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Dimensioning Mobile WIMAX in the Access and Core Network: A case Study

Master's Thesis submitted in partial fulfilment of the degree of Master of Science in Technology

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ABSTRACT of the Master's thesis

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Existing broadband wireless technologies such as evolving 3G and WiFi have enjoyed widespread adoption but are far from offering the flexibility in deployment and high data rates. Mobile WiMAX, an emerging broadband wireless technology promises to bring a new experience to mobile broadband services by offering users high data rates and efficient network access techniques.

This thesis work provides a technical description of mobile WiMAX and compares its technical capabilities with the existing technologies such as WiFi and 3G. The work continues further on dimensioning mobile WiMAX in the access and core network.

In the access network, we determine the number of base stations required to cover a given metropolitan area, explore their configurations, and perform frequency selection. In the core network we dimension the interfaces, and nodes involved. From the study we will show that WiMAX provides the operator with the antenna configurations options of high capacities, large cell coverage area, and a wide selection of QoS classes. The study will also show that the data density requirements of customers, resulting from the capacity analysis are fulfilled by properly dimensioning the elements in the access and core network.

Keywords: WiMAX, mobile WiMAX, broadband, dimensioning
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Mwesiga W. Barongo
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Contents

Abbreviations

3G	3rd Generation
3GPP	3rd Generation Partnership Project
AAA	Authentication Authorisation and Accounting
AMC	Adaptive Modulation and Coding scheme
AP	Access Point
ASN	Access Service Network
ASN-GW	Access Service Network Gateway
ASP	Application Service Provider
AWS	Advanced Wireless Services
BE	Best Effort
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BTS	Base Transceiver Station
CDMA	Code Division Multiple Access
COTS	Commercial Off The Shelf
CPE	Customer Premises Equipment
CSN	Connectivity Service Network
DCF	Distributed Coordination Function
DHCP	Dynamic Host Control Protocol
DNS	Domain Name System
DL	Downlink

DSCP	Differential Service Code Points
DSL	Digital Subscriber Line
E1	E-carrier level 1, a Europian communication standard for 2Mbps
EAP	Extensible Authentication Protocol
ert-PS	extended real time Polling Service
FDD	Frequency Division Duplex
FTP	File Transfer Protocol
FUSC	Fully Used Subcarrier
Gbps	Gigabit per second
GPRS	General Packet Radio Service
GRE	Generic Routing Encapsulation
GSM	Global System for Mobile Communication
GTP	GPRS Tunnelling Protocol
HA	Home Agent
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Server
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IMS	IP Multimedia Subsystem
ITU	International Telecommunications Union

kbps	kilobit per second
LAN	Local Area Network
LTE	Long Term Evolution
MAC	Medium Access Control layer
MAN	Metropolitan Area Network
Mbps	Megabit per second
MIMO	Multiple In Multiple Out
MPEG	The Moving Picture Expert Group
MS	Mobile Station
MIP	Mobile IP
NAP	Network Access Provider
NAPT	Network Address Port Translation
NAT	Network Address Translation
NLOS	Non Line of Sight
NMS	Network Management System
NRM	Network Reference Model
NSP	Network Service Provider
nrt-PS	non real time Polling Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PBH	Peak Busy Hour
PUSC	Partially Used Subcarrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service

QPSK	Quadrature Phase Shift Keying
RADIUS	Remote Authentication Dial In User Service
RF	Radio Frequency
rt-PS	real time Polling Service
SDU	Service Data Unit
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SOHO	Small Office Home Office
SME	Small Medium Enterprises
SS	Subscriber Station
SSID	Service Set Identifier
T1	T-carrier 1, a North America and Japan communication standard for 1.544 Mbit/s
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
UGS	Unsolicited Grant Service
UHF	Ultra High Frequency
UL	Uplink
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WWW	Worldwide Web

List of Figures

List of Tables

1 Introduction

1.1 Motivation for the thesis

Recent trends in Information and Communications technologies (ICT) have seen the explosion of Internet as a new form of communications among communities. New media channels have been devised by which various groups of people can communicate and share information affecting their daily lives. The need for the broadband wireless communication has become a vital part of our daily lives. Voice communication has moved from the technology based on the circuit switched network to the one based on packet switched networks. Internet infrastructure can now transport voice, video and multimedia content through high capacity fiber links and wireless channels.

The explosion of the Internet and broadband wireless access has already been felt to a large extent in communities around developed countries. The infrastructure is continuously evolving to accommodate the ever increasing tremendous flow of information.

Emerging markets in sparsely populated areas such as Africa, have a limited access to broadband wireless access. The present wireline technologies based on copper and fiber do not promise to provide Internet access to people far in rural areas at an affordable cost. Emerging technology such as Wireless Interoperability for Microwave Access (WiMAX) is a suitable choice for providing access to the remote areas at a lower cost but at the same time with a high capacity and coverage range. The typical or optimum coverage range of WiMAX is 6 - 9 kilometres, with a capacity of up to 72Mbps for a point to point range of 48 kilometres. WiMAX promises to deliver a system with a high data rate, high capacity, low cost per bit, low latency, good quality of service and good coverage which makes broadband access to rural and suburban communities in developing countries a reality.

Existing broadband technologies such as cable and digital subscriber line (DSL) face practical limitations whereby the possible distance that a subscriber can be served from the central office is about 5 kilometres.

This hampers the service from reaching all the potential customers. WiMAX promises to provide broadband wireless connectivity beyond the reach of traditional wireline technologies. WiMAX technology enables an operator to economically provide broadband wireless access under a variety of demographics conditions.

Understanding the benefits such as fast Web surfing and quick downloading that the WiMAX technology brings to the users, this study aims to further investigate some of its technical aspects. These include an understanding of how WiMAX compares with the existing broadband technologies such as the Third generation (3G) and Wireless Fidelity (WiFi), its architecture, and how to dimension the access and core part of the network. The desire to learn how to provide affordable broadband wireless access to communities in rural and suburban areas is the motivating factor in pursuing this thesis work.

1.2 Objectives of the thesis

This thesis work has two objectives. The first one is to investigate the end-to-end aspects of WiMAX network architecture, and provide a comparison with the existing broadband wireless technologies such as 3G and WiFi. The second objective is to gain an understanding of how to dimension a mobile WiMAX network in the access and core service network. The access network comprises of the air interface aspects of WiMAX such as radio link budgets, antenna configurations, frequency reuse schemes and so on while the core service part provides the Internet Protocol (IP) connectivity and core network functions.

1.3 Scope of the thesis

The thesis work focuses on the essentials of dimensioning a mobile WiMAX network in the access and core service network. Further, the thesis work provides a technical comparison of WiMAX with similar broadband technologies. It does not address in detail the provision of end-to-end quality of service, actual radio network planning taking into account the morphology and topography details of a particular area of deployment. It also does not address the end-to-end service aspects such as IP connectivity, session management, and mobility management. It addresses the key issues that are taken into consideration in the access and core service network when dimensioning the mobile WiMAX network.

1.4 Methodology

The thesis work is conducted as a literature review as well as a case study based on the published technical papers from academic institutions, and standardisation bodies such as a WiMAX Forum. The other sources of information are from the textbooks describing broadband technologies and white papers that are published under the domain of telecommunications operators and communications equipment manufacturers.

1.5 Thesis Outline

Chapter 2 presents the overview of the existing broadband wireless networks, describing their architectures, technical capabilities, and technical differences. Chapter 3 provides key factors to take into account prior to deploying a WiMAX network, and presents the requirements for the coverage and capacity planning. Chapter 4 describes the dimensioning of the mobile WiMAX network in the radio interface and core service network for the selected regions of deployment; Helsinki, Espoo, and Kirkkonummi. Chapter 4 takes into account the demographics, geographical factors, and data density requirements of the selected regions so as to analyse how the network can be dimensioned. Finally chapter 5 presents the conclusions and future work.

2 Broadband wireless networks

One of the major driving forces for the wide acceptance of WiMAX is the interoperability of different solutions for broadband wireless network provided by a WiMAX Forum. The WiMAX Forum is an industry led, non-profit organisation formed to certify and promote the compatibility and interoperability of broadband wireless products based upon the harmonised IEEE 802.16 standard. It brings together vendors and equipment manufacturers of communications networks enabling equipment to interwork and thus driving down cost to operators. WiMAX offers an alternative access to the Internet with a ubiquitous access to high quality voice, data, video and streaming video services. It is an affordable and easy to access means compared to already existing broadband access technologies such as cable, DSL, and T1 lines.

2.1 WiMAX network

WiMAX is a broadband wireless technology that provides wireless data access to fixed, nomadic and mobile users. It conforms to two standard technologies IEEE 802.16d and IEEE 802.16e. IEEE 802.16d is a fixed wireless technology optimised for fixed and nomadic applications in Line of Sight (LOS) and Non-Line of Sight (NLOS) environments. It promises to provide a metropolitan area with a high bandwidth and larger coverage area than is currently available with the existing technologies such as WiFi and 3G. It uses Orthogonal frequency division multiplexing (OFDM) physical layer technology and smart antenna techniques which makes it strong and robust. The use of OFDM allows large amount of data to be transmitted over a chunk of spectrum with greater efficiency than existing wireless technologies such as time division multiple access (TDMA) and code division multiple access (CDMA). The OFDM technique splits a radio signal into multiple small signals which are then transmitted simultaneously at different frequencies to the receiver.

802.16e is a mobile WiMAX standard targeted for portable, mobile application as well as fixed and nomadic applications in NLOS environments. Mobile WIMAX extends the fixed WiMAX standard by giving users the ability to keep ongoing connections active while moving at vehicular speeds.

WiMAX system is able to support up to 74Mbps peak physical data rate when using 64 QAM modulation scheme. When using a 10MHz spectrum operating using the Time Division Duplex (TDD) scheme with a 3:1 downlink-to-uplink ratio, WiMAX achieves peak physical data rates of about 25Mbps and 6.7Mbps per sector for the downlink and uplink respectively. WiMAX supports a wide variety of features including Multiple Input Multiple Output (MIMO) techniques, smart antenna technologies, a wide range of bandwidths, operating frequencies in the licensed and unlicensed bands, TDD and frequency division duplex (FDD) operating modes and fractional frequency reuse. These features contribute to the high data throughput and wide coverage area.

Fixed WiMAX uses radio interface that is based on OFDM while mobile WiMAX uses a radio interface based on OFDMA. Fixed WiMAX allows operation on both TDD and FDD while mobile WiMAX is initially set to operate on TDD only.

OFDM divides a very high rate data stream into multiple parallel low rate data streams. Each low rate data stream is then mapped to an individual sub-carrier and modulated by some modulation scheme. OFDMA is a variation of OFDM where multiple closely spaced subcarriers are divided into groups of subcarriers called subchannels that are then allocated to the subscriber stations. Figure 1 presents the OFDM and OFDMA techniques.

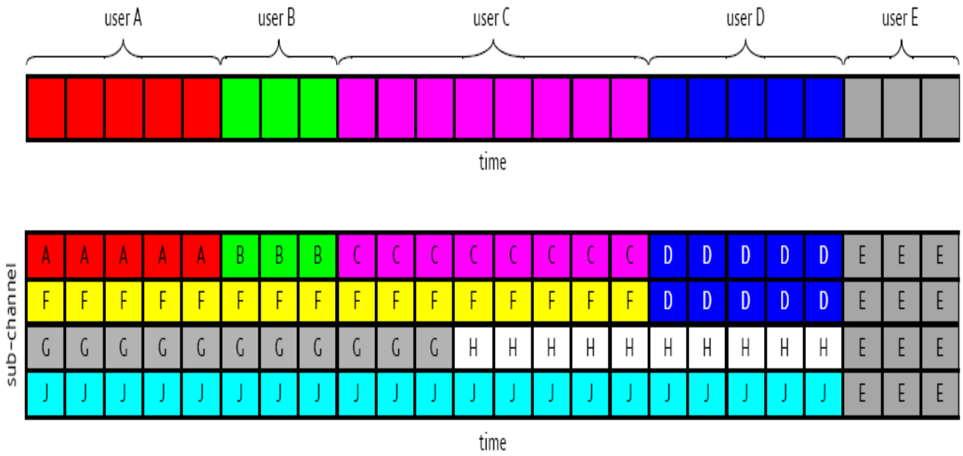

Figure 1: Time division multiplexing with OFDM as used in fixed WiMAX (top) and OFDMA as used in mobile WiMAX (bottom) [1]

In OFDM, only one subscriber station transmits in a time slot while in OFDMA several subscriber stations can transmit in the same time slot over several subchannels. OFDM provides resistance to multipath interference and is therefore suitable for urban NLOS environments. IEEE 802.16 standard for broadband wireless networks can operate on licensed 2.5GHz and 3.5GHz bands, and 2.4GHz and 5.8GHz unlicensed bands. Licensed bands provide operators with the control over usage of the bands, allowing them to build high quality networks. Unlicensed bands, on the other hand, allow the provision of backhaul services for hotspots (in case WiMAX interworks with WiFi network to provide backhaul connectivity). The 3.5GHz band is a licensed band available in most countries for deployment of wireless metropolitan area networks (MAN).

With a MIMO technique, WiMAX effectively utilises the effect of multipath signal. MIMO technique, as described in Figure 2, combines the radio signals reflected from the buildings, trees and other obstructions to effectively increase the capacity of the system.

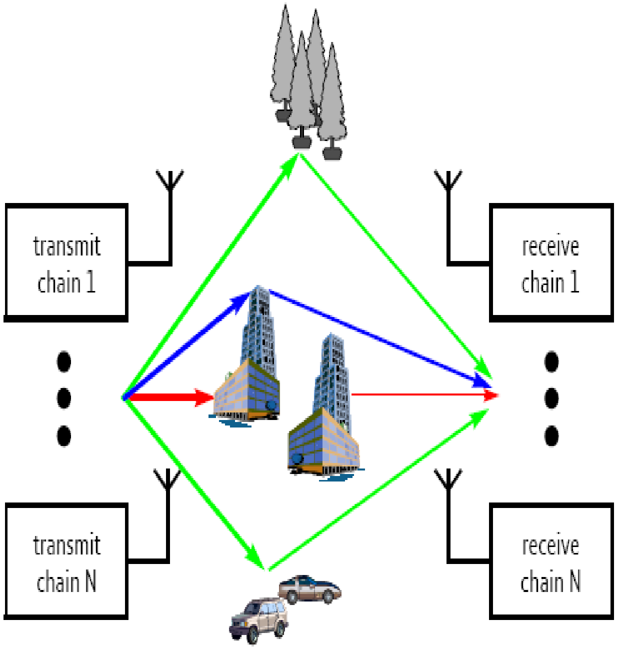

Figure 2: Multiple In Multiple Out (MIMO) [1]

WiMAX provides both LOS and NLOS coverage range, with 50 km coverage distance for the LOS and a cell radius of 8 km for NLOS transmission. LOS and NLOS conditions are governed by the propagation characteristics of their environments, path loss and radio link budget. NLOS is suitable for situations that require strict planning requirements and antenna height restrictions that do not allow the antenna to be positioned for LOS.

