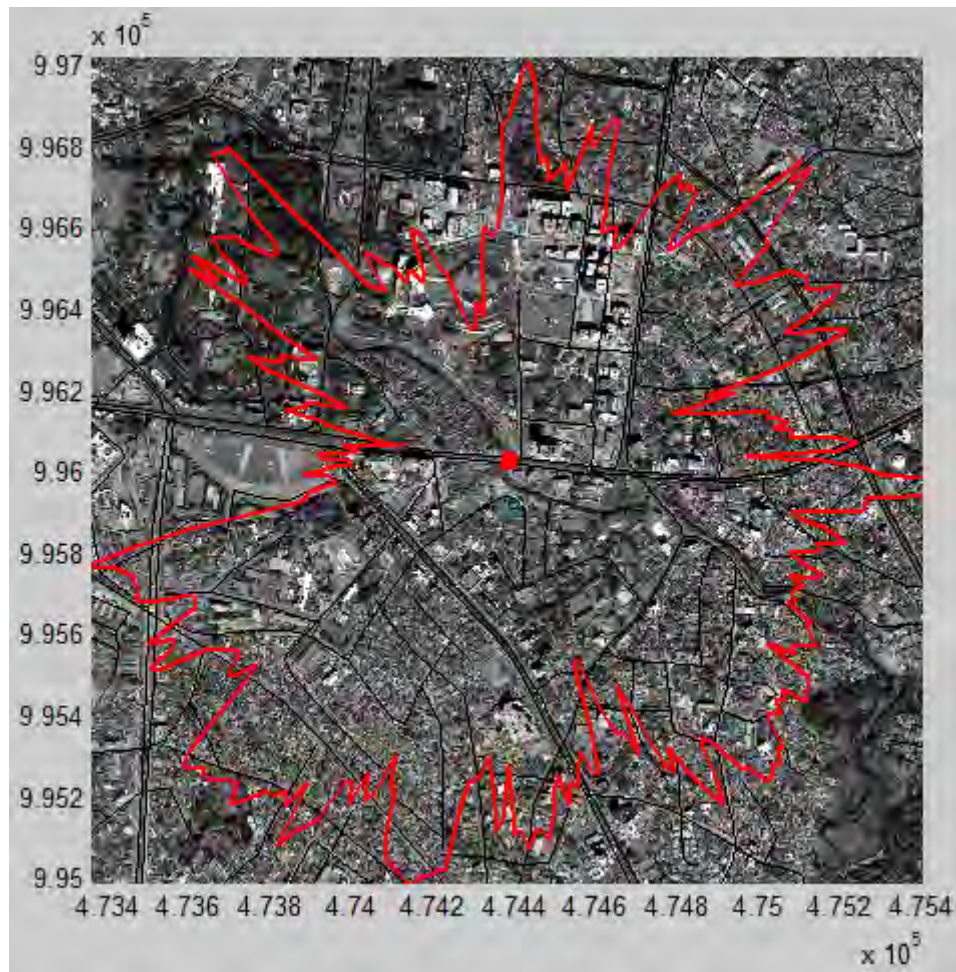


Figure 5.9: A close up view of the Meskel Square coverage area

The Meskel square coverage area exhibits highly irregular patterns owing to the fact that the buildings are located ‘here and there’ instead of in clusters. Due to this irregularity, the coverage area is slightly lower as compared to the previous two metropolitan areas, namely, Bole Medhaniamem and Gerji. The average cell radius is **0.769 km** and the corresponding coverage area is **1.15 km<sup>2</sup>**. The bar plot is presented in Figure 5.10.

