WIMAX PERFORMANCE ANALYSIS IN A SELECTED RURAL AREA IN SOUTH AFRICA

By

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DISSERTATION TITLE

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ABSTRACT

Bringing broadband access to rural and remote communities has been a very difficult task due to the high cost of installation and complete lack of infrastructure in certain areas. Options currently under serious consideration to enable this access have included GSM, CDMA, Power line telecommunications, and DSL technologies. However, with the addition of the IEEE 802.16 standard - commonly referred to as WiMAX – with its various advantages, another serious option is now being considered. WiMAX is standard developed to provide wireless broadband access to metropolitan area networks. It is capable of providing LOS and NLOS coverage in the range of 3-50 km with data rates up to 75 Mbps.

This research therefore looks at the WiMAX standard MAC and PHY layers with special focus on the PHY layer properties enabling provision of NLOS coverage (WirelessMAN OFDM PHY). The research evaluates the performance of WiMAX in a rural environment in terms of coverage and traffic analysis. Other aspects include multipath fading and channel estimation. The traffic analysis is carried out using traffic projection formulated over a period of ten years for Nkandla, a typical rural area in South Africa. This is done to evaluate the sustainability of the designed base stations over the ten-year period with the growing traffic.

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KEY CONCEPTS

Broadband service	Data service offering data rates of at least 256 kbps in both upstream and downstream directions
Fixed wireless access	Wireless access application in which the location of the end-user terminal and the network access point are fixed
IEEE 802.16-2004	Technical standard for fixed wireless access networks
Non-line-of-sight	Condition where a radio link between a transmitter and a receiver is obstructed by e.g. buildings or vegetation
Point-to-multipoint	Network topology in which a single network access point communicates directly with multiple end-user terminals
WiMAX Forum	Non-profit organization that promotes the deployments of fixed wireless access networks and certifies products conforming to the IEEE 802.16a standard

ACRONYMS

ARQ	Automatic Repeat Request
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
BPSK	Binary Phase Shift Keying
BRAN	Broadband Radio Access Network
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
DLC	Data Link Control (layer)
DOCSIS	Data-Over-Cable Service Interface Specification
DSL	Digital Subscriber Line
EIRP	Effective Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FSK	Frequency Shift Keying
HIPERLAN	High Performance Radio Local Area Network
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication sector
ISO	International Organization for Standardization
LAN	Local Area Network
LLC	Logical Link Control (layer)
LMSC	(IEEE 802) LAN MAN Standards Committee
LOS	Line-Of-Sight
MAC	Medium Access Control
MAN	Metropolitan Area Network
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency Division Multiplexing

OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PC	Personal Computer
PHY	Physical Layer
PMP	Point-to-multipoint
PSK	Phase Shift Keying
PTP	Point-to-point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RLAN	Radio Local Area Network
STC	Space Time Code
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TG	Task Group
WG	Working Group
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

1. INTRODUCTION

This chapter gives a brief background on the motivation of this thesis work together with the objectives of the study. Finally the structure of the thesis is presented.

1.0 The Rural Telecommunication Scenario

In most of the rural areas in South Africa, wired infrastructures for the delivery of residential and business broadband do not exist. In order to extend broadband communications to our rural areas service providers must establish a new infrastructure from the ground up, which would be a very costly affair. This is largely due to the fact that most of the rural areas in South Africa have low population densities hence telecommunication infrastructure would have to cover large distances between users. This means that a larger quantity of cable or fibre would be required, thereby drastically increasing the costs incurred compared to urban areas or population centers. Also the terrain characteristics of many of the rural areas make it difficult for service providers to set up infrastructure; for example laying cable or fibre in hilly, mountainous areas with thick dense vegetation is most cumbersome. Furthermore provisioning telecommunication services for rural areas poses a high investment risk for service providers since many of the individuals living in rural areas earn their living from subsistence farming and have low and seasonal incomes thus resulting in very few subscribers.

Some of the possible fixed broadband access technologies that have been considered as possible solutions include Digital Subscriber lines (DSL), Power Line Communications, Fibre Optics and Cable networks. However all of these technologies are plagued with high cost of installation, low scalability and limited range which makes them unsuitable for rural areas. This has been the major contributing factor that has led to the low density of telecommunication services in South Africa today. However with the introduction of the IEEE 802.16 family of Standards, another serious option can now be considered.

The IEEE 802.16 Family of standards, otherwise known as WiMAX (Worldwide Interoperability of Microwave Access), is a revolutionary new technology designed to provide fixed broadband wireless access (FBWA) to large metropolitan area networks (MANs). WiMAX networks provide line-of-sight (LOS) and non-line-of-sight (NLOS) coverage in the range of 3-50 km with data rates up to 75Mbps.

These attributes thus make it particularly beneficial to rural areas, since no major infrastructure is then required.

WiMAX networks may very well mark the beginning of a new era for the rapid growth of broadband services in South Africa.

1.1 Purpose and Objectives of the Thesis

The objectives of this thesis are as follows:

- Firstly to study the IEEE 802.16-2004 standard with special focus on the OFDM wirelessMAN physical (PHY) layer that enables non-line-of-sight coverage and the Medium Access Control (MAC) Layer.
- Secondly to evaluate the performance of WiMAX in a typical rural area in terms of coverage and capacity.
- Finally to ascertain whether or not using WiMAX in rural area is a feasible solution in terms of sustainability.

1.2 Own Contribution

WiMAX's wireless nature and other features make it particularly beneficial to rural areas. This has led to a growing interest in WiMAX technology as a means of providing broadband services to rural areas. Regardless of this detailed procedures for coverage and capacity performance evaluation of WiMAX networks in rural areas are not clearly covered in the literature. This is largely due to the fact that coverage prediction models suitable for frequencies ranging from 2 GHz – 6 GHz are not currently available. Also the IEEE 802.16 family of standards (WiMAX) fails to provide a clear description of the quantitative influence of system parameters on the performance of the network.

This thesis provides a means of performing coverage evaluation of WiMAX networks in rural areas, based on the most appropriate coverage models currently available and the key system characteristics of the IEEE 802.16-2004 standard. The influence that system parameters have on the performance of the network is also incorporated in the study.

1.3 Structure of Thesis

Chapter 2 provides a background on the evolution of the WiMAX standards, together with a brief description of each of the IEEE 802.16 standards developed so far. Some of the features and applications of the most recently developed IEEE802.16-2004 standard for fixed wireless access are also presented.

In Chapter 3 the RF characteristics of the IEEE 802.16-2004 standard is discussed. Some of the aspects discussed are as follows: reflection, diffraction, refraction, network topology, multiple access techniques, duplexing techniques, frequency band selection and its modulation and coding characteristics.

Chapter 4 provides an overview of 802.16-2004 OFDM PHY layer specification that enables NLOS operation in the 2-11 GHz frequency band. It begins with a discussion of OFDM modulation and then moves on to provide a detailed description of each base-band building block used in the physical specification. A brief summary of the RF band is also provided.

In chapter 5 the architecture of the IEEE 802.16 MAC layer is discussed and an overview of each of its functions is provided. The network entry process, PDU creation, and service classes are discussed in detail.

In chapter 6 a performance analysis of WiMAX in rural South Africa is carried out. The capabilities of WiMAX networks in terms of coverage and capacity are evaluated in two ways: firstly by means of an analytical model and secondly by simulating a WiMAX network in a typical rural area. The results obtained from the simulation are compared with the analytical results to ascertain which path loss model provides a better coverage prediction for rural areas. The influence that system parameters have on the coverage and capacity of the network is also investigated.

2. IEEE 802.16 FAMILY OF STANDARDS

This Chapter provides a background on the evolution of the WiMAX standards, together with a brief description of each of the IEEE 802.16 standards developed so far. Some of the features and applications of the most recently developed IEEE 802.16-2004 standard for fixed wireless access are also presented.

IEEE 802.16 family of Standards was developed by the IEEE 802 LAN MAN Standards Committee. The IEEE 802.16 LAN MAN Standards Committee was formed by the Institute of Electrical and Electronic Engineers (IEEE) to develop air interface standards for wireless Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Personal Area Networks (PANs). Projects currently overseen by the committee include [1]:

- IEEE 802.16 wireless MAN standards – designed to support high-rate broadband wireless access (BWA) services to subscriber stations from central base stations
- IEEE 802.11 wireless LAN standards – designed to support users roaming within homes, office buildings, campuses, hotels, airports, restaurants cafes, etc.
- IEEE 802.15 wireless PAN standards – deigned to support short-range links among computers, mobile telephones, peripherals, and other consumer electronics that are worn or carried.

