MOBILE WiMAX IMPLEMENTATION IN GHANA- A COMPARATIVE RADIO INTERFACE DIMENSIONING AND A TECHNO-ECONOMIC STUDY

by

Samuel Kwasi Agyekum

KNUST

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NYANSAPƆ WƆSANE NO BADWENMA

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CERTIFICATION

I hereby declare that this submission is my own work towards the MPhil and that, to the best of my knowledge, it contains no material previously published by another person which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

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ABSTRACT

The voice market in Ghana as it stands now is saturated. Migration to integrated service platforms (e.g. voice, data, video) with mobility- leaves both incumbent and prospective mobile operators

with two investment choices-3G+ HSDPA or the Mobile WiMAX. HSDPA is a data enhancement on the voice-centric 3GPP system whilst Mobile WiMAX is intrinsically a data-centric technology being optimized with voice-support and mobility functionalities. HSDPA is already being rolled out by mobile carrier giants, MTN and Airtel. Currently, the country's communications regulator is auctioning the 2.5-2.69 GHz RF spectrum to prospective licensees to fulfill its quest to actualize the country's National Broadband Strategy. One of the most essential technical and business issues of any wireless access technology is efficiently (cost and performance) providing coverage and capacity, while avoiding the initial roll-out of a large number of new cell sites to reduce initial investment. In this study the researcher, through a radio interface dimensioning study, investigated the technical relevance of one of the technologies for which the aforementioned band is being auctioned- the Mobile WiMAX; yet doing so in comparison with the HSDPA which is already a commercial reality in Ghana. It was discovered that WiMAX's OFDMA radio interface coupled with such technical features as Adaptive Modulation Coding schemes, Hybrid Automatic Repeat Request, Frequency Reuse and the MIMO made it a preferred investment candidate for the new market entrant. By performing a techno-economic evaluation of the WiMAX 16e technology using Accra Metropolis as the study area, the researcher concluded that even with worst-case market share scenario the new entrant could arrive at a positive NPV and still break-even early in time within the 10 year license period as stipulated by the National Communications Authority.

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LIST OF ABBREVIATIONS

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AMC- Adaptive Modulation and Coding

CAPEX-Capital Expenditure

CDMA- Code Division Multiple Access

CF- Cash Flow

CINR- Carrier to Interference-plus-Noise Ratio

CTC-Convolutional Turbo Code

CQI-Channel Quality Indicator

DL-Down Link

EV-DO-Evolution Data Only

FBSS- Fast Base Station Switching

FDD-Frequency Division Duplexing

FFT-Fast Fourier Transform

FUSC-Fully Used Sub-Carrier

GIFEC- Ghana Investment Fund for Electronic Communications

HARQ-Hybrid Automatic Repeat Request

HHO-Hard Handoff

HSPA-High Speed Packet Access

HSDPA-High Speed Downlink Packet Access

IEEE- Eye-Tripple- E

IFFT-Inverse Fast Fourier Transform

IP-Internet Protocol

IRR- Internal Rate of Return

ISP-Internet Service Provider

LAN-Local Area Network

LLC-Logical Link Control

LOS-Line of Sight

MAC- Media Access Control

MAN-Metropolitan Area Network

MAP-Media Access control Protocol

MAPL- Maximum Allowable Path Loss

MCS-Modulation Coding Scheme

MDHO- Micro-Diversity Hand Off

MIMO-Multiple Input Multiple Output

MTG-Mobile Technical Group

MTN-Mobile Telecommunications Network

NLOS-Non Line of Sight

NPV-Net Present Value

OFDM-Orthogonal Frequency Division Multiplexing

OPEX-Operational Expenditures

OFDMA- Orthogonal Frequency Division Multiple Access

PCS-Personal Communication Systems

PUSC-Partially Used Sub Carrier

QAM-Quadrature Amplitude Modulation

QoS-Quality of Service

QPSK-Quadrature Phase Shift Keying

RF- Radio Spectrum

ROI- Returns on Investment

SIMO-Single Input Multiple Output

SISO-Single Input Single Output

SNR-Signal to Noise Ratio

STC-Space Time Coding

STBC-Space Time Block Coding

TDD-Time Division Duplexing

TOTEX-Total Expenditure

UL-Up Link

UMTS-Universal Mobile Telecommunication Systems

VoIP- Voice over Internet Protocol

WiMAX-Worldwide Interoperability for Microwave Access

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CHAPTER ONE- INTRODUCTION

1.1 Background

In just a few years the Internet has transformed the way we access information, communication and entertainment services at home and at work. It is an undeniable fact that broadband connections have made the Internet experience richer for millions of people across the world. Ghana in the mid-1990s was among the first countries in Africa to be connected to the Internet and to introduce broadband services using the Asynchronous Digital Subscriber Line (ADSL) technology. According to Ghanaian-based *Internet Research*, the total number of Internet subscribers as of June 2009 was 47,000 signifying 0.2% of the population with one in every three Internet subscribers having broadband connectivity **[1].** The total number of Internet users was 1,000,000 representing 4.5% of Ghana's population. International Telecommunication Union (ITU) statistics has it that that there were 12,700 broadband Internet subscribers in Ghana as of September 2007 **[1]**. It suffices to pinpoint that the ratio of broadband subscribers to Internet is woefully inadequate**.**

The provision of data-centric broadband services by incumbent mobile carriers over GPRS/EDGE/WCDMA/HSDPA/ CDMA 2000 has not significantly increased the percentage of the population that uses the Internet **[2]**. It is somewhat disheartening to mention that the Internet World Stats ranks Ghana's Internet penetration way behind countries such as Egypt, Nigeria, Morocco, South Africa, Sudan, Kenya and Zimbabwe. Meanwhile, according to a 2009 World Bank Information and Communication for Development report on the impact of broadband on growth in 120 countries from 1980 to 2006, each 10% increase in broadband penetration resulted in 1.21% increase in per capita Gross Domestic Product in developed countries and 1.38% increase in developing countries **[3]**. It does presuppose that broadband penetration has more impact on developing economies than those of developed countries. As outlined in the National Broadband

Strategy a projected 10% annual increase in broadband penetration coupled with bandwidth increase from 256 kbps to 2Mbps is an expected phenomenon from 2010 to 2015**.** The objective of this strategy could only be realized through the usage of mass market technologies, providing the necessary economy of scale for affordable broadband services delivery in Ghana. It is in pursuance of this that the National Communications Authority now deems it necessary to issue licenses for the provision of cost-effective Broadband Wireless Access (BWA) in the 2,500 – 2,690MHz radio band **[4]**.

Broadband is a term used to describe a high-speed connectivity for high bandwidth applications and services such as mobile TV, Video On-Demand, and Voice over Internet Protocol, user generated contents and managed/hosting services to both residential and business users **[5]**. A wide range of alternatives are available for broadband access but wireless and mobile technologies are in massive commercial deployment across the world, receiving so much attention in operator strategies and policy makers' decision due to customers' pressing demand for anywhere personal broadband communications. While there is a host of technologies competing to deliver commercial mobile broadband services worldwide, two IMT-based technologies, Mobile WiMAX and High Speed Packet Access (HSPA) are quickly gaining grounds on the mobile broadband market worldwide, with each technology presenting itself as the more cost-effective and spectrally-efficient evolutionary path to herald the next generation of high-speed IP-based communication networks- the 4G **[6].**

In Ghana however, a sub-variant of the HSPA technology, High Speed Downlink Packet Access (HSDPA) has already been rolled out by mobile carrier giants, MTN and Airtel under the generic label 3.5G. Talk of commercial deployment, IEEE's 802.16 OFDMA technology, the Mobile WiMAX, is yet to be licensed for operation in the IMT 2,500-2690MHz band by the National Communications Authority **[7].** It is thus opportune that an academic research based on the technical relevance of such new technology be critically investigated, more so in the light of its bearing on the roll-out of cost-efficient broadband services in the country.

1.2 Problem definition

With increasing popularity of mobile applications and the reality of an already crowded wireless spectrum, it has become imperative for network operators to leverage on the advanced principles of modern telecommunication design to competitively meet the capacity, coverage and quality of service demands on their legacy networks **[8]**. In the wake of the global economic recession, mobile operators and service providers needing to maximize return on investment whilst maintaining competitive service offerings to existing and would-be customers, have to critically ascertain the cost-savings advantage of whichever technologies they have in their portfolio to deploy. It is interesting to mention that the subject of WiMAX as far as performance and cost-efficiency are concerned have been received with a lot of hypes and abuses. In terms of economies of scale**,** industry pundits at Ericsson have made a swipe against Mobile WiMAX for its claims as a major cost-effective evolutionary candidate to the 4G **[9] [10]**. According to Intel Corporation, however, TDD-based Mobile WiMAX technology compared to the traditional FDD-based 3G/3G+ cellular alternatives, offer a more cost-efficient platform for transferring large amounts of data with high throughput **[11]**. With two conflicting positions being established perhaps along techno-political frontiers, there is therefore the need for an unbiased intellectual brainstorming by the academia in lieu of the touted technical advantages of the technology as well as what it stands to offer per consideration as an investment choice in the delivery of affordable broadband services in the country.

1.3 Justification for Research

3G systems have been providing service to the mobile market for some years now. Although voice-centric in nature, they do lack the strong capacity to support data services. However, given the heavy investment by some wireless ISPs and cellular operators in ADSL and 3G networks such as UMTS and CDMA 2000, some question the need for WiMAX at all, especially Mobile WiMAX. On the contrary, Mobile WiMAX presents existing cellular operators with the opportunity to address the network capacity management issues required to maintain a high level of competiveness in their service offerings for data applications. According to **[12]** more and more operators need to deploy Mobile WiMAX in order to meet the growing demand for access to mobile broadband Internet**.** But the question comes up as to whether it really stands out as an economically feasible investment alternative for prospective and existing broadband operators. The thrust of this research is to technically assess the Mobile WiMAX technology as well as find out the cost-effectiveness of its deployment from a techno-economic standpoint.

1.4 Research Methodology

The research was conducted in two phases-

In phase one of the research further comparative studies of the OFDMA-based Mobile WiMAX and CDMA-based HSDPA technologies have been investigated using the link budget as the performance metric. For WiMAX major considerations to such technical features as OFDMA sub-channelization, Adaptive Modulation and Coding (AMC), Hybrid Automatic Repeat Request, Frequency Reuse and MIMO schemes were the main cost-sensitive areas the research focused on.

In phase two of the research, a techno-economic evaluation of an IEEE 802.16e project in the 2,500-2690 MHz band was performed to ascertain the economic feasibility or otherwise in rolling out the Mobile WiMAX technology over a 10-year license period within a “capacity-driven” study environment such as the Accra Metropolis. It is the hope of the researcher that this material would serve as a reference to would-be operators that are considering deployment in an urbanized market.

Numerous sources of literature have been surveyed and used. These include research publications from international organizations such as International Telecommunications Union (ITU), Institute of Electrical & Electronic Engineering (IEEE) and WiMAX Forum. Books, technical reports and white papers on current broadband access technologies by equipment vendors have also been indispensable to the writing of this thesis. The selection of the materials has been based on their characteristic relevance to the purpose of the study.

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Consultations with network operators, the country's communications regulator, investors and stakeholders of Ghana's broadband market have been useful as far as the data collection phase of the research work was concerned. Respondents included Ericsson Radio Systems Ghana, Huawei Technologies Co. Ltd, MTN, DiscoveryTel Ghana Ltd and the National Communications Authority (NCA).

1.5 Scope of Research

The scope of this research work is defined by the following criteria:

- *Technology*: Mobile WiMAX compared with 3G/3G+ wireless systems, especially the High Speed Downlink Packet Access (HSDPA) technology.
- *Target Group***:** Mobile equipment vendors, mobile cellular operators and wireless ISPs, subscriber groups (both business and residential) and the National Communications Authority
- *Geographical Study Area*: Ghana, specifically the metropolitan area of Accra.

1.6 Limitations to the study

The project described in this document suffered from some constraints. Of significant mention is inaccessibility to digital maps and relevant simulation and radio planning software due to proprietary and confidential reasons. Non-disclosure of certain network parameters by some mobile carriers and service providers is also note-worthy.

1.7 Structure of Report

The thesis is divided into four chapters:

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Chapter 1**:** This chapter provides an introduction to the study. A background to the study is given on the broadband phenomenon, its related impact on the economy, emerging wireless technologies and the place of Mobile WiMAX on Ghana's broadband market. Problem definition, research justification, methodology, scope of research, organization of study and statement of objectives are also highlighted as prelude to the development of the research.

Chapter 2**:** In this chapter the reader is introduced to an overview and evolutionary trends in the development of the Mobile WiMAX technology, a theoretical background of its technical features, a review account of deployment considerations and a performance evaluation study of how Mobile WiMAX compares with 3G/3G+ enhancement technologies such as HSPA and EV DO, considering such performance metrics as data throughput, spectral efficiency and coverage.

Chapter 3**:** The actual research work is reported in this chapter bearing in mind the objectives of the study. To investigate the technical relevance of the Mobile WiMAX, a comparative study with the HSDPA would be carried out to ascertain or prove otherwise the touted cost-savings advantage of this technology using the link budget as performance metric. Also, a techno-economic model developed in the European TONIC and ECOSYS research projects is used as a guide to investigate the economic feasibility of rolling out the technology, as would apply to a new market entrant [45].

Chapter 4: In this chapter a summary of results and its analysis is given. Conclusion as well as recommendation for future work is also captured.

1.8 Statement of Objectives

- Review literature relevant to purpose of study in order to gain a thorough understanding of the evolution, the technical features and the concepts of operation of the technology.

- Conduct comparative radio interface dimensioning studies of Mobile WiMAX and the 3.5G High Speed Downlink Packet Access (HSDPA) systems using the link budget as the performance metric.

- Perform an in-depth study into the techno-economic feasibility of launching an IEEE 802.16e technology for a new market entrant in the Accra Metropolis over a 10 year license period as stipulated by the National Communications Authority.

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CHAPTER TWO- INTRODUCTION TO WiMAX & LITERATURE REVIEW

2.1 Introduction to WiMAX

WiMAX, an acronym for Worldwide Interoperability for Microwave Access, is a telecommunication broadband technology that supports the delivery of high-speed multimedia content data using a variety of transmission methods, from point-to-multipoint links to portable and fully mobile Internet access **[13].**

The IEEE 802.16 standard, first published in 2001, specified a frequency range of 10-66 GHz, punting a theoretical maximum bandwidth of 120Mbps and a maximum link range of 50 km. However, the initial standard only provided support to line-of-sight (LOS) transmissions and thus was scarcely deployed in urban areas. A variant of the standard, IEEE 802.16d-2004, approved in April 2004, could support non-LOS transmission and implemented the Orthogonal Frequency Division Multiplexing multicarrier modulation technique at the physical layer. It also supported operation in the 2-11GHz range in addition to the original 10-66 GHz spectrum. From the initial variants, the IEEE 802.16 standard went through a number of amendments and finally became Mobile WiMAX. The objective of IEEE's 802.16 Mobile WiMAX standard was to provide convergence of mobile and fixed broadband wireless networks, supporting high data rate transmissions over long-range coverage area comparable to cellular technologies **[14].**

The WiMAX Forum, a non-profit organization, was formed to define and conduct conformance and interoperability testing to ensure that WiMAX systems and products can co-exist and work seamlessly with each other on a heterogeneous network. Within the forum is the Mobile Technical Group (MTG) which develops the Mobile WiMAX system profiles that define the mandatory and optional features of the IEEE standard that are required to build the Mobile WiMAX-compliant air interface certifiable by the Forum. WiMAX certification profiles specify such characteristics as spectrum band, duplexing and channelization. Currently, there are two waves of certification planned for Mobile WiMAX equipments [**14].**

- Wave 1: Mobile WiMAX system profiles with single input single output (SISO) terminals for the 2.3 GHz and 3.5 GHz bands
- Wave 2: Mobile WiMAX system profiles with multiple input multiple output (MIMO) terminals and beamforming support for the 2.5 GHz band.