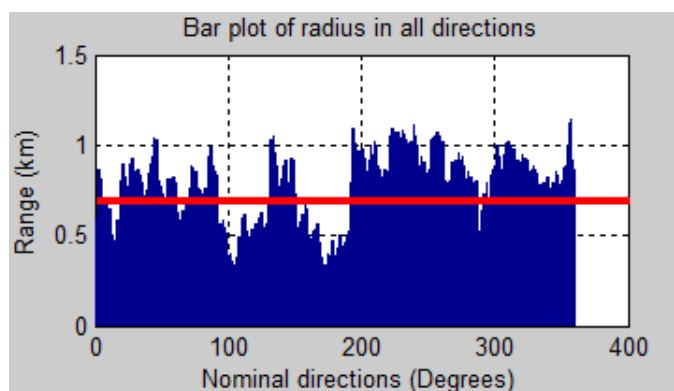


Figure 5.10: The calculated range for each direction (Meskel Square)

#### 4) Piassa (Arada Mobile)

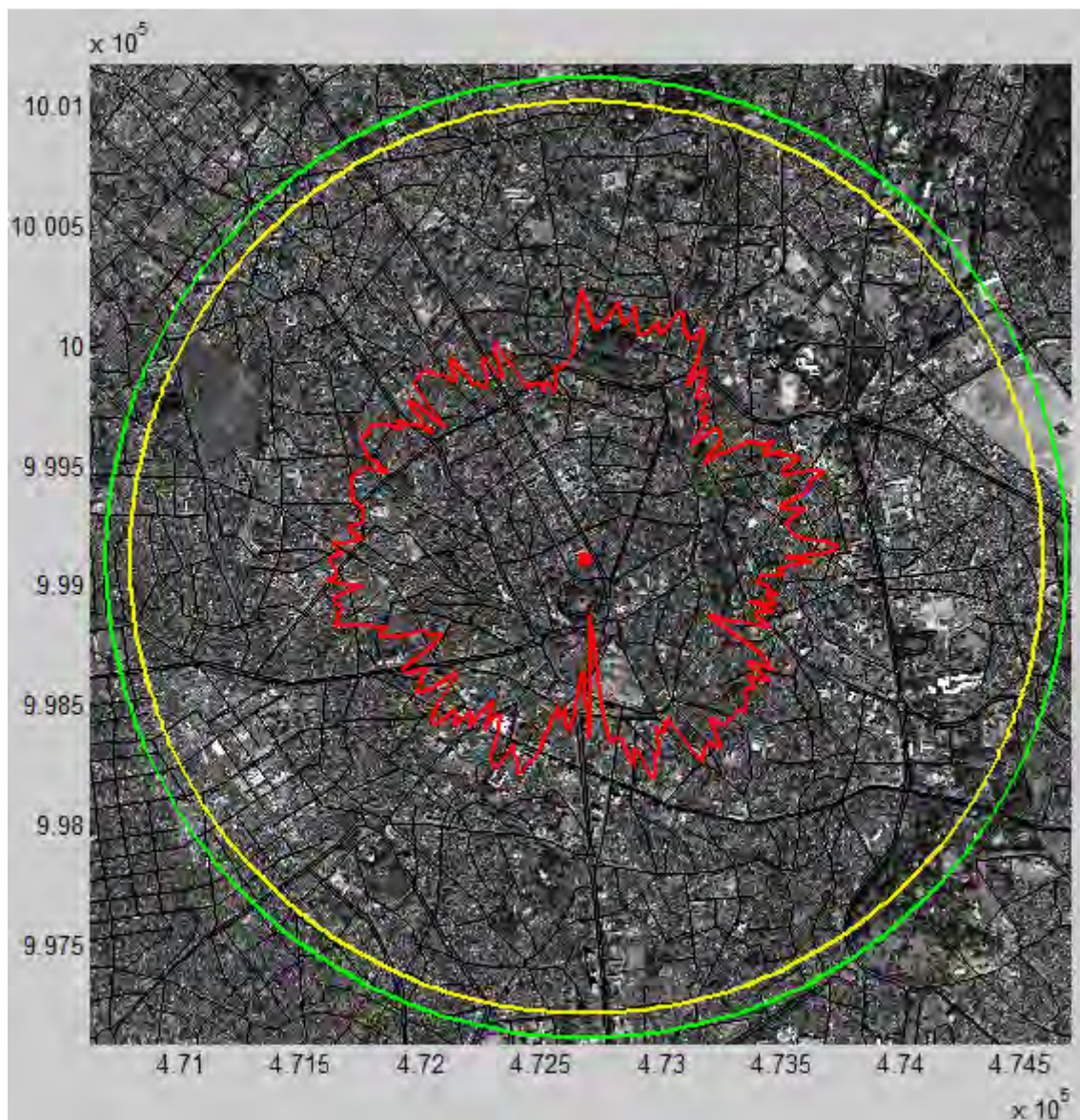


Figure 5.11: The Piassa coverage area using different propagation models

The piassa coverage area, apart from a few isolated severe losses in some directions, exhibits a regular pattern. This is an area with supposedly moderate building density in comparison to the former three (Bole Medhaniale, Gerji and Meskel Square). The average cell radius for this area is **0.873 km** and the corresponding coverage range is **1.49 km<sup>2</sup>**. A close up view of the coverage area and a bar plot of the radius in all directions is provided in Figure 5.12 and Figure 5.13 respectively.