2.1 The IEEE Standards Association

The IEEE is a non profit organization dedicated to the development of telecommunications standards. The standardization program is carried out through the IEEE Standards Association (IEEE-SA). The IEEE-SA oversees the standardization process through the IEEE-SA Standards Board. Project development is delegated to individual standard sponsors that are generally units of the IEEE's technical societies. One of the most important of the IEEE-SA sponsor groups is the IEEE 802 LAN MAN Standards Committee [1].

2.2 IEEE 802 LAN MAN Standards Committee

The IEEE 802 LAN MAN committee formed in 1980 is sponsored by the IEEE computer society. It develops and maintains standards for the lowest layers of the open systems interconnection (OSI) reference model i.e. the physical layer (PHY) and the data link layer (see Figure 2.1). The OSI model is a standard of the international standards organization (ISO).

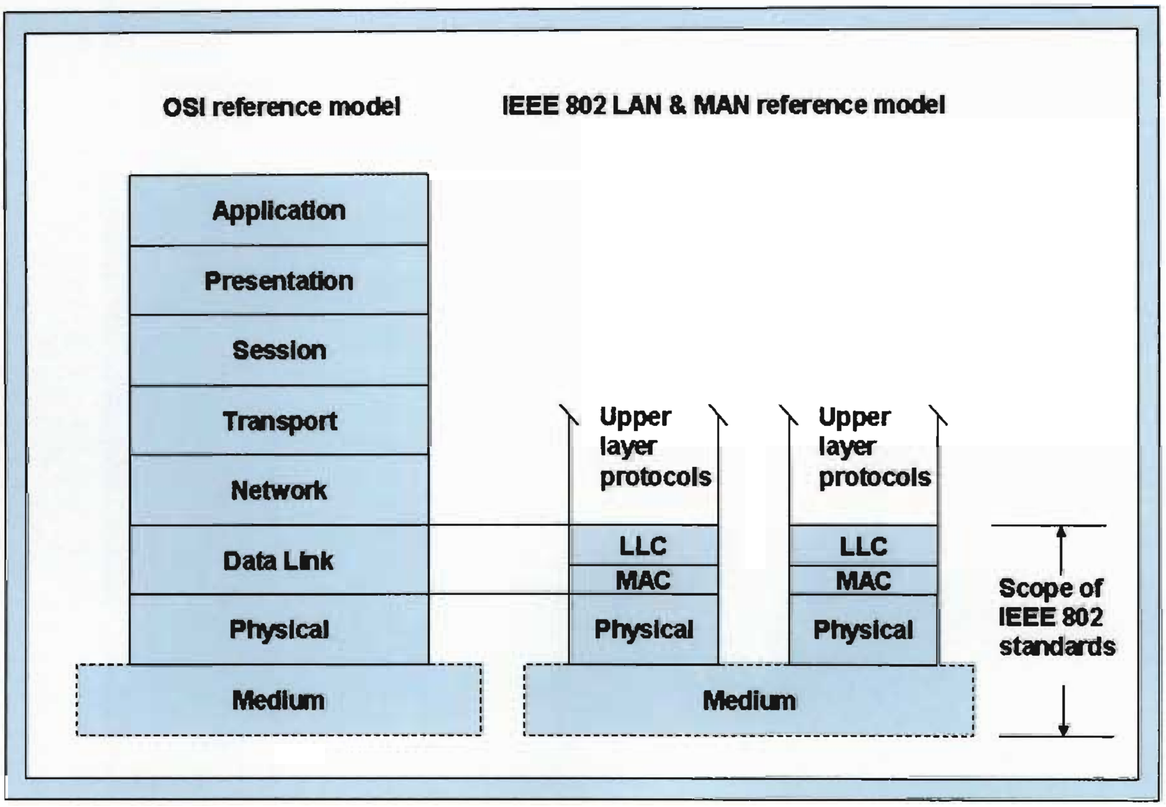

Figure 2.1: IEEE 802 LAN & MAN reference model [2]

The data link layer is divided into 2 sub-layers, the logical link control (LLC) layer and the medium access control layer (MAC layer). The LLC operates over the MAC layer and is common for all IEEE 802 Standards.

2.3 IEEE 802 Standardization Process

The standardization process adapted by the IEEE ensures the quick development of standards. The process comprises the following steps:

- The formation of a study group to revise the prospects for a standard in a field and potentially to develop a project authorization request (PAR) requesting IEEE-SA approval of a new project.
- Assigning each new approved project to an existing or new working group. Working groups are made of a number of highly skilled individuals chartered with the task of developing the standard.
- Developing the initial draft.
- Obtaining a working group letter ballot –a voting procedure whereby each working group member votes on whether or not he/she believes that the technical aspects of the standard are sound or if more work is required. An approval rate of 75% is required to pass the standard.
- Sponsor ballot – a voting procedure whereby a broad group of interested individuals vote on whether or not they believe the standard is adequate or not.

The IEEE 802 development process takes into account the constructive suggestions made by each working group member and interested party during the ballot process thereby ensuring the continual improvement of the standard. In this way the IEEE ensures that the draft is passed through the system within a reasonable time [1].

2.4 IEEE 802 Wireless Standards Program

The IEEE 802 Wireless Standards Program is made up of three working groups [1]:

- IEEE 802.11 working group develops the IEEE 802.11 standards for wireless LANs
- IEEE 802.15 working group develops the IEEE 802.15 standards for wireless PANs
- IEEE 802.16 working group develops the IEEE 802.16 standards for wireless MANs

The working groups work in loose association to co-ordinate their activities especially for the unlicensed bands. For the purpose of this thesis only the IEEE 802.16 and the IEEE 802.11 working groups will be considered.

2.4.1 IEEE 802.11 Wireless LANs

The IEEE 802.11 working group develops standards for wireless LANs. Wireless LANs are used as extensions or replacements for traditional wired LANs which feature indoors. The first IEEE 802.11standard was ratified in 1997, and since then several new updates of the standard have been developed with new PHY layer specifications and an enhanced MAC. The original IEEE 802.11 standard has three PHY specifications and can achieve data rates up to 2Mbps. The updated versions of the standards; 802.11b, 802.11a, and 802.11g can achieve data rates from 11-54Mbps.

Standard	**Ratified**	**Frequency Range**	**Data Rate - typical (Mbits/s)**	**Data rate - MAX (Mbits/s)**	**Range - (Meters)**
IEEE 802.11	1997	2.4-2.5 GHz	2	2	<50
IEEE 802.11a	1999	5.15-5.35/5.47-5.725/5.725-5.875 GHz	25	54	50
IEEE 802.11b	1999	2.4-2.5 GHz	6.5	11	100
IEEE 802.11g	2003	2.4-2.5 GHz	25	54	100

Table 2.1: IEEE 802.11 Family of Standards [2]

The original IEEE 802.11 MAC layer specification is based on a Carrier Sense Multiple Access with collision Avoidance (CSMA/CA) multiple access scheme; thus a significant percentage of the available raw channel capacity is sacrificed in order to improve the reliability of data transmissions under harsh environmental conditions. The medium access is contention based and connectionless, and does not support any QoS mechanisms or traffic differentiation. Also the security mechanisms of the original MAC layer are flawed. The QoS and security mechanisms have been enhanced by 802.11e and 802.11i working group respectively [2].

2.4.2 IEEE 802.16 Broadband Access Standards

Historically the activities which led to the development of the IEEE 802.16 family of standards were initiated in 1998 at the IEEE Radio and Wireless Conference. The conference was organized by the National Wireless Electronics Systems Test-bed (N-West) of the United States (U.S.) National Institute of Standards and Technology to kick off the development of the IEEE 802.16 standards.