Because the IEEE 802.16e Mobile Amendment profiles cover basic connectivity to the media access control (MAC) level, the WiMAX Forum also considers the design of a network architecture that provides the platform for deploying an end-to-end Mobile WiMAX network. Release 1.0 of the WiMAX Forum network architecture specification focused on the delivery of wireless Internet with mobility. Later on the Release 1.5 introduced support for telecom-grade mobile services, supporting full Information Management System (IMS) interworking, carrier-grade VoIP, broadcast applications such as Mobile TV and over-the-air provisioning. Table 2.1 provides an evolutionary account of Wireless MAN (802.16 family of standards) **[10].**

Table 2.1: Evolution of Wireless MAN (802.16 family of standards) [10]

Version	**Released**	**Information**
IEEE 802.16d IEEE 802.16-2004	2004 Q 2	Replaced all previous 802.16 specifications. Support for non-line-of-sight operation
IEEE 802.16e IEEE 802.16-2005	2005 Q 4	Enhanced 802.16-2004 with support for user mobility

WiMAX Forum Network Architecture Specification Release 1.0	2007 Q1	Networking specifications for fixed, nomadic and mobile WiMAX systems. Release 1.0 covers Internet applications and user mobility
WiMAX Forum Network Architecture Specification Release 1.5	2008 Q3	Enhancement to the Release 1.0 specification for carrier grade VoIP, location-based service, MBMS, full IMS interworking and over-the-air provisioning

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2.2 Literature Review

2.2.1 Technical features of Mobile WiMAX

IEEE's 802 family of standards addresses local area networks (LANs) and metropolitan area networks (MANs). The lowest two layers of the Open System Interconnections (OSI) reference model, physical layer and data link layer have been the focus for the development of these standards. In addition, the IEEE 802 divides the data link layer into two sub-layers: the Logical Link Control (LLC) and the Media Access Control (MAC) sub-layers. Moreover, in broadband wireless communications networks, most of the things occur in these two layers **[15].**

2.2.1.1 Physical Layer description

The physical layer is the first level of the 7-layer ISO/OSI reference model for communication systems with the most basic being the network layer. Some functions of this layer include providing an interface to the physical medium, modulation, coding, flow control, bit synchronization and circuit-mode multiplexing. The 802.16e -2005 standard uses a physical layer called scalable Orthogonal Frequency Division Multiple Access (SOFDMA) **[15].**

OFDM

As a multiplexing technique the OFDM splits the input data stream into a large number of parallel substreams of reduced data rate and each substream is modulated and transmitted on a separate orthogonal subcarrier. Each subcarrier is modulated with conventional modulation scheme. At reduced data rate, symbol duration is increased, thus improving the robustness of OFDM to channel-induced delay spread. The principle of orthogonality ensures that there is no cross-talk between subcarriers despite the fact that their spectra are very close to each other or even overlapping. This is because the peak of one subcarrier coincides with the null of an adjacent subcarrier **[16] [17]**. When subcarriers overlap, they give the added advantage of increasing the bandwidth efficiency since the spectrum required to transmit a symbol is reduced. To ensure an ISI-free multipath operation, a cyclic prefix is used. The ratio of the cyclic prefix to the useful symbol duration is indicated by G and can take values of $1/4, 1/8, 1/16$ or $1/32$. Thus given that, $Ts = Tg + Tu., G = Tg / Ts = \{1/4, 1/8, 1/16, 1/32\}$. Fig 2.1 shows the OFDM symbol structure containing a Cyclic Prefix

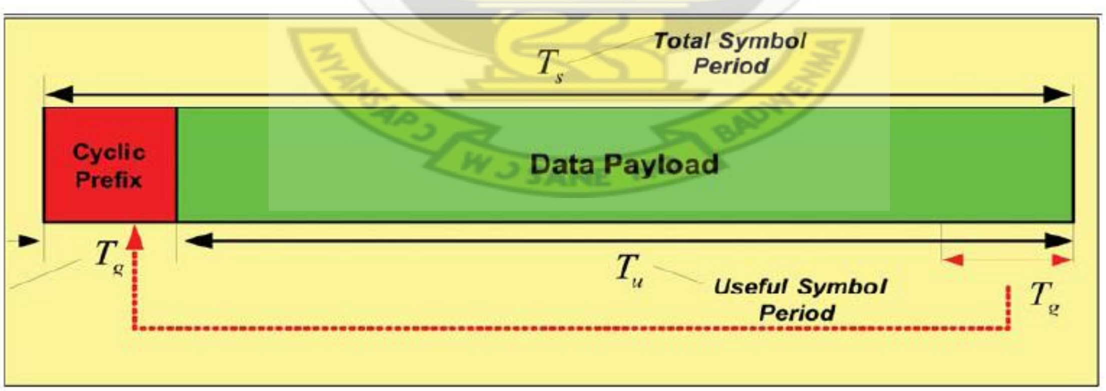

Fig 2.1: OFDM Symbol Structure with Cyclic Prefix [17]

The OFDM signals are generated with an efficient Inverse Fast Fourier Transform (IFFT) method, which can generate as many as 2048 subcarriers with low complexity. The resources of an OFDM system in the time domain are the OFDM symbols and sub-carriers in the frequency domain. The time and frequency resources can be organized into subchannels for allocation to individual users. Fig. 2.2 shows a sample OFDM sub-carrier structure in the frequency domain **[17].**

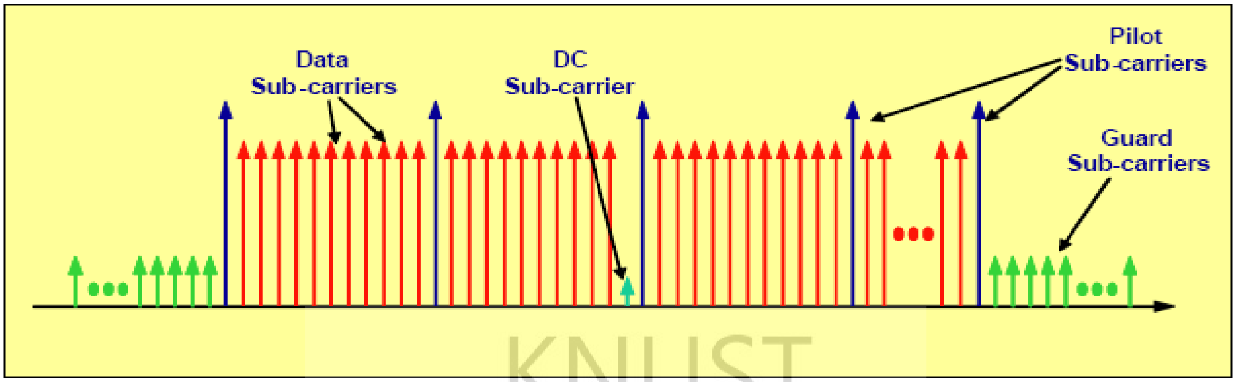

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Fig 2.2: OFDM Sub-Carrier Structure [17]

There are three types of OFDMA sub-carriers:

• Data sub-carriers for data transmission as the name implies

• Pilot sub-carriers for various estimation and synchronization purposes.

• Null sub-carriers for no transmission at all, used for guard bands (left and right) and DC carriers (used at the transmission frequency). Active sub-carriers are divided into subsets of sub-carriers called sub-channels

OFDMA and Scalable OFDMA

OFDMA is a multiple-access/multiplexing scheme that divides the available channel in such a manner as can be shared by multiple users. OFDMA is a multi-user version of OFDM that involves assigning an individual sub-carrier or a group of sub-carriers to different users depending on the type of service requested for by the user and the prevailing channel conditions. OFDMA compares with CDMA with regards to how orthogonal spread code sequences are assigned to different users with different data rates **[17].** The need to address the problem of different channel sizes in different countries has seen the evolution of the aforementioned modulation/ multiple access methods. With its ability to support bandwidth scaling from 1.25MHz to 20MHz, Mobile WiMAX provides the operator with a wide range of configurable channel size options to choose from. Scalability is supported by adjusting the FFT size while maintaining a fixed sub-carrier spacing of 10.94 kHz. When scaling bandwidth there is minimal impact on the higher layers of the OSI model since the resource unit subcarrier bandwidth and symbol duration is fixed. The SOFDMA parameters are listed in Table 2.2. Highlighted in the table are system bandwidths- (5 MHz and 10 MHz-) for two of the initial planned profiles intended for Release 1 by the WiMAX Forum Technical Working Group.

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Table 2.2: OFDMA Scalability Parameters [17]

Parameters	**Values**			
System Channel Bandwidths (MHz)	1.25	5	10	20
Sampling Frequency (Fp in MHz)	1.4	5.6	11.2	22.4
FFT Size	128	512	1024	2048
Number of Sub-Channels	2	8	16	32
Sub-Carrier Frequency Spacing (f)	10.94 kHz			
Useful Symbol Time (Tb= 1/f)	91.4 microseconds			
Guard Time (Tg= Tb/8)	11.4 microseconds			
OFDMA Symbol Duration (Ts =Tb+Tg)	102.9 microseconds			
Number of OFDMA Symbols (5 ms Frame)	48			

OFDMA Frame Structure

The two-dimensional frame structure in OFDMA as shown in Fig 2.3 indicates that multiple users may access the radio interface in parallel through allocation of sub-channels **[18]**. Since different subcarriers can be selected and mapped to different sub-channels, it is possible to assign the same FFT instance to different bursts.

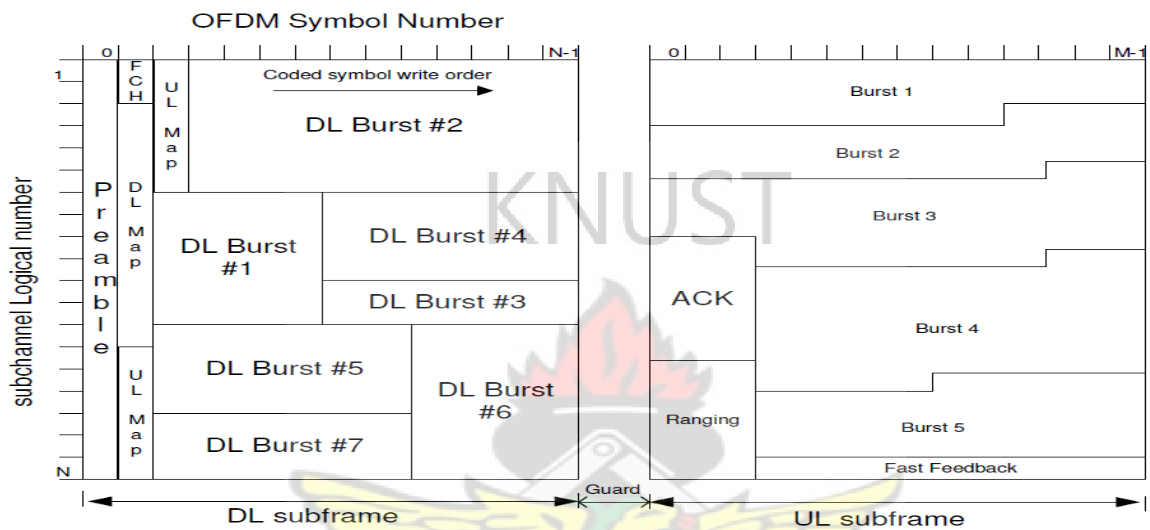

Fig 2.3: OFDMA Frame Structure [42]

Each burst may utilize modulation and coding scheme independent of the other bursts. Burst 2 may for instance adapt to convolutional coding and QAM 64 modulation, whereas Burst 3 may adapt to QAM 16 and a convolutional-turbo coding. The two bursts will then carry different amount of bits per sub-carrier. Allocation of the "Ranging Subchannel" to mobile stations is required to perform closed-loop time, frequency and power adjustment as well as bandwidth requests. The UL CQICH provides fast feedback about channel state information, and UL ACK is needed for feedback acknowledgement **[18].**

Sub-Carrier Permutation Schemes

There are sub-carrier permutation modes for subchannelizations namely- "Diversity" and "Contiguous" Permutation. The former involves the pseudo-random selection of subcarriers to constitute a sub-channel whereas the latter involves subcarriers that constitute a contiguous portion of the bandwidth are aggregated to form a sub-channel **[19].**

The diversity permutation includes the DL FUSC (Downlink Fully-Used Sub-Carrier), DL PUSC (Uplink Partially-Used Sub-Carrier) and UL PUSC. DL AMC (Adaptive Modulation and Coding) and UL AMC constitute contiguous permutations. Diversity permutation is best applied to mobile applications, while contiguous permutations is best suited for fixed, portable and low mobility situations **[20].**

Duplexing Mode

At the Physical Layer, the IEEE 802.16 OFDMA standard supports the TDD and the Full and Half-Duplex FDD operation. However, TDD is hitherto the duplexing mode of choice whereas the FDD will be considered later to address specific market opportunities **[21]**. In TDD systems, the transceiver switches between transmit and receive modes based on units of time within the same channel. TDD allows simple and efficient dynamic allocation of the available bandwidth to the uplink and downlink of the radio channel in response to asymmetric data traffic. TDD DL/UL ratio determines how time is shared between them. For example, the ratio 3:1 means that the downlink gets three times more time for transmission than the uplink. The reciprocity of TDD allows spatial diversity and channel equalization to be performed at base station only, resulting in a more flexible trade-off between CPE and base station equipment costs. TDD implementation requires less complex and less expensive transceiver designs [**22]**.

Modulation and Coding Schemes

In Mobile WiMAX QPSK, 16-QAM, 64-QAM are considered as mandatory modulation options in the DL whereas in the UL 64-QAM is optional. Also, both convolutional code and convolutional turbo codes are implemented. Table 2.3 shows the modulation and coding schemes supported in Mobile WiMAX and how PHY DL rates vary by choosing different MCS levels using PUSC for 5 and 10MHz channel bandwidth **[23].**

Table 2.3: MCS Levels and PHY Data rates in Mobile WiMAX [23]

Modulation	**Code rate**	**DL PHY data rate (5 MHz)**	**DL PHY data rate (10MHz)**
QPSK	½ CTC	1.63	6.34 Mb/s
QPSK	¾ CTC	2.45	9.50 Mb/s
16 QAM	½ CTC	3.26	12.67 Mb/s
16 QAM	¾ CTC	4.90	19.01 Mb/s
64 QAM	½ CTC	4.90	19.01 Mb/s
64 QAM	2/3 CTC	6.53	25.34 Mb/s
64 QAM	¾ CTC	7.34	28.51 Mb/s

Other features of the PHY layer include:

Adaptive Modulation and Coding (AMC): This is a link adaptive mechanism where the modulation and coding schemes and other signal and protocol parameters are adjusted in response to the conditions in the radio link. Adaptive modulation and coding significantly improves the system capacity as it ensures real-time tradeoff between throughput and link robustness [**15] [24].**

Hybrid Automatic Repeat Request (HARQ): This is a hybrid of the ARQ and the FEC. It is a feature that provides rapid response to particular errors as well as asynchronous operation, with variable delay between retransmissions. There are basically two types of the fast retransmission mechanisms- Type I and II. Type I, also called chase combining, involves retransmitting a re-encoded block to increase the receiver's probability of correctly decoding the information bits in the previously transmitted block. Type II, also called incremental redundancy, on the other hand, requires multiple retransmissions but each of different coding **[24].**

Fast Channel Feedback: With the Channel Quality Indicator (CQI) feature, the subscriber terminal reports channel-state information to the base station scheduler. Some important channel-state information that is fed back by the CQI channel includes physical carrier-to-interference-plus-noise ratio (CINR), MIMO mode selection and frequency-selective sub-channel selection **[17].**

2.2.1.2 MAC Layer description

As highlighted in the introductory section of the technical overview, the second level of the OSI model, the data link Layer can be divided into two sub-layers, MAC and LLC sub-layers. The MAC sub-layer serves as an interface between the LLC and the physical layer. It provides the channel access control and addressing mechanisms required to make communication between terminals and/or networks possible. In other words, it provides the control and signaling procedures that enable several stations to share the same physical medium **[25].**

QoS Support

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QoS refers to the control mechanisms that assign different priority to different users or data flows **[17],** guaranteeing a certain level of performance in accordance with requests from the application program. In Mobile WiMAX MAC Layer QoS is provided via service flows as illustrated in Fig 2.4. The base station (BS) and the user terminals initially establish a unidirectional logical link between the peer MACs. The QoS parameters associated with the specific kind of data to be transmitted define transmission ordering and scheduling on the air interface. Through MAC messages, the service flow parameters can be managed to accommodate dynamic service demand. The service flow-based QoS mechanism is applied to both DL and UL for better QoS in both directions. A wide range of data services are supported by Mobile WiMAX.