WiMAX supports adaptive modulation and coding schemes (AMC) that allow the schemes to be changed on a per user and per frame basis depending upon the channel conditions. AMC assigns the highest modulation and coding scheme that can be supported by the signal to noise plus interference ratio at the receiver. This enables users to receive the highest possible data rates that can be supported in their respective links.

WiMAX uses TDD transmission methods to divide subchannels among users in the Uplink (UL) and Downlink (DL) direction. It uses OFDMA to assign subcarriers (as a function of channel bandwidth) to different users.

Channel allocation for the subscribers in WiMAX network depends on the available spectrum. Channel bandwidth in WiMAX can be a multiple of 1.25 MHz, 1.5MHz, and 1.75MHz with a maximum of 20MHz. A channel size between 1.25MHz and 20MHz is an important feature of WiMAX allowing it to operate in small segments of spectrum that are available.

WiMAX employs dynamic adaptive modulation which allows it to trade throughput for range. The system dynamically adjusts the modulation scheme from higher to lower order modulation if the base station cannot establish a link to a distant subscriber. The aforementioned process reduces throughput but increases the effective range. WiMAX standard supports BPSK, QPSK, 16QAM, and 64QAM modulation schemes.

WiMAX supports a connection-oriented architecture that is designed to support a variety of applications, including voice, video and data. It supports data that are of constant bit rate, variable bit rate, real time and non-real time traffic data as well as best effort data. The physical layer of WiMAX supports large number of users with multiple connections per terminal, and each with its own quality of service (QoS) requirement.

WiMAX provides end-to-end services based on IP architecture that relies on IP-based protocols for end-to-end transport, QoS, session management, security and mobility. Using an IP-based architecture enables easy convergence with the other networks, and simplifies the core network architecture resulting into low cost processing. The low cost processing is attributed to the fact that WiMAX does not need to have separate core networks for voice and data/multimedia services as is the case for the 3G networks.

2.1.1 WiMAX network architecture

WiMAX Forum has developed a standard network reference model (NRM) for open-network interfaces in order to support air-link interoperability as well as inter-vendor inter-network interoperability for roaming, multi-vendor access networks and inter-company billing. The WiMAX NRM is a logical representation of the network architecture. The NRM identifies the functional entities and reference points between functional entities over which interoperability is achieved.

The NRM consists of the logical entities Mobile Station(MS)/Subscriber Station(SS), Access service network (ASN) and Connectivity Service Network (CSN). As shown in figure 3, each logical entity represents a set of functions that may be realised in a single physical device or distributed over multiple physical devices.

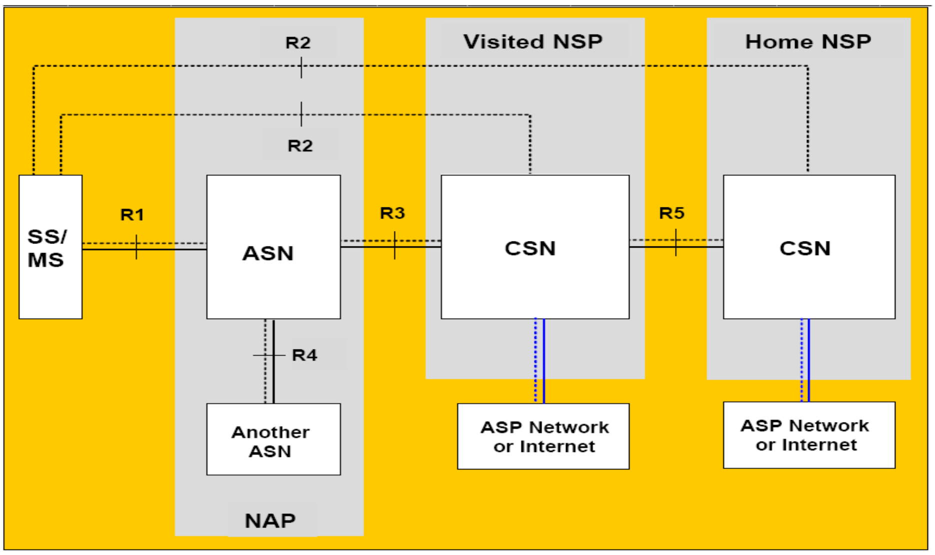

Figure 3: WiMAX network reference model [23]

The ASN defines the logical boundary for functional interoperability with WiMAX clients, connectivity service functions and aggregation of functions embodied by different vendors. ASN deals with the message flows associated with the access services. ASN also provides an IP packet delivery service between WiMAX subscribers and the CSN. The ASN connects base stations to the WiMAX ASN gateway using transport networks such as microwave, copper or fibre links. The WiMAX ASN gateway provides connectivity to the Internet through Home agent (HA) or a routing device.

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

Figure 3 shows that WiMAX supports network sharing and variety of business models. The architecture allows for the logical separation between the network access provider (NAP), network service provider (NSP), and application service provider (ASP). NAP is an entity that owns and operates the ASN, NSP is the entity that owns subscribers and provide the broadband service. ASP provides value added services such as multimedia using IP multimedia subsystem (IMS) framework.

Figure 3 also shows reference points R1-R5 that bind functional entities. The reference points are defined by the WiMAX Forum [2] as follows:

- **R1**: This is the interface between the MS and ASN. It implements air-interface (IEEE 802.16e) specifications.
- **R2:** This is the interface between the MS and CSN. It is a logical interface that is used for the authentication, authorisation, IP host configuration management, and mobility management.
- **R3:** This is the interface between the ASN and CSN. It encompasses the bearer plane methods to transfer IP data between ASN and CSN.

- **R4:** This is a set of control and bearer plane protocols originating or terminating in various entities within the ASN that coordinates MS mobility between the ASNs.
- **R5:** This is a set of control and bearer plane protocols for interworking between the home and visited network.

Figure 4 shows the detailed view of the entities within the main functional entities ASN and CSN.

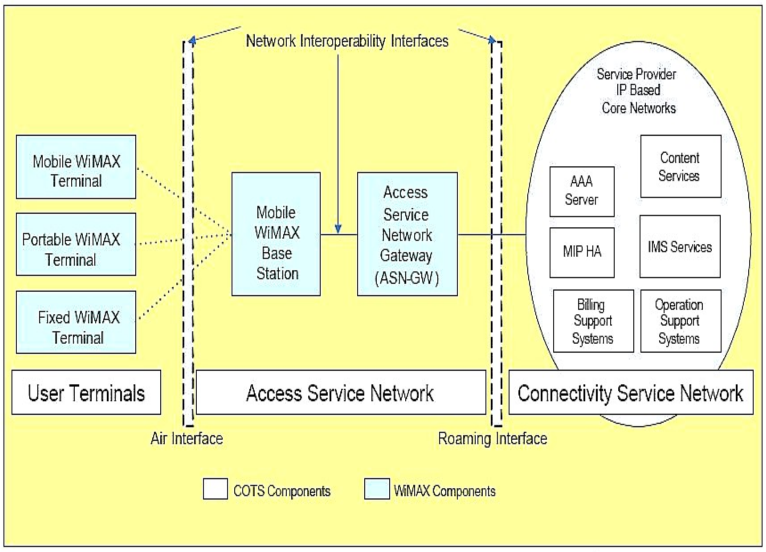

Figure 4: WiMAX network IP based architecture [23]

The WiMAX network architecture also consists of a network management system (NMS) which can be part of a CSN functional entity or a stand-alone entity. The NMS provides centralised management of the whole network. It also provides a framework for visualising the network and traffic operations so as to maintain the preferred quality of service and perform network optimisation.

2.1.2 WiMAX quality of service

The IEEE 802.16 standard supports up to five QoS classes. The level of quality of service differentiation is per service flow. Each of the service flow is having one of the scheduling types; best effort (BE), non-real time polling service (nrtPS), real-time polling service (rt-PS), extended real-time polling service (ert-PS) or unsolicited grant service (UGS).

WiMAX provides the five QoS classes through an architecture that is able to process requests, perform access control and allocate the required radio resources that are able to meet the requests that are accepted. The five QoS classes are described as follows.

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

WiMAX differentiates the service flows at the IP layer through the DiffServ code points (DSCP). DSCP is a field in the header of IP packets used for classifying packets entering the network in order to provide QoS guarantees.

From an IP transport perspective, the WiMAX network is divided into multiple DSCP domains. One domain is between the base station and the ASN gateway (ASN-GW) in every ASN termed as ASN DiffServ domain. The second domain, CSN DiffServ domain, is between the ASN-GWs and the HAs. The third domain is between the HAs and Internet or operator service network.

2.2 3G and HSPA networks

The term 3G refers to the third generation Mobile system, which is a mobile telephony technology under the umbrella of the 3rd Generation Partnership Project (3GPP). It delivers broadband applications to subscribers, with data throughput capabilities on the order of a few hundred kilobits per second to a few megabits per second; 550kbps – 14.4Mbps. 3GPP is a collaborative agreement which brings together telecommunications standardisation bodies with the aim of providing technical specifications and technical reports on the 3G mobile system based on the evolved Global System for mobile communications (GSM) core networks and the radio access technologies that they support.

3G mobile systems enable provision for the multimedia content such as video streaming, gaming and music download. 3G technology such as wideband code division multiple access (WCDMA) is based on the use of CDMA technology where users are separated by unique codes, which means that they can use the same frequency and transmit at the same time. This means that the system can pack considerable number of users with increased data rates and high quality of service.

Figure 5 shows the simple architecture of WCDMA network whereby it re-uses the core network together with the GSM network.

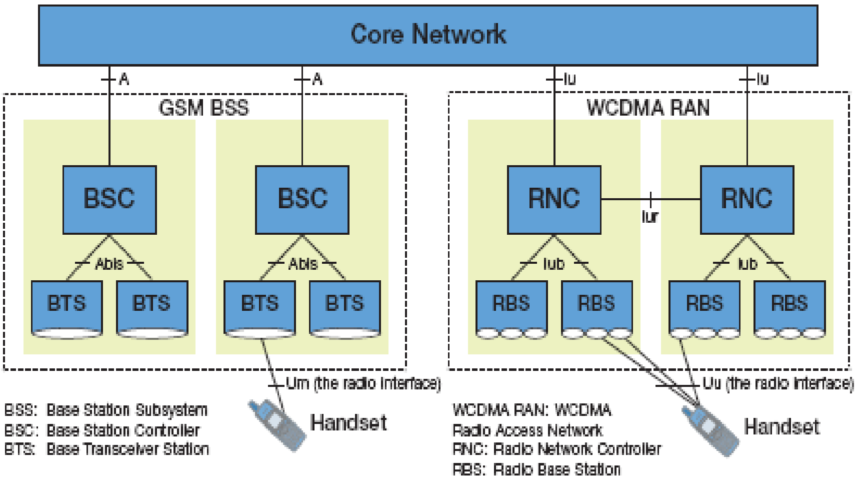

Figure 5: GSM-WCDMA architecture [7]

High Speed Packet Access (HSPA) is an enhanced WCDMA technology that offers higher bit rates and reduced latency than what is provided in WCDMA 3GPP Release 99. Current 3G mobile systems provides less capabilities for data networks such as high latency (200 – 300ms) associated with setting up the data session, and low data rates (128 – 512kbps). HSPA addresses these issues by providing a series of upgrades to both the base stations and receivers. HSPA splits the upgrades into High Speed Downlink Packet Access (HSDPA) for the downlink (from the base station to the mobile station) and High Speed Uplink Packet Access (HSUPA) for the uplink (from the mobile station to the base station).

Figure 6 shows the theoretical downlink and uplink capacity for HSPA as compared to 3G (WCDMA) mobile system. In practice, HSPA offers a measured throughput on the TCP layer of approximately 184kbps downlink with a one-way delay of 75ms and 148kbps uplink with a delay of 85ms [1].

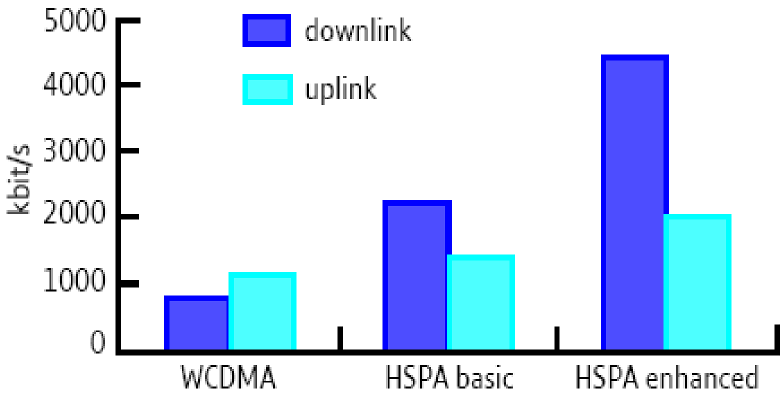

Figure 6: Capacity evolution with HSPA [1]

HSPA offers four QoS classes ranging from a guaranteed data rate to a best effort service. These classes include conversational class (conversational real time), streaming class (streaming real time), interactive class (interactive best effort) and background class (background best effort).

The HSPA architecture is based on the 3G direct tunnelling protocol (GTP) that optimises the delivery of mobile and wireless broadband services. The direct tunnel architecture provides a direct path from the RNC to GGSN. The use of the GTP as shown in figure 7, allows direct user plane traffic from RNC to GGSN, thus by-passing the SGSN [8]. GTP also provides an efficient way of handling QoS and of creating binding to radio bearers.