The IEEE 802.16 working group began work on the original IEEE 802.16 standard in July 1999 and two years later in December 2001 the first draft of the standard was released. However the final version was only published on April 8th, 2002. The spectrum range of this standard is 10-66 GHz. It consists of one PHY specification based on single carrier modulation and requires line-of-sight (LOS) propagation. From then several more updates to the standard have been developed, namely 802.16c, 802.16a, 80216d/2004 and 802.16e. .

a) IEEE 802.16c

This standard was approved in December 2001. It included detailed system profiles for the 10-66 GHz range. With the 802.16, there was a great deal of options available to vendors in general; this made it hard for vendors to compete and have a profitable business. So with the 802.16c the system profile methodology evolved to define what would be mandatory features and what would be optional features. This task was undertaken by the WiMAX forum with the intention of providing vendors with guidelines on the mandatory elements that must be met to ensure interoperability. Optional elements such as different levels of security protocols incorporated gave vendors a chance to differentiate their products by price, functionality and market role [5].

b) IEEE 802.16a

The 802.16a update added support for the spectrum range of 2 GHz to 11 GHz. The standard addresses both licensed and unlicensed ranges. It also has non-line-of-sight (NLOS) capability. This version has enhanced medium access control (MAC) layer capabilities such as improved quality of service (QOS) features. The standard provides support for three PHY layer specifications. Support for time division duplexing (TDD) and frequency division duplexing (FDD) are also incorporated, and, in the case of FDD, provisions are also made for both half duplex and full duplex data transmission. Transmission protocols such as Ethernet, ATM or IP are supported [5].

c) IEEE 802.16-2004(d)

The IEEE 802.16-2004 comprises all of the fixed WiMAX standards mentioned thus far. It is made up of the original 802.16 developed for operation in the frequency range from 10-66 GHz, 802.16a developed for operation in the frequency range from 2-11 GHz and the 802.16c updates for the 10-66 GHz spectrum range. It is the final standard developed so far for fixed broadband wireless access (BWA). This standard supports data rates of up to 75Mbps, with each base station covering a radius of 3 to 50 km.

The technology supports both TDD and FDD and several PHY layer specifications. The multiple versions of PHY layer are listed below [5]:

- WirelessMAN-SC: based on single-carrier modulation, designed to support LOS operation in the 10 to 66 GHz frequency range.
- WirelessMAN-SCa: based on single-carrier modulation, designed to support NLOS operation for frequencies below 11 GHz.
- WirelessMAN-OFDM: based on orthogonal frequency division multiplexing (OFDM), with a 256 point transform. This air interface is mandatory for license-exempt bands. It is designed for NLOS operation in the frequency bands between 2-11 GHz.
- WirelessMAN-OFDMA: based on an Orthogonal Frequency Division Multiple Access (OFDMA). This version supports NLOS operation in frequencies below 11 GHz.
- WirelessHUMAN: based on a flexible channelization scheme, which includes 10 and 20 MHz channels, with 5 MHz spacing. This version is named "High-speed Unlicensed Metropolitan Area Network" (HUMAN), as it supports functionalities for operation in license-exempt frequencies. It can operate at frequencies between 5 and 6 GHz,

The multiple PHY layer specifications render the IEEE 802.16 standard flexible in terms of operation frequency, supporting both licensed and license-exempt bands.

Some of the MAC enhancements included in this version are as follows: support for concatenation of both protocol data units (PDU) and service data units (SDU) which reduces the MAC overhead, improvements in the quality-of-service (QOS), particularly with very large SDUs, and the ability to perform polling individually or in groups. This version of the MAC can access allocated bandwidth to make requests, or signal that it needs polling. It can even piggyback polling requests over other traffic thereby reducing packet collisions and system overhead [5].

d) IEEE 802.16e

IEEE 802.16e conserves the technical updates of fixed WiMax while adding robust support for mobile broadband. It is based on orthogonal frequency division multiple access (OFDMA) technology. This OFDMA technique supports 2k-FFT, 1k-FFT, 512-FFT and 128-FFT. The OFDMA system allows signals to be divided into many lower-speed sub-channels to increase resistance to multi-path interference. For example, if a 20 MHz channel is subdivided into 1000 sub-channels, each individual user would be allowed a dynamic number of sub-channels based on their distance and needs from the cell (i.e. 4, 64, 298, 312, 346, 610 and 944). If closer to the BS, a higher modulation methodology such as 64 quadrature amplitude modulation (QAM) can be used for higher bandwidth across more channels. If the user is farther away, the number of channels can be reduced with a resultant power increase per channel. Throughput reduces a bit, but distant users are not dropped [5].

The IEEE 802 maintains close working relationship with standards bodies in the International Telecommunications Union (ITU) and the European Telecommunications Standards Institute (ETSI), particularly with the HIPERACCESS and the HIPERMAN programs of the ETSI's Broadband Radio Access Networks (BRAN) project. ETSI is an independent, non-profit organization, dedicated to the development of telecommunications standards.

The HIPPERACCESS standard is designed for fixed wireless access (FWA) networks operating in the frequency range above 11GHz. It is similar to the original IEEE 802.16 standard. The working bandwidth of this standard is the 40.5-43.5 GHz band.

The HIPPERMAN standard is designed for FWA networks operating in the frequency range below 11GHz. The standard is interoperable with the IEEE802.16a standard. It operates primarily on a point-to-multipoint basis with additional support for mesh and can provide non-line-of-sight coverage.

ATTRIBUTES		**STANDARDS**	
	IEEE 802.16	**IEEE 802.16a/2004**	**IEEE 802.16e**
Completed	Dec 2001	802.16a: 01/03 802.16-2004: 06/04	2nd half of 2005
Spectrum	10-66Ghz	<11GHz	<6GHz
Channel Conditions	LOS only	NLOS	NLOS
Bit Rate	32-134Mbps at 28MHz BW	Up to 75Mbps at 20MHz BW	Up to 15Mbps at 5MHz BW
Modulation	QPSK, 16-QAM, 64-QAM	OFDM 256, OFDMA 64-QAM, 16-QAM, QPSK, BPSK	Same as 802.16d
Mobility	Fixed	Fixed and portable	Mobility , Regional Planning
Channel Bandwidths	20,25 and 28MHz	Selectable channel BW Between 1.25 and 20MHz	Same as 802.16d
Typical Cell Radius	1-3 miles	3-5miles	1 to 2 miles

Table 2.2 : IEEE 802.16 Family of Standards [6]

2.5 The WiMAX Forum

In order for a market to be truly enabled, products must be certified that they do adhere to the standard first, and once certified it must also be shown that they interoperate. For the IEEE 802.16 family of standards, this role is played by the Worldwide Interoperability for Microwave Access (WiMAX) Forum [5].

The WiMAX Forum is a non-profit industry trade organization established in 2001. Its main function is to promote the adoption of the IEEE 802.16 family of standards by assuring interoperability between system components. Interoperability means the end user can buy the brand they like, with the features they want, and know it will work with all other like certified products.

The WiMAX forum develops conformance and interoperability test plans, selects certification labs and hosts interoperability events for IEEE 802.16 equipment vendors. By defining and conducting interoperability testing, and by awarding vendor systems a "WiMAX Certified™" label, the WiMAX Forum will model the approach pioneered by the WiFi Alliance that ignited the wireless LAN industry, bringing the same benefits to the BWA market segment [7].

2.6 Applications of the IEEE 802.16 Family of Standards

WiMAX MAN (see Figure 2.2) is based on the IEEE 802.16 family of standards; it is suited for number of BWA applications including: provisions for high capacity "last mile" wireless communication for the carriers of service providers around the world; residential broadband access; T1/E1 level services for enterprise- all of which support both video and voice; wireless backhaul for hotspots; and cellular tower backhauls and rural connectivity [8].