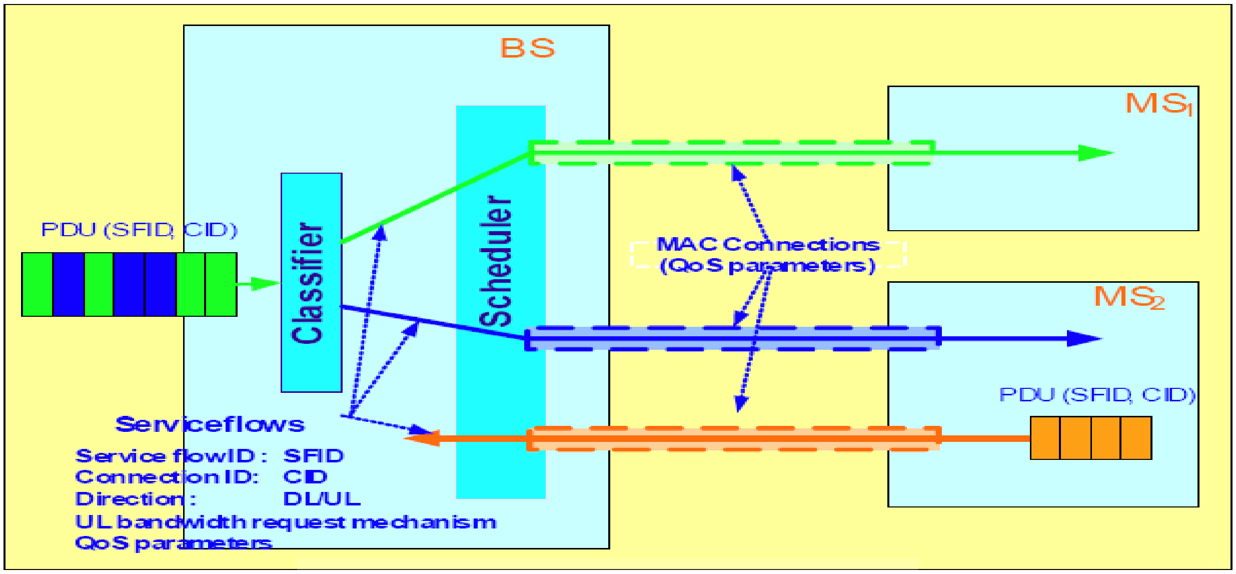

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Fig 2.4: Mobile WiMAX QoS Support [17]

WiMAX supports service quality differentiation for different kinds of applications. The BS scheduling algorithm ensures the control of QoS parameters by balancing the timeslot allocation among the application needs of several subscriber stations. The 802.16 standard provides QoS support to the following classes of services **[26].**

- **Unsolicited Grant Services (UGS):** UGS is designed to support Constant Bit Rate (CBR) services, such as T1/E1 emulation, and Voice over IP (VoIP) without silence suppression at periodic intervals.

- **Real-Time Polling Services (rtPS):** rtPS is designed to support real-time services that generate variable size data packets at periodic intervals, such as MPEG video or VoIP with silence suppression and interactive gaming.

- **Extended real-time Polling Service (ertPS):** This service class supports real-time applications, such as VoIP with silence suppression, that have variable data rates but require guaranteed data rate and delay.

- **Non-Real-Time Polling Services (nrtPS):** nrtPS provides support to non-real-time variable-sized data packets on a regular basis such as file transport protocol (FTP), browsing, video download and video on demand.

- **Best Effort (BE) Services**: This category supports data streams with minimal service requirement. BE services include the e-mail and the sending and receiving of http traffic through web browsing **[26].** Table 2.4 provides a summary of applications supported by Mobile WiMAX.

Table 2.4: Summary of WiMAX Applications [26]

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CLASS DESCRIPTION	REAL TIME	APPLICATION TYPE	BANDWIDTH
Interactive Gaming	Yes	Interactive Gaming	50-85 Kbps
VoIP, Video Conferencing	Yes	VoIP	4-64 Kbps
		Videophone	32-384 Kbps
Streaming Media	Yes	Music/Speech	5-128 Kbps
		Video clips	20 – 384 Kbps
		Movies streaming	> 2 Mbps
Information Technology	No	Instant Messaging	< 250 byte messages
		Web browsing	> 500 Kbps
		Email (with attachments)	> 500 Kbps
Media Content download (store and forward)	No	Bulk data, Movie download	> 1 Mbps
		Peer to Peer	> 500 Kbps

Power Management

The Sleep mode and idle mode are the two modes of power-efficient operation supported by Mobile WiMAX. Sleep mode aims to reduce power consumption as the MS conducts pre-negotiated periods of absence from the serving BS air interface. In the Idle mode, however, the MS avails itself to receive DL broadcast traffic messages as it traverses multiple BS without registration to a specific BS **[17][27].**

Mobility Management

Mobile WiMAX provides three handoff procedures namely hard handoff (HHO), fast base station switching (FBSS), and macro-diversity handoff (MDHO). HHO is mandatory, where as FBSS and MDHO is optional. In both FBSS and MDHO, a MS and BS maintain a so-called Active Set which is a list of BSs that are involved with the mobile user's handover. An anchor BS is chosen from the set. In FBSS a MS only communicates with the anchor BS and the handoff requires switch-over to a new anchor BS. MDHO supports user communication with all BSs in the Active Set, but the regular mode of operation is the particular case when there is only one BS in the Active Set **[17].**

2.2.1.3 Advanced Features of Mobile WiMAX

Smart antenna technologies typically involve complex vector or matrix operations on signals due multiple antennas. OFDMA shows a great deal of amenability to multiple input multiple output (MIMO) implementations, allowing smart antenna operations to be performed on vector-flat sub-carriers **[24][28].** Smart antenna techniques provide the platform whereby high data rates and link reliability through spatial diversity can be achieved without increasing the transmit power or the bandwidth **[29]**.

The smart antenna technologies supported include:

Space-Time Coding (STC): The most popular multi-antenna processing scheme is space-time coding, where a code known at the receiver is applied at the transmitter. Of the many space-time codes studied, space-time block code (STBC) approaches are supported in WiMAX systems and it is easily implemented. The Alamouti code, a type of orthogonal STBC is easily implemented and provides optimal diversity order notwithstanding that it is limited to certain combinations of antenna numbers **[30]**.

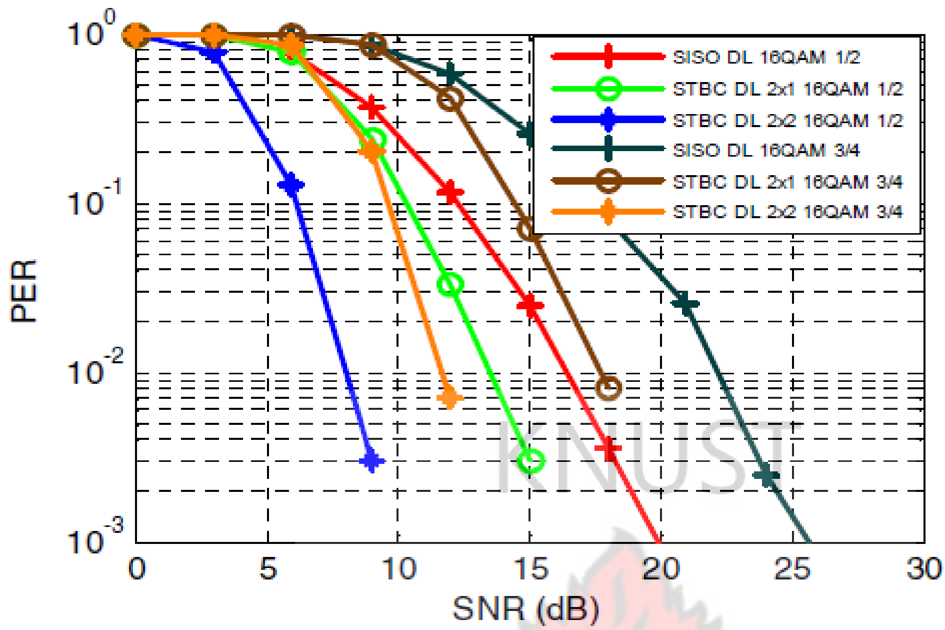

Fig 2.5: Packet Error Rate (PER) of SISO versus Space-Time Block Coding (STBC) [30]

Fig 2.5 compares the packet error rates (PER) for the SISO and STBC DL, in both 2x1 and 2x2 STBC systems. It can be observed that the PER performance is enhanced by 2x1 and 2x2 STBC. More specifically, at a PER of 10^{-2} and for 1/2 rate 16QAM the improvement is 3dB and 9dB respectively for 2x1 and 2x2 STBC over SISO.

Spatial Multiplexing (SM): Spatial multiplexing is supported to take advantage of higher peak rates and increased throughput. With spatial multiplexing, multiple streams of data are transmitted over multiple antennas. If the receiver also has multiple antennas, it can separate the different streams to achieve higher throughput compared to single antenna systems. With 2x2 MIMO, SM increases the peak data rate two-fold by transmitting two data streams. In UL, each user has only one transmit antenna, two users can transmit collaboratively in the same slot as if two streams are spatially multiplexed from two antennas of the same user. This is called UL collaborative SM.

Table 2.5 shows the peak data rates for various SIMO and MIMO configurations for 10-MHz bandwidth **[17, 27, 28].**

Table 2.5: Data Rates for SIMO and MIMO configurations for different DL: UL ratios [17, 27]

DL/UL Ratio			1:0	3:1	2:1	3:2	1:1	0:1
User Peak Rate (Mbps)	SIMO (1x2)	DL	31.68	23.04	20.16	18.72	15.84	0
		UL	0	4.03	5.04	6.05	7.06	14.11
	MIMO (2x2)	DL	63.36	46.08	40.32	37.44	31.68	0
		UL	0	4.03	5.04	6.05	7.06	14.11
Sector Peak Rate (Mbps)	SIMO (1x2)	DL	31.68	23.04	20.16	18.72	15.84	0
		UL	0	4.03	5.04	6.05	7.06	14.11
	MIMO (2x2)	DL	63.36	46.08	40.32	37.44	31.68	0
		UL	0	8.06	10.08	12.10	14.12	28.22

Beamforming: With beamforming, the system uses multiple-antennas to transmit weighted signals to improve both coverage and capacity of the system and reduce outage probability **[17, 27].**

Fractional Frequency Reuse

In implementing the full frequency reuse scheme it is required of mobiles in different sectors to use the same frequency. This, however, leads to low data rates for cell edge users due to co-channel interference. By taking advantage of the flexible resource allocation on frequencies utilizing OFDMA Mobile WiMAX supports full frequency reuse, partial frequency reuse and even a mixture of full and partial frequency reuse within one TDD frame. This feature of Mobile WiMAX is known as fractional frequency reuse and can provide significant coverage gains whilst retaining optimum utilization of the spectrum **[31, 32].**

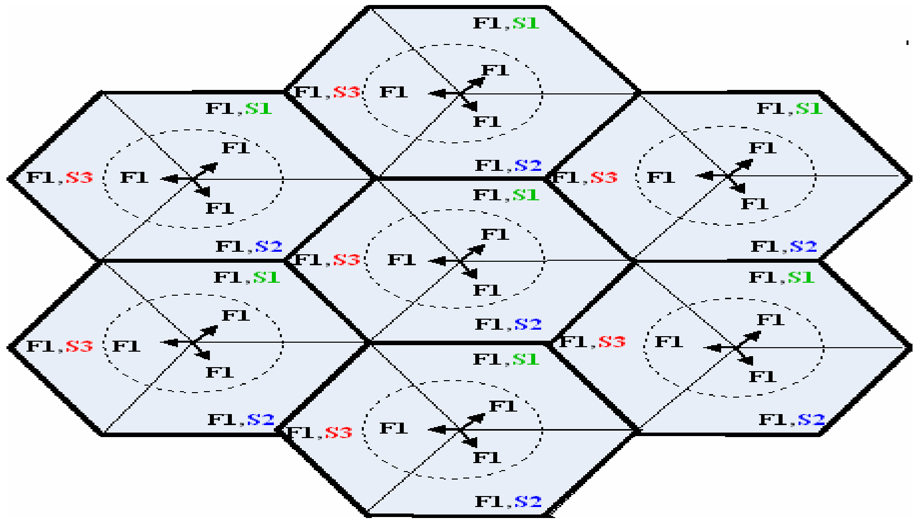

Fig 2.6: Fractional Frequency Reuse scheme [43].

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2.2.1.4 Network Architecture

The IEEE 802.16e end-to-end network architecture is entirely based on an IP platform; an all packet technology with no legacy circuit connections. The proposed architecture **[26]** divides the WiMAX system into three logical parts: (1) Mobile Station (MS) (2) Access Service Network (ASN), which consists of a number of BS and the (3) Connectivity Service Network (CSN) which supports IP connectivity and core network functionalities. The home Network Service Provider is where the subscriber belongs and the visited NSP is where users are currently being provided with network service. As depicted in Fig 8 the ASN comprises the BS and ASN gateways. The BS primarily handles channel allocation, providing the OFDMA-based radio interface to the MS **[33]**. In addition, it carries out such functions as scheduling, service flow management, Dynamic Host Configuration Protocol (DHCP) functionality, tunneling and relaying authentic messages. The ASN-GW, on the other hand, handles authentication, authorization, accounting (AAA) functionality, location management and paging and admission control and routing. CSN which serves one or more ASNs provides the added functionality of IP address range allocation for each BS, AAA proxy, QoS management, inter-CSN tunneling, billing and policy management and access to miscellaneous services provided by the IP network **[33].** A simplified logical representation of the network reference model of mobile WiMAX is illustrated in Fig 2.7.

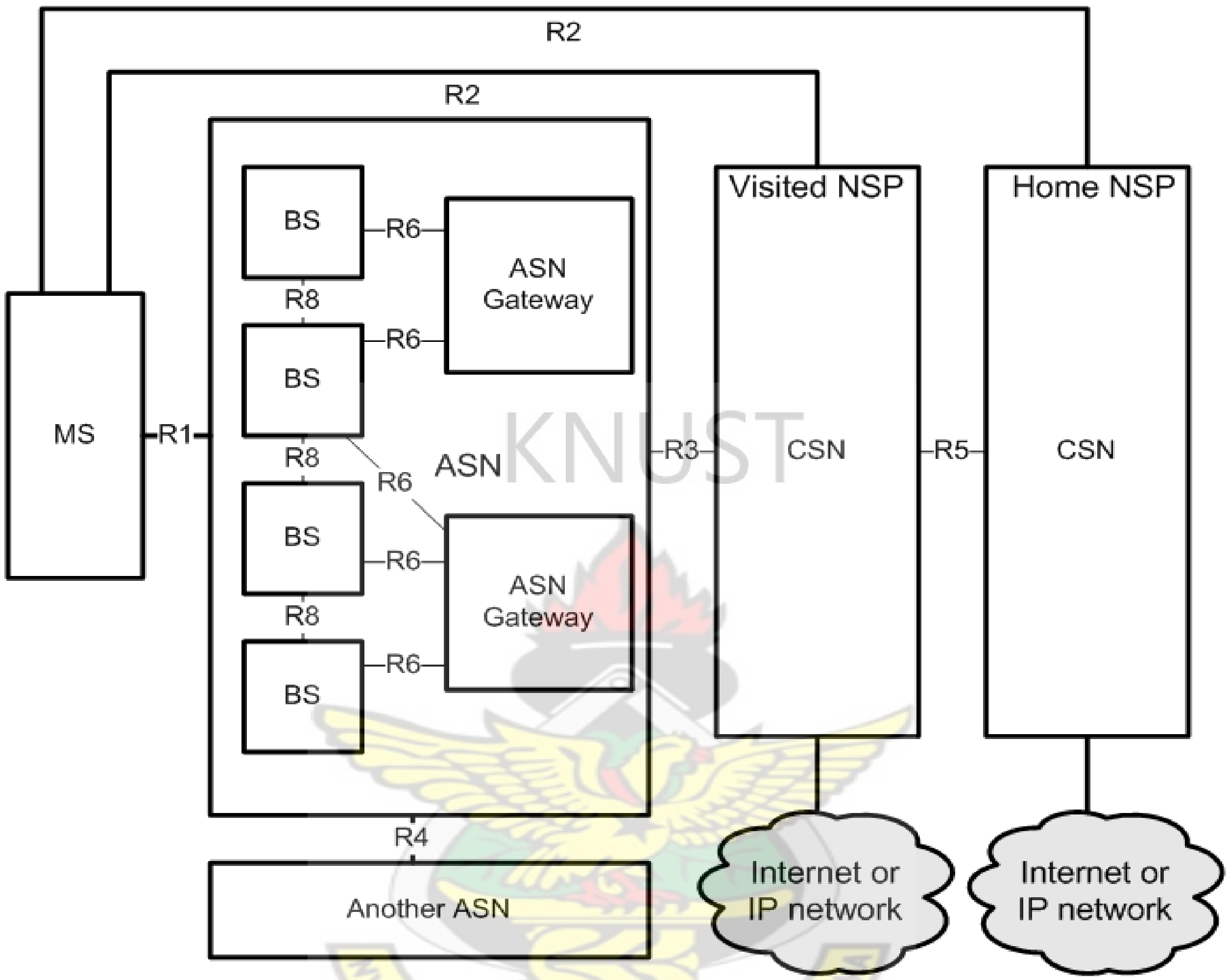

Fig 2.7: IP-based Mobile WiMAX Network Reference Model [33]

2.2.2 Deployment Considerations for Mobile WiMAX

Just as such fundamental issues as system capacity and interference are always paramount to the design of wireless systems, so are link budget and signal-to-noise ratio (SNR) calculations also considered as major deployment considerations. For Mobile WiMAX the cost-savings opportunities made possible by low-cost chipsets and flexible bandwidth scalability sets the platform for quite a wide range of so-called capacity-driven and coverage-limited deployment scenarios. This segment of the review informs the reader of deployment considerations for Mobile WiMAX as put together in a white paper research conducted by Fujitsu Microelectronics Inc.