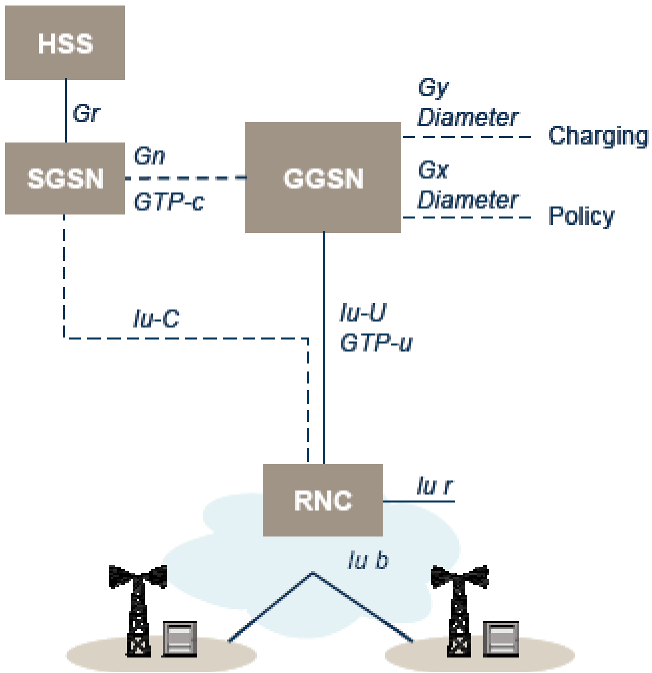

Figure 7: HSPA 3GPP R7 architecture [8]

HSDPA is a downlink only air interface defined by the 3GPP. It is capable of providing peak user data rates of 14.4Mbps using a 5MHz channel. HSDPA aims at increasing the efficiency by supporting more users and more data into a given chunk of spectrum, reducing the latency to 50ms, and increasing maximum data rate for users to over 2Mbps. HSDPA uses high-speed shared channel with a very short transmission interval (approximately 2ms). It uses higher order modulation to send more data on a particular radio channel, fast link adaptation to adjust the amount of error coding used on the radio channel, and fast hybrid automatic repeat to combine two frames containing errors into one, error-free frame. These techniques altogether increase the overall performance of the system as compared to the 3G systems. The peak data rates, 14.4Mbps, offered by HSDPA are only achievable if the mobile terminal implements all the available 15 codes specified in the UMTS release 5 specifications.

Typical average rates that a user obtains are in the range of 250kbps to 750kbps. Using 5 and 10 codes, HSDPA supports peak data rates of 3.6Mbps and 7.2Mbps respectively.

HSUPA is an enhancement to the WCDMA network where it adds a new transport channel termed as enhanced dedicated channel (E-DCH). HSPA improves uplink performance by reducing the latency, increasing data rates and capacity. HSUPA introduces several features which have minimal impact on the existing radio interface protocol architecture. These features include multi-code transmission, short transmission time interval, fast hybrid automatic repeat request and fast scheduling. With HSUPA, user equipments can achieve a bit rate of 1.4Mbps.

Although it employs similar techniques as HSDPA, there are differences between HSUPA and HSDPA. The shared resource in the HSUPA is the total received power at the base station, which depends on the decentralised power resource in each MS. In HSDPA, the shared resource consists of transmission power and channelisation codes, and is centralised to the base station.

Currently the 3G mobile system is being evolved into a long term evolution architectural plan. The long term evolution (LTE) concept entails further enhancement in both the uplink and downlink of the radio channel. It is aiming at improving the user experience in terms of latency, capacity and throughput. It is also optimised for the packet data services based on the IP so as to facilitate the use of mass market IP-based services. Although it is still undergoing standardisation work, LTE targets at providing the following performance and capabilities:

- The potential to provide significantly high data rates with peak data rates of 100Mbps over the downlink (high speed downlink packet access) and 50Mbps over the uplink (high speed uplink packet access).
- Improved coverage with higher data rates than WCDMA and HSPA mobile networks.

- Reduced latency in the user plane as well as reducing the delay associated with the control plane procedures such as session set-up. Radio access network latency is reduced to 10ms.
- High system capacity complemented by the support of scalable bandwidth of 20MHz, 15MHz, 5MHz and below 5MHz. It provides support for the paired and unpaired spectrum, and consists of ten paired and four unpaired spectrum bands.
- LTE uses flat architecture where the base station called eNodeB is connected to the core network using the core network RAN interface, S1. The flat architecture reduces the number of involved nodes in the connections.

2.3 WiFi networks

WiFi stands for *wireless fidelity,* a wireless local area technology designed for home and small implementation. WiFi is a data transmission system designed to provide location-independent network access between computing devices by using radio waves rather than a guided medium. WiFi is aimed at providing in-building broadband coverage. It is based on the published IEEE 802.11 standard for short range wireless communication. It is being deployed to provide coverage in the University campuses, hotels, and airports using what is termed as hotspot. A hotspot is the region covered by one or several access points (AP). A wireless access point connects a group of wireless devices to an adjacent wired Local Area Networks (LAN), relaying data between connected wireless devices in addition to a single connected wired device.

It is based on the family of standards such as IEEE 802.11a, 802.11b, 802.11g, and 802.11n. Table 1 shows the IEEE 802.11 standard variants. The throughput in Table 1 refers to the theoretical maximum throughput provided by the Medium Access Control (MAC) layer. The theoretical maximum throughput of the IEEE 802.11 standard is defined as the maximum amount of MAC layer service data units (SDUs) that can be transmitted in a time unit [13].

Table 1: Family of IEEE 802.11 [16]

Standard	**Operating frequency [GHz]**	**Throughput [Mbps]**	**Data rate [Mbps]**
802.11a	5	23	54
802.11b	2.4	4.3	11
802.11g	2.4	19	54
802.11j	4.9 - 5	23	54
802.11h	5,15 – 5,35 (indoor) 5,47 – 5,725 (outdoor)	23	54
802.11n	2.4/5	74	248
802.11y	3.7	23	54

2.3.1 WiFi network architecture

The WiFi network setup consists of one or more APs and one or more clients. The AP communicates with the client by broadcasting its Service Set Identifier (SSID)/network name through packets called beacons. The AP broadcasts the beacons every 100ms, and at a rate of 1Mbps. Based on the settings of the SSID, the client decides whether to connect to the AP or not. If there are several APs with the same SSID, the client firmware uses the signal strength as a measure of which AP to connect to. Figure 8 describes the WiFi architecture in detail.

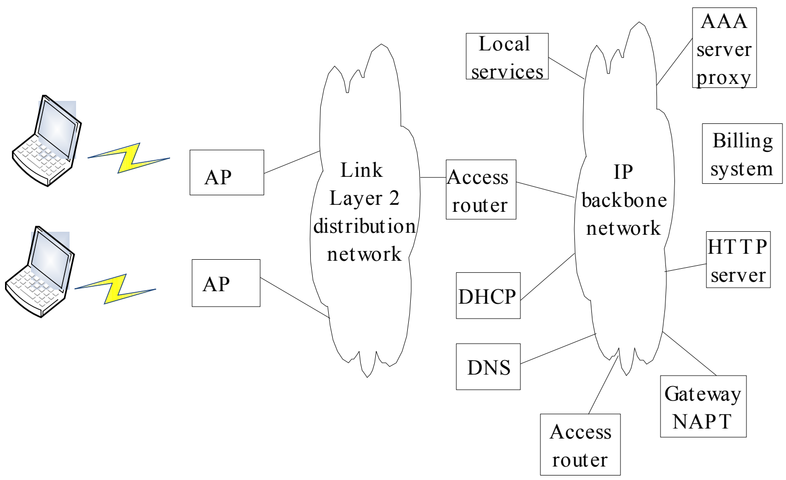

Figure 8: A WiFi network architecture [15]

The WiFi network uses radio signals to provide connectivity to the Internet or to the mobile operator's network. It provides services only up to the link layer level, and therefore depends on the wired IP infrastructure for the end to end connectivity [15]. As shown in figure 8, the Gateway NAPT provides connectivity to other IP based networks while the AAA server proxy handles access control and authentication of portable terminals. WiFi uses remote authentication dial in user service (RADIUS) protocol together with the extensible authentication protocol (EAP) to authenticate a terminal that is trying to gain access to the network. Each AP in a WiFi network has a finite range with which the client can connect. The actual distance varies depending upon the environment, that is, whether the client is located in indoor or outdoor environment. The typical indoor range is 45 - 90 metres, while outdoor range is 300 metres.

From the QoS point of view, WiFi was not designed with in-built QoS support. It was designed for the best effort data services but several studies such as [4] have explored various QoS schemes. There is also an extended IEEE 802.11e standard for delay sensitive multimedia applications such as voice over IP, and video streaming [10].

The widely researched QoS schemes are based on the Distributed Coordination Function (DCF) medium access protocol. The schemes are classified as service differentiation, admission control and bandwidth reservation, and the link adaptation. The schemes are defined as follows [4]:

- **Service differentiation**: this is achieved by priority and fair scheduling mechanisms. Priority mechanism binds channel access to different traffic classes by prioritised contention parameters. Fair scheduling fairly partitions the channel bandwidth by regulating waiting times of traffic classes in proportion according to the given weights.
- **Admission control and bandwidth reservation**: this scheme provides QoS guarantee for flows during high traffic load conditions. It performs admission control and reserves bandwidth so as to provide good quality for the multimedia data traffic.
- **Link adaptation**: uses algorithms such as the channel signal-to-noise ratio, received power level, average payload length, and transmission acknowledgements to maximise the throughput under dynamically changing channel conditions.

2.4 Comparison of broadband wireless networks

2.4.1 WiMAX vs WiFi

The major notable difference between WiFi and WiMAX networks is the coverage area. While WiFi covers a region of up to 300 metres, WiMAX can cover the region of up to 48 kms under NLOS and LOS conditions. Therefore, when it turns to covering large metropolitan area, WiFi network requires an operator to deploy more number of base stations than WiMAX network. This means that it is more costly using WiFi network to provide broadband wireless services that spans over a large area.

WiFi network was designed and optimised for indoor use and short range coverage while WiMAX network is designed and optimised for long range coverage and outdoor usage. WiFi serves local area networks whereas WiMAX serves metropolitan area networks (MAN).

WiFi supports fewer users per base station, typically one to ten users with a fixed channel size of 20MHz per base station. WiMAX on the other hand supports one to five hundred users per base station with variable channel size of 1.5MHz to 20MHz [18].

WiMAX uses both licensed and unlicensed spectrum whereas WiFi uses only unlicensed spectrum. Operating in the licensed band means WiMAX has the ability to cover long distances and support more number of users by using sub-channelisation.

The WiMAX architecture consists of base stations that process requests to send or receive data from terminals, performs access control and allocates the required radio resources to meet the requests that are accepted. In terms of security, WiMAX as opposed to WiFi, is designed with strong security mechanisms in mind with layer upon layer for authentication, authorisation and accounting in place. WiMAX defines a privacy sub-layer at the lower edge of the media access control sub-layer of TCP/IP to handle encryption of packets and key management.

WiMAX has typically less interference while WiFi suffers from interference in metropolitan areas where there are many users. WiFi access is highly contended and has a poor upload speed between the router and Internet while WiMAX provides connectivity between network endpoints without the need for the direct line of sight.

2.4.2 WiMAX vs 3G and HSPA

WiMAX and 3G technologies were initially designed to serve different sectors of the mobile telephone market. This trend will change in the coming years, and both technologies will converge to provide almost the same set of capabilities and services. WiMAX provides high data rates (up to 72Mbps) but provides less mobility. On the other hand, 3G provides smaller data rates (from 384kbps to 3Mbps) than WiMAX but provides users with seamless mobility using existing and evolved cellular mobility protocols and handover mechanisms.

Another notable key difference between WiMAX and 3G is the fact that 3G technologies such as HSPA have been the evolution of the existing GSM technology that only require software upgrade, while for the case of WiMAX the whole network has to be built from scratch. The fact that WiMAX requires green field implementation has a consequence on time and cost when deploying the network as compared to the 3G network. 3G systems have fixed channel bandwidth while WiMAX has scalable channel bandwidth from 1.25MHz to 20MHz that allows for a very flexible deployment and high throughput capabilities. Table 2 compares the WiMAX and 3G based upon the indicated performance metrics.

Table 2: Technical comparison of HSPA and WiMAX [1]

	WiMAX	**HSPA**
Initial downlink data rate (max)	23Mbps	14.4Mbps
Initial uplink data rate (max)	4Mbps	384kbps
Evolved downlink data rate (max)	46Mbps	28Mbps
Evolved uplink data rate (max)	4Mbps	11Mbps
Latency	50ms	100ms
Spectrum	2.5, 3.5GHz (licensed bands); 2.4, 5.8GHz (unlicensed band)	850MHz to 2,600 MHz
QoS	Supports five QoS classes	Supports four QoS classes
Mobility support	Limited mobility; based on mobile IP protocol for mobility management	Seamless mobility
Security	Based on certificates or EAP	SIM-based security
Service set-up time	50ms	2sec reducing to 0.6sec
Link adaptation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM
Duplex scheme	FDD, TDD	FDD

The other major difference between WiMAX and 3G mobile systems is that a user in WiMAX transmits in a subchannel and therefore does not occupy an entire channel. This is due to the fact that WiMAX is based on the OFDM and OFDMA technologies that divides a single channel into sub-channels. The subchannels allow users to transmit using only a fraction of the bandwidth allocated by the base station.

WiMAX and HSPA also differ in the way they utilise spectrum efficiently - spectrum efficiency. Spectrum efficiency can be defined as the measure of the amount of data that can be carried by a cell per unit of time, normalised with the occupied system bandwidth. Figure 9 compares the spectrum efficiency between HSPA releases and WiMAX.

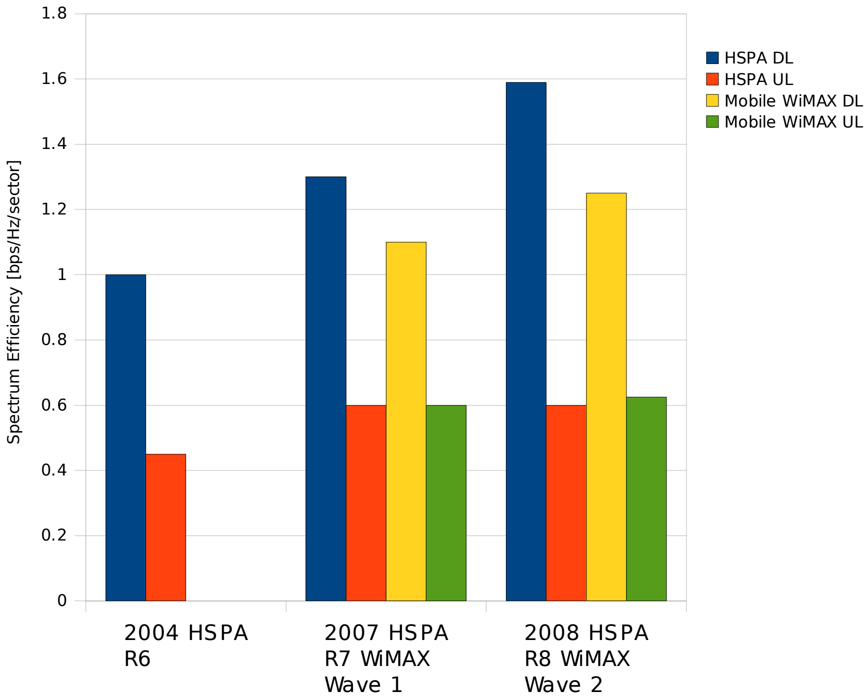

Figure 9: Spectrum efficiency comparison [8]

WiMAX has a better spectrum efficiency than HSPA R6 with basic RAKE receivers. A RAKE receiver is the radio receiver designed to counter the effects of multipath fading. With the use of advanced receivers, such as GRAKE with receive diversity, HSPA has 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 [8]. Since WiMAX operates in a higher frequency than HSPA, and path loss is proportional to the square of the frequency in use, this amounts to less coverage for WiMAX system. In a coverage limited network, WiMAX requires 2.2 times as many access points as HSPA for a 6 dB less in link budget [8].