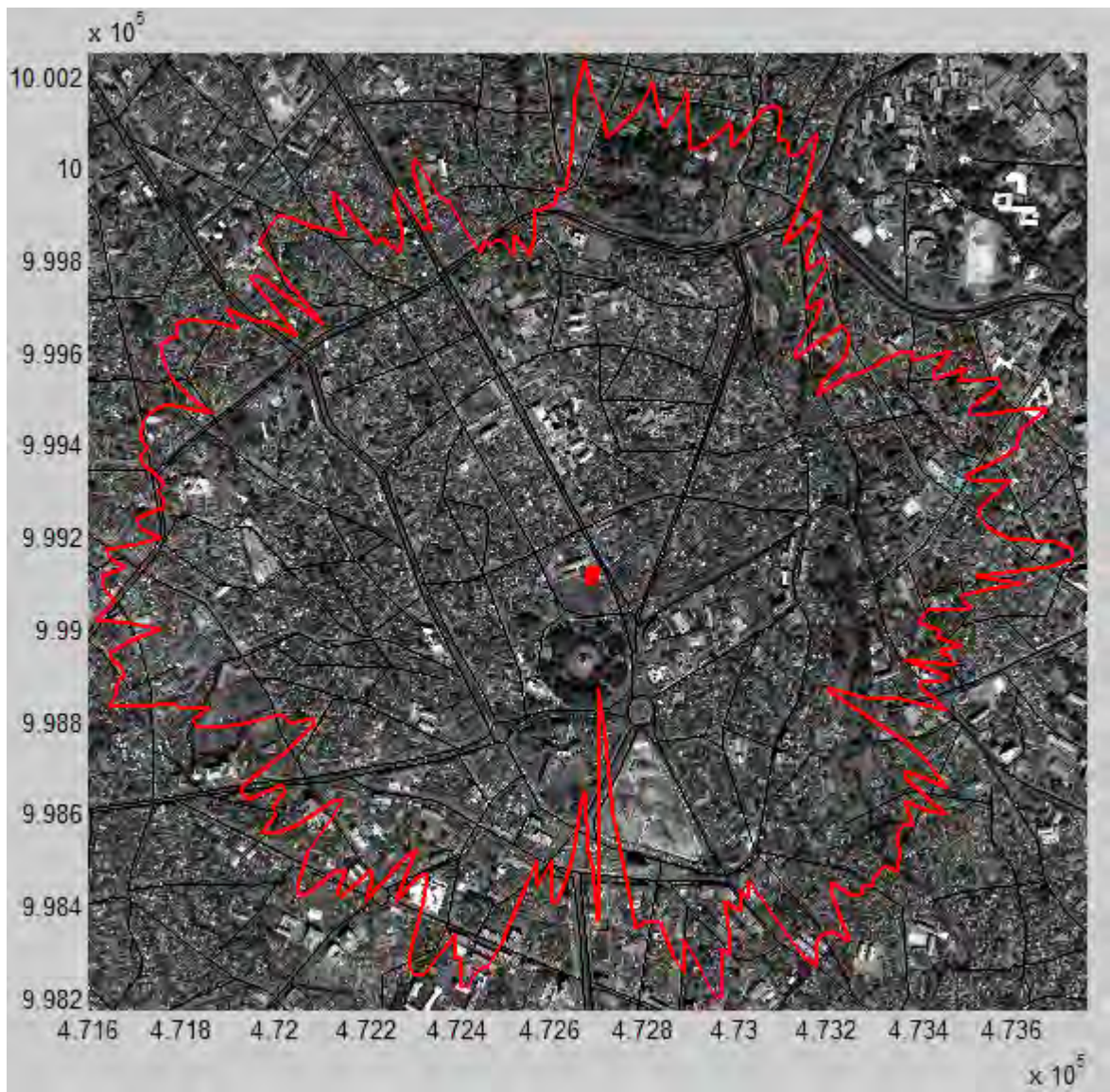


Figure 5.12: A close up view of the Piassa coverage area

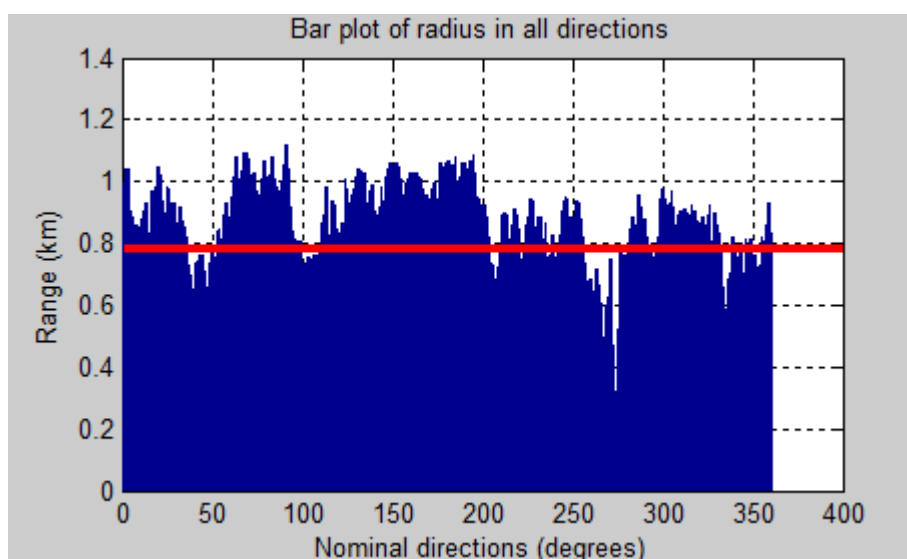


Figure 5.13: The calculated range for each direction (Piassa)