2.2.2.1 Designing a Mobile WiMAX Network

The link budget often sets the pace as one important factor to consider in wireless mobile network design. Mathematically, it is the loss and gain sum of signal strengths through the varying medium of the transmission path. It enables the maximum radius of a cell to be determined for an adequate service level agreement (SLA). Additionally, a good SNR is critical for the system to perform at its optimum level **[34].**

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2.2.2.2 Determining coverage boundaries

Fujitsu also proposed that to take full advantage of Mobile WiMAX feature of scalability, system operators needed to employ the right software tools to pre-determine suitable coverage boundaries for their network. These tools perform propagation simulation and drive tests. Careful deployment planning is often critical so as to provide the room to scale in response to growing customer demands. It is particularly an issue of concern for urban communities where deployments are most likely to be capacity-driven **[34].**

2.2.2.3 Sector and Frequency Reuse

A 3-sector base station is recommended for cellular and Personal Communication Systems and it equally suits WiMAX systems as depicted in Fig. 2.8. To make optimum use of the available wireless spectrum, Mobile WiMAX systems can make use of both sector and frequency reuse. Sector reuse requires using one sector to cover several areas, at least one of which is adjacent to another base station. Frequency Reuse means using frequency to serve multiple sectors that do not experience mutual interference [**34]**. With a reuse of one each of the base station's three sectors use the same set of channels, thus effectively combining the three sectors into one. Co-channel interference is eliminated at the sector boundaries. In addition, co-channel interference between neighbouring cells is significantly reduced due to the spatial separation for channels operating at the same frequency, considering the fact that cell sector boundaries are properly aligned. Correct alignment means down-tilting antennas and performing drive tests to see if each sector covers the proposed azimuths. It is also noteworthy that Mobile WiMAX's scalable OFDMA scheme provides some restraints on adjacent channel interference (ACI) at the sector boundaries.

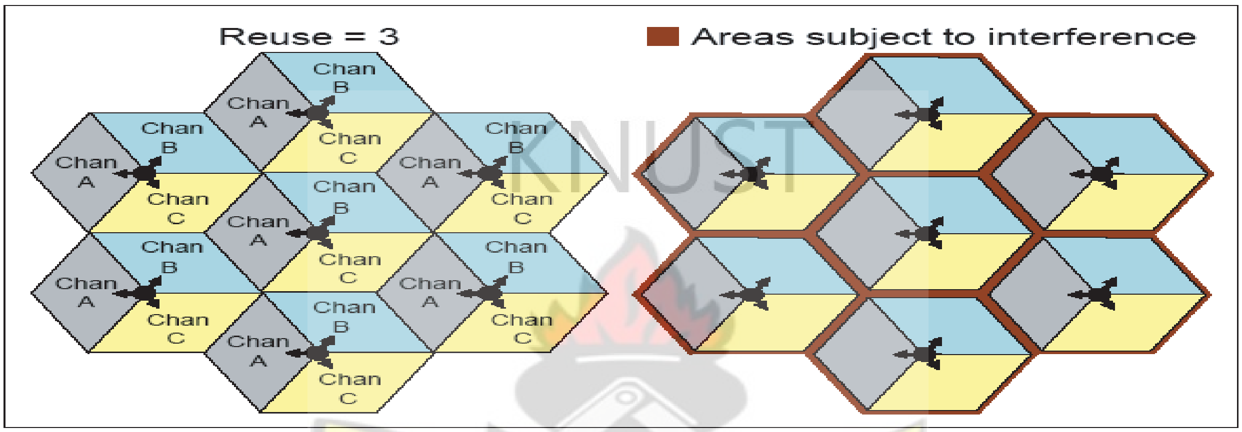

Fig 2.8: Sectorized Wireless System with Frequency (Channel) Reuse [34]

2.2.2.4 Frequency Band and Other Considerations

Link margins and SNR calculations must take advantage of a number of factors, mostly related to the deployment environment and service quality requirements. Operator implementation strategy of the Mobile WiMAX technology strongly influences these trade-offs. Because good reception inside buildings and vehicles is important, Fujitsu Microelectronics suggested that due considerations be given to penetration loss, utilizing the normalization factor (n-factor) of a given medium. The n-factor is dependent on the choice of modulation scheme and must be used to achieve the same average power for all mappings. Quadrature Amplitude Modulation, with 2M-point constellation, where M is the number of bits transmitted per modulated symbol, is recommended for WiMAX systems. For Mobile WiMAX downlinks, 4-QAM (QPSK, M = 2) and

16-QAM (M = 4) are mandatory, while 64-QAM (M = 6) is optional. For the uplink 4-QAM and 16-QAM are suggested as mandatory and optional, respectively.

The Modified Hata COST-231 propagation model is a very suitable model for mobile applications in the 1900 MHz as well as the designated 2500 MHz and 3500 MHz bands where Mobile WiMAX operates. Another factor considered was the antenna gain, which can increase coverage with the trade off that with an increase in gain there is a corresponding decrease in the carrier-to-interference-plus-noise ratio (CINR). A CINR of 25dB or better is recommended as normal for most mobile systems. Other link parameters which include fade margin and interference margin are assumed to be the same for each of the licensed spectrum bands- 2500 MHz and 3500 MHz as well as for the unlicensed 5800 MHz band **[34].**

2.2.3 Comparative Performance Evaluation of Mobile WiMAX and 3G+ technologies-HSPA and EV-DO

Outlined below are simulation-based findings on the aforementioned comparison, at least as required to build a business case on the efficiency of Mobile WiMAX systems.

2.2.3.1 WiMAX Forum Research

In September 2006 Doug Gray prepared a research paper titled "Mobile WiMAX: A performance and comparative summary" on behalf of the WiMAX Forum, showing a simulation-based performance comparison of Mobile WiMAX and 3G+ enhancement technologies**[35]**. The simulation parameters for the comparison were similar except for the following:

- EV DO and HSPA are FDD implementations operating on a carrier frequency of 2000MHz whereas the Mobile WiMAX is TDD-based operating at 2500 MHz

- EV-DO and HSPA used a single TX antenna and dual RX antennas (1*2 SIMO) with RAKE receiver in both DL and UL. Mobile WiMAX implemented 1*2 SIMO for one case and for a second case, 2*2 MIMO with Space Time Coding and Vertical Spatial Multiplexing with Adaptive MIMO Switching being considered in the DL and two user spatial multiplexing in the UL. Maximum Likelihood Symbol Detection was assumed at the RX in both DL and UL.

Fig 2.9 and Fig 2.10, respectively, provide a throughput and spectral efficiency comparison of Mobile WiMAX with EV DO and HSPA for a DL/UL ratio of 1:1 and 3:1 **[35].**

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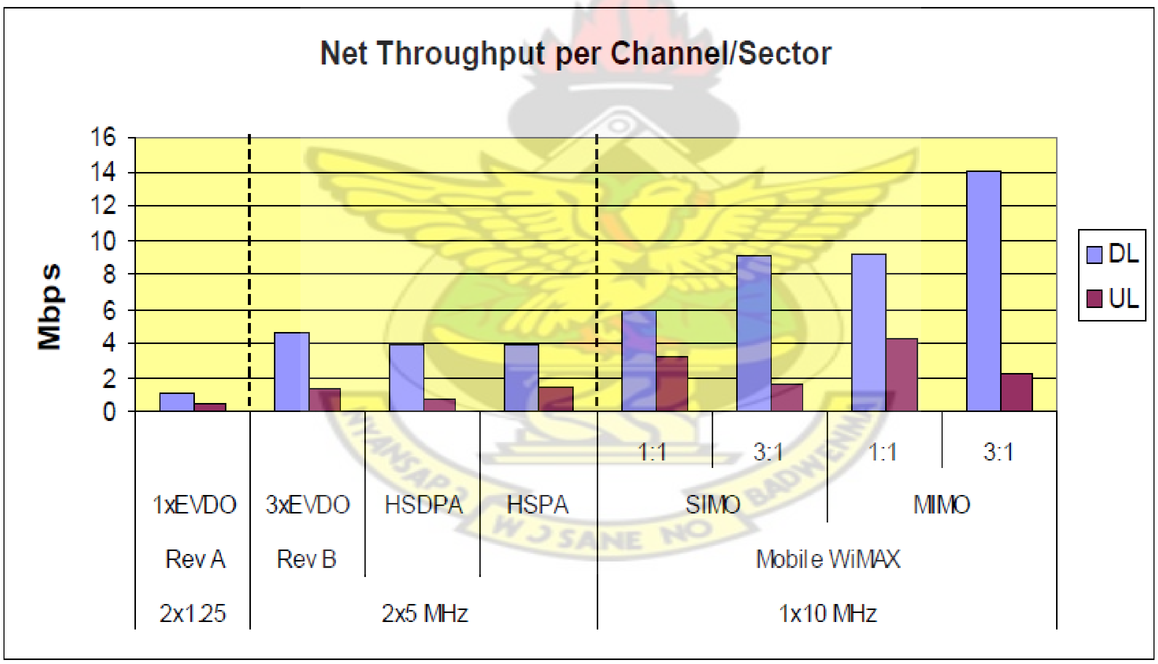

Fig. 2.9: Sector Throughput Comparison [35]

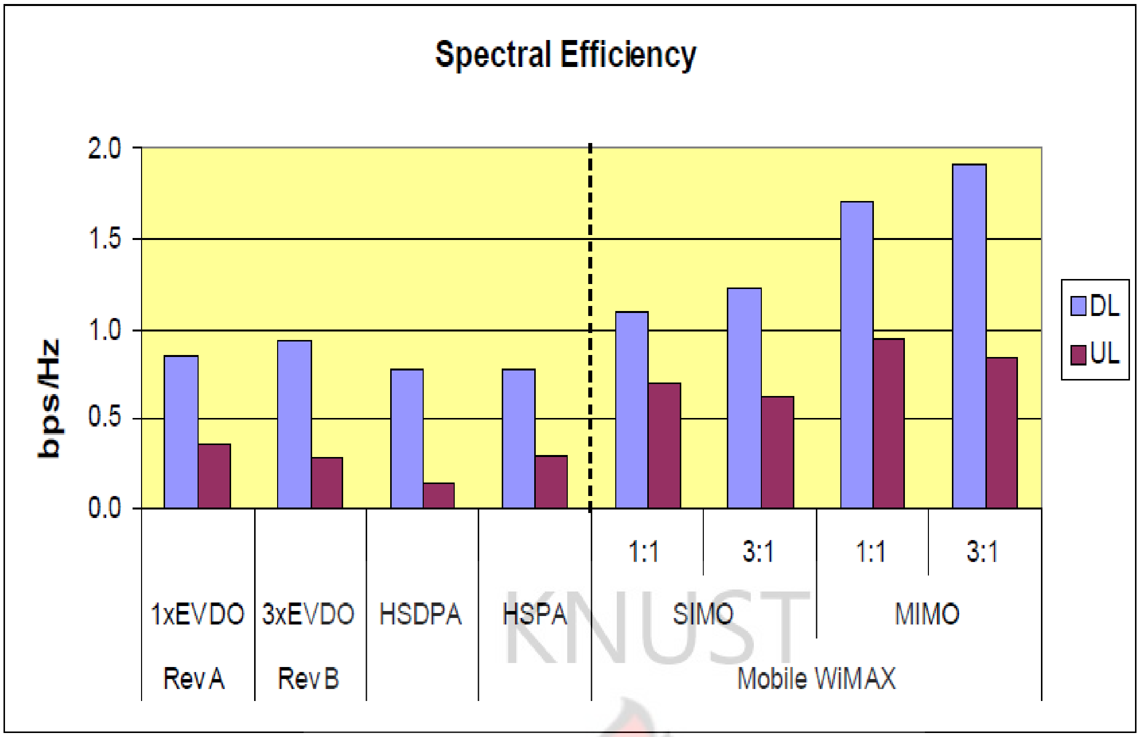

Fig 2.10: Spectral Efficiency Comparison [35]

2.2.3.2 Ericsson White paper Research

In their white paper research titled, "Technical Overview and Performance of HSPA and Mobile WiMAX" a comparative performance evaluation study of the HSPA and Mobile WiMAX technology in terms of throughput, spectral efficiency and coverage is carried out and captured in Fig.2.11, Fig. 2.12 and Fig.2.13.

One remarkable observation of the research was that rather than just covering one version or release of each system family which might give a misleading picture, the study compared fairly a set of HSPA and Mobile WiMAX releases. Though both technologies share in such technical features as antenna diversity schemes, dynamic scheduling and link adaptation performance differences in uplink bit rates and coverage was perhaps accounted for by such technical differences as duplexing scheme, frequency bands and multiple access technology **[10].**

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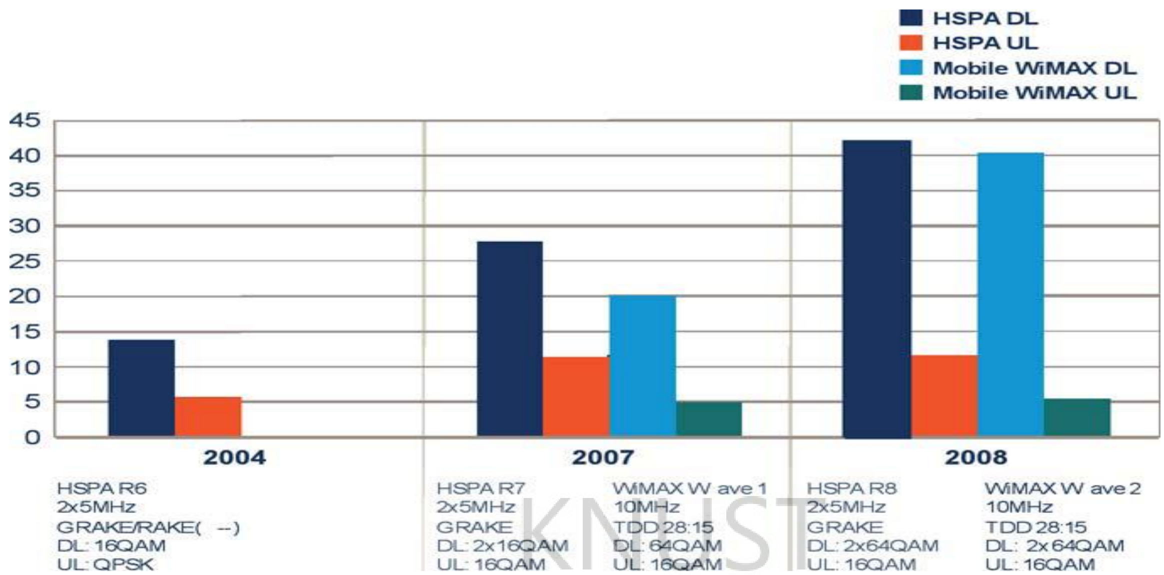

Fig 2.11: Peak data rates for a set of HSPA releases and WiMAX waves [10].

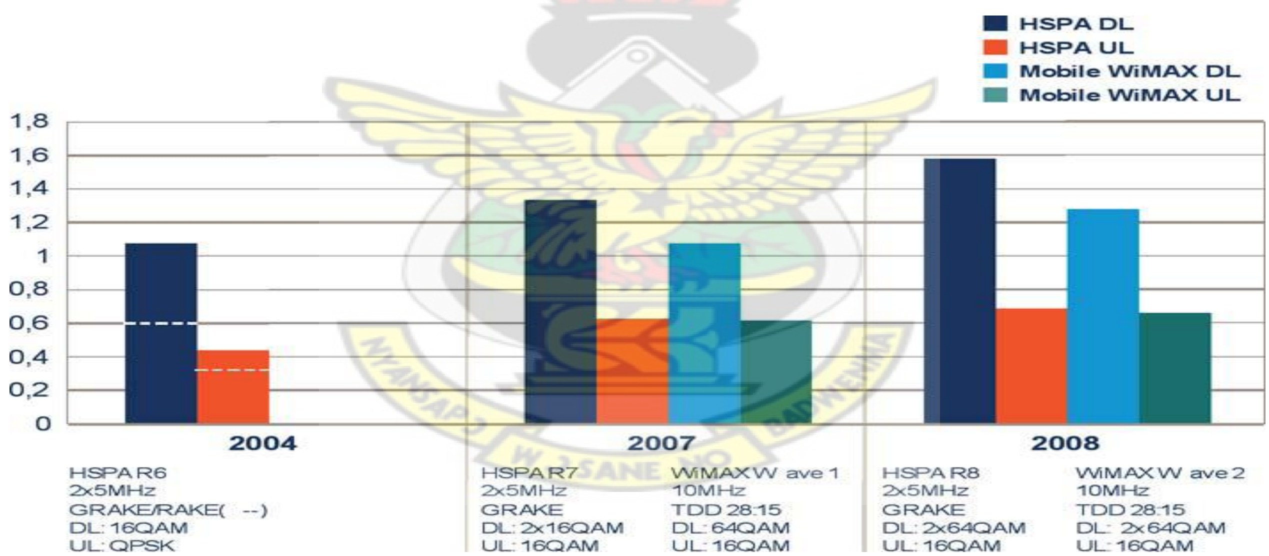

Fig 2.12: Spectrum efficiency comparison [10].