2.5 *Summary and Conclusion*

This chapter presented the comparison of WiMAX with the other broadband wireless technologies, and it can be said that WiMAX offers significant advantages when it comes to deployment. For a given region selected for the deployment, WiMAX allows an operator to select a channel bandwidth from 1.25MHz to 20MHz. This gives the operator some flexibility during the deployment where he can select the appropriate channel bandwidth to serve the targeted market segment. Since the target for a broadband wireless technology is to offer high data rates, WiMAX is a better choice for that purpose than 3G and WiFi, as it relies on OFDM and OFDMA technologies. Although WiFi also relies on OFDM technology, it is faced with limited mobility.

WiMAX technology incorporated MIMO techniques during its initial design phase, providing it with higher spectral efficiency than 3G systems. 3G systems are implementing MIMO techniques in phases leading into low spectral efficiency. For a multicellular deployment, OFDM physical layer technology used by WiMAX gives it an advantage to exploit frequency and multiuser diversity to improve capacity.

When it comes to choosing the right technology for the broadband wireless access, WiMAX has the potential to become the cost effective technology for the operators who lack 3G infrastructure but can obtain access to either 2.5GHz or 3.5GHz spectrum. WiMAX also provides cost efficient wireless extension to areas without the DSL or wireless infrastructure. For 3GPP operators with limited spectrum, it offers the possibility to provide an alternative broadband wireless access.

Compared to WiFi, WiMAX provides symmetrical bandwidth over a considerable distance with much stronger encryption and less interference. WiMAX spectrum applies over a wide range of the radio frequency (RF) spectrum.

On the other hand, for operators with existing GSM and WCDMA technologies, HSPA-LTE is a promising choice as it can be easily integrated with existing radio networks, core networks, networks operations and subscription management. Therefore, HSPA-LTE offers GSM-WCDMA network an evolution path towards the provision of broadband wireless services.

3 WiMAX deployment considerations

Before starting to deploy a mobile WiMAX network, the operator usually determines if the business model and financial aspects of the network are economically viable. Also, prior to deployment, the operator needs to undertake initial site survey whereby the physical conditions of the areas of deployment are assessed. After being satisfied with the results of the site survey, the operator lays down the preliminary network design. The preliminary network design includes the following [17]:

- A summary of the overall network objectives, goals, expectations, advantages and challenges from a user and network architecture perspective. These include factors like bandwidth considerations, link availability, frequency selection, number of sites and sectors, and so on.

- The list of vendors recommended for the access points, cabling, back-up power units, antennas, switches, surge suppressors, connectors, jumpers, and so on.

- Costs associated with the site acquisition, integration, testing, site optimisation, and other related costs.

- Details of the point to point backhaul RF link budgets and path profiles for each link in the network.

- A detailed path analysis and link budget for each link in the network including calculations for the free space loss, connector and cable losses, link availability and downtime in a projected year.

- Expected number of users and their use of services.

- Results of spectrum and noise analysis that were performed during the site survey. The noise analysis is required to determine the baseline for acceptable signal strength levels.

WiMAX deployments can be range limited or capacity limited. The user data rate is less for a range limited deployment as compared to a capacity limited case. During deployment, co-channel interference needs to be taken into account as the link that is affected tends to move to a robust modulation. This is not a preferred case as moving to a robust but less efficient scheme such as moving from 64 QAM to QPSK reduces the channel capacity.

When deploying a mobile WiMAX network, the base stations need to be located within areas where the majority of users are found in order to maximise the use of higher order modulation schemes.

Base stations also constitute a big part of the network infrastructure cost. Base station deployment can be divided into base station infrastructure, base station equipment and backhaul connection. Base station infrastructure includes civil work activities such as site acquisition, antenna towers, environmentally controlled enclosures for the indoor electronics, primary and back up power, conduits, cabling and so on.

Possible locations for the WiMAX base stations deployment are building rooftops, existing radio cellular towers and mountain tops. Details about the terrain of the place of deployment need to be obtained (terrain morphology map). The base stations configuration can be determined based on the terrain map to provide an acceptable WiMAX performance.

Another important issue that an operator needs to consider prior to designing and deploying a mobile WiMAX network is to address key issues pertaining to the deployment. Issues to be addressed include:

- Network topology
- The kinds of links to be used; mesh, star or ring
- The frequency to be used
- Multipath tolerance

Network topology plays a crucial role in determining the robustness, and reliability of the network. The operator has to choose either the star or mesh topology that achieves high reliability for a given deployment region. This means that depending upon the geographic conditions of the area set for the deployment, star or mesh topology has to be selected so as to deliver the optimal performance.

Also, a decision has to be made on whether to employ point-to-point or point-to-multipoint links. Obstructions such as trees or buildings that may block the line of sight also need to be taken into account, and the decision on where to deploy WiMAX technology for LOS and NLOS conditions needs to be clear from the outset. Whether to use LOS or NLOS solutions may depend on the planning requirements and antenna height restrictions on a particular area.

In order to achieve effective range or coverage for the network, a balance between throughput, range and bit error rate (BER) has to be determined. Since BER is limited by the technology itself, the effective range at a given throughput has to be calculated from the link budget analysis. This means that link budget analysis has to be performed prior to deployment of the network. Link budget analysis takes into account factors such as path loss, receiver sensitivity, noise, gain and losses from the antennas and cables. The link budget analysis results into a transmit power required to achieve a given BER at the receiver.

For the case of providing WiMAX services, the operator needs to carefully choose the spectrum to be used. The chosen spectrum has the consequence on the overall costs of deploying the WiMAX network. Using a 3.5GHz spectrum requires considerable number of base stations to cover a given area as compared to 2.5GHz. In planning service requirements, there is a need to define the flow of service between the subscribers and service provider (that is, service requirements), and to also study to what extent a large proportion of subscriber can access different services from different access and distribution networks while still fulfilling the service requirements.

3.1 *Introduction to WiMAX network planning*

Planning of a wireless network usually involves a number of steps that are essential for a successful business case. The first step is to define the geographic area where the service is expected to be offered. Key metrics to specify for the geographic area are population density, number of households, and number of small and medium businesses. The terrain type also needs to be specified. In order to ensure smooth signal propagation over the wireless networks, flat or moderately hilly terrain is preferred.

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

The step that follows involves determining the technological parameters to calculate range and capacity. Parameters of interest include link budget, spectral efficiency, and antenna configurations (SISO, SIMO, MIMO), frequency reuse factor, which altogether control the coverage area per cell site and the total number of cell sites or base stations needed to cover the desired geography.

In order to achieve end-to-end connectivity, the next step is to dimension and plan the elements that form the core service network. Since WiMAX is an IP-based technology, this involves dimensioning and planning of ASN elements; ASN-GWs and BSs, as well as CSN elements (AAA servers, DHCP/DNS servers, HA, and so on). The choice of ASN and CSN elements and how to configure them is made based upon the type of service that is to be offered, market segment, the available spectrum and topography of the area as reflected in the earlier sections.

Quality of service is another important aspect when planning a mobile WiMAX network. This determines the level of service that users will experience when they access the network for voice, data or multimedia communication.

WiMAX network planning follows the flow of activities as presented in figure 10.

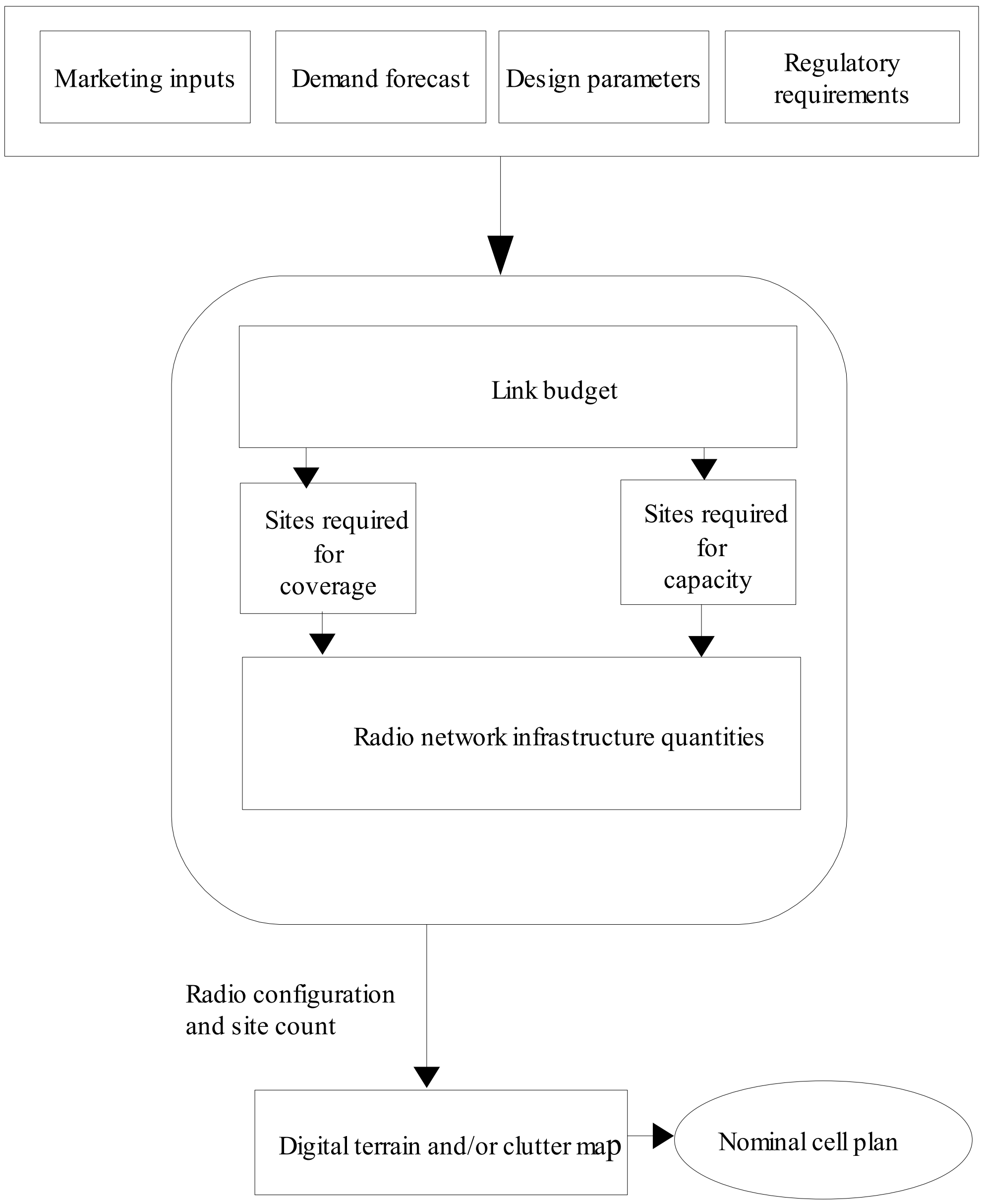

Figure 10: Network dimensioning and planning process [11]

In order to minimise the interference in WiMAX system, there is a need for a careful RF planning. A potential source of interference in WiMAX system is the loss in frame synchronisation between the base stations using the same channels or when the UL-DL ratio in a TDD system is different for each BS. WiMAX supports channel reuse frequency factor of one for operators that have limited amount of spectrum.

For a WiMAX system, the downlink coverage is easier to plan than uplink. This is due to the fact that in the downlink, the interference originates from the same location, that is, from a neighbouring base station transmitting on the same channel.

In network planning, the operator makes assumptions on the data rate, sectorisation, frequency reuse plan, and type of cell (pico, micro or macro cells) to be deployed. The operator also predicts how users will use the services.

3.2 Coverage planning

The target for the coverage planning is to find optimal locations for the base stations to build a continuous coverage according to the planning requirements. Coverage planning is performed with a planning tool that includes a digital map with topography information of a particular region. Propagation models that aid in determining the coverage area are then selected based on the planning parameters (frequency, base station antenna height and so on). The overall coverage prediction is then determined based upon the combination of the digital map information and the selected propagation model.

During this phase, the link budget analysis is performed that defines the maximum allowed path loss with certain configurations. Different parameters that constitute the link budget leads to the determination of the theoretical maximum cell size. The cell size or range leads to the determination of the coverage area with a certain location probability. Location probability is the probability of the receiver being able to capture the signal, that is, the signal level is higher than the receiver sensitivity.

The first step in coverage planning is to create a preliminary plan based upon the calculated number of base stations [3]. In this step, the theoretical locations of the BTSs are determined and the decision on whether to use omni cells or sectorised cells is made. Omni cells are better suited for rural areas or sparsely populated areas where there is not a need for a high capacity. Sectorised cells are better suited in areas where there is a need for coverage in precise locations.

The next step is to find the actual location of the base stations. This task involves site acquisition team whose task is to determine proper locations where the sites can be located and the transmission requirements be fulfilled. After the actual locations have been determined, the plan based on the preliminary location is updated and cell coverage areas are calculated again using the new parameters. During this step, the coverage and capacity requirements are aligned with the actual base station locations.

During coverage planning, ways for future enhancement of coverage are taken into consideration. Techniques for enhancing coverage prove to be beneficial in situations where the base station is incorrectly located as a result of preliminary planning process. One method to enhance coverage is to optimise the link budget parameters within the given range, using base stations with high power as possible and having high gain antennas. To ensure sufficient coverage, base station power and antenna heights need to be considered and mechanical and electrical downtilts used when needed. Also coverage is enhanced by using supplementary hardware such as mast-head amplifier that strengthens uplink by giving more sensitivity to base station and enables reception of weak signals.

Coverage analysis is one of the crucial step in designing and deploying a mobile WiMAX network. Based on the coverage analysis, cells can be designed that lead to minimal interference between each other. This is achieved by selecting appropriate propagation models and fade margins for the area coverage probability.

As the range of WiMAX network is increased, WiMAX network steps down to a low order modulation whereas as the range is reduced the high order modulation is selected resulting into increased data throughput. The low modulation scheme has an effect on channel capacity of a base station resulting into small data rates.