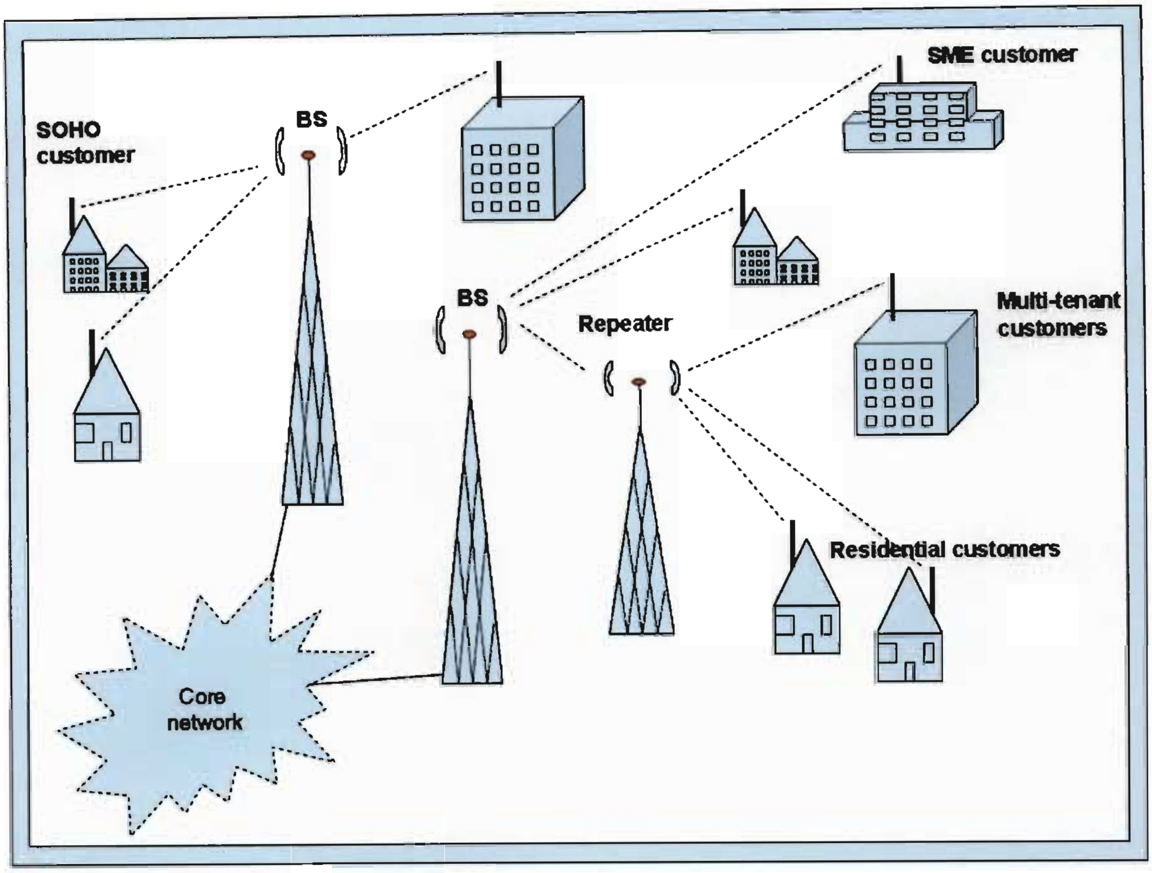

Figure 2.2: WiMAX Metropolitan area network (MAN)

a) Last mile connectivity

The growing demand for fast, low latency, broadband communications to homes and businesses has made cost effective information distribution and delivery increasingly important. As demand has escalated, the need for cost effective broadband access technologies by end-users located at millions of locations has also increased, thereby rendered existing systems inadequate [9]. This problem has been termed "The Last Mile Problem". However with the introduction of WiMAX a possible solution for providing "last mile" connectivity is now available. Because of its wireless nature, high data rates, and NLOS capabilities, WiMAX will provide a cost effective solution for homes and business users. Even in areas where no infrastructure is available, WiMAX could allow access to all users within range of the base station.

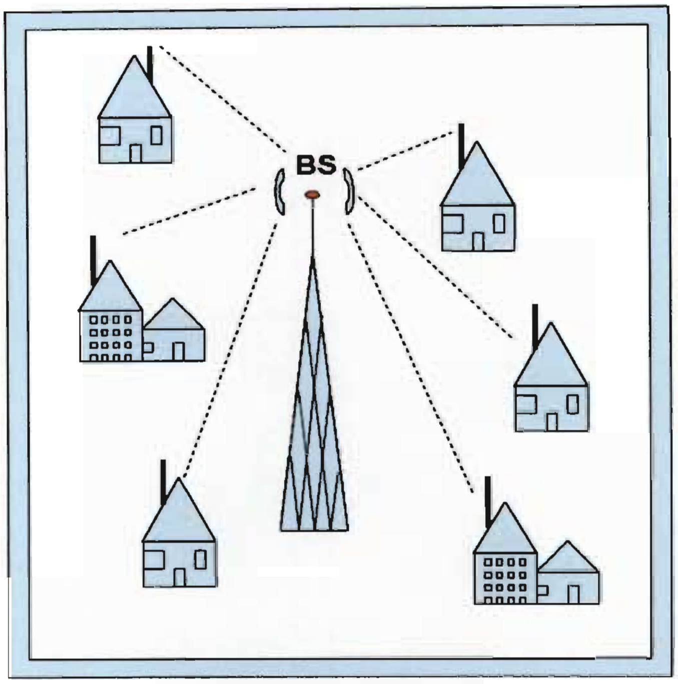

Figure 2.3: 'Last mile' wireless access using WiMAX

b) Cellular Backhaul

As competition in the cellular market rises, cellular operators are constantly looking for ways to reduce operating costs. Backhaul is one of the most significant costs incurred by cellular operators; it makes up about one-fifth of the overall mobile network cost. Backhaul is the network component that connects the subscriber access section of the network with its core switching and management elements. In order to reduce costs, cellular operators can use WiMAX equipment to backhaul BS traffic to their Network Operation and Switching Centers (NOSC) (see Figure 2.4). This is the case since WiMAX can provide Point-to-Point links of up to 50 km, with data rates capable of supporting multiple E1/T1s and the QoS features of WiMAX is highly suited for cellular traffic [9, 10].

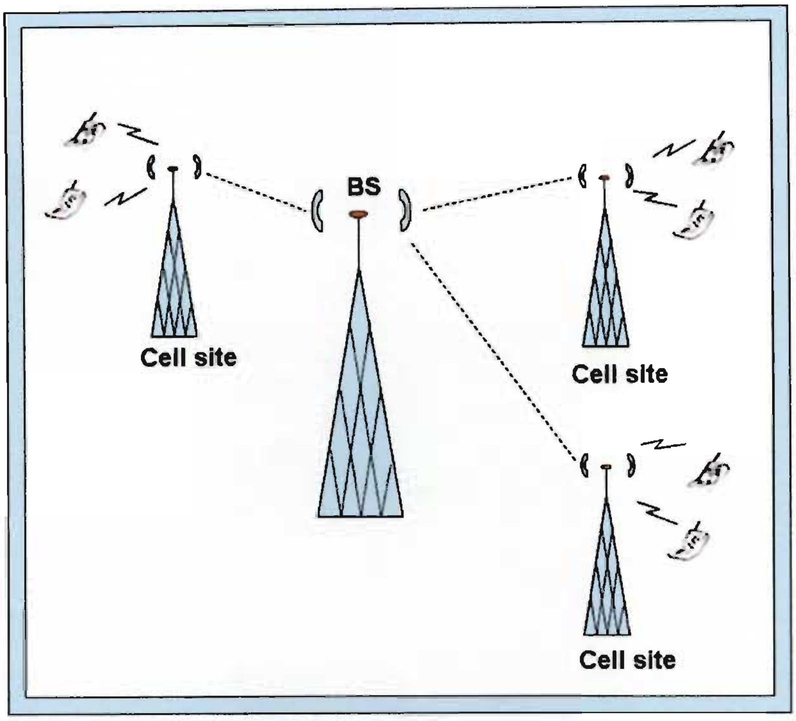

Figure 2.4: Cellular Backhaul using WiMAX

c) Wireless Service Provider Backhaul (Hotspots)

Wireless Service Providers (WSPs) use WiMAX equipment to backhaul traffic from BSs in their access networks. Access networks may be based on WiFi, WiMAX or any proprietary wireless access technology. If the access network uses WiFi equipment, the overall WSP network is referred to as a Hot Zone. Since WSPs typically offer voice, data and video, the built-in QoS feature of WiMAX will help prioritize and optimize the backhauled traffic. WiMAX equipment can be deployed quickly, facilitating a rapid rollout of the WSP network [10].