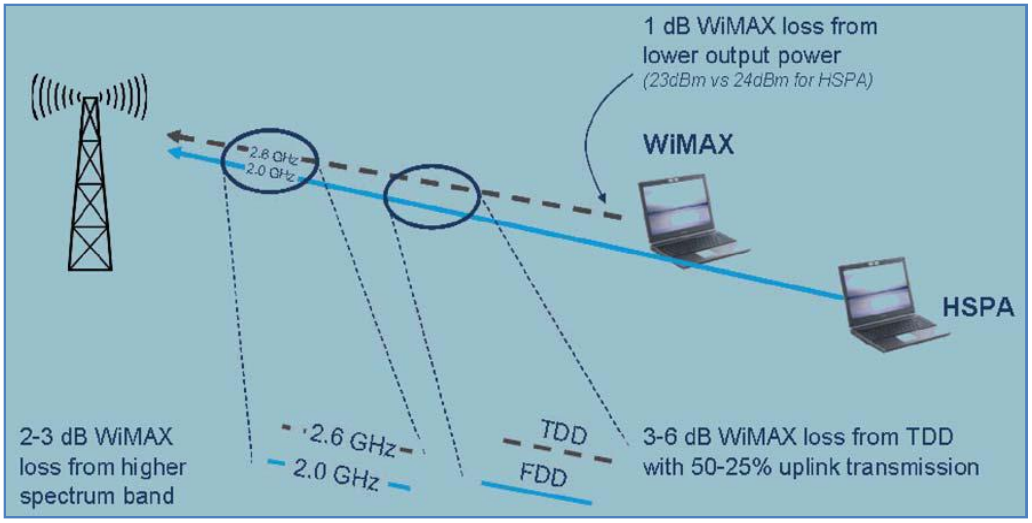

Fig 2.13: HSPA typically has 6-10dB greater coverage than Mobile WiMAX [10].

HSPA (R6) with basic RAKE receivers compared to WiMAX performed rather poorly in terms of throughput and spectrum efficiency. A RAKE receiver is the radio receiver designed to mitigate the effects of multipath fading. With the use of complex and quite advanced receivers, such as GRAKE with receive diversity; HSPA achieves a greater spectrum efficiency than WiMAX. In terms of coverage, HSPA has typically 6-10 dB greater coverage than Mobile WiMAX. The maximum output power of WiMAX terminals (23 dBm) is 1 dB lower than for HSPA (24 dBm) which amounts to a difference of 1 dB in link budget. Since WiMAX operates in a higher frequency than HSPA, and with path loss being proportional to the square of the frequency in use, coupled with a 3-6dB TDD implementation loss for a 50-25% uplink transmission it was observed that the WiMAX link budget was on the whole 6-10dB less than that of HSPA. In all the site count were 2.2 times as many for WiMAX as there are for HSPA considering that the deployment scenario was coverage-limited. According to Ericsson WiMAX, compared to HSPA, does not pass as a cost-effective technology to deploy given the same service area.

CHAPTER THREE- COMPARATIVE STUDIES & A TECHNO-ECONOMIC EVALUATION OF MOBILE WIMAX ROLL OUT IN ACCRA METROPOLIS

3.1 Introduction

Chapter three presents further comparison of the IEEE 802.16e system with the currently deployed 3.5G High-Speed Downlink Packet Access technology by Airtel and MTN using link budget calculations as the primary performance metric. In Ghana Mobile WiMAX happens to be the latest technology yet to become a commercial reality in the 2.5-2.69 GHz band, link range calculations and system capacity estimations are also carried out to project the site count for a network roll out in the Accra Metropolis. The chapter thus concludes with a study into the techno-economic viability of an IEEE 802.16e project within the aforementioned study environment over a 10-year license period using a typical business case scenario of a new market entrant. This project is carried out with the support of the technical staff of DiscoveryTel Ghana Ltd, an Accra-based Internet/VPN solutions provider preparing to upgrade their network to Mobile WiMAX.

3.2 Radio Network Planning

3.2.1 Spectrum

A major consideration to make in radio planning and network dimensioning of wireless communication networks is the frequency band in which the network is to be operated. Radio spectrum is a limited and costly resource whose usage in any country is usually regulated by the government. Having met the terms and conditions under which a given frequency band should be operated, network operators are invited by the regulator to partake in a 'beauty contest' or a rather competitive auctioneering process. Frequency band can either be classified as licensed or unlicensed **[36].** Licensed bands are legally protected against interference especially for an urban deployment scenario where a number of operators compete within the same market space.

Unlicensed spectrum, on the other hand, is used by operators who with low initial start-up are capable of managing the risks associated with interferences from neighbouring operators.

The spectrum band plan proposed by the NCA for the 2,500MHz-2,690MHz radio band was found to be service and technologically neutral and is summarized as follows:

- Three (3) slots of 30-MHz blocks nationwide for operators using technologies that require unpaired spectrum for a 10-year period
- Two (2) slots of 2x15 MHz blocks nationwide for operators using technologies that require paired spectrum for a 10-year period **[4].**

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It is noteworthy that paired and unpaired spectrum would serve FDD and TDD-based technologies, respectively.

3.2.2 Propagation models

Radio propagation models also referred to as path loss models provide the framework for conducting feasibility studies for any initial network roll out. They also serve as an indispensable tool when carrying out interference studies as the deployment proceeds **[37].** Path loss is a phenomenon which occurs when a received signal becomes weaker and weaker due to increasing distance of separation between the MS and BS. It can also be said to be influenced by such factors as terrain contours, environment (urban or rural, vegetation cover), propagation medium (dry or moist air) as well as the height and location of antennas **[38]**. Path loss calculations are usually conducted using analytical models based on the fundamental physics of radio wave propagation or a statistical curve fitting of data obtained through field measurements. Though most statistical models have been conventionally developed to parameterize mobile environments, quite a number of them can be used for NLOS fixed networks with a few modifications of the parameters **[39].** For LOS radio propagation however, the free space model is preferred. It establishes the dependence of the power loss of a signal on the square of its frequency (f_c) and the square of the separation distance between the transmitter and receiver (d). The free space path loss is mathematically represented as: **[38]**

$$Lp\ (dB) = 32.45 + 20\log f_c\ (MHz) + 20\log d\ (km) \quad (3.1)$$

Empirical models which are statistical models obtained from extensive field measurements are often used for real-life deployment studies. In our comparative study of the HSDPA and the Mobile WiMAX two major empirical propagation models which predict the mean path loss as a function of the link range, antenna height and the environment are discussed herein.

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COST-231 Hata Model

For cellular networks operating in the 800/900MHz band the Hata model is usually used for field analysis. With the introduction of PCS deployment in the 1800/1900 MHz band the European COST (Co-operation in the field of Scientific and Research) group modified the Hata model. The extended model, often referred to as the COST-231 Hata model is deemed valid for the following range of parameters.

$$1500MHz \leq f \leq 2000MHz$$

$$30m \leq hb \leq 200m$$

$$1m \leq hm \leq 10m$$

$$1km \leq d \leq 20km$$

The mathematical relation for the mean path loss is illustrated below:

$$PL = 46.3 + 33.9\log10\ f - 13.82\log10\ h_b + (44.9 - 6.55\log10\ h_b)\log10\ d - a(h_m) + CF \quad (3.2)$$

The MS antenna-correction factor, also termed the MS antenna gain function is given by

$a(h_m) = (1.11\log10 f – 0.7)\, h_m – (1.56\log10\, f - 0.8)$ (3.3)

where

f is the carrier frequency in MHz,

h_b is the base station height in meters,

h_m is the mobile station antenna height in meters,

d is the distance between the base station and mobile station in km.

For urban and suburban areas, the area correction factor CF is 3dB and 0dB respectively. Since the comparison will be done for the case of a metropolitan urban environment such as the metropolis of Accra we choose a CF of 3dB **[38] [39].**

Erceg-Greenstein Model

Erceg-Greenstein model is yet another popular model used for estimating the maximum allowable path loss during any initial network roll out. The path loss model is derived from experimental data collected by AT&T Wireless Services across the United States in 95 existing macrocells at 1900 MHz. The model is applied to suburban areas, and it distinguishes between three different terrain categories.

- Erceg A is used for hilly terrain with moderate to heavy tree density.
- Erceg B is used for hilly terrain with light tree density or flat terrain with moderate to heavy tree density.
- Erceg C is applicable to flat terrain with light tree density **[39].**

The model is deemed valid for the following range of parameters **[39]**:

$$1900MHz \leq f \leq 3500MHz$$

$$10m \leq hb \leq 80m$$

$$2m \leq hm \leq 10m$$

$$0.1km \leq d \leq 8km$$

The formula for this model is given by:

$$L = Ld_0 + 10*n*\log(d/d_0) + X_f + X_h + s \quad (3.4)$$

Where

Ld_0 is the free space path loss at d0,

d_0 = 100 meters,

n is the path loss exponent,

d is the distance in meters,

X_f is the frequency correction term,

X_h is the receive antenna height correction term,

s is a log-normally distributed factor that is used to account for the shadow fading owing to trees and other clutter in the study environment

The formula to calculate the path loss exponent, *n* is **[39]**:

$$n = a - b* h_b + c/h_b \quad (3.5)$$

To calculate the frequency correction term we use:

$$X_f = 6 * \log(f_c/2000) \quad (3.6)$$

To calculate the receive antenna height correction term we have:

$X_h = -10.8 * \log(h_m/2000)$ (for Erceg A and B) (3.7)

$X_h = -20 * \log(h_m/2000)$ (for Erceg C) (3.8)

Table 3.1: Model Parameters [39]

Parameters	**Erceg A**	**Erceg B**	**Erceg C**
A	4.6	4	3.6
B	0.0075	0.0065	0.005
C	12.6	17.1	20

where a, b and c are constants that represent different terrain categories. The values of a, b and c for the three terrain-dependent Erceg variants can be seen in Table 3.1.

3.2.3 Link Budget Design

A link budget is defined as the sum of the loss and gain of the signal strength of a radio signal as it travels different path media from the transmitter to the receiver. The link budget provides the operator with a quantitative measure of the required transmit power that can compensate for the inherent losses in a radio transmission link so that the received signal level will just be enough to meet the target bit error rate (BER) of the system **[11][36][39].** Link budget calculations are thus required to estimate the theoretical maximum range of a given radio link using the MS or BS as a reference node for either an uplink or downlink scenario. However, in cell radius calculations the uplink is usually the limiting link. The link budget comprises two components namely:

- System level components- They include receiver sensitivity, power levels, modulation and coding schemes and do not show significant variation across different frequency bands **[36].**

- Non-system related components- These components include path loss, physical environment, cable loss and shadow margin, just to mention a few and they show significant variation with frequency **[36].**

In our comparative study common as well as system-specific link budget parameters for Mobile WiMAX and HSDPA are obtained and optimized with careful consideration to the amount of spectrum made available **[4]** (30MHz spectrum block) to the operator, the expected traffic demand, MCS distribution and the radio environment being used for the study. In the course of the study references to link-level simulations performed in **[6][17][24][27]** will be made so as to appreciate the impact such features as PUSC subchannelization, frequency Reuse, link adaptation, Hybrid Automatic Repeat Request and multiple antenna schemes, such as the space-time coding (STC) and maximal ratio combining (MRC), are likely to have on the link budget. Maximum allowable path loss or the link margin for the radio links serving both systems will then be determined using the COST-231 Hata urban propagation model.

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Table 3.2: Common System Parameters for Mobile WiMAX and HSDPA [6][15] [17] [27]

Parameters	Values
Cell Configuration	3 sectors per cell
BS Antenna Height	30m
BS Antenna Gain	18dBi
MS Antenna Height	2m
MS Antenna Gain	0dBi
Log-normal shadowing	8dB
Penetration Loss	15dB
Fading Margin	9 dB
Interference Margin	3dB (assuming 50% loading)
Path loss model	Cost 231 HATA/ Erceg

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Table 3.3: System Specific Radio Parameters [6] [17]

Parameters	HSDPA	Mobile WiMAX
Multiplexing technique	WCDMA	S-OFDMA
Duplexing mode	FDD	TDD

Channel Bandwidth	5MHz	10 MHz
Modulation scheme/ code rate	16QAM/QPSK-code rate ½ ,3/4	64 QAM/16 QAM/QPSK-code rate ½, ¾
Max. Subchannelization Gain	Not applicable	15dB
Processing Gain	12 dB for DL, 17.8 for UL	Not applicable
Max. number of user codes	15	Not applicable
TTI/Frame size	2ms	5ms
Symbols per frame	520	48
Spreading Factor (Fixed)	16	Not applicable

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Table 3.4: System Link Budget, 2.5GHz Mobile WiMAX, 10MHz, Reuse 1/3, 2*2 MIMO

Parameters	**Uplink**	**Downlink**
Maximum Tx Power (dBm)	27	43
Tx Diversity Gain (dB) due to Space-Time Coding	3	3
Tx Nominal Antenna gain (dBi)	0, Outdoor mobile 6dBi Indoor CPE	18
Transmitter losses (dB)	0	3

Effective Isotropic Radiated Power (dBm)	**30, 36**	**61**
Avg. PUSC gain (for Receiver sensitivity) in dB	-12.3	-2.0
Rx Nominal Antenna Gain (dBi)	18	0, Outdoor mobile 6dBi indoor CPE
Rx Diversity Gain (dB) due to Maximum Ratio Combining (dB)	3	3
Rx cable/body loss (dB)	3	0
Rx Noise Figure (dB)	4	7
Margins		
Log-Normal (shadow) Fade Margin (dB)	9	9
Co-channel Interference Margin(CCI) (dB)	0, Assuming Reuse (1,3,3)	0
Building Penetration Losses (dB)	15 , Assuming an indoor scenario	15
Total Margin	**24**	**24**

Table 3.5: System Link budget, 2.1GHz HSDPA, 5MHz, Reuse 1/1, 2*2 MIMO

Parameters	**Uplink**	**Downlink**
Maximum Tx Power (dBm)	24	43
Tx Diversity Gain (dB) due to Space-Time Coding	3	3
Tx Nominal Antenna gain (dBi)	0	18
Transmitter losses (dB)	0	3
Effective Isotropic Radiated Power (dBm)	**27**	**61**
Processing Gain (dB)	17.8	12
Rx Nominal Antenna Gain (dBi)	18	0
Rx Diversity Gain due to Maximum Ratio Combining (dB)	3	3
Rx cable/body loss (dB)	3	0
Rx Noise Figure (dB)	4	7
Margins		
Log Normal (shadow) Fade Margin (dB)	9	9
Multiple Access Interference Margin (MAI) (dB)	3	3

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Building Penetration Losses (dB)	15	15
Total Margin	**27**	**27**

- **Max. Transmit Power:** Having made references to **[24][27][36]** the recommended maximum UL transmit power in the case of Mobile WiMAX was found to be 27dBm whereas for references made to **[6][15]** we found HSDPA's to be 24dBm.

- **Antenna Gain-** Comparable nominal antenna Tx gain of 18dBi in the DL and 18dBi Rx gain in the UL was applied to both Mobile WiMAX and HSDPA whilst 0dBi and 6dBi was used for Mobile WiMAX as the antenna Rx gain for both outdoor and indoor scenarios respectively, considering the downlink direction. Diversity gain was obtained by finding the logarithmic scale of the number of transmit antennas which was 3dB.

- **Tx/Rx Losses-** This loss is also referred to as cable loss in the case of BS and body loss in the case of the User Equipment. 3dB Tx loss in the DL and 0 dB in the UL is assumed where as 0dB Rx loss in the DL and 3dB Rx loss in the UL is assumed.