In achieving coverage in a region, several factors have to be taken into consideration such as buildings heights, terrain, building densities and so on. Mobile WiMAX can be deployed for coverage without regard to capacity requirements. This means at first, the minimum number of base stations are deployed to provide ubiquitous coverage in a particular area. Capacity is only increased whenever the need arises, and this can be done by adding more channels to the existing base stations assuming there is available spectrum. This kind of technique is useful in situations where there are uncertainties about market requirements and therefore difficult to predict how the subscriber base will evolve.

The WiMAX base station connects the core service network to the end user, and therefore it is an important metric in determining the coverage of the network and end-users experience. Network coverage is calculated based on the path-loss data between the base stations and users as well as using antenna configuration parameters such as antenna type, power, radiation characteristics, tilt and azimuth.

3.3 Capacity planning

Capacity planning is based on the coverage maps and traffic estimates obtained from the coverage planning. For a broadband service such as WiMAX, capacity planning involves anticipating how users will use the system and the demand they place on the system.

The metric that is used in determining the capacity planning is the data density expressed as Mbps per km^2. Given a certain demographics region, determining the required data density is a multi-step process involving classifying users of the systems on different categories. User categories depend on the load they place on the system in terms of usage. Various demands that are placed by the users on the system include browsing the web, e-mailing, VoIP, download or upload of video content (real time services), which altogether pose different requirements on the system. For example business users can be categorised as the ones who demand high data rates and consequently load the system more frequently.

WiMAX capacity involves giving a user an access to the demanded traffic for the different service requirements considering the activity factor, overbooking or contention ratio, and TDD ratio for the uplink and downlink. Capacity of the WiMAX network is determined by calculating the cell throughput based on the area of each modulation scheme.

Throughput calculation for a particular modulation scheme is based on the following formula [11]:

$$R_b = R_s \frac{MC}{R_r} \qquad (1)$$

where:

M: modulation gain (2 for QPSK, 4 for 16 QAM, and 6 for 64 QAM)

R_b: bit rate

R_r: repetition rate of 1, 2, 4 or 6

C: Coding rate (0.5, 0.75, and so on)

R_s: Symbol rate

In determining the capacity requirements of a WiMAX system, the following factors are taken into account:

- Target market segments (SOHO, SME , and so on)
- Area demographics
- Services to be offered (QoS, bit rate)
- Expected market rate
- Expected number of customers
- Required data density Mbps per sq-km

One of the key metrics used in matching the base station capacity to the market requirements is the data density. Projected market requirements in turn determine the base station capacity requirements. For example assuming that the addressable market is of business category, then we expect that they create a traffic data of around 800kbps which the base station consequently has to support.

Expected market penetration or take-up rate is the other factor that the operator has to take into account when analysing capacity requirements. In this case, the operator has to forecast how the market will evolve after several years of operation, and consequently address its capacity needs.

WiMAX base station offers between approximately 14 – 30Mbps per sector in downlink and 2 – 6Mbps per sector in uplink [2], depending upon the antenna configuration (2×2 MIMO, 2×4 MIMO, or 4×2 MIMO). The key determinant of the average throughput per sector is the spectrum efficiency which is roughly in the range of 1.95 – 4.55bps/Hz downlink, and 0.94 – 2.19bps/Hz uplink depending upon the antenna configuration [2]. Given the spectrum that has been allocated to the operator (for example 10MHz), spectrum efficiency determines the average throughput per sector for the base station. The average throughput per sector is shared equally by all the users that are currently served in the sector.

3.4 *Summary and conclusion*

Dimensioning and planning of a mobile WiMAX network is a compromise between coverage and capacity. The required coverage can be extended by reducing the maximum load. Whenever there is a need of more capacity, the coverage area of an individual cell shrinks resulting into an increase in the number of required network elements. From an operator perspective, it is important to plan carefully for coverage, predetermine the capacity requirements and deploy according to how subscribers evolve over time. Since WiMAX is a broadband wireless service that demands a certain level of quality of service guarantee, careful planning also ensures that the deployment for coverage does not sacrifice capacity and vice versa. Careful coverage and capacity considerations lead to an acceptable quality of service at times when the network is the busiest.

In order to take into account traffic variation in the network, mobile WiMAX supports fractional frequency reuse where a mobile station uses all the available subchannels when it is close to the cell. When approaching the borders of the cell it uses only part of the subchannel set. This approach enables an operator to avoid the need for manual networking planning and optimisation.

The following chapter gives the rough estimates of the average values for coverage and capacity requirements. For example, it provides the average values for the number of base stations required for a metropolitan area plus the peak throughput per sector to serve the estimated data density. We do not go into the detail of the actual planning phase as there is a lack of access to a planning tool with a digital map that includes topography information.

4 Case Study

This research work assumes deployment in Finland's municipalities of Helsinki and Espoo, as well as the region of Kirkkonummi. Helsinki and Espoo municipalities are assumed to be urban and suburban regions respectively while Kirkkonummi is assumed to be a rural area. Table 3 in section 4.1 presents the characteristics of the regions. The Espoo region is regarded here as a suburban area although, according to the Espoo municipality maps, it is half rural half suburban. Suburban in this case therefore refers to areas where base stations are likely to be deployed; that is, areas within Espoo that inhabitants live. These areas are along the coastline, near the railway lines, and along the ring lines.

The three regions; Helsinki, Espoo and Kirkkonummi, are classified as urban, suburban and rural areas based on the population density, land area as well as on the scale of existing infrastructure. Based on the total land area of the metropolitan, we determine the number of base stations needed for coverage. From the population of each region, we provide an estimate of the expected number customers and their data density requirements. The number of base stations and the data density required form the key elements in planning end-to-end mobile WiMAX network.

4.1 Dimensioning WiMAX Radio Interface

This section presents the dimensioning of the radio network part of the network. Parameters that are considered include estimation of the traffic expectations, population density in the area of deployment, spectrum allocation, link budget analysis, antenna configurations, and frequency reuse scheme. The main outcome out of the dimensioning phase is to come up with an estimate of the number of base stations required to cover a given area, to determine the requirements for the coverage, capacity and quality of service, and to estimate the supported traffic volume per base station.

The key aspects the operator has to consider when planning to deploy a mobile WiMAX technology is the demographics. Demographics data include population density and population growth in a particular area, distribution of age groups among the population, and proportion of household densities. This research work assumes the demographics regions are divided into urban, suburban, and rural areas. Table 3 presents the assumed key characteristics defining the demographics regions.

Table 3: Characteristics of the demographic regions

Area	Characteristics
Urban	• High density of potential mobile WiMAX subscribers • low market penetration due to the existence of strong competitors • presence of multiple offices and residential buildings • presence of operators using licensed spectrum • strong market driven by availability of access technology
Suburban	• Moderate density of potential subscribers • access to DSL and cable technologies • possibility of a high market penetration for a new operator • presence of business parks and malls • considerable concentration of computer users • high percentage of commuters that need services • possibility to deploy large cell sizes
Rural	• High concentration of residential and small businesses • high demand for Internet access and services • limited competition • very high market penetration and rapid adoption rate expected for a new operator

Table 4 presents the geographic scenarios for the proposed demographics regions; Helsinki, Espoo and Kirkkonummi.

Table 4: Geographic factors for the deployment

Element	Helsinki	Espoo	Kirkkonummi
Market segment	Residential/urban	Residential/small medium enterprises	Rural area
Size	186 sq km	312 sq km	365 sq km
Population	568,531	241,881	131,585
Population density	3057 per sq km	775 per sq km	360 per sq km

Source: Statistics Finland, 2007- http://www.stat.fi,

The first decision an operator has to make before starting deploying the mobile WiMAX network is to choose the spectrum to be used. While WiMAX offers operation on both licensed and unlicensed bands, the choice between either of the two bands depends on the region of deployment. Since licensed spectrum offers the benefit of controlling the interference, it is therefore best suited for urban and suburban areas. For this research work, licensed bands 2.5GHz and 3.5GHz are therefore assumed for the deployment. The licensed bands are also selected because regulations allow the bands to be used also for fixed broadband services. Table 5 presents two frequency bands that are assumed for the deployment in the regions.

Table 5: Assumed parameters for the deployment

Parameter	Helsinki	Espoo	Kirkkonummi
Frequency band	3.5GHz	3.5GHz	2.5GHz
Channel bandwidth	10MHz TDD	10MHz TDD	10MHz TDD
Assumed spectrum	30MHz	30MHz	30MHz

After defining the demographics, geographical parameters of areas set for the deployment and selecting the frequency to be used, the operator provides an estimate of the data density requirements. The estimated data density is used to determine how the base station sites can be configured to support the projected data density. Data density estimation task starts by categorising the expected customers within the target market segments as follows [22]:

- **Professional users**: These are the business type of users who are most demanding in terms of broadband data usage. This type of users are assumed to be using the services in stationary, nomadic and mobile environments. The type of services that are perceived to be mostly used are file download, streaming media, video conferencing, and e-mail.
- **High end users**: These are type of users who use the services mostly for their personal use. They use the services on regular basis, and the dominant applications that they use the most are web browsing, gaming, music downloads, and so on.
- **Casual users**: These are type of users who need access to use broadband services (web browsing, data oriented services) but are only connected few hours in a day.

Each of the category of users demand different data density requirements, and it is projected that the professional and high end users are mostly found in urban and suburban areas. Casual type of users are mostly located in the rural area of the metropolitan.

The study assumes that the services that the users demand conform to the services/applications that the WiMAX standard addresses. Table 6 defines the WiMAX services [27].

Table 6: WiMAX service classes [27]

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

Table 6 also presents the characteristics of the data services that the operator can offer. Data services in this study refer to mobile data services that are based on the IP architecture. The data services are assumed to be content oriented, and having interactive and/or background characteristics.

When determining the data density requirement, the impact of commuting subscribers is taken into consideration. Commuting traffic is mostly experienced within the urban (Helsinki) and suburban (Espoo) regions because of the presence of considerable number of businesses. Commuting traffic therefore places an additional demand on the network during the day time hours, and it is assumed that the daily commuter traffic flow (within urban and suburban areas) increases the daytime population by more than 15%.

In order to estimate the required data density per end user for the three regions, the peak busy hour (PBH) activity level has to be defined or assumed by the operator. Downlink duty circle (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 that are used in combination with the PBH activity level to determine the minimum per end user rate.

Table 7 presents the values for the PBH activity level, customer mix, downlink duty circle, and the minimum per end-user rate during PBH. The overall customer average downlink rate estimation is over the metropolitan population of 941,997. Customer mix in table 7 applies to the whole metropolitan area.

Table 7: Estimated peak busy hour data requirement [22]

Customer type	**Customer mix**	**Peak Busy Hour Activity: 1 of N active**	**Downlink duty circle**	**Minimal per end-user down-link rate during PBH**
Professional users	50%	N = 5	25%	600kbps
High-end users	35%	N = 7	25%	480kbps
Casual users	15%	N = 20	25%	240kbps
Customer average over metropolitan area		N = 7.9	25%	504kbps

The values in table 7 are based on what we regard to be the condition of the network during the peak busy hour. For example 600kbps minimal PBH data rate for a professional user is based on the assumption that in an extreme case the user is able to download at maximum a 30 page document e-mail attachment in about 4 seconds which is a tolerable download time during PBH traffic conditions. Typical size of a 30 page document that consists of graphs and figures is between 250 – 350kilobytes [22], therefore with a downlink rate of 600kbps the download speed is approximately 4 seconds. The minimal downlink data rates address the time at which the network is busiest and therefore much higher data rates can be achieved if there are variations in the downlink duty circle and activity level. The addressable market pertaining to the data rate requirement in table 7 are of the age of 20 to 75 which amounts to almost 80% of the metropolitan population (statistics Finland, 2007).

Table 8 shows the expected number of customers and their projections for downlink data density requirements by the tenth year of operation. The expected number of customers are obtained under the assumption that in the beginning 9 percent of the population in the urban and suburban areas are going to subscribe for the service while 10 percent subscribe for the case of rural area. This is based on the reasoning that customers evolve over time, and in the initial phase the number of customers is small.

Table 8: Downlink data density estimation over years [22]

Metropolitan region	**Expected number of customers**	**Adjust-ments to account for mobility during PBH**	**Downlink data density requirements in 10th year**
Urban	50,000	15%	20Mbps/km2 over 186 km^2
Suburban	20,000	15%	1.6Mbps/km^2 over 312 km^2
Rural	10,000	0%	0.15Mbps/km^2 over 365km^2

4.1.1 Frequency selection

The frequency bands selected for the deployment are 3.5GHz band for the urban and suburban areas and 2.5GHz band for the rural area. The 3.5GHz band operates in the frequency range 3.3 − 3.6GHz resulting into 300MHz of spectrum. 2.5GHz band operates in the frequency range 2.3 – 2.690GHz resulting into 390MHz of spectrum. Bands of 300MHz or 390MHz are the total available spectrum that the regulator can allocate to all existing operators in a particular country. In this research work, it is assumed that the 30MHz spectrum is allocated to the operator in the region of Helsinki, Espoo, and Kirkkonummi, with a channel bandwidth 10MHz and a TDD duplexing scheme. The choice of the above selected frequency bands is influenced by the fact that licensed spectrum provides good protection against interference especially in the urban areas where the number of competing operators is predominant. 2.5GHz is preferred for the rural area because it allows for a flexible deployment since it promises to provide a high range as well as mitigating the interference.

Given the population density of the particular region, say Helsinki, the key question is how to determine the number of base stations to cover that particular area. The number of base stations that can be deployed depends on the operator's spectrum. Before embarking on determining the capacity and number of base stations, it is important to calculate the link budget. The link budget is used to determine the coverage or range of the single base station.

4.1.2 Link budget analysis

A link budget is the sum of the loss and gain of the signal strength as it travels through different components down the path from the transmitter to the receiver. The link budget allows determining the required transmit power that is able to overcome losses in the transmission medium so that the receive power is adequate for the reception of the signal.

As a result of the link budget, the receive power is sufficiently greater than the noise power, and the targeted bit error rate can be achieved.

The link budget determines the theoretical maximum cell radius of each base station and comprises of two types of components [17]:

- System level components which include receiver sensitivity, power level and modulation efficiency. These components do not vary significantly across different frequency bands.
- Non-system related components, that are expected to vary across different frequencies. These components include:

-Path loss: is the propagation loss that the radio frequency signal experiences and is frequency dependent. The lower the frequency of operation, the smaller the path loss and the further the signal can propagate. The higher the frequency, the larger the losses, and the smaller the signal can propagate. In the presence of obstacles, high frequency signals cannot penetrate obstacles and require LOS conditions for efficient operation.