## 5) Sidist Kilo

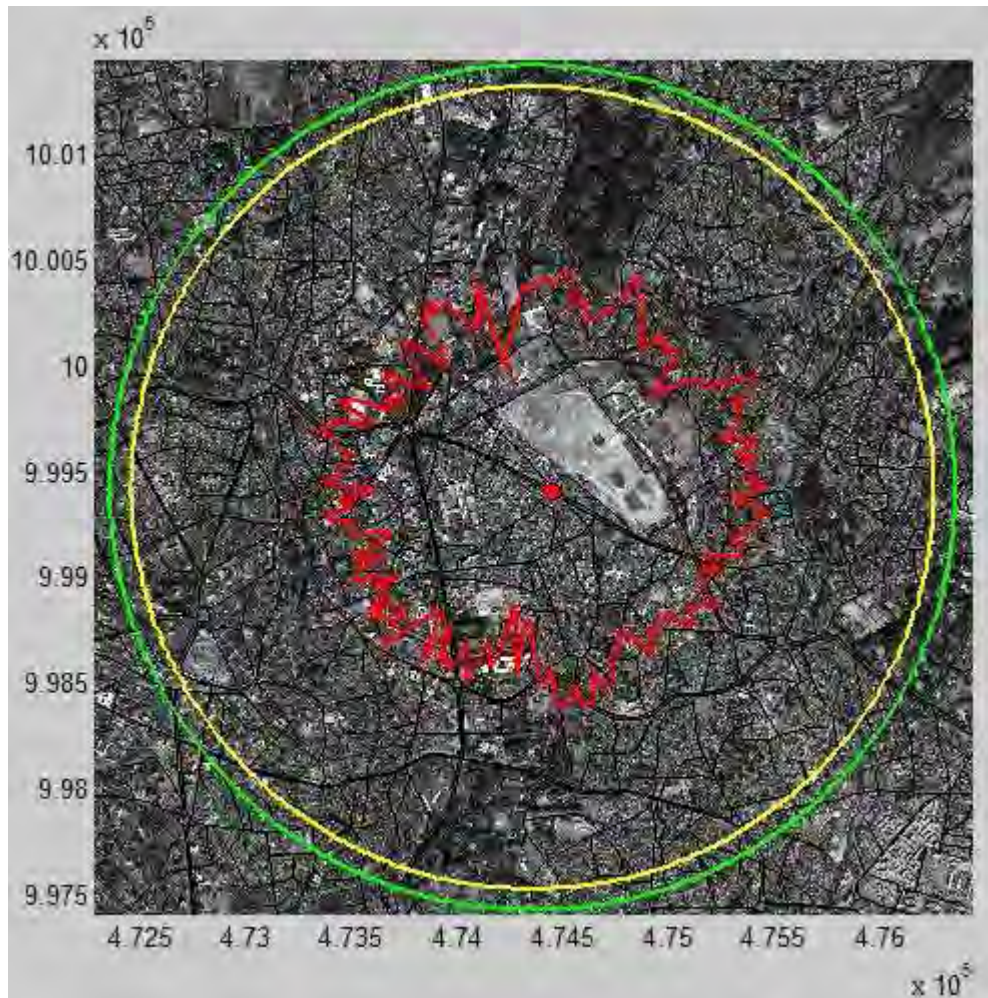


Figure 5.14: The Sidist Kilo coverage area using different propagation models

As can be expected, the Sidist kilo coverage area is the highest of all five metropolitans. The average cell radius is **0.904 km**. The corresponding coverage area will be **1.59 km<sup>2</sup>**. The area enclosed in this particular region is mostly a campus compound with few tall buildings. The shape of the coverage area is almost entirely uniform as can be seen from Figure 5.14 as well as the bar plot in Figure 5.16.