- **EIRP-** It 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. The EIRP is often stated in terms of decibels over a reference power emitted by an isotropic radiator with equivalent signal strength. The EIRP allows comparisons between different emitters regardless of type, size or form. From the EIRP, and with knowledge of a real antenna's gain, it is possible to calculate real power and field strength values **[39].** Mathematically, EIRP is given as:

EIRP= Max. Transmit Power + Antenna Gain (Nominal and/or Diversity) – Transmitter losses (cable, connector) (3.9)

- **Avg. PUSC Gain-** In the uplink direction, it will hardly occur that data is transmitted over all subcarriers simultaneously. For 10-MHz bandwidth in OFDMA there are 1024 subcarriers organized into 34 subchannels. When all available power is concentrated into one subchannel the gain is of factor 34 equaling 15 dB on the logarithmic scale. This however provides an improvement in the uplink budget. Subchannelization gain is given by the formula: **[24] [39]**

Subchannelization gain = -10log (Nused subCHUL / NsubCHUL) (3.10)

- **Processing Gain-** In CDMA-based 3G/3G+ systems the length of the orthogonal spread code determines the spreading factor or the extent to which a signal can be spread. The ratio of the spread bandwidth to the unspread bandwidth is often referred to as the processing gain. Assuming a 64kbps data rate transmission on the UL the processing gain can be obtained as 10log (3840kbps/64kbps) which leaves as with 17.8dB. Should a fixed Spread Factor of 16 be assumed for the DL, the processing gain however drops to 12dB since the downlink data traffic is greater than that of the uplink **[15].**

- **Log-normal fade margin-** Log-normal fading, also referred to as slow fading is caused by obstacles (buildings, trees, etc.) that change the average received signal level due to shadowing. 9dB was assumed for both technologies. Fast fading is overlooked because the radio interface of each technology has the inherent ability to counter multipath fading **[39].**

- **Interference Margin-** HSDPA systems require that part of the transmission power be used to compensate for multiple access interference (MAI) in a cell. MAI can be expressed as a function of the cell loading factor. In other words the more load the cell is allowed to carry the higher the interference margin required. The interference margin is calculated as: **[40]**

$$\text{Interference Margin} = -10 \log (1-\boldsymbol{n}) \text{ where } \boldsymbol{n} \text{ is the loading factor} \quad (3.11)$$

In IEEE 802.16 OFDMA systems co-channel interference (CCI) is often accounted for by assigning an interference margin which often is quoted as 2-3dB even for both technologies. 3dB (assuming 50% loading in urban scenario) is however listed in the HSDPA link budget where as 0dB is indicated in the case of Mobile WiMAX. This is because by implementing the (1, 3, 3) reuse scheme inter-sector/cell-edge interferences is reduced appreciably. This decision was made in the light of the fact that adequate spectrum is available to the operator for deployment. Fig. 3.1 shows the variation of the interference margin with the loading factor for a HSDPA system.

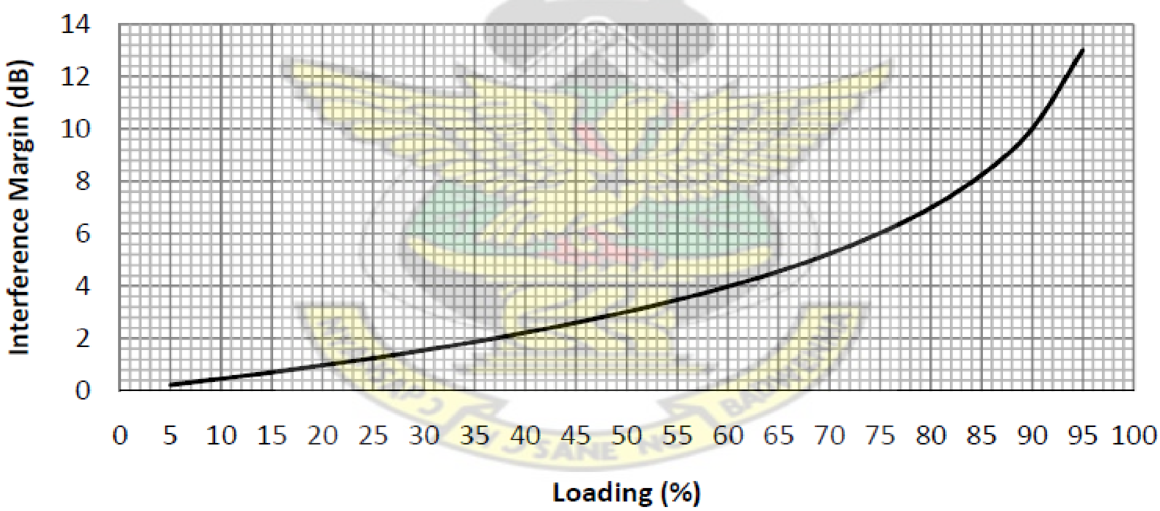

Fig 3.1: Loading effect in HSDPA [40]

- **Penetration Loss-** It is the loss the signal experiences when it travels through walls of buildings and is added to the link budget to allow for indoor coverage. 15 dB is a typical assumption that applies to both technologies **[15] [39][40].**

3.3 Radio Interface Dimensioning

3.3.1 Coverage Estimation for Mobile WiMAX and HSDPA networks

Having specified and optimized the system radio parameters for both technologies as is practicable to the study environment we first calculate the receiver sensitivity, then determine the link margin and estimate the cell radius using the COST 231 HATA model.

Receiver Sensitivity Calculation

Although a few inclusions will be made in the determination of the receiver sensitivity we briefly describe the major components that necessitate the use of the aforementioned parameter in link budget calculations:

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- Thermal Noise- The thermal noise is dependent on the channel bandwidth. Mathematically this parameter is represented in (dBm) as:

$$\text{Thermal Noise} = -174 + 10\log(\Delta \mathbf{f}) \text{ (Mobile WiMAX)} \tag{3.12}$$

Where ($\Delta \mathbf{f}$) is the bandwidth in hertz over which the noise is measured. For the calculation of the thermal noise, the bandwidth, $\Delta \mathbf{f}$ has to be scaled to the effectively used bandwidth. So the value of **BW** has to be multiplied by the ratio between the numbers of used subcarriers (**NUsed**) and the total number of OFDM subcarriers or FFT size ($\mathbf{N_{FFT}}$), and the sampling factor (***n***). Thus the thermal noise equation can be re-written as: Thermal Noise = -174 + 10log (BW* n* Nused / NFFT)

Thermal noise is also expressed as KTB in the case of HSDPA where K is the Boltzmann constant, T is the room temperature, B is the RF carrier bandwidth.

- Noise Figure- The noise performance of a receiver is described by a figure of merit called the noise figure. It is a measure of the degradation in the received SNR as a result of the components in the RF signal chain. Mathematically the noise figure in logarithmic scale can be expressed as:

Noise Figure = 10Log (Noise output of actual receiver/Noise output of ideal receiver)

The noise figure assumed were 4 dB and 7dB for BS and MS respectively **[39]**

- Implementation Loss- The implementation loss includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. The assumed value is 5 dB for both technologies.

- Received SNR- This parameter depends on the modulation and coding scheme. Since both HSDPA and Mobile WiMAX adaptively select the modulation scheme per user, the appropriate SNR value used in the link budget calculation is dynamically adapted. However in our estimation of the link range the most robust but least efficient MCS scheme, QPSK ½ will be most preferred. When the MS move away from the BS the bit energy is increased but there is a trade off in terms of the number of bits per symbol of data sent. Table 3.6 shows the received SNR values for both technologies.

Table 3.6: Received SNR values for different MCS levels [15] [39]

Modulation /Coding Scheme	**Mobile WiMAX**	**HSDPA**
QPSK ½	5	4.6
QPSK ¾	8	7.04
16QAM ½	10.5	9.23
16QAM ¾	14	12.7

64QAM1/2	16	N/A
64QAM3/4	20	N/A

We now calculate Receiver Sensitivity, Rss values for the different modulation and coding schemes implementable under each technology:

The minimum sensitivity, Rss from IEEE 802.16e standard is as shown below **[41]**

$$Rss = -114 + SNR_{RX} + 10\times\log[(F_S \times Nused)/N_{FFT}] + ImpLoss + NF \qquad (3.13)$$

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Where,

$-114 = -174 + 10\log(1MHz)$

SNR_{RX} is the receiver SNR

F_S, sampling frequency

Nused, number of used carriers

N_{FFT}, number of FFT size used, NF is the Noise Figure

ImpLoss, implementation loss, includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise **[41]**. The assumed value is 5dB.

For an Optimized Mobile WiMAX BS that considers the HARQ repetition factor and PUSC Subchannelization Gain, the receiver sensitivity will be re-expressed as:

$$Rss = -114 + SNR_{RX} - 10\times\log(R) + 10\times\log[(F_S \times Nused)/N_{FFT}] + ImpLoss + NF + Avg.\ PUSC\ gain \qquad (3.14)$$

For 1024 FFT 10 MHz IEEE 802.16 OFDMA system,

Rss (QPSK ½) dB= -114 + 5 -10log 2 + 10log [(11.2*841)/1024] + 5 + 4 + (-12.3) = -105.7 dB

Rss (QPSK 3/4)dB= -114 + 8 -10log2 + 10log [(11.2*841)/1024] + 5 + 4 + (-12.3) = -102.7dB

Rss (16QAM ½)dB= -114 +10.5 -10log2 +10log [(11.2*841)/1024] +5 + 4 + (-12.3) = -100.2dB

Rss (16QAM 3/4)dB= -114 + 14 -10log2 + 10log [(11.2*841)/1024] + 5 + 4 + (-12.3) = -96.7dB

Rss (64QAM 1/2)dB= -114 + 16 -10log2 + 10log [(11.2*841)/1024] + 5 + 4 + (-12.3) = -94.7dB

Rss(64QAM ¾)dB= -114 + 20 -10log2 + 10log [(11.2*841)/1024] + 5 + 4 + (-12.3) = -90.7dB

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HSDPA system

To calculate the Rx sensitivity we will use the following equation:

$$Rss = KTB_{RF}\ (dBm) + SNR\ (dB) - PG\ (dB) + NF\ (dB) + ImpLoss\ (dB) \quad (3.15)$$

Where:

NF: Receiver noise figure

K = Boltzmann's constant = 1.381 × 10-23 W/Hz/K,

T = 290K at room temperature and

B= RF carrier bandwidth (Hz)

But KTB_{RF} is given by: -174dBm + 10*log (3.84MHz) = -108.1 dBm

P.G: Processing gain, 17.8 dB for uplink, 12 dB for downlink.

ImpLoss, implementation loss, includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. The assumed value is 5dB **[15] [39] [41]**

Rss(QPSK 1/2)dB = -108.1 + 4.6 -17.8 + 4 +5 = -112.3 dB

Rss(QPSK3/4)dB = -108.1 + 7.04 -17.8 +4 +5 = -109.9 dB

Rss(16QAM1/2)dB = -108.1 + 9.23 -17.8 +4+5 = -107.7 dB

Rss (16QAM ¾)dB = -108.1 +12.7 -17.8 + 4 +5= -104.2 dB

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The afore-computed Rx sensitivity values are thus summarized in Table 3.7.

Table 3.7: Calculated Rx sensitivity values for Mobile WiMAX and HSDPA

Modulation /Coding Scheme	**Mobile WiMAX(Rss in dB)**	**HSDPA(Rss in dB)**
QPSK ½	-105.7	-112.3
QPSK¾	-102.7	-109.9
16QAM ½	-100.2	-107.7
16QAM ¾	-96.7	-104.2
64 QAM ½	-94.7	N/A
64QAM ¾	-90.7	N/A

Having obtained the Rx sensitivity values for both technologies we now compute the System gain for the uplink budget.

System Gain $_{UL}$ = EIRP $_{UL}$ - Rx Sensitivity + Rx Antenna Gain –Rx losses (3.16)

Mobile WiMAX, Mobile Hand-held in Outdoor Scenario

System Gain (dB) $_{UL}$ = EIRP $_{UL}$ – Rss (QPSK ½) + Rx (Nominal) Antenna Gain + Rx Diversity Gain due to Maximal Ratio Combining (MRC) –Rx losses

System Gain (dB) $_{UL}$= 30 dBm – (-105.7dB) + 18dBi +3dB -3dB = 153.7 dB

Link Margin = System Gain (dB) $_{UL}$ – (Interference Margin + Lognormal Fade Margin) (3.17)

Link Margin = 153.7dB– (0dB + 9dB) =144.7 dB

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Link Margin, also referred to as the Maximum Allowable Path Loss is found to be 144.7dB for a mobile hand-held in outdoor scenario

Mobile WiMAX, Indoor CPE Scenario

System Gain (dB) $_{UL}$ = EIRP $_{UL}$ – Rss (QPSK ½) + Rx (Nominal) Antenna Gain + Rx Diversity Gain due to Maximal Ratio Combining (MRC) –Rx losses

System Gain (dB) $_{UL}$ = 36dBm – (-105.7dB) + 18dBi + 3dB -3dB = 159.7dB

Link Margin = System Gain (dB) $_{UL}$ – (Interference Margin + Lognormal Fade Margin + Building Penetration Losses)

Link Margin, MAPL = 159.7dB – (0dB + 9dB +15dB) = 135.7dB

HSDPA, Mobile Hand-held in Outdoor scenario

System Gain (dB) $_{UL}$ = EIRP $_{UL}$ – Rss (QPSK ½) + Rx (Nominal) Antenna Gain + Rx Diversity Gain due to Maximal Ratio Combining –Rx losses

System Gain (dB) $_{UL}$ = 27dBm – (-112.3dB) + 18dBi +3dB -3dB =157.3 dB

Link Margin = System Gain (dB) $_{UL}$ – (Interference Margin +Lognormal Fade Margin + Building Penetration Losses)

Link Margin = 157.3dB – (3dB + 9dB) = 145.3dB

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HSDPA, Mobile Hand-Held in Indoor Scenario

System Gain (dB) $_{UL}$ = EIRP $_{UL}$ – Rss (QPSK1/2) + Rx (Nominal) Antenna Gain + Rx Diversity Gain due to Maximal Ratio Combining –Rx losses

System Gain (dB) $_{UL}$ = 27dBm – (-112.3dB) + 18dBi +3dB -3dB = 157.3dB

Link Margin = System Gain (dB) $_{UL}$ – (Interference Margin +Lognormal Fade Margin + Building Penetration Losses)

Link Margin = 157.3dB – (3dB + 9dB +15) = 130.3dB

Having obtained the link margin, or the maximum allowable path loss, MAPL for that matter, we now employ the COST 231 HATA and Erceg propagation models to determine the link range or the cell radius for each technology.

In making the cell radius, d the subject of the path loss equation we obtain,

$$d= 10^{(MAPL - 46.3 - 33.9\log f + 13.82\log hb + \mathbf{Y} + CF)/ \mathbf{X}} \qquad (3.18)$$

where **X** = 44.9 - 6.55loghb

Y = a(hm) = (1.11log10f – 0.7)hm – (1.56log10 f - 0.8)

However, since the MS antenna height, hm = 2m satisfy the model requirement where 1m ≤ hm ≤ 10m, the a(hm) term will be excluded leaving us with, d= $10^{(MAPL - 46.3 - 33.9\log f + 13.82\log hb + CF)/\mathbf{X}}$

Thus given hm = 2m and hb = 30m, the cell radius can be calculated for both outdoor and indoor scenarios. Table 3.8 shows the results obtained for each technology under the aforementioned scenarios using the path loss equation for the COST-231 HATA propagation model.

Table 3.8: Cell Radii for Mobile WiMAX and HSDPA using COST 231 HATA

Technology	**Outdoor (in meters)**	**Indoor (in meters)**
Mobile WiMAX (f= 2500MHz)	1500	850
HSDPA (f= 2100 MHz)	1900	700

We will as well test the technical feasibility of applying the Erceg-Greenstein model to our urban study area. The Accra Metropolis from a geographical survey has flat terrain with light tree density, thus we use Erceg C's parameters, where (a, b, c) maps to (3.6, 0.005, 20) in our coverage prediction.

From Erceg model formula as expressed in equation (3.4), the path loss exponent for our study environment can be determined as follows:

Path loss exponent, n = a - b* hb + c/hb,

Pathloss exponent, n = 3.6 -0.005*30+20/30, assuming hb =30m

Path loss exponent, n = 4.1

The Free Space Loss term, $Ld0$ in equation (3.4) can be obtained as, $Ld0 = 32.45 + 20\log f_c$ (MHz) + 20log d_0 (km).