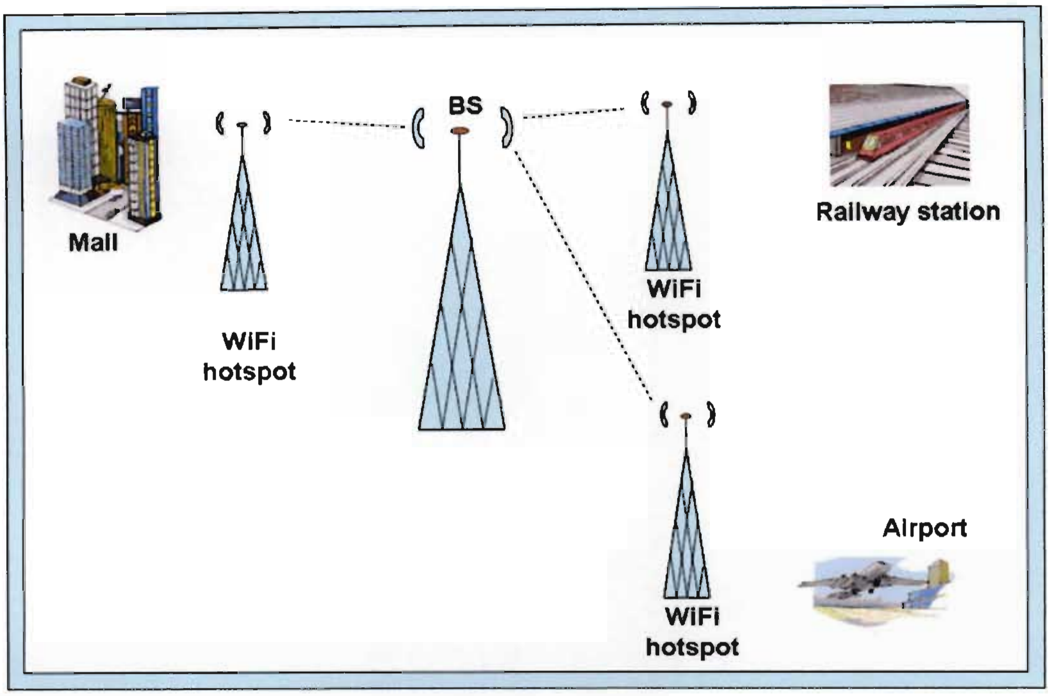

Figure 2.5: WSP Backhaul using WiMAX

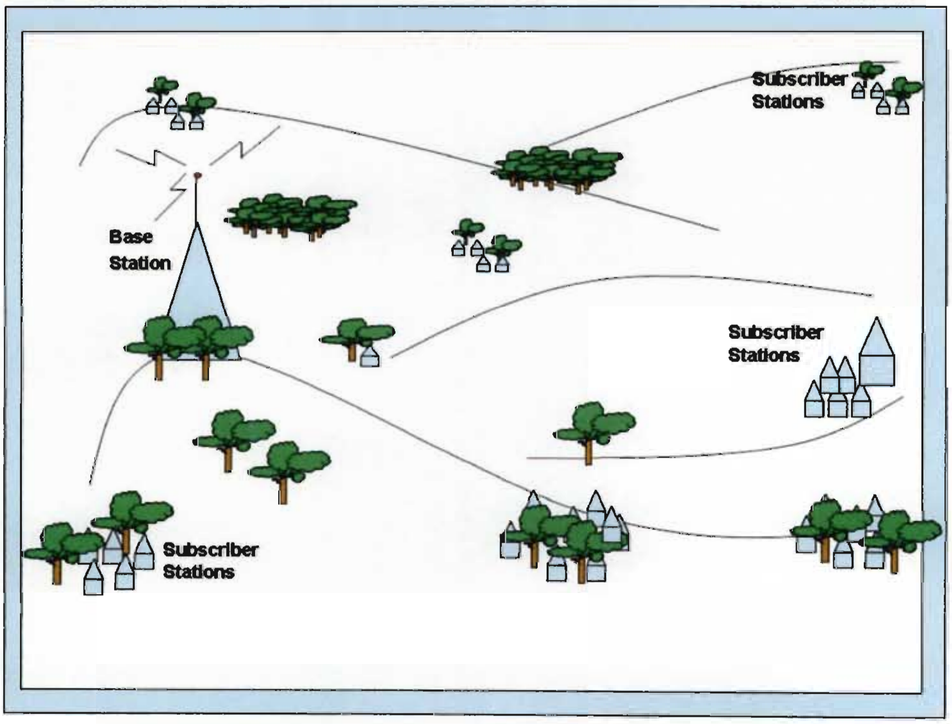

Figure 2.6: Rural Connectivity using WiMAX base stations

d) Rural Connectivity

Service providers can use WiMAX networks to deliver broadband services to underserved markets in rural areas and the suburban outskirts of cities, (see Figure 2.6). The delivery of rural connectivity is critical in many developing countries and underserved areas of developed countries, where little or no infrastructure is available. Rural connectivity delivers much-needed voice telephony and Internet service. Since the WiMAX solution provides extended coverage, it is a much more cost-effective solution than wired technology in areas with low population densities. WiMAX solutions can be deployed quickly, providing communication links to these underserved areas, providing a more secure environment, and helping to improve local economies [10].

2.7 Chapter Summary

This chapter aims at providing the reader with a brief overview of the IEEE 802.16 standards. The chapter begins by outlining the structure of the IEEE 802.16 (WiMAX) standards. It then moves on to provide vital information on the origin and evolution of the WiMAX standards to date. Finally the chapter discusses some of the various applications that WiMAX is suitable for.

3. RF Channel Characteristics

In this Chapter the RF characteristics of the IEEE 802.16-2004 standard are discussed. Some of the aspects discussed are as follows: diffraction, refraction, reflection, network topology, multiple access techniques, duplexing techniques, frequency band selection, and modulation and coding characteristics.

3.1 RF Characteristics

As radio waves travel through a medium they interact with objects within the medium. This interaction causes the radio signals to be reflected, refracted, diffracted or absorbed and hence change direction. This change in direction makes it possible for the radio signals to reach areas that are not within its line-of-sight.

3.1.1 Refraction

When radio signals move from one area of refractive index to another they change direction. This change in direction is referred to as refraction. The angle of incidence and the angle of refraction are linked by Snell's Law that states [11]:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{3.1}$$

Where:

- n is the refractive index
- θ is the angle of incidence

For radio signals there are not many instances when the signals move abruptly from a region with one refractive index, to a region with another. It is more likely that the change is gradual. This causes the direction of the signal to bend rather than undergo an immediate change in direction [11]. So the path traveled by the radio signal appears curved rather than straight. This phenomenon increases the coverage area of the transmitter.

3.1.2 Diffraction

When radio signals meet an obstruction, they have a natural tendency to bend around it. This bending is referred to as diffraction. It occurs towards the edge of the obstruction where the radio waves are scattered. This process makes it possible to receive radio signals when the line-of-sight condition is not satisfied. This is referred to as non-line-of-sight (NLOS) propagation.

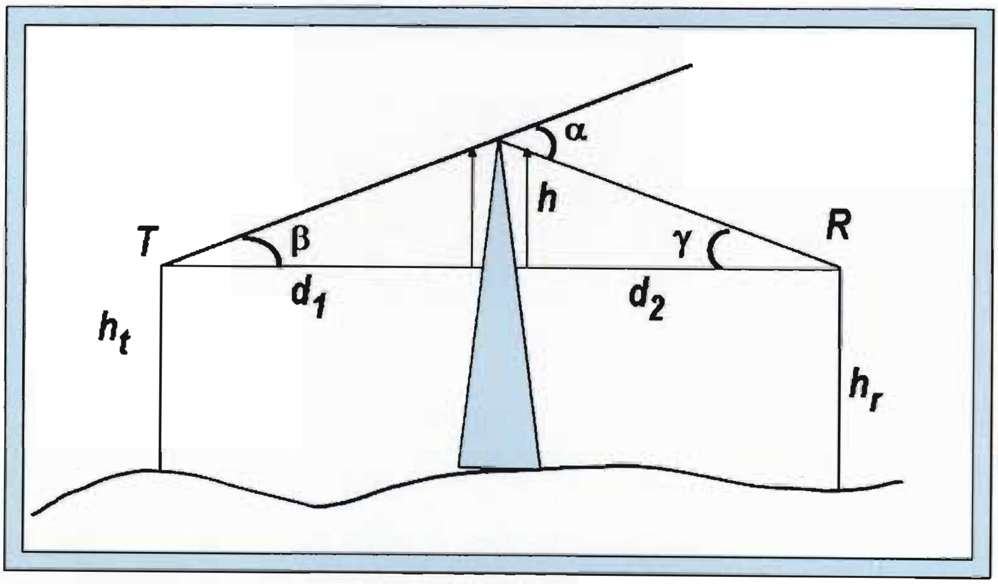

Figure 3.1: Knife–Edge Diffraction Geometry

The difference between the direct and diffracted path is referred to as the excess path length (Δ), calculated as follows [12]:

$$\Delta \approx \frac{h^2(d_1 + d_2)}{2d_1d_2} \tag{3.2}$$

Where:

- d_1 is the distance from the transmitter to the obstruction
- d_2 is the distance from the receiver to the obstruction
- h is the height of the obstruction above the direct line of sight between the receiver and the transmitter

The corresponding phase difference is given by:

$$\varphi = \frac{2\Pi\Delta}{\lambda} \qquad (3.3)$$

Where:

- c is the speed of light
- f is the frequency, $\lambda = \frac{c}{f}$ and

$$\alpha \approx h\frac{d_1 + d_2}{d_1 d_2} \qquad (3.4)$$

- Then the Fresnel- Kirchoff Diffraction parameter v is given by:

$$v = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1 + d_2)}} \qquad (3.5)$$

- v is used to determine the diffraction loss

3.1.3 Reflection

Reflection occurs when a radio wave propagating in one medium impinges upon another medium having different electrical properties. The wave is partially reflected and partially transmitted. If the plane wave is incident on a perfect dielectric, part of the energy is transmitted into the second medium and part of the energy is reflected back into the first medium. No energy is absorbed [12].