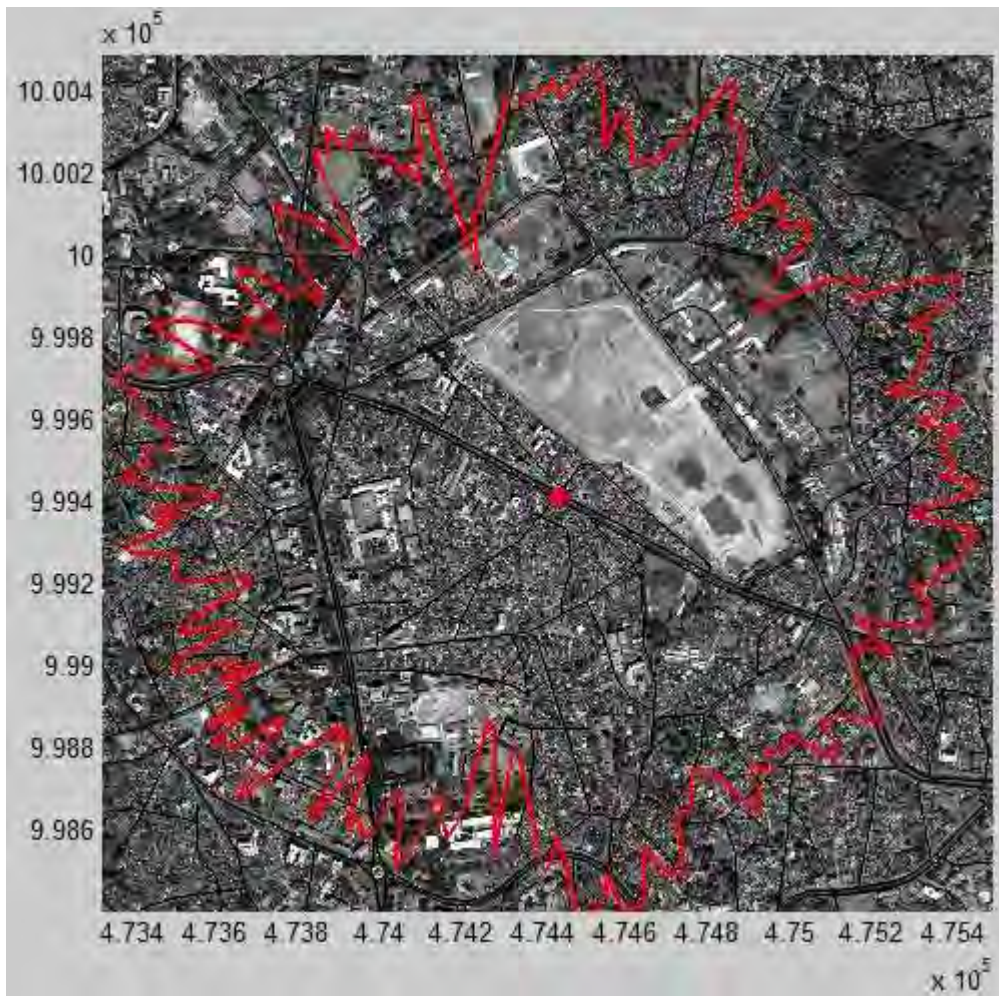


Figure 5.15: A close up view of the Sidist Killo coverage area

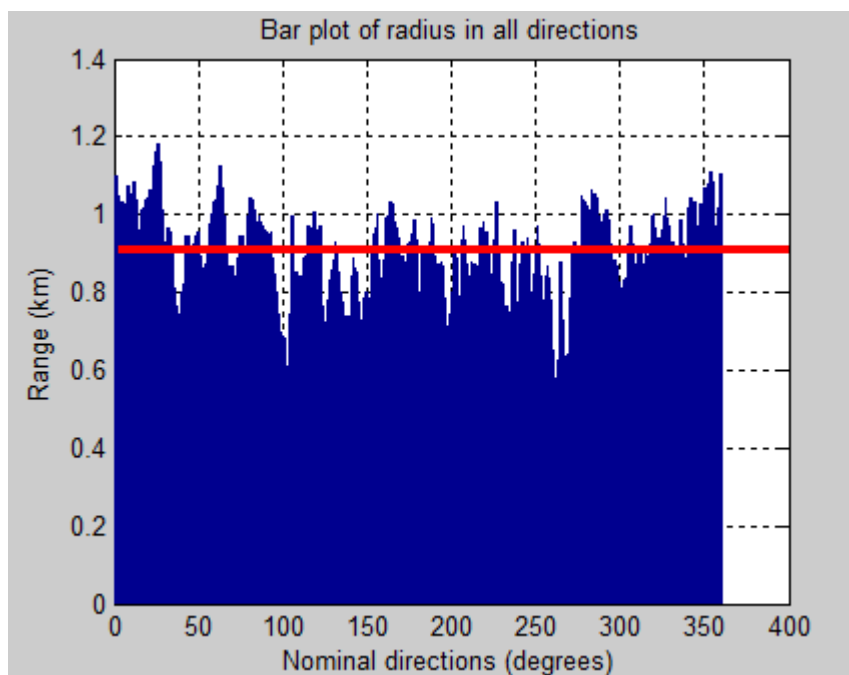


Figure 5.16: The calculated range for each direction (Sidist Killo)

Taking the average of the above five cases, we can expect an average cell radius of **0.856 km** and a coverage area per base station of **1.43 km<sup>2</sup>**. It would mean we would require **372** base stations to cover the entirety of Addis which is 530.14 km<sup>2</sup>. This is considerably higher than our dimensioning result suggested (243). Radio network planning allows us to take into account all terrain factors such as building heights, building to building distance and street width which makes it more specific and more accurate than the dimensioning computations which made use of empirical propagation models. Therefore, we will take the radio network planning results as they represent closer values to the ones we can expect in actual deployments.