-Physical environment: the presence of buildings and other man-made structures have a significant effect on the losses introduced to the frequency band in use. For instance, higher frequency signals suffer considerable losses upon encountering concrete and metal surfaces. This emphasises the need of taking into account the losses introduced by these structures into the link budget.

-Cable loss: has an impact on cases where the base station is tower mounted. In this case, cable loss increases with frequency.

-Shadow margin: The terrain and man-made objects have significant impact on the variation of the signal power, and therefore additional margin needs to be added to the path loss to achieve the desired coverage probability.

Table 9 presents link budget parameters for the deployment in urban and suburban areas for the frequency band of 3.5GHz, channel bandwidth 10MHz TDD, and spectrum 30MHz.

Table 9: Link budget [2]

Parameter	**Mobile handheld in outdoor scenario**		**Notes**
	Downlink	**Uplink**	
Power amplifier output power	43.0 dB	27.0 dB	A1
Number of transmit antennas (assuming 2×2 MIMO Base stations)	2	2	A2
Transmit antenna gain	18 dBi	0 dBi	A3
Transmitter losses	3.0 dB	0 dB	A4
Effective isotropic radiated power	66 dBm	27 dBm	A5 = A1 + $10\log_{10}$(A2) + A3 - A4
Channel bandwidth	10MHz	10MHz	A6
Number of subchannels	30	35	A7
Receiver noise level	-104 dBm	-104 dBm	A8 = -174 + $10\log_{10}$(A6×1e6)
Receiver noise figure	8 dB	4 dB	A9
Required SNR	0.8 dB	1.8 dB	A10
Subchannelisation gain	0 dB	12 dB	A11 = $10\log_{10}$(A7)
Data rate per subchannel (kbps)	151.2	34.6	A12
Receiver sensitivity (dBm)	-95.2	-110.2	A13 = A8 + A9 + A10 -A11
Receiver antenna gain	0 dBi	18 dBi	A14
System gain	156.2 dB	155.2 dB	A15 = A5 – A13 + A14
Shadow-fade margin	10 dB	10 dB	A16
Building penetration loss	0 dB	0 dB	A17
Link margin	160 dB	151.64 dB	A18 = A15 – A16 - A17
Cell radius	1.86 km (urban), 2.26 km (suburban)		Assuming COST-231 Hata urban model

The number of subchannels (30 and 35) is based on the initial mobile WiMAX profile for 10MHz channel bandwidth that defines 30 and 35 subchannels for uplink and downlink respectively.

The coverage ranges shown in Table 9 are determined based on the COST-231 Hata propagation Model [2]. Link margin used is 160dB. Although COST-231 Hata model applies to mobile applications in the 1900MHz band, it is assumed acceptable for 2500MHz and 3500MHz band. See *Appendix A* for more information on this propagation model.

Furthermore, coverage ranges in table 9 are determined assuming that the mobile base station antenna height is 30m, and the mobile station height is 1m. These are the typical values for most deployment scenarios [2].

For the case of rural area, 1×2 SIMO scheme is used. With the same parameters for the link budget as in table 9 except a change in the number of transmit antenna, this translates into a link margin in excess of 150 dB for the rural area.

4.1.3 Determining the number of Base Stations

The WiMAX base station is the key network element in connecting the core network to the end user, it determines the coverage of the network and defines the end-user experience. The link budget analysis as presented in section 4.1.2 results into determining the cell radius, R, of the base station. Based on the cell radius, we determine the coverage area of a single base station. The coverage area of a single base station leads into determining the total number of base stations required to cover a particular region in a given metropolitan area.

The base station coverage area is determined depending upon the number of sectors that the base station has. There are three sectoring techniques that are employed in cellular systems. These include either the use of omni-directional sector (one cell with one antenna covering all directions), bi-sector (two cells per one base station) and tri-sector (three cells per one base station). For this case study, tri-sector cells in a single base station are preferred to others in order to provide precise coverage for the selected regions pertaining to the deployment. The coverage area A_{cell} of the tri-sector base station is determined using the following formula [20]:

$$A_{cell} = 1.95\ R^2 \qquad (2)$$

Figure 11 depicts the model for a three sectored base station.

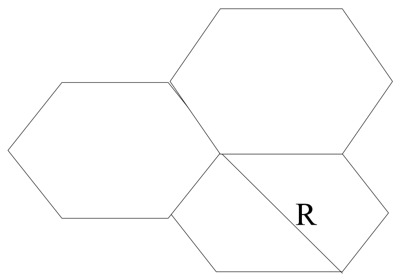

Figure 11: Tri-sector base station

In order to determine the number of base stations, K, needed to cover a given area, A, the following formula [20] is used:

$$K = A/A_{cell} \qquad (3)$$

Using equations 2 and 3 above, approximately 28 base stations are needed to cover Helsinki region, while 31 base stations are needed to cover Espoo region over the land areas of 186 and 312 square kilometres respectively.

For the case of rural area, Kirkkonummi, operating at 2.5GHz band, assuming the link margin of 150dB, the cell radius results into 2.66 km. Using formulas (2) and (3), 2.66 km cell radius leads to 26 base stations needed for coverage over the 365 square kilometres.

4.1.4 Choosing Antenna Configuration

WiMAX technology offers a range of smart antenna technologies that improve the system performance and enhance both coverage and channel throughput. Mobile WiMAX also supports MIMO antenna solutions that offer advantages such as increasing the system reliability, increasing the achievable data rates, increasing the coverage area and decreasing the transmit power.

Smart antenna technologies that are supported include adaptive beam-forming, transmit diversity, and spatial multiplexing. Adaptive beam-forming uses multiple antennas to transmit the same signal appropriately weighted for each antenna element such that the effect is to focus the transmitted beam in the direction of the receiver and away from the interference, thereby improving signal to interference plus noise ratio.

Transmit diversity provides the possibility to have two or more transmit antennas and one or more receive antennas. Spatial multiplexing transmits multiple independent streams across multiple antennas. In spatial multiplexing, the multiple antennas are used to increase data rate or capacity of the system.

MIMO techniques that are supported by WiMAX include 1×2 SIMO and 2 × 2 MIMO. 1 × 2 SIMO scheme uses one transmit antenna and two receive antennas, while 2 × 2 MIMO scheme uses two transmit antennas and two receive antennas at the base station.

With the existence of the aforementioned antenna techniques, the key issue of concern when deploying the base station is determining the configuration that counter the effects of propagation environment such as multipath and fading, but at the same time resulting in tremendous throughput performance. For urban and suburban areas, Helsinki and Espoo, 2×2 MIMO is a suitable choice since it offers improved performance over regions with considerable multipath effects. Since urban and suburban areas are normally occupied by buildings and man-made structures that reflect signals, 2×2 MIMO scheme takes advantage of the reflected signals by superimposing them at the receiving end.

2×2 MIMO antenna offers per sector throughput of 14.61Mbps (downlink) and 2.34Mbps (uplink) in a 10MHz channel [2]. With 2×2 MIMO, spectral efficiency is 1.95 bps/Hertz downlink and 0.94 bps/Hertz uplink. Mobile WiMAX supports downlink to uplink ratio from 1:1 to 3:1. This presents a significant increase in throughput in downlink as compared to uplink, thereby providing an advantage to data-centric traffic which are expected to be downlink oriented.

A 3:1 downlink to uplink ratio for instance represents a 50% increase in downlink data throughput as compared to a ratio of 1:1 for the same channel bandwidth [22].

As for the case of the metropolitan area, Helsinki and Espoo regions use channel bandwidth of 10MHz with a TDD scheme, therefore assuming a downlink to uplink ratio of 3:1 the peak data rate per sector results to roughly 25-27Mbps downlink and 6.7Mbps uplink. With the base stations in Helsinki and Espoo configured as tri-sector base stations as shown in Figure 11, and each sector consisting of antenna configuration 2×2 MIMO, the resulting throughput is roughly 25Mbps per sector [2]. Due to the low probability that all customers are going to be served in a single base station, it is assumed that at least 10 customers can be served per sector.

Since mobile WiMAX uses shared resources, the data rate per sector is shared equally among all users currently served under the cell. For example, if there are currently 10 users in the cell, each is then having an access to 2.5 Mbps of data rate. If there is only one user currently being served in cell, then he gets the total data rate, that is 25Mbps. Again assuming the reasonable overbooking factor of 10, then it means that a single sectored cell can handle up to 100 customers [31]. This therefore results into a total of 300 customers that can be served by a single base station in Helsinki and Espoo regions. The assumption presented here seems to be reasonable in the sense that we fulfil the projected downlink data density requirement as presented in Table 8. This means that the capacity of the base station is adequate to meet users demand as in Table 8.

For the case of rural area, Kirkkonummi, 1×2 SIMO antenna configuration is a suitable choice. This configuration uses a single transmit antenna and two receive antennas at each end of the link. Although there is expected to be little presence of man-made structures such as buildings and bridges which can reflect the signal, 1×2 SIMO scheme still takes advantage of multipath to improve both uplink and downlink received signal strength. On the other hand this configuration saves antenna costs as only a single transmit antenna is utilised, and this seems to be a reasonable choice for a rural area since the subscriber base and take up rate at the beginning are expected to be low. In terms of data rates per sector, 1×2 SIMO offers downlink data rates up to 9 Mbps per sector assuming the downlink to uplink ratio of 3:1 [22]. With the same set of assumptions as in Helsinki and Espoo regions, (10 customers can be served per sector), a 9Mbps is shared equally by all 10 users if they are currently on the cell giving them 0.9Mbps each. If there is only one customer in a cell (sector) he gets the total 9Mbps. Again with this assumption we fulfil the data rate requirements presented in Table 8.

4.1.5 Frequency Reuse Scheme

Frequency planning for the WiMAX network involves the use of two common frequency reuse schemes that are available for multicellular deployment with 3-sectored base stations. These are the frequency reuse of 1 (universal frequency reuse), denoted as (1,1,3), where all the sectors in a base station use the same channel, and frequency reuse of 3, denoted as (1,3,3) whereby a channel is used only one of every three sectors in a base station. The nomenclature for naming the frequency reuse patterns is (c,n,s) where *c* stands for the number of base stations, *n* the number of channels and *s* the number of sectors per base station site.

In most cases, the universal frequency reuse is a preferred option for the deployment since it has the advantage of using the least amount of spectrum. Given that the more spectrum the operator needs the higher the cost, this scheme helps in improving coverage while spending less money on spectrum. The downside of the universal frequency reuse is that it results into co-channel interference at the sector boundaries and cell edges. The co-channel interference reduces the downlink channel capacity as the subcarriers allocated are not fully utilised throughout the entire cell.

In order to achieve an acceptable cell-edge performance with universal frequency reuse, mobile WiMAX supports the fractional frequency reuse with the segmentation mechanism. With the segmentation mechanism, mobile WiMAX gives users subchannels that are only a small part of the whole bandwidth.

With the fractional frequency reuse the MS uses part of the subchannel set, Partially Used Subcarriers (PUSC), when approaching the borders of the cell. When it is close to the middle of the cell, the MS uses all the subchannels, Fully used Sub-Carrier (FUSC). Figure 12 illustrate the principle of fractional frequency reuse.

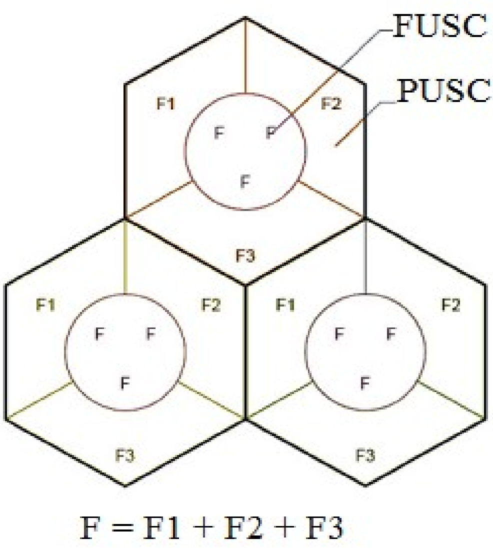

Figure 12: *Fractional frequency reuse[21]*

The frequency reuse of 3 scheme needs three times as much spectrum as the universal frequency reuse but it eliminates the co-channel interference at the sector boundaries. It also reduces the the co-channel interference between neighbouring cells due to increasing spatial separation for channels operating on the same frequency band. Figure 13 illustrate the frequency reuse of 3.

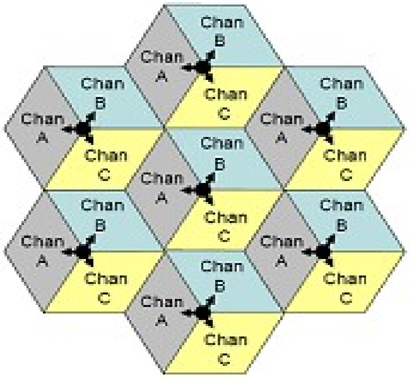

Figure 13: Frequency reuse of 3 with 3 sectors base station

The key questions to address for this deployment are: how to choose the frequency re-use plan that enables optimal use of the available spectrum; and on what basis should one select the frequency plan for the urban, suburban and rural areas. With the assumed 30MHz spectrum and a 10MHz TDD channel, it means that if the operator adopts the frequency reuse plan of 1 then each sector is allocated three 10MHz TDD channels [2]. The determining factor for assigning the channels in a single base station is the spectrum that the operator has acquired from the telecommunications regulatory authority. The regulatory authority allocates the 10MHz TDD channel depending upon the frequency of operation;3.5GHz and 2.5GHz bands, as used in this study.

With the frequency reuse plan of 3 then each sector is allocated a single 10MHz TDD channel. The overall capacity for (1,1,3) reuse pattern is higher than (1,3,3) reuse pattern since each sector is allocated three channels as opposed to one channel in the case of (1,3,3) reuse.

Based on the overall capacity and cost-effectiveness, a universal frequency reuse is preferred for this case study. The frequency reuse of 1 enables better utilisation of the assumed spectrum as well as the increase in capacity.

Frequency reuse distance

Cellular network planning requires that cells using the same frequency be separated by the frequency reuse distance *D* in order to achieve tolerable signal to interference plus noise ratio [14]. For the frequency reuse distance, *D*, the following relationship holds:

$$D = R\sqrt{3\mathrm{M}} \qquad (4)$$

where *R* is the radius of the cell, and *M* is the frequency reuse pattern factor; $M \in \{1,3,4,7,9,12,...\}$. Equation 4 is based on the assumption that the cells are hexagons, are equally sized and the same frequency reuse pattern is used for all the cells.

This research study assumes that the universal frequency reuse factor is deployed for all the regions; Helsinki, Espoo, and Kirkkonummi. In this case, the value of M in equation 4 is 1.