Mobile WiMAX

Ld_0 =32.4 + 20log (2500) + 20log (0.1) =80.36dB

HSDPA

Ld_0 = 32.4 + 20log (2100) + 20log (0.1) =78.84dB

Since our chosen MS antenna height and operating frequency are within the range of values for which Erceg-Greenstein model apply, we now determine the cell radius leaving out both Xf and Xh correction terms. In making cell radius, d (km) the subject of the path loss equation in the Erceg model formula we now have,

$d\,(km) = d_0 * 10^{\wedge\, [MAPL - (Ld0 + s)]/10n}$

Table 3.9 summarizes the results obtained in the calculation of cell radii for these two IMT-2000 technologies as it relates to our study environment.

Table 3.9: Cell Radii for Mobile WiMAX and HSDPA using Erceg Model

Technology	Outdoor (in meters)	Indoor (in meters)
Mobile WiMAX (f= 2500MHz)	2400	1400
HSDPA (f= 2100 MHz)	2400	1100

3.3.2 Site Count Determination using Coverage dimensioning

In making reference to **[36]** the area covered by a tri-sectored BTS is given by, $Acell = 1.95d^2$ where "d" is the cell radius. Using cell radii results obtained from the COST-231 Hata model, corresponding cell size for the two technologies are determined as follows:

For Mobile WiMAX, $Acell = 1.95(0.85km)^2 = 1.4\ km^2$ (approx.)

For HSDPA, $Acell = 1.95\ (0.70km)^2 = 1.0\ km^2$ (approx.)

Number of BTS = Total Land Area of Accra Metropolis/

Area covered by each BTS

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For an Optimized Mobile WiMAX system,

Number of BTS $= 200km^2 / 1.4\ km^2 = 143$ **sites** (approx.)

For an Optimized HSDPA system,

Number of BTS $= 200km^2 / 1.0\ km^2 = 200$ **sites** (approx.)

3.4 Techno-economic Evaluation of a Mobile WiMAX project in the Accra Metropolis

Since mobile WiMAX technology has been born into a tough world where competing alternatives such as DSL, fiber and high-speed cellular technologies already exist, mobile WiMAX needs to have a significant advantage over these incumbent technologies in order to justify its investment. In this segment of our study we investigate the business case viability of an IEEE 802.16e project as pursued by a new market entrant in the Accra Metropolis. We make significant reference to the spreadsheet–based techno-economic model developed in European research projects TONIC and ECOSYS. The model considers a number of technology and market related parameters and assumptions and provides basic profitability measures such as Net Present Value (NPV) and Internal Rate of Return (IRR). Some inputs and internal logic found in Fig.3.2 would hence be discussed.

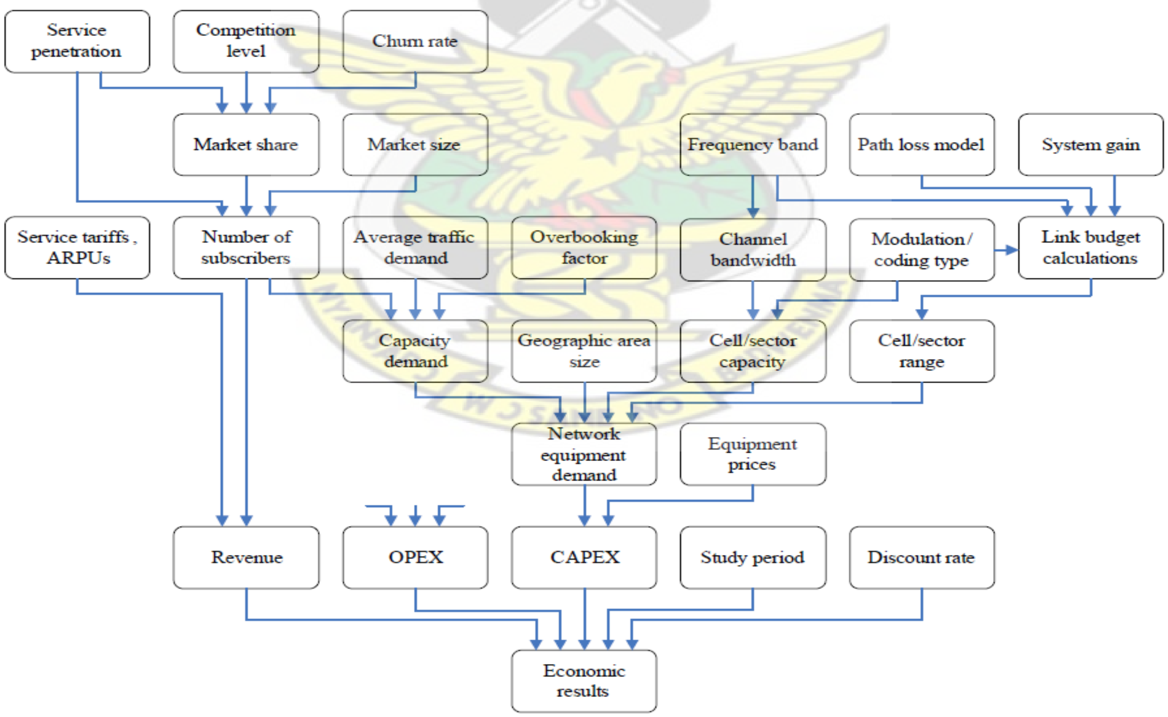

Fig. 3.2: A techno-economic model for an IEEE 802.16e network roll-out [45]

Demographics of Accra Metropolis

Total Land Size = $200km^2$

Population Size = 4.5 million

Population Density = Population Size/ Total Land Size= 4.5 million / $200km^2$ = 22500 / km^2 **[46]**

Market Segmentation

In our study we gathered that consumers that patronized broadband data services within our study environment could be put in one of two categories. Users could significantly be distinguished based on usage time as well as their application needs.

Professional Users (Business): This market group comprises the small & medium-scale enterprises and large corporate firms that are most demanding in terms of broadband data service. They are assumed to use the service in stationary, nomadic and mobile environments. Notable amongst services used by this group are file download, VoIP, video conference and e-mail.

High-End Users (Residential): This category of subscribers regularly uses data services mostly for their personal use. Dominant applications include web browsing, online gaming, music and video download.

Market Size

With reference to broadband statistics made available by Ghanaian-based *Internet Research*, the following estimations are made to typify the market size for our study environment over the 10-year license period **[1].**

Table 3.10: Market Size estimations

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
150,000	200,000	250,000	300,000	400,000	450,000	500,000	1mil.	1.5mil.	2mil

Market Share

The LTE and Mobile WiMAX are the two IMT-2000 technologies being auctioned for the 2.5-2.69GHz band. However, currently the 3.5G HSDPA and 1* EV DO are the two major mobile broadband technologies providing competitive high-speed broadband data connectivity in excess of 5Mbps to business and residential users in the Accra Metropolis. That notwithstanding the broadband market in the metropolis still appears unsaturated. In this project the market share forecasts for the technology under study would be put under three categories- pessimistic, moderated, and optimistic. This is done so potential operators and investors would appreciate the business case viability or otherwise in operating such new technology under unpredictable market conditions. It is expected that the LTE in a few years will replace the HSDPA and prove to be a major 4G combatant to the mobile WiMAX in Ghana.

Churn rate

In our study churn is assumed to have no effect on the new entrant's market share, i.e. the number of both incoming and outgoing subscribers are assumed to be equal.

Table 3.11: Projected market share over a 10-year network lifecycle

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Pessimistic	0.5%	1%	3%	5%	7%
Moderated	4%	6%	8%	12%	15%
Optimistic	5%	8%	12%	18%	20%
	Year 6	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Pessimistic	7%	7.5%	8%	9%	10%
Moderated	15%	17%	18.5%	20%	25%
Optimistic	25%	28%	30%	35%	40%

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Service Tariffs

Revenue generation has a direct bearing on the monthly payments made by subscribers for broadband connectivity. Service tariffs are developed in correspondence with the bandwidth needs of different subscriber profiles. Tables 3.12, 3.13 and 3.14 show typical price offerings tailor designed for the addressable market within the study environment depending on their data rate consumption and whether they are shared or dedicated customers.

Table 3.12: Prices and bandwidth allocation for different service classes (Residential)

Service Class (Shared-1:50)	Bandwidth (in Kbps)	Monthly Service Tarrif (in GH cedis)
A.	256	100
B.	512	160

C.	1024	200

Service Classes A, B, C and D are only descriptive, since every ISP can come up with its own way of describing its service class or subscription type

Table 3.13: Prices and bandwidth allocation for different service classes (Business)

Service Class (Shared-1:15)	Bandwidth (in Kbps)	Monthly Service Tarrif (in GH cedis)
A.	128	150
B.	256	225
C.	512	370
D.	1024	555

Table 3.14: Prices and bandwidth allocation for different service classes (Residential/ Business)

Service Class (Dedicated-1:1)	Bandwidth (in Kbps)	Monthly Service Tarrif (in GH cedis)
A.	256	1225
B.	512	2150
C.	1024	3990

D.	2048	7150

Source: DiscoveryTel Ghana Ltd, Accra

3.4.1 Capacity demand Estimation

It is imperative that the new entrants competing in an urbanized market space with incumbents estimate the required system capacity or data density per end-user before proceeding with deployment. The peak busy hour (PBH) activity level (showing the percentage of active users simultaneously using the system) has to be defined or assumed by the operator. Downlink duty ratio (showing the fraction of time the system is in active state) and customer mix (percentage distribution of customers among the category of users) are other parameters used in combination with the PBH activity level to determine traffic demand for a given service area [36].

In our study we consider total subscriber capacity for our new market entrant, residential and business users alike, to rise to 40% (optimistic market share) of an estimated 2,000,000 market size in the 10^{th} year of the project.

Estimated Subscriber Capacity (Residential/Shared) = 50% * 40% * 2,000,000= 400,000

Estimated Subscriber Capacity (Business/Shared) = 40% * 40% * 2,000,000 = 320,000

Estimated Subscriber Capacity (Dedicated) = 10% * 40% * 2,000,000 = 80,000

Residential (Shared) users

Assume 50%, 30% and 20% constant customer mix for service classes A, B, C respectively.

Assume PBH activity level of 60%, downlink duty ratio of 50% and contention ratio of 1:50 or an overbooking factor of 0.02. A contention ratio of 1:50 means up to 50 users can share the system bandwidth and still get the data rates they have paid for.

Maximum DL data rate required to support Residential (Shared) users = 400,000 * [0.5(256kbps) +0.3(512kbps) + 0.2 (1024kbps)] * 0.6 * 0.5 * 0.02 = 1167Mbps

Business (shared) users

Assume 40%, 30%, 20% and 10% constant customer mix for service classes A, B, C and D respectively.

Assume PBH activity level of 60%, downlink duty ratio of 50% and contention ratio of 1:15 or an overbooking factor of 0.067

Maximum DL data rate required to support Business (shared) users = 320,000* [0.4(128kbps) +0.3(256kbps) + 0.2(512kbps) + 0.1(1024kbps)] * 0.6 * 0.5 *0.067 = 2,140Mbps

Residential/ Business (Dedicated) users

Assume 40%, 30%, 20% and 10% constant customer mix for service classes A, B, C and D respectively.

Assume PBH activity level of 60%, downlink duty ratio of 50%. No contention ratio or overbooking factor is specified since users do not share their bandwidth with other users subscribing for similar bandwidths.

Maximum DL data rate required to support Residential (dedicated) users = 80,000 * [0.4(256kbps) + 0.3(512kbps) + 0.2(1024kbps) + 0.1(2048kbps)] * 0.6 * 0.5 = 15,974Mbps

Summing up the maximum DL throughputs we obtain a total estimated system capacity of 19, 281 Mbps for an IEEE 802.16e project whose lifetime per the license period is 10 years.

3.4.2 Site Count Estimation using Capacity dimensioning

Here, we make reference to the downlink budget in Table 3.4 for the capacity dimensioning of the IEEE 802.16 OFDMA system, specifically the aggregate downlink traffic that each BS can support. Having estimated the system capacity demand we can obtain the site count for our capacity-driven study area by dividing total traffic demand in the 10th year of the project by the capacity per BS. We will begin by first and foremost determining the receiver sensitivity values of the user equipment for different MCS levels **[34].**

Mathematically, the receiver sensitivity can be expressed as: Rss = Thermal Noise + Receiver SNR + Noise Figure + Implementation losses + Avg. PUSC gain

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Rss(QPSK1/2) = -114 + 10log [(11.2*841)/1024] + 5dB+ 7dB + 5dB + -2dB = -89.36dB

Rss(QPSK3/4) = -114 + 10log [(11.2*841)/1024] + 8dB+ 7dB + 5dB + -2dB= -86.36dB

Rss(16QAM1/2) = -114 + 10log [(11.2*841)/1024] + 10.5dB + 7dB + 5dB + -2dB = -83.86dB

Rss(16QAM3/4) = -114 + 10log [(11.2*841)/1024] + 14dB + 7dB + 5dB + -2dB = -80.36dB

Rss(64QAM1/2) = -114 + 10log [(11.2*841)/1024] + 16dB + 7dB + 5dB + -2dB = -78.36dB

Rss (64QAM3/4) = -114 + 10log [(11.2*841)/1024] + 16 + 7 + 5 + -2dB = -74.36dB

We will then go ahead to calculate the DL system gain, the link margin and consequently the area coverage probability for each MCS level.

Downlink System Gain (QPSK1/2) = 61dB – (-89.36dB) + 6dB +3 dB + 0dB = 159.36dB

Link Margin (QPSK1/2) = 159.36dB – (0dB+9dB+15dB) = 135.36dB

Downlink System Gain (QPSK3/4) = 61dB – (-86.36dB) + 6dB+ 3dB + 0dB = 156.36dB

Link Margin (QPSK3/4) = 156.36dB – (0 + 9dB + 15dB) = 132.36dB

Downlink System Gain (16QAM1/2) = 61dB – (-83.86dB) + 6dB +3 dB + 0dB = 153.86dB

Link Margin (16QAM1/2) =153.86dB – (0 + 9dB + 15dB) = 129.86dB

Downlink System Gain (16QAM3/4) = 61dB – (-80.36dB) + 6dB +3 dB + 0dB = 150.36dB

Link Margin (16QAM3/4) = 150.36dB – (0 +9dB +15 dB) = 126.36dB

Downlink System Gain (64QAM1/2) = 61dB – (-78.36dB) + 6dB +3 dB + 0dB = 148.36dB

Link Margin (64QAM1/2) = 148.36dB – (0dB + 9dB+ 15dB) = 124.36dB

Downlink System Gain (64QAM3/4) = 61dB – (-74.36dB) + 6dB +3 dB + 0dB = 144.36dB

Link Margin (64QAM3/4) = 144.36dB – (0dB + 9dB +15dB) = 120.36dB

Th afore-computed values are summarized in Table 3.15 and Fig.3.3 below.