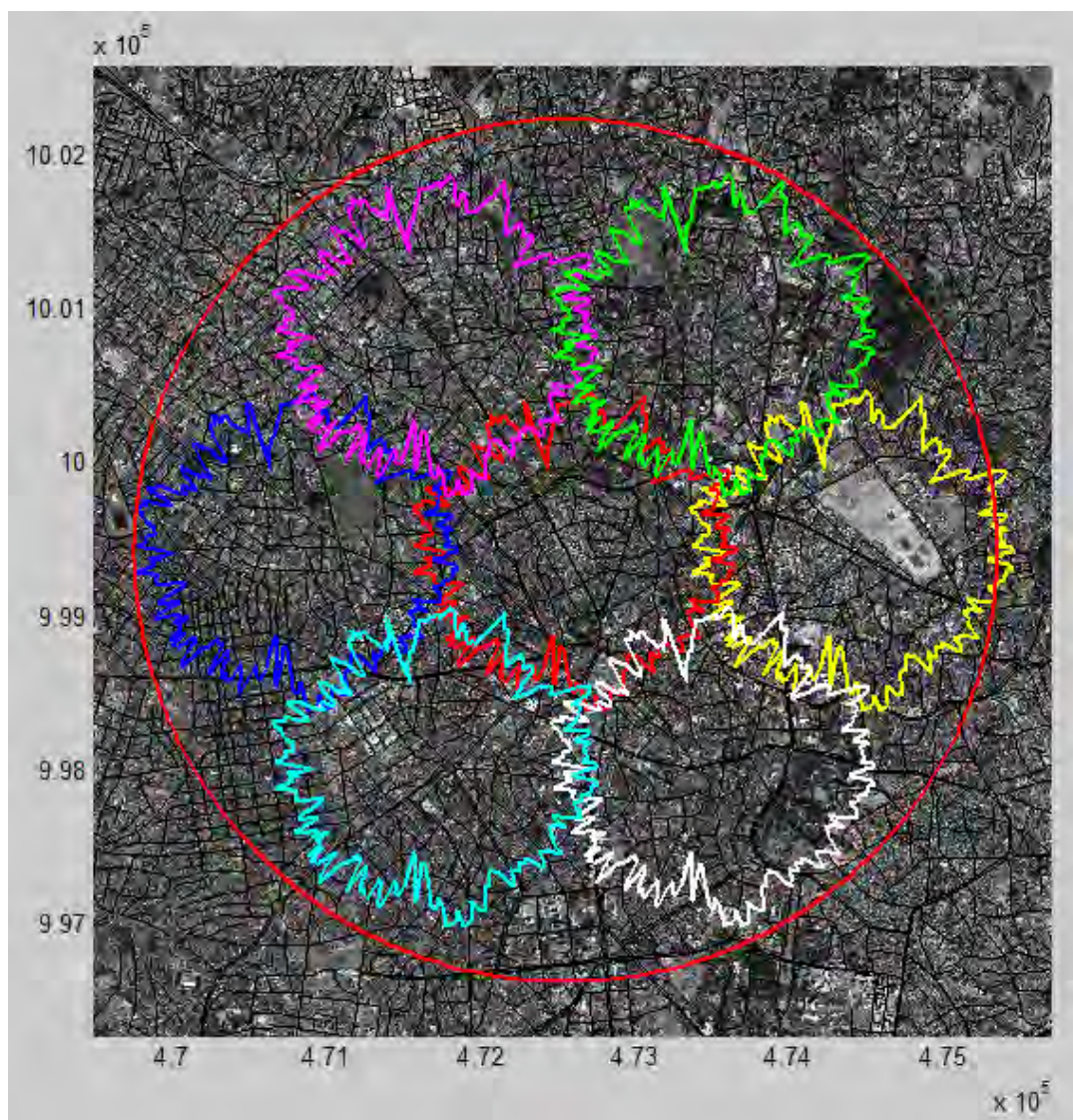


Figure 5.17: Covering an 11 km<sup>2</sup> area using 7 base stations

Figure 5.17 shows how we can cover an 11 km<sup>2</sup> area (around piassa) using 7 base stations. The individual cells used as a sample in this case are actually the RNP results for the Sidist Kilo region.