Based on the equation 4, the frequency reuse distances for the regions of Helsinki, Espoo, and Kirkkonummi are as indicated in Table 10. With frequency reuse of 1, the resulting frequency reuse distances are smaller than in the case of frequency reuse of 3. Frequency reuse of 1 results into an increase in spectrum efficiency because for a given distance the given frequency can be reused more number of times than in the case of frequency re use of 3.

Table 10: Reuse distance

Region	Cell radius [km]	Reuse distance [km]
Helsinki	1.86	3.22
Espoo	2.26	3.91
Kirkkonummi	2.66	4.61

4.1.6 Duplexing method

WiMAX technology uses two types of duplexing methods to separate downlink and uplink transmission and communication of signals. These are TDD and FDD duplexing schemes. TDD uses the same frequency for both downlink and uplink transmission, but the transmission occurs at different time slots. FDD on the other hand uses different pair of frequencies for the downlink and uplink transmission.

In deploying a mobile WiMAX technology, the choice of either of the duplexing scheme is dictated by the telecommunications regulatory authority of a particular country. Prior to deploying the mobile WiMAX network, the operator determines if the frequency band that the network is to operate on permits the use of either one of the duplexing scheme or both. This enables the selection of the duplexing method that gives the acceptable throughput performance depending upon the type of services to be offered.

For the deployment of mobile WiMAX in the three regions, Helsinki, Espoo and Kirkkonummi, TDD scheme is selected as a duplexing method (10MHz bandwidth channel). Since services offered by mobile WiMAX are data centric, typical of Internet access services, this means that the downlink traffic dominates as compared to the uplink traffic. With these types of services, TDD is a suitable duplexing method since it allows the operator to define the percentage of bandwidth to be allocated for both the downlink and uplink. Since TDD method supports downlink to uplink ratio of 1:1 to 3:1, it is expected that the subscribers are bound to experience up to 50 percent increase in downlink data throughput when 3:1 ratio is used in a 10MHz channel [22].

This is because with 3:1 TDD scheme a shared channel is used three quarter of the time for downlink and one quarter of the time for the uplink. Selecting a 10MHz TDD channel for the regions achieves efficient usage of the limited spectrum while at the same time offering the expected quality of service for the mobile WiMAX service.

Figure 14 shows the gains achieved for 1:1 versus 3:1 downlink to uplink ratio when TDD method is used with various antenna configurations. This justifies the selection of TDD as a duplexing method for the regions.

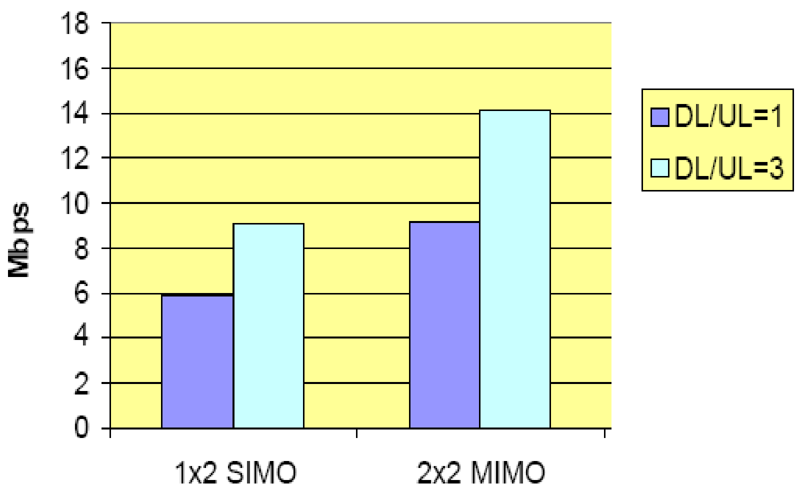

Figure 14: Downlink throughput for TDD with 10MHz channel bandwidth [22]

4.1.7 Backhaul transport solutions

After determining the number of base stations required in a particular area, there is a need to address the issue of how to provide a transport solution to ensure point to point or point to multipoint connectivity of the base stations. There are several topology options that are available for planning transport network; point-to-point, chain, loop, tree and mesh topologies.

However, this section does not detail the implementation of the topologies for the particular area, but rather provide an overview for dimensioning the transport network. This is due to lack of access to topography maps of the regions selected for the deployment. The most critical part in dimensioning a transport network is in finding a transmission solution for the connection between the transmission network and base station site. The transmission solution can be based on the leased Time Division Multiplexing (TDM) or Asynchronous Transfer Mode (ATM). The other solution is to build own network using microwave radio links. This is the preferred case if copper or fibre-based backbone network does not exist. Also, if microwave links are used, environmental factors such as line of sight, restrictions on building permissions or access to microwave radio frequency licence are taken into considerations.

The increasing demand for bandwidth intensive applications will also demand for IP and Ethernet transport in the backhaul. Metro Ethernet is also the transport solution that can be used to backhaul the base stations to the core network. For the mobile broadband technology such as WiMAX, metro Ethernet can be a suitable transport solution.

Figure 15 shows the process flow for dimensioning transport network.

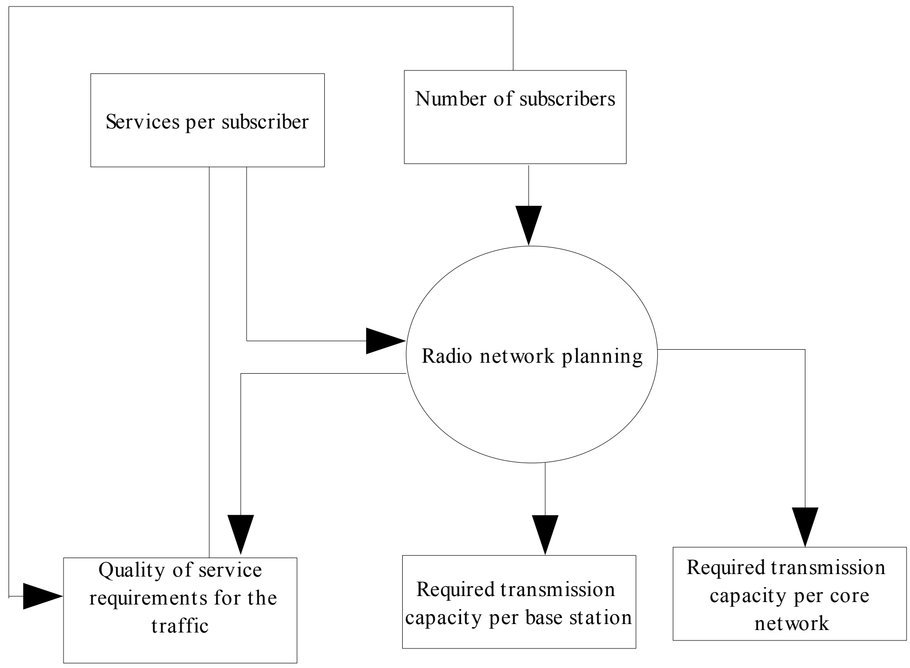

Figure 15: Dimensioning transport network [3]

The following are the steps involved in dimensioning the transport network:

- **Calculation of the required transport network capacity**: This includes the required transmission capacity for the base station. The needed transport network capacity depends on the radio network configuration, which again is based on the estimated number of subscribers and the services that they use. As presented in Section 4.1.4, the capacity per base station for the deployment is 25Mbps downlink for Helsinki and Espoo (using 2×2 MIMO antenna) and 9 Mbps uplink for Kirkkonummi (using 1×2 SIMO antenna).
- **Selection of the transport network media**: this depends on the environment and network configuration. The choices include cables, radios, metro ethernet and leased lines as mentioned earlier.

- **Planning the transport network topology**: planning is based on the existing topology options; chain, mesh, loop, and tree.
- **Planning of the transport network protection**: this is achieved by securing the connections so that information is transferred through two different routes. The other option is through equipment redundancy, which means that if one equipment is broken then the redundant equipment takes over.

This section presented the network topologies that can be employed for the proposed regions of deployment; Helsinki, Espoo and Kirkkonummi, and the steps that are to be followed. Depending upon the layout of the buildings, terrain and other man-made and natural features, the suitable network topology is selected that can deliver high throughput, strong robustness, and high reliability.

4.2 *Dimensioning WiMAX Network*

This section describes the dimensioning of a mobile WiMAX network which includes elements ASN-GW and in the CSN. This includes dimensioning interfaces between the base station and the ASN-GW, between ASN-GWs, and between ASN and CSN. Dimensioning also includes configuration of the CSN elements based on the estimate of traffic generated by the subscribers/customers as presented in section 4.1. Before detailing the dimensioning of the core network part, Figure 16 presents the detailed architecture of the WiMAX end-to-end network.

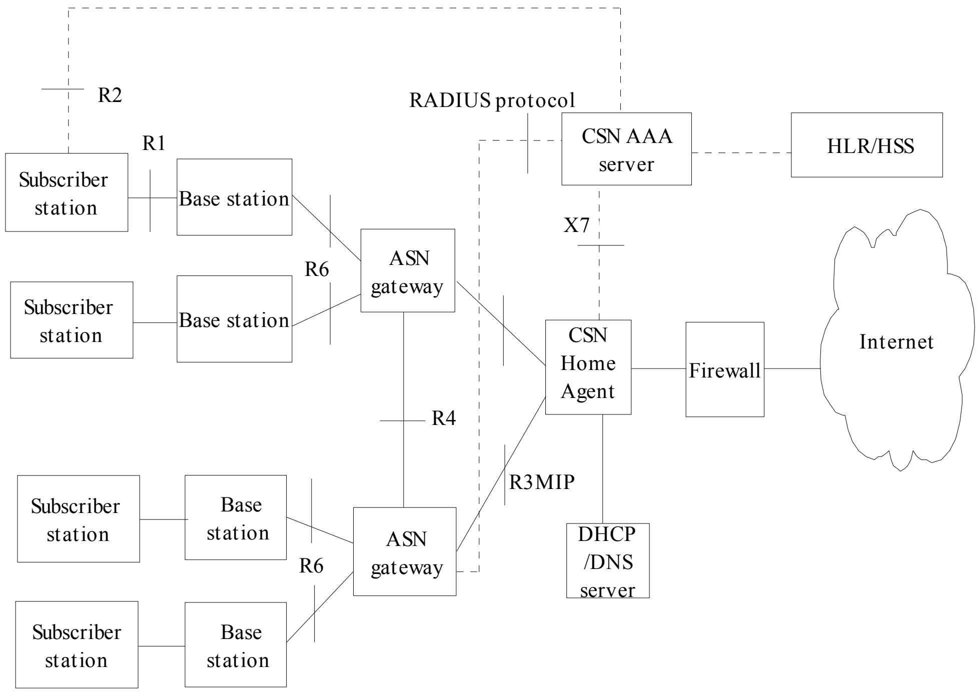

Figure 16: Detailed WiMAX architecture [2]

Figure 16 shows an extended WiMAX reference network model. The elements that form the core service network are dimensioned based upon the traffic estimation coming out of the base station. The traffic estimation determines how the elements and interfaces are configured to enable end-to-end connectivity.

The WiMAX architecture supports both the IP packets and Ethernet frames. The ASN part of mobile WiMAX network handles routing of packets between the base stations and ASN-GWs. Routing over the ASN is performed using IP-in-IP encapsulation protocols such as generic routing encapsulation (GRE). Packets within the ASN are either bridged or routed.

The WiMAX base station consists of Ethernet interface which can support capacity of 10-100Mbps [28]. The ASN-GW which interfaces with the base station, supports capacity on the levels of Gbps; it supports 100/1000 Base-T Ethernet interface adapter. A single ASN-GW can handle up to 100,000 users and 20,000 VoIP calls [28]. According to the dimensioning rule, one ASN-GW manages 200 cells, therefore one ASN-GW can connects as many as 66 base stations with one base station consisting of three cells.

In order to dimension the mobile WiMAX end-to-end network, assumptions on the subscriber usage of the network services, and end-to-end traffic model are given. We also provide the traffic related events having an impact on ASN elements as well as ASN QoS mechanisms.

4.2.1 End-to-end traffic model

The end-to-end traffic model describes the subscriber behaviour for an aligned capacity planning of the mobile WiMAX network elements. It includes the subscriber traffic model as well as the subscriber mobility model. The subscriber traffic model provides the state of the subscribers on the network and their share on the interfaces. Table 11 lists the parameters that are defined for the subscriber traffic model.

Table 11: Subscriber traffic model

Parameter	Unit	Description
Subscriptions	80,000	Sum of all subscribers of the provider. (refer to Table 8)
Powered on subscribers	80%	Percentage of subscribers that have powered on their mobile stations
Active subscribers	50%	Percentage of ASN subscriber stations in an active state
Subscribers in sleeping state	20%	Percentage of ASN subscribers in sleeping state.
Subscribers in idle state	30%	Percentage of ASN subscribers in idle state.

In table 11, the assumption used is that a significant percentage (50%) of subscribers are in active state, which is the obvious case for most of mobile and wireless networks, and the rest are in idle and sleeping state. Active, idle and sleeping subscribers refer to powered on subscribers.

The subscriber mobility model provides mobility events in the busy hour at the R6, R4, and R3 interfaces. The mobility events occur when either the subscriber station is in active, idle or sleeping state. The state of the subscriber station determines the frequency of mobility events. For active or sleeping subscriber stations mobility occurs at the sector crossings, while for idle subscriber stations mobility occurs as a consequence of a location update. Table 12 presents parameters for the subscriber mobility model.

Table 12: Subscriber mobility model

Parameter	Unit	Description
Percentage of subscribers in the R6 interface	50%	Percentage of subscribers located in ASN-GW area
Percentage of subscribers in the R4 interface	4%	Percentage of subscriber that are in handover between ASN gateways
Percentage of subscribers in the R3 interface	46%	Percentage of subscriber that are mobile

The values in table 12 are based on the reasoning that the subscriber distribution over the interfaces is such that the subscribers over R6 interface is the sum of subscribers over R4 and R3 interfaces. Out of 50% active subscribers in an ASN gateway area, 4% are assumed to be using that ASN gateway as a serving gateway. Remaining subscribers are mobile in the R3 interface.

4.2.2 ASN Gateway dimensioning

In order to dimension the ASN gateway, the data density requirements by the tenth year and VoIP generated traffic are used. The generated VoIP traffic is a result of powered on subscribers while for the case of the data traffic, the maximum value of the data density requirements in the three regions is used. For this case study, it is assumed that there are three ASN gateways located in each region, Helsinki, Espoo and Kirkkonummi. The ASN-GWs are distributed across regions so that traffic is minimised across the transmission network. Table13 presents parameters that are used for the ASN gateway node dimensioning.