Table 3.15: Downlink MAPL, Area Coverage Probability and MCS distribution for different MCS levels

Modulation/Coding Scheme (MCS)	**DL Maximum Allowable Path Loss**	**Coverage Area Probability**	**MCS Distribution**
QPSK ½	135.36dB	98.57%	32.1%
QPSK ¾	132.36dB	66.43%	19.3%
16QAM ½	129.86dB	47.14%	17.9%
16QAM ¾	126.36dB	29.29%	5.72%
64QAM1/2	124.36dB	23.57%	10.00%
64QAM3/4	120.36dB	13.57%	15.00%

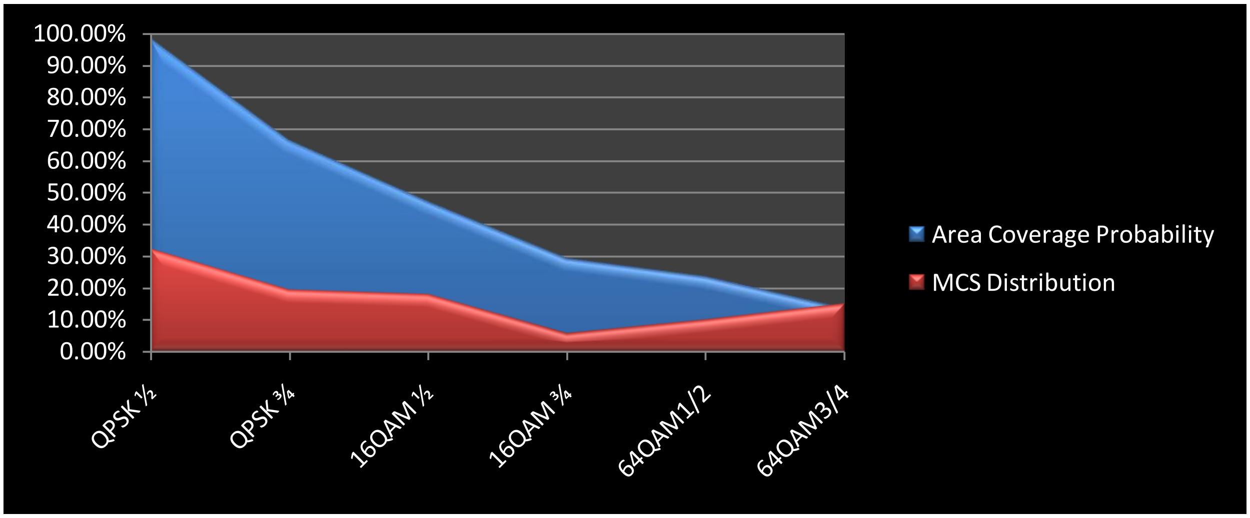

Fig. 3.3 Coverage Area Probability and MCS distribution chart

A spreadsheet-based WiMAX OFDMA Capacity calculator made available by INTRACOM, a Greece-based Wireless Network Solutions provider, is used to determine corresponding (layer 1) data rates for different modulation /coding schemes per the following configurations-

Frame interval- 5msec

DL Permutation mode- PUSC 1/3

TDD (DL/UL) Ratio- 2:1

Channel Bandwidth- 10MHz

Antenna configuration in DL– 2* 2 MIMO (Matrix B)/sector

Table 3.16: Peak DL Data rates for different modulation and coding schemes

Modulation /Coding Scheme	Code-efficiency	Data bits per symbol	Peak DL Data rate (Mbps) per sector
QPSK1/2	0.5	2	7.48
QPSK3/4	0.75	2	11.23
16QAM1/2	0.5	4	14.98
16QAM3/4	0.75	4	22.46
64QAM1/2	0.5	6	22.46
64QAM3/4	0.75	6	33.70

Source: INTRACOM

Given that users within the study area are evenly distributed throughout the cell,

Average DL throughput per sector = 33.7Mbps * 0.15 + 22.46Mbps (0.100 +0.572) + 14.98Mbps * 0.179 +11.23Mbps * 0.193 + 7.48Mbps * 0.321= 27.4Mbps

Aggregate DL throughput per BS = 3 sectors * 27.4Mbps/sector =82.2 Mbps per BS

Site Count = Estimated System Capacity Demand / Aggregate DL throughput per BS

Site Count (Optimistic) = 19,281 Mbps / 82.2Mbps = 235 sites

We also consider other market share scenarios and summarize all results in Table 3.17:

Table 3.17: Market Share scenarios and their corresponding traffic demand and site counts

Market share scenario	**Traffic demand in the 10th year of IEEE 802.16e project**	**Number of BS required to fulfill both capacity and coverage requirements per license conditions**
Pessimistic (Worst-case)	4,821Mbps	143
Moderated (Good-case)	12,051Mbps	147
Optimistic (Best-case)	19,281Mbps	235

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3.4.3 Estimating CAPEX and OPEX

The National Communications Authority has issued roll-out criteria for licensees of the 2,500-2690 MHz radio band. The Accra Metropolitan Area is one of the ten district capitals placed in the Zone A category whose roll-out conditions are quote-on-quote defined below:

- By the end of 18 months, the Licensee shall cover a minimum of six (6) district capitals.
- By the end of 36 months, the Licensee shall cover all ten (10) district capitals **[4].**

Table 3.18: ZONE A- Greater Accra Region [4]

District Area	**Capital**
Accra Metropolitan Area	Accra
Dangbe East	Ada-Foh
Dangbe West	Dodowa
Ga West Municipal	Amasaman
Tema Metropolitan	Tema

Ga East Municipal	Abokobi
Adenta Municipal	Adenta
Ashaiman Municipal	Ashaiman
Ga South Municipal	Gbawe
Ledzekuku-Krowor	Teshie-Nungua

It can be inferred however that within the first three months of deployment, the first district capital, which happens to be our study area can comprehensively be covered with all 143 base stations per the directive given by the country's communications regulator. A breakdown of the Capital and Operational Expenditures for our network roll-out is captured in Table 3.19**.**

Table 3.19: CAPEX & OPEX Parameters and their corresponding cost figures [4]

CAPEX Parameter	**Cost/Price**
License charges for 2.5GHz-2.69GHz band	
Application Fee	$50,000
Minimum Reserve Price for WiMAX license	$5,000,000 for a 10-year license
Equipment Cost	
MIMO A/B-enabled WiMAX Base Station including radios	$40,000 per BS
ASN gateways, AAA, DHCP server etc.	$600,000
Other Core Network elements such as routers, NMS, Radius servers etc	$200,000
Microwave Backhaul (PTP radio links)	$20,000 per link (PTP)

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Installation Cost for a new site	$5,000
Installation Cost for co-location	$1,000
Acquisition cost for new site	$60,000
CPE equipment	$200 per Outdoor CPE, $150 per indoor CPE, usb dongles,$ 100
OPEX Parameter	**Price/Cost**
Annual Regulatory fee	One percent (1%) of Net Revenue payable quarterly by the last business day of the month succeeding the quarter for which payment is being made. (Net Revenue = Gross Revenue – (Value Added Tax + National Health Insurance Levy + Communication Service Tax)
Ghana Investment Fund for Electronic Communications (GIFEC)	One percent (1%) of Net Revenue

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Site Rental/lease charges (co-location) per month	$2,000
Operations /Maintenance per annum	$150,000
Customer support per annum	$100,000
Sales/ Marketing per annum	$100,000
Miscellaneous (transport, manpower, subsidy etc) per annum	$120,000

Source: National Communications Authority & DiscoveryTel Ghana Ltd, Accra

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Estimating the required Investment Capital

- Total Spectrum Cost per licensee = Application fee + WiMAX License Acquisition fee = $50,000 +$5,000,000 = $5,050,000
- Total MIMO-enabled BS Equipment Cost = $40,000 per BS* 100 BS = $4,000,000
- Acquisition Cost for new sites (Greenfield) = $60,000 * 100BS = $6,000,000
- Installation Cost for new sites (Greenfield) = $ 5,000 * 100 BS = $5,000,000
- Installation Cost for co-located sites = $1000 * 43 BS = $43,000
- ASN Gateways, AAA proxy server, DHCP server = $600,000
- Core Network Cost(Assuming one core network is deployed to serve all 10 districts) = $200,000
- Microwave Backhaul Cost = $ 20,000 per link * 143 PTP = 2,860,000

- Total CPE (start-up) Cost, Assuming 100,000 usb dongles, 100,000 CPE units for outdoor, 100,000 CPE units for indoor = $100 per unit *100,000 + $200 per unit * 100,000 + $150 per unit * 100,000 = 45,000,000

Summing all CAPEX figures, the required investment capital for our IEEE 802.16e project in the aforementioned band is given as **$68,753,000** or **GH ¢ 103,129,500**

OPEX Calculation

- Total Operational Expenditure = Annual Regulatory Fee (ARF) + GIFEC + Operations/Maintenance cost + Customer support + Sales/Marketing + Site rental/lease charges due to co-location + Miscellaneous (transport, manpower, overhead). The National Communications Authority specifies, ARF = 1% * Net revenue.

From the table, Net Revenue = Gross Revenue – (Value Added Tax + National Health Insurance Levy + Communication Service Tax). Net revenue = Gross revenue - [15%*Gross revenue + 3.75% * Gross revenue + 6% * Gross revenue] = 75% * Gross revenue

Total Operational Expenditure (in GH ¢) = [2(1% * 75% * Gross Revenue) + 225,000 + 150,000 +150,000 + 43 * 3000 * 12 + 180,000].

Table 3.20: TOTEX, Revenue and Cash Flow over a 10-year license period (worst-case)

YEAR	TOTEX (GH ¢)	Gross Revenue = subscriber capacity * service tarrif (GH ¢)	Cash Flow (GH ¢)	Accumulated Cash Flow(GH ¢)
Year 1 (Incusive of Investment Capital	-105,441,441	3,929,400	-101,512,041	-101,512,041

Year 2	-2,410,176	10,478,400	8,068,224	-93,443,817
Year 3	-2,842,410	39,294,000	36,451,590	-56,992,227
Year 4 (Break-even point)	-3,431,820	78,588,000	75,156,180	18,163,953
Year 5	-4,453,464	146,697,600	142,244,136	160,408,089
Year 6	-4,728,522	165,034,800	160,306,278	320,714,367
Year 7	-5,200,050	196,470,000	191,269,950	511,984,317
Year 8	-8,540,070	419,136,000	410,595,930	922,580,247
Year 9	-12,862,380	707,292,000	694,429,620	1,617,009,867
Year 10	-17,970,600	1,047,840,000	1,029,869,400	2,646,879,267

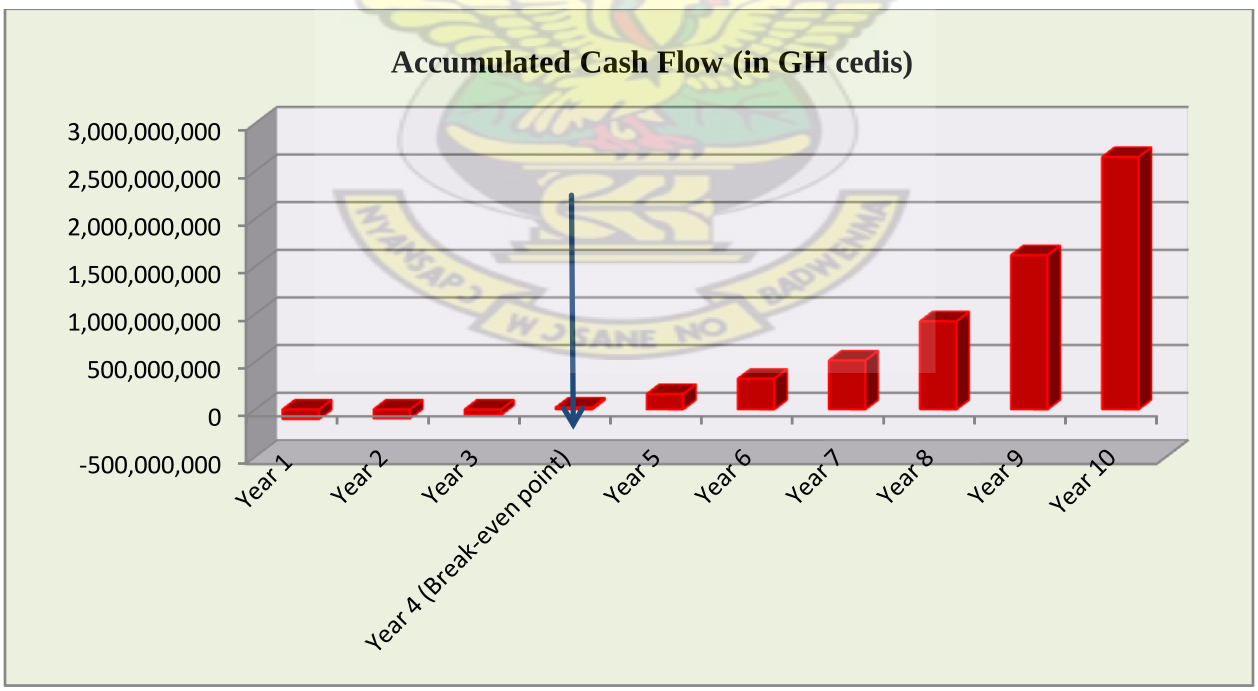

Fig. 3.4 Accumulated Cash Flow showing break-even point

3.4.4 Net Present Value (NPV) Calculation

In most engineering projects the net present value parameter is preferably used to determine their measure of profitability. It is mathematically given as the difference between the discounted value of the project's cash flows (C.F) and the amount of investment involved**.** A telecommunication project with a positive NPV is said to be economically feasible.

Thus given a discount rate, r = 15% and study (license) period, N = 10 years **[47]**

NPV = Initial Investment Capital + C.F for Year 1/ (1 +r) +C.F for Year 2/ $(1+r)^{2}$+……..+ C.F for Year N/ $(1+r)^{N}$

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NPV(Pessimistic) in GH ¢ = $-103{,}129{,}500+2{,}311{,}941/(1+0.15)+8{,}068{,}224/(1+0.15)^{2}+36{,}451{,}590/(1+0.15)^{3}+75{,}156{,}180/(1+0.15)^{4}+142{,}244{,}136/(1+0.15)^{5}+160{,}306{,}278/(1+0.15)^{6}+191{,}269{,}950/(1+0.15)^{7}+410{,}595{,}930/(1+0.15)^{8}+694{,}429{,}620/(1+0.15)^{9}+$

$1{,}029{,}869{,}400/(1+0.15)^{10}$

NPV (Pessimistic) in GH ¢ = -103,129,500 + 2,010,383 + 6,100,736 + 23,967,512 + 42,970,789 + 70,720,475+69,304,827+71,905,458 + 134,224,538 + 197,400,239 +254,567,965 =

GH ¢ 770,043,422

CHAPTER FOUR- SUMMARY, CONCLUSION & FUTURE WORK

4.1 Summary

The link budget calculations we used for our comparative study into the radio interface dimensioning of both Mobile WiMAX and HSDPA technologies showed site count advantages for the former over the latter only for an indoor scenario. The business case for the new market entrant was thence justifiable. Here, we summarize and conclude on how having optimized radio parameters for our system model we could arrive at a profitable business model for our IEEE 802.6e project considering the fact that the study environment was "capacity-driven".

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Receiver sensitivity indicates the lowest energy in an RF signal to be detected by the receiver and processed by the RF signal chain within the receiver circuit **[48].** The lower the signal level that the receiver can successfully process, the better the receiver sensitivity. For Mobile WiMAX, receiver sensitivity values obtained were -105.7dB, -102.7dB, -100.2dB, -96.7dB, -94.7dB, -90.7dB for QPSK1/2, QPSK3/4, 16QAM1/2, 16QAM3/4, 64QAM1/2, 64QAM3/4 respectively. In the case of HSDPA we obtain receiver sensitivity values of -112.3 dB, -109.9dB, -107.7dB, -104.2dB for QPSK1/2, QPSK3/4, 16QAM1/2, 16QAM3/4 respectively. The difference between corresponding Modulation and Coding Scheme (MCS) levels was in the range 6.6dB to 7.5dB. Mathematically, the system gain relates to the receiver sensitivity of the base station equipment by the expression, system gain = EIRP –Rx sensitivity + Rx Antenna Gain – Rx losses. Should the EIRP values be made same for both systems by fine-tuning the transmit power levels at the BS, the system gain will show direct dependence on Rx sensitivity levels. In addition, should interference margins and log-normal fade margins be made same, then for an outdoor mobile hand-held scenario, a higher Rx sensitivity for HSDPA would translate into a higher link margin. For a 1/2–rate QPSK modulation and coding scheme it could be estimated that an Rx sensitivity difference of 6.6dB could account for a node density difference of a little over 50%.

For all MCS levels the HSDPA showed better receiver performance in terms of signal sensitivity than the WiMAX OFDMA system and determined to a greater extent the outcome of the system link budget in the uplink direction. Significant observation was the fact that the UL EIRP for the WiMAX indoor Customer Premises Equipment (CPE) scenario does compensate for poor receiver performance in the uplink enough to provide a marginal increase in maximum allowable path loss (MAPL) over the HSDPA.

Implementing a PUSC frequency Reuse pattern 1/3/3 for the WiMAX OFDMA means there was no need to use part of the BS transmit power to mitigate inter-sector co-channel interference thus, providing a better link margin than the HSDPA whose recommended reuse pattern is 1/3/1. This decision was made because given a 30-MHz spectrum block the WiMAX operator can assign 10-MHz TDD channel to each sector of the cell and still take advantage of MIMO Matrix B option to economically serve the data transmission needs of users within the metropolis.

Since the NPV turned out to be positive our IEEE 802.16e project can be said to be economically feasible albeit worst-case (pessimistic) projections for the new market entrant.

4.2 Conclusion

It is worth concluding that even with worst-case market share scenario the new entrant could arrive at a positive NPV and still break-even early in time within the 10 year license period as stipulated by the National Communications Authority. This was as a result of the optimization of link budget parameters and the application of best-fit frequency planning methods. The OFDMA radio interface was found as amenable to MIMO implementation, providing increased capacity and coverage for the 802.16e network. Mobile WiMAX is thus a recommended choice for would-be operators of the 2.5-2.69GHz band from both technical feasibility and techno-economic standpoints.

4.3 Future Work

It is recommended that when finally the Mobile WiMAX technology becomes a commercial reality in the 2.5-2.69GHz band, field studies should be performed to identify technical limitations likely to derail its successful implementation in Ghana albeit strides being made by the country's communications regulator in the achieving affordable Broadband Wireless Access objective by 2015 as spelt out in our National Broadband Strategy.

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