## Chapter 6: Conclusion and Future Works

### 6.1 Conclusion

From the results in Chapter 5, we can conclude that the theoretical performance figures, specially the once pertaining to “coverage range” (2km per base station), quoted in most references can be slightly misleading. In this thesis work, we have taken into consideration terrain factors and managed to come up with more plausible results. Our dimensioning results based on the link budget calculations and the COST-231 Hata propagation model suggests that we should expect a cell radius of around 1km as opposed to the two (or in some cases several) kms mentioned in most sources. The result of the developed radio network planning tool is also more in line with our dimensioning result at 0.856 km. However, to be fair, the metropolitan area chosen for this thesis work is an urban area where multipath fading would be expected to be prominent. The range shall be considerably higher for other metropolitan areas such as rural and open space, bringing the average closer to the theoretical value.

It is also worth noting that the similarity in pathloss versus distance curve for the COST-231 Hata Model and COST-231 Walfish-Ikegami (W-I) model (figure 4.3) is again reflected in the results of this chapter. The dimensioning result predicts a cell radius of 1 km and the RNP result only falls short by a mere 100 meters or so. This difference would have been further reduced if we had also done the RNP for other areas of Addis where there is lower building density and consequently lesser pathloss. In addition, both propagation models have the highest pathloss in comparison with the other models that we studied (as can be seen in figure 4.3) so in essence, we have “prepared for the worst”.

The cell radius for the Sidist Killo region was the highest among the five selected areas owing to the fact that there are relatively fewer buildings, making the area more suited to smoother signal propagation.

As mentioned above, the discrepancy in results between the dimensioning and RNP is relatively small but the large size of the city of Addis means that additional 129 base stations are required since our RNP result suggests we need 372 base stations, 129 more than the 243 we anticipated in the dimensioning result. These results are assuming that the service will be provided in every corners of the city.

Mounting our WiMAX transmitting antennas on existing towers will spare us huge cost as we will avoid site-leasing costs not to mention the cost of the tower. With such configuration, the WiMAX base station will cost around 70,000 USD [8]. Prospective operators need to explore the option of deploying WiMAX “step-by-step” in selected areas for providing high speed data service. The full scale deployment would require 372 base stations (according to our result) and consequently, a capital expenditure of a whopping 26,040,000 USD! This might not be affordable especially considering the operator might resort to first recovering its 3G investments.

## 6.2 Future Work

This thesis has outlined and conducted the dimensioning and radio network planning procedures of mobile WiMAX. Similar researches should be conducted on other technologies such as the LTE (it is my understanding that a research is being conducted in this area), High Speed Packet Access (HSPA), Universal Mobile Telecommunication Systems (UMTS) and the like to determine the most viable solution that represents better value for money.

One of the challenges in deploying WiMAX is the availability and affordability of consumer electronics. However, for data services, we can make use of the synergetic nature of the technology and use it in collaboration with Wi-Fi where Mobile WiMAX would serve as the backhaul. Wi-Fi equipments are relatively cheap and have enjoyed a good mass adoption rate. Therefore, it might be beneficial to conduct further researches on Wi-Fi/WiMAX synergy and interfaces.

Operating parameters such as base station antenna height could also be altered and played around to get better coverage. Step-by-step deployment scenarios should also be researched to allow an easier barrier to entry for prospective operators.

Marketing studies should also be conducted by prospective Telecom operators to see how these technologies would fare in emerging markets such as ours. Expected market penetration rates, capital and operational expenditures, alternative revenue sources etc... should be thoroughly studied.

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