If the second wave is a perfect conductor, then all incident waves are reflected back into the first medium without loss of energy. The electric field intensity of the reflected and transmitted waves maybe related to the incident wave in the medium of the origin through the Fresnel reflection coefficient (Γ). The reflection coefficient is divided into two: the parallel and perpendicular polarization [12]:

$$\Gamma_{11} = \frac{-\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}{\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}, \tag{3.6}$$

and

$$\Gamma_{\perp} = \frac{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}} \tag{3.7}$$

Where:

- ε_r is the relative permeability
- θ_i is the incident angle of the second medium .

3.2.1 Line-of-Sight Propagation

Line-of-sight (LOS) propagation occurs in wireless communications when a signal travels over the air from a transmitter to a receiver without encountering any obstructions. It is the ideal case for wireless communications since the only difficulties the signal experiences comes from weather, atmospheric parameters and the characteristics of its operating frequency [11]. LOS systems provide better coverage and higher throughput.

3.2.2 Non-Line-of-Sight (NLOS) Propagation

Non-line-of-sight (NLOS) propagation in wireless communications occurs when a signal from a transmitter passes several obstructions before reaching the receiver. The signal may be scattered, diffracted, absorbed, reflected or refracted, thus creating multiple signals, each one arriving at the receiver at different times, having used different paths and with different strengths [11]. This phenomenon is known as the multipath effect. Systems able to provide NLOS coverage will make the complicated task of network planning and site acquisition a lot simpler.

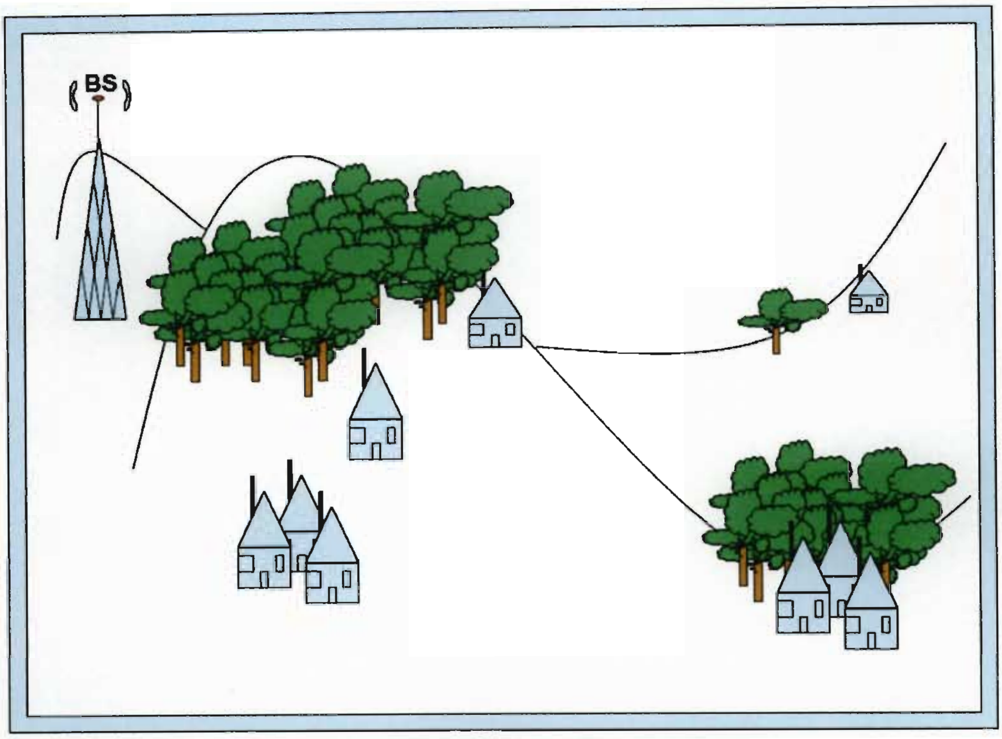

Figure3.2: NLOS environment

3.2.3 Multipath

Multipath is a term used to describe the scenario when transmitted signals arrive at the receiver from various directions over a multiplicity of paths, as a result of obstructions and reflectors in the propagation channel. It is an unpredictable set of reflections and direct waves each with its own degree of attenuation and delay.

Multipath may cause amplitude and phase fluctuations and time delay in the received signals. When waves of multipath signals are out of phase, reduction of the signal strength at the receiver can occur [11].

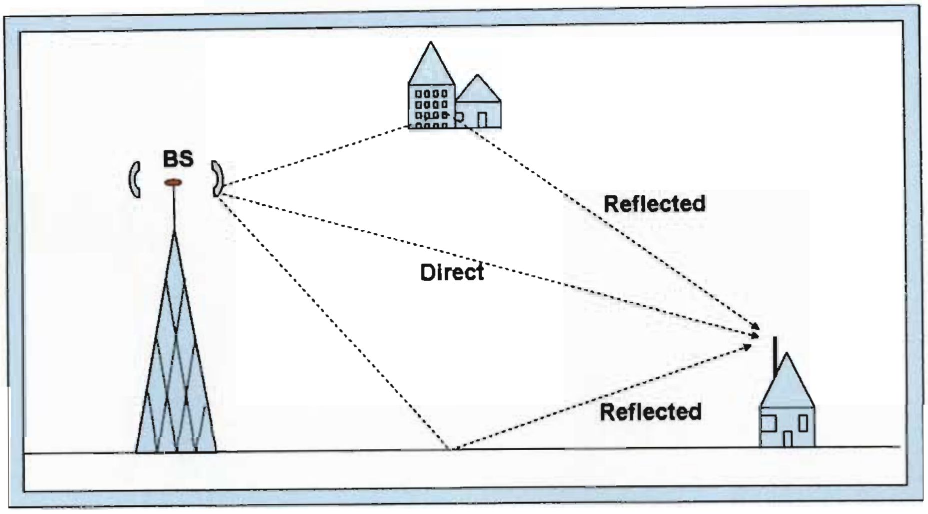

Figure 3.3 Multipath

3.3 RF Planning

3.3.1 Frequency band Selection

One of the most important aspects involved in planning a fixed wireless access (FWA) network is choosing the appropriate frequency band. This decision plays a major role in the dimensioning of the network.

The 2.4 GHz Industrial, Scientific, and Medical (ISM) band is unlicensed. It was originally reserved internationally for noncommercial use of the RF electromagnetic fields for industrial, scientific, and medical purposes. It is now used for license-exempt error-tolerant communications applications such as cordless phones, Bluetooth, and wireless LANs [13].

The 5 GHz radio LAN (RLAN) band comprises two frequency bands: 5.150 GHz – 5.350 GHz and 5.470 GHz – 5.725 GHz. These frequency bands are known as the U-NII bands. They are unlicensed and support the creation of wireless (MANs). The 5.150 – 5.350 GHz band is suitable for indoor, short distance network devices whilst the 5.470 GHz – 5.725 GHz range is suitable for outdoor, long distance network devices. The 5.470 GHz – 5.725 GHz range allows more radio channels to be used in the same geographical area, thereby increases the potential capacity of the network, and decreasing interference.

The 3.5 GHz, 10.5 GHz, and 26 GHz frequency bands are allocated to FWA systems in Europe. They are licensed frequency bands. The 3.5 GHz and the 10.5 GHz bands are suitable for point-to-multipoint applications only, while the 26 GHz band is suitable for both point-to-point and point-to-multipoint applications.

3.3.2 Network topologies

One of the major factors that determine throughput, robustness, reliability, security and cost is the geometric arrangement of the network components or topology. FWA network topologies can be divided into three main categories:

- Point-to-point (PTP) – consists of a single transmitting point and a single receiving point with highly directional antennas at either end.
- Point-to-multipoint (PMP) - consists of a number of base stations, each one connected to multiple end-user terminals. This offers a more economical solution than using multiple PTP links, since base station can be used to serve multiple end users.
- Mesh networks - consists of a number of base stations, each one connected to multiple end-user terminals that act as routers for each other's traffic. Mesh networks improve the coverage of a wireless network but increase the complexity of end user terminals because of the additional routing functionality required.

The IEEE 802.16 standards are designed primarily to support PMP architecture with additional support for Mesh topology. Most of the FWA systems available today are PMP based. This thesis focuses on PMP networks. Figure 3.4 shows an example of a possible point-to-multipoint network arrangement.