Table 13: Parameters for the node dimensioning

Parameter	Value	Description
Powered on subscribers	64,000 subscribers	refer to 80% of subscriptions as in table 11
Maximum throughput over all subscribers	20Mbps	
Bit rate of a VoIP call (for G.729 codec)	40kbps	Maximum bit rate of a VoIP call including overheads, MAC/RTP/UDP/IP without compression
Number of expected VoIP calls	2059 calls	
Average throughput capacity per cell	31Mbps	Total throughout per cell (downlink + uplink)

We assume that a G.729 codec is used on top of IPv4 backbone, where a frame is produced every 20ms, and the VoIP packet size is as follows [5]:

VoIP packet size = Ethernet frame header (42 bytes) + IPv4 header (20 bytes) + UDP header (8 bytes) + RTP header (12 bytes) + voice payload size (20 bytes) = 102 bytes.

We calculate the expected VoIP calls in table 13 using the Erlang C formula for a given traffic in Erlangs, and a delay probability. Erlang C formula is used because it takes into account the metrics used to dimension voice for the data networks such as mobile WiMAX. The metrics include packet loss and delay probability.

Assuming a normal dimensioning value for traffic per user of 30 mErl during the network busy hour [3], 64,000 users create a traffic of 64,000 × 30 mErl = 1920 Erl. Therefore for a traffic of 1920 Erl assuming a delay probability of 0.1%, the resulting number of voice calls according to Erlang C formula is approximately 2059. For dimensioning purposes the voice calls is the same as the number of traffic channels. *Appendix A* provides more information on the Erlang C formula

The ASN-GW node is dimensioned based on the following steps.

- First the offered load generated by all subscribers is calculated. For the metropolitan area, this translates into the following offered load for VoIP and data traffic:

  Offered load for VoIP traffic = 2059 calls × 40kbps (bit rate of a VoIP call, G.729 codec) = 82Mbps

  Offered load for the data traffic = 20Mbps, which is a result of data density requirement.

- The offered load is then distributed to all ASN-GW interfaces (R6, R4, R3).

The offered traffic is distributed based upon the subscriber distribution as in Table 12. Assuming that the percentage of subscribers in an interface is proportional to the offered traffic on that interface, then the proportion of traffic load per interface is as follows:

- R6 interface: For VoIP traffic, 50% of the offered load for VoIP traffic = 41Mbps is distributed to the interface, while for the data traffic 10 Mbps is distributed to the R6 interface.
- R4 interface: For VoIP traffic, 4% of the VoIP traffic load = 3.3Mbps is distributed to the interface, while 0.8Mbps data traffic is distributed to the interface.
- R3 interface: For VoIP traffic, 46% of the VoIP traffic load = 37.7 Mbps is distributed, while 9.2Mbps data traffic is distributed to the R6 interface.

In order to determine the capacity of the ASN transport link, R6, a formula based on the average radio cell throughput [3] is used. With this formula, the capacity of the R6 interface between the base station and ASN-GW is limited by the capacity of the radio cell served by the base station. The radio cell capacity depends on the radio configuration and air interface condition as it is presented in Section 4.1.4. Therefore R6 capacity requirements on the transport level is calculated based on the following formula [3]:

$$R6_{bandwidth} = number\,of\;cells\;per\;BS \times Average\;cell\;capacity \times scaling_{fator} \qquad (5)$$

Scaling factor in equation 5 accounts for a higher than average traffic to be accommodated, and takes into account the R6 transport overhead. The suggested value for the scaling factor is 1.25. BS is assumed to be a tri-sectored BS, and the average cell capacity is 31Mbps.

Using these values results into approximately 116Mbps R6 transport capacity. This capacity fits well within the limits posed by the ASN-GW [28], as ASN-GW supports 100/1000 Base-Tx Ethernet interface connection. With 116Mbps transport capacity, R6 interface can support the offered load.

4.2.3 ASN QoS mechanisms

This section describes the QoS issues that are having an impact on ASN dimensioning. With mobile WiMAX, it is possible to select the QoS classes that are suitable for the services that the operator expects to offer. With the type of services such as file download, interactive gaming, web browsing and so on, that the operator can offer to customers in the metropolitan area, two QoS classes ert-PS and BE fulfil those service requirements.

QoS handling in the ASN is performed on per service flow basis. The service flows are characterised by the set of parameters such as latency, throughput and jitter. In order to deliver the expected quality of service to subscribers, a QoS profile is defined for each category of users, that contains all service flows along with their associated service classes. Table14 presents the QoS profile for each category of users as defined in section 4.1.

Table 14: QoS profile for the subscribers

Service	**Definition**	**Application**	**Subscriber category**	**QoS parameter**
ert-PS	Real-time service flows that generate variable-sized data packets on a periodic basis.	VoIP with silence suppression, interactive gaming, video telephony.	Professional and High end users.	Average throughput = 504kbps per subscriber, maximum latency = 50ms, maximum jitter = 100ms
BE	Data streams for which no minimum service level is required and can therefore be handled on space available basis.	Internet applications including http, ftp and e-mail.	Casual users	Average throughput = 240kbps per subscriber, maximum latency and jitter not guaranteed.

Subscriber's flows are permitted to the network based upon the traffic rates specified in the QoS profile, and the availability of the network resources. Connection admission decision is located in the base station, and is executed only for the ert-PS service class. The BE service does not need an admission mechanism and flows are always admitted. For the real time service set up, such as video telephony or VoIP, the available air interface bandwidth resources are compared with traffic rates specified in the subscriber profile, and if there are not enough resources the connection is rejected. The service flows are rate limited after being admitted so that the subscribed bit rate are not exceeded. R6 interface enforces rate limiting both in the uplink (in the base station) and in downlink (in the ASN-GW).

4.2.4 CSN traffic and performance model

This section describes the dimensioning of the CSN elements including AAA servers, HA, DHCP and firewall. In dimensioning the mentioned elements, the node performance parameters are taken into account. This section also provides the description of the traffic and performance model of the HA, AAA servers, DHCP server and firewall.

Home Agent (HA)

The performance parameters for the HA are the Mobile IP (MIP) registration rate, binding capacity, throughput and packet rate. HA also generates accounting events that constitute additional load to the system. The MIP registration rate is the sum of the MIP registration due to powered on plus percentage of active subscribers in the R3 interface. HA also handles additional AAA authentication requests due to MIP renewal and R3 mobility.

The binding capacity is the number of subscriber stations in the CSN. With the number of subscribers in the R3 interface proportional to subscribers in the CSN, the binding capacity of HA results into 29,000 subscribers. In mobile WiMAX release 1.1 [28] ASN gateway does not support redundancy of the HA, therefore HA redundancy can depend on the redundancy of the deployed home agent only. Load sharing for the Home Agent is implemented by the following means:

- Dividing subscribers in groups and configuring different HA addresses for each subscriber group.
- AAA server assigns HA address out of pool of HA addresses in each access request.
- By implementing a mechanism in the AAA server to reply a different HA address depending on the HA load information.

AAA Server

The performance parameters for the AAA server are the database capacity for authorisation and accounting, authentication transactions and accounting transactions. The required database capacity for authentication is the number of all subscribers, 80,000. The required database capacity for accounting depends on the average size of the accounting ticket, the number of accounting transactions and the time that accounting ticket needs to be stored.

The accounting transaction load is the sum of accounting events due to powered on subscribers, subscribers in the R3 interface, MIP renewal and subscribers due to accounting update. An accounting update is triggered by an expiration of an accounting timer. As in HA, the redundancy depends on the redundancy of the AAA server.

DHCP server

The node performance parameter for the DHCP server is the number of transactions or requests. The DHCP is dimensioned according to the total number of DHCP requests during the busy hour with respect to its handling capacity in terms of requests per second. The transactions or requests occur during power on/off and in case of DHCP renewal. DHCP renewal depends on the configured DHCP renewal time.

Firewall

The firewall is dimensioned based upon the total required traffic during the busy hour with respect to the equipment processing capacity. The firewall is expected to be implemented on an “n+1” configuration running the Virtual Router Redundancy protocol (VRRP) for equipment redundancy and load sharing functionality.

4.2.5 Summary and conclusion

This chapter presented the dimensioning of the mobile WiMAX in the access and core network, using three regions; Helsinki, Espoo and Kirkkonummi as the case study for the deployment. In dimensioning the radio interface part of the mobile WiMAX, we observed that using licensed band 3.5GHz band for Helsinki and Espoo regions as well as 2×2 MIMO scheme resulted into a reasonable number of base stations required for coverage. Although the case study did not detail the optimum locations for the base stations, the number of base stations were determined so as to ensure that minimal cost is incurred during the deployment phase. This is achieved by optimising the link budget parameters, such as the number of subchannels, so as to achieve sufficient link margin. For the rural area, using the 1×2 SIMO scheme resulted into a bit lower link margin than to urban (Helsinki) and suburban (Espoo) , and consequently to fewer number of base stations.

The analysis presented in this chapter shows that deploying in the 2.5GHz band in the rural area resulted into fewer number of base stations compared to the case of 3.5GHz deployment despite the fact that it has the largest area size. This is because 2.5GHz band has smaller propagation losses than 3.5 GHz band and thus the base station signal propagates further. 2.5GHz is preferred in the rural area due to the probability of providing wide coverage without worrying much about capacity needs since we project few subscribers to be present. The total number of base stations required for ubiquitous coverage as well as addressing capacity needs is 85 for a metropolitan area of the size of 863 km^2.

It is also observed that the universal frequency reuse adopted in the case study provides the highest per sector average throughput but it does so while sacrificing the performance at the cell-edge. Although frequency reuse of 3 achieves an acceptable level of user data rate at the cell-edge, it is not preferred since there is a limited amount of spectrum. In order to efficiently address the capacity needs, the MIMO and SIMO schemes with sufficiently high spectral efficiency (averaged over 1.7bps/Hz) are selected.

The choice of 10MHz channel bandwidth is based on achieving higher capacity per sector, since taking into account the spectral efficiency, the higher the channel bandwidth the greater the capacity.

In dimensioning WiMAX network, we observed that the elements ASN-GW and in the CSN, are dimensioned based upon the traffic estimation that is a result of downlink data density requirements. The projected downlink data density requirements and the traffic load by powered on subscribers are fulfilled by selecting the appropriate antenna technologies and core network elements. The study showed that with careful determined data density requirements in the regions selected for the deployment, suitable antenna technologies can be selected that will result into a capacity across R6 interface that supports the offered load. Equipments pertaining to the HA, DHCP, AAA servers are selected based upon the number of subscribers, and their processing capacities against the number of transactions or requests per second. These nodes are essential for providing access control and authorising entry to the use of the mobile WiMAX services, and therefore it is important that careful selection be performed. From the QoS point of view, we observed that the mobile WiMAX network gives an operator the ability to select QoS classes that are suitable for the type of services expected to be offered.

5 Conclusions and Future work

Despite the advantages that WiMAX technology offers during deployment, it requires careful dimensioning and eventually planning in the access and core part of the network so that the estimated downlink data density requirements are fulfilled. Aspects of the access network such as link budget calculation, antenna configurations and frequency reuse schemes, need to be carefully performed. The study showed that by optimising the link budget parameters such as the number of transmitting antennas and number of sub-channels both for the uplink and downlink, the cell radius is increased leading to few number of base stations. This translates to significant cost savings as base station infrastructure costs amount to a high value on the overall end-to-end investment. Using the universal frequency reuse scheme ensures an effective use of the available spectrum but sacrifices the cell edge performance.

The study showed that, when deploying a mobile WiMAX network in a low density area such as Kirkkonummi, 1×2 SIMO scheme is a good choice. With this scheme, the resulting cell radius leads to fewer base stations needed than in the case of 2×2 MIMO scheme. It is also observed that 1×2 SIMO and 2×2 MIMO schemes are good choices for range limited deployment and as such can be used to get ubiquitous coverage over the metropolitan area. Although 2×2 MIMO scheme in Helsinki resulted into fewer base stations than other regions in such a densely packed environment, upgrades to the base stations configurations with adaptive beamforming technique can help meet the capacity requirement.

Based on this study, it is worth noting that the increase in the number of expected customers will lead into an increase in the downlink data density requirements. This has a consequence on the antenna configurations that are to be used for the base stations. From the network point of view, the increase in the number of customers will lead into increase in the number of base stations and consequently the number of ASN-GWs.

When selecting the CSN elements (HA, AAA server, DHCP server, and firewall) for the deployment, the operator has to make sure that their processing capacities take into account the increase of customers.

From the ASN QoS point of view, we observed that mobile WiMAX provides an operator the flexibility in choosing the QoS model that can suit the type of services that he expects to offer. This allows the operator to deliver the broadband service with an acceptable quality as agreed on the service level agreement.

It is expected that the knowledge gained on dimensioning mobile WiMAX can be transferred to deploy similar technology in developing country such as Tanzania. The three regions (Helsinki, Espoo and Kirkkonummi) compare fairly well in terms of population density to the Tanzanian capital of Dar es Salaam. Dar es Salaam city is made up of three districts (Ilala, Kinondoni, and Temeke) with the total land area of 1590 km^2 and population density of approximately 1500 people per km^2.

However there is still further research that needs to be done, and below is a list of areas for further work:

- Actual radio network planning taking into account taking into account environmental factors such as terrain, topography and morphology.
- Actual transmission network planning specifying the optimum locations for the base stations sites, and topology to be used. This task also involves site surveys, equipment selection, selection of the transmission medium (radio, optical cables or leased lines) leading to a final network design.
- IP planning so as to determine how to set up correct IP addresses to all the elements in the core service network. This will enable end-to-end IP connectivity for the user sessions.

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Appendix A

COST-231 Hata Model

This is an extended pathloss model of the widely used Hata propagation Model. It provides an expression for the median pathloss as a function of carrier frequency, base station and mobile station antenna heights, and the distance between the base station and the mobile station. The model is given by the following formula:

$$PL = 46.3 + 33.9log_{10} f – 13.82log_{10} h_b + (44.9 – 6.55log_{10} h_b)log_{10} d – a(h_m) + C_F$$

The MS antenna-correction factor, $a(h_m)$, is given by

$$a(h_m) = (1.11log_{10} – 0.7)h_m – (1.56log_{10} f - 0.8),$$

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 metres, and d is the distance between the base station and mobile station in km. For urban and suburban areas, the correction factor C_F is 3dB and 0dB respectively.

The model is valid for the following range of parameters:

- 150MHz $\leq f \leq$ 2000MHz
- 30m $\leq h_b \leq$ 200m
- 1m $\leq h_m \leq$ 10m
- 1km $\leq$ d $\leq$20km

Erlang C formula

The erlang C formula calculates the probability of queuing *Pc* for traffic *T* with the amount of channels *C*. The traffic is given in Erlangs. The formula calculates the probability that the user has to wait to be served.

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