3.3.3 Modulation and coding [14]

Many of the advances in communications technology in the recent years have been in the ways that the transmitted signals are coded, modulated, demodulated, decoded, and otherwise structured to enable reliable communications and maximize the efficient use of the spectrum. The modulation and coding methods introduced in this section are those seen as the most important for digital FWA networks.

A transmitted signal has three fundamental characteristics - frequency, amplitude, and phase - all of which can be changed individually or in combination in response to the information that is to be transmitted. The fundamental modulation types can therefore be grouped as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). A variety of modulation methods can be derived by combining these. As the number of discrete amplitude levels, frequencies, or phase states increases, more information bits can be conveyed with one symbol. At the same time, however, noise, interference, and channel impairments make it increasingly difficult to detect which symbol has been transmitted. This trade-off problem can often be solved automatically by the system, if it applies an adaptive modulation mechanism.

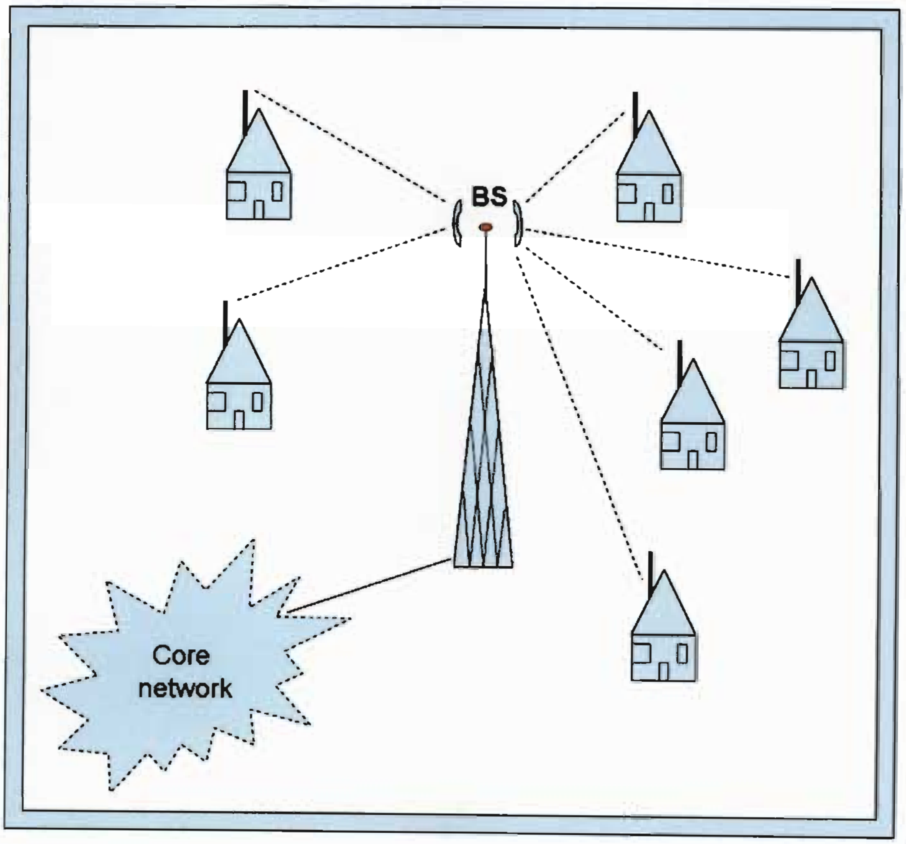

Figure 3.4: Point-to-multipoint network architecture

FWA systems use either single-carrier or multicarrier modulation. In the single-carrier modulation, data is transmitted using a single carrier wave that is modulated in accordance to the data stream. In the multicarrier modulation, the data stream is divided in the transmitting end to multiple parallel data streams, each of which modulates its own subcarrier. In the receiving end, the subcarriers are demodulated and the data streams combined.

a. Single-carrier modulation methods

Binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) are two of the most simple and robust single-carrier modulation methods. BPSK switches between two phase states to convey the bit pattern, while QPSK switches between four states. The number of bits per transmitted symbol is therefore one (0 or 1) for BPSK and two (00, 01, 10, or 11) for QPSK.

In order to increase data rate, modulation methods with more information bits per symbol are needed. The family of modulation types known as quadrature amplitude modulation (QAM) is often used to achieve these higher rates. In QAM modulation, both the amplitude and the phase of the symbol are altered. The number of constellation points defines the name of the modulation method; e.g. 16-QAM and 64-QAM are commonly used in FWA systems. For instance, when applying 64-QAM, six bits can be transmitted per symbol ($2^6 = 64$).

b. Multicarrier modulation using OFDM

OFDM (Orthogonal Frequency Division Multiplexing) is an example of a multicarrier modulation method. In OFDM, a number of relatively low bandwidth sub-carriers are modulated, using, for example, QAM modulation on each. The composite data rate of the sub-carriers is comparable to the data rate of a single carrier system using the same modulation at a higher rate in the same channel bandwidth.

OFDM has become an important option for FWA systems, especially for non-line-of-sight point-to-multipoint systems. New wireless LAN standards are already using OFDM with 64 subcarriers and for FWA systems the IEEE standard 802.16-2004 defines an OFDM physical layer using 256 sub-carriers. OFDM technology has also been proposed as a possible technology for next generation mobile system.

c. Coding methods

Coding is used to add redundancy to the transmitted signal in order to allow errors to be detected in the data reception. Detected errors can then be corrected at the receiving end using forward error correction (FEC), or the data block can be requested to be retransmitted using an automatic retransmission request (ARQ) mechanism. FEC is preferable to ARQ because retransmissions decrease the throughput of the system and cause delays often unsuitable for real-time applications such as voice or video conversations.

Coding methods commonly used in FWA systems include block codes, convolutional codes, and space-time codes. Block and convolutional codes add redundancy in the time domain by adding code bits to the time sequence of information bits.

Space-time codes (STCs) make use of the uncorrelated channel responses that exist when using multiple transmit and receive antenna elements. They are used together with multiple-input, multiple-output (MIMO) antenna systems, and use both the time and space domains to send redundant information to the receiver. In FWA systems, the use of OFDM with MIMO antenna systems and STCs is seen as an enabler to non-line-of-sight capabilities.

3.4 Antenna Selection

The choice of antennas has a great impact on the capacity and the coverage of fixed wireless systems. The choice is based on the antenna's efficient frequency of operation, bandwidth, and directivity characteristics [14].

A typical point-to-multipoint FWA network consists of a number of sectorized base stations. The sector antennas used by the BSs are directional antennas with beam widths varying from 15 degrees up to 360 degrees. Directional antennas transmit and receive RF energy more in one direction than others. The beam widths of the antennas depend both on the service area and the capacity requirements of the systems [14].

The type of antenna used by the subscriber depends on whether or not the system is capable of providing NLOS coverage. In LOS systems directional antennas are used whilst in NLOS systems directional antennas with larger beam widths or omni-directional antennas are used.

Omni directional antennas propagate RF signals in all directions equally on the horizontal plane, but limited in the vertical plane. Directional antennas typically have gains much higher than omni-directional antennas.

In order to increase range and improve performance, BSs and SSs use adaptive antenna systems (AAS). AAS is the term used to describe beam-forming techniques, where an array of antennas is used at the BS to increase gain to the intended SS while nulling out interference to and from other SSs and interference sources. It also introduces space diversity to the network, so that multiple SSs that are separated in space can receive and transmit on the same subchannel at the same time [13].

3.5 Multiple Access Techniques and Duplexing

In multiple access radio systems transmission medium is shared among all the terminals. In order to avoid overlapping transmissions and interference, the access to the medium has to be controlled in some way. Multiple access and duplexing methods are needed to allow many users to share a finite amount of radio spectrum simultaneously.

3.5.1 Time Division Multiple Access (TDMA)

TDMA is a multiplexing technique based on time division multiplexing (TDM). It divides the signal into different time slots thereby making it possible for multiple users to share the same channel. Each user transmits within his/her timeslot. The transmissions occur in rapid succession.

3.5.2 Frequency Division Multiple Access

Frequency Division Multiple Access is a multiplexing technique based on frequency division multiplexing (FDM), where multiple baseband signals are modulated on different frequency carriers called sub-carriers and then combined into one composite signal. FDMA makes it possible to separate the signals from different users thereby making it possible for multiple users to share the channel. TDMA and FDMA systems are used in conjunction with duplexing techniques.

3.5.3 Duplexing Techniques

In a two way wireless transmission, the arrangement of the uplink and downlink data is known as duplexing. In the downlink (forward link) data is transmitted from the base station (BS) to the subscriber stations (SSs). In the uplink (reverse link) data is transmitted from the SS to the BS. Two types of duplexing techniques are currently available, namely Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD).

FDD uses two separate channels to transmit the downlink and uplink sub-frames within the same time slot. FDD systems can further be divided into full-duplex FDD and half-duplex FDD (HFDD or HD-FDD). In full-duplex FDD a user can transmit and receive simultaneously whereas in half-duplex FDD simultaneous transmission is not possible, i.e. the user can either transmit or receive at any given time. This makes FDD inapt in handling asymmetrical traffic since data traffic may only occupy a small part of the allocated channel bandwidth.

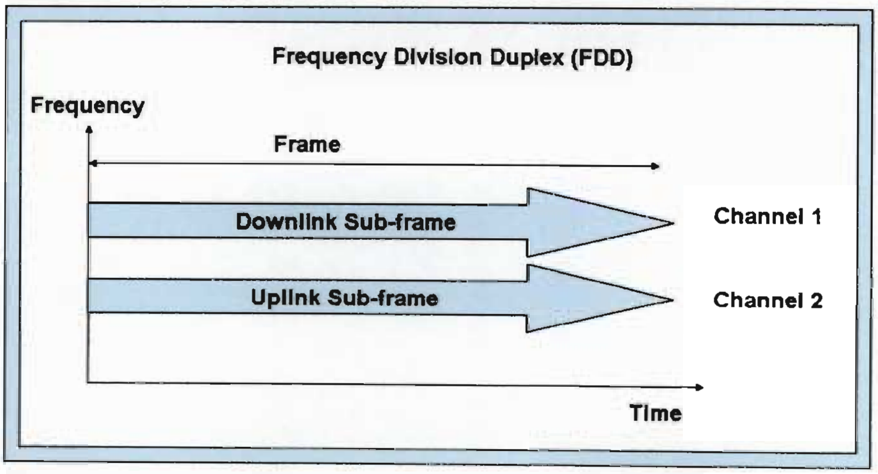

Figure 3.5: FDD Operation

TDD uses one channel to transmit the uplink and downlink sub-frames at two separate time slots, which makes TDD more spectrally efficient than FDD. Furthermore TDD allows the downlink to uplink (DL/UL) ratio to be adjusted dynamically, making it well suited to handle both symmetrical and asymmetrical traffic.

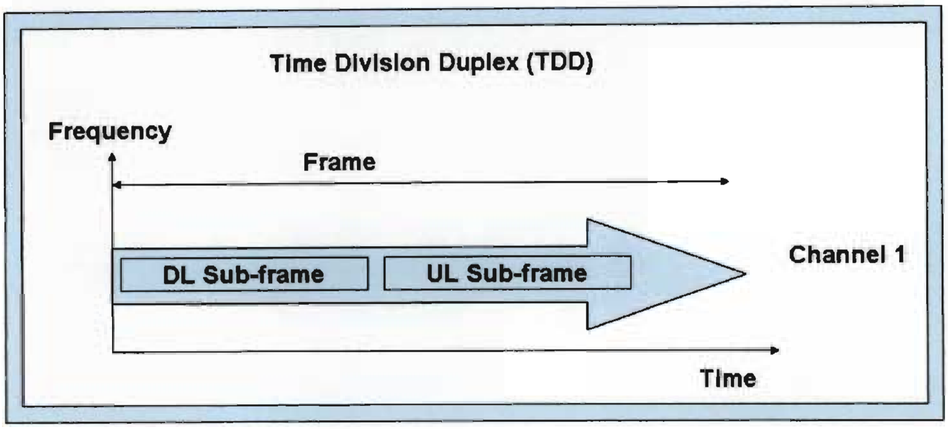

Figure 3.6: TDD Operation

3.6 Chapter Summary

This chapter outlines the basic principles used by the IEEE 802.16 standard that make wireless communications a reality. It begins with simple fundamental principles that facilitate FR communications such as reflection, refraction and diffraction. The chapter then tackles some of the more complex techniques behind RF communications such as modulation types, coding schemes, duplexing techniques and multiple access techniques - all of which form the basis any RF communication system.

4. BASEBAND MODEL OF 802.16-2004 OFDM-PHY

This chapter provides an overview of 802.16-2004 OFDM PHY layer specification. It begins with an explanation of OFDM modulation and then moves on to provide a detailed description of each baseband building block used in this physical specification. A brief summary of the RF band is also provided.

4.1 Overview of 802.16-2004 OFDM PHY

The 802.16-2004 OFDM PHY layer commonly referred to as the WirelessMan OFDM PHY is based on OFDM modulation and is designed for NLOS operation in the frequency band between 2-11 GHz [17].

4.1.1 OFDM Modulation

Orthogonal Frequency division multiplexing (OFDM) is a multicarrier transmission technique that dates back to the 1960's. OFDM is based on frequency division multiplexing (FDM), which is a technology that uses multiple frequencies to simultaneously transmit multiple signals in parallel [18]. OFDM divides the available spectrum into N carriers, sometimes referred to as sub-carriers and converts the high bit rate (R) data stream into N low bit rate parallel data streams. Each parallel data stream has a bit rate of R/N and modulates one of N subcarriers. The N low-data rate subcarriers are then combined by the receiver into a high data rate carrier, thereby reducing the inter-symbol interference (ISI) since in a multi-path environment shorter symbol periods implies a greater chance for ISI. Each of the modulated signals is kept orthogonal to each other. The orthogonality of the subcarriers means that each carrier has an integer number of cycles over a symbol period and as a result the spectrum of each carrier has a null at the centre frequency of each of the other sub-carriers in the system [19]. This results in no interference between the sub-carriers, and allows them to be squeezed as close together as possible so that they can even overlap each other. This makes OFDM spectrally efficient (see Figure 4.1).

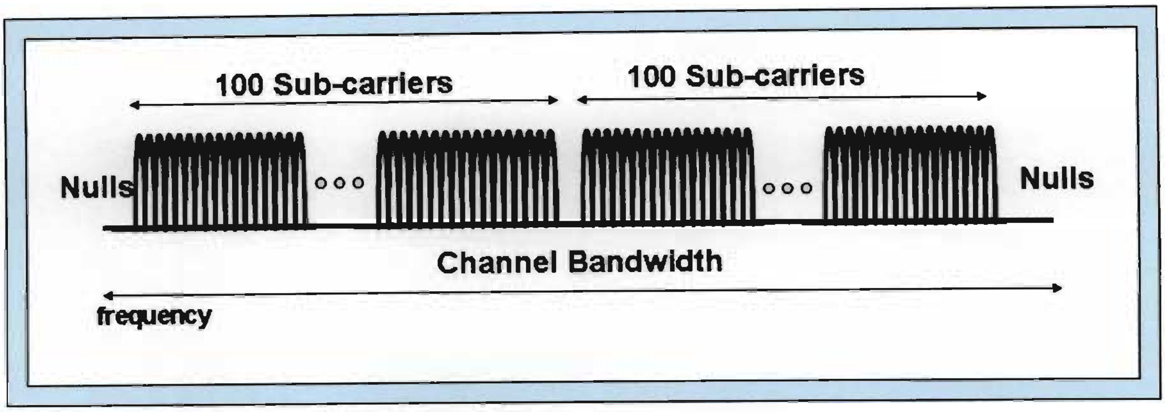

Figure 4.1: OFDM Modulation

4.1.2 OFDM Symbol Description

OFDM symbols can be described in one of two ways: the frequency domain description or a time domain description.

In the time domain, an OFDM symbol is made up of two parts, an OFDM waveform created by Inverse Fourier Transforming (IFFT) and a Cyclic prefix (CP). The duration of the OFDM waveform created is referred to as the useful symbol time T_b ; it is within this time duration that data is transmitted. The CP is merely a copy of the last T_g of the useful symbol time, and is used to collect multipath while maintaining the orthogonality of the tones. This can be seen in Figure 4.2 below.

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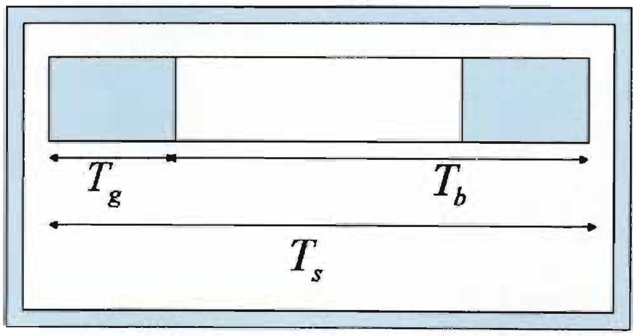

Figure 4.2: OFDM symbol time domain structure [17]

In the frequency domain an OFDM symbol is made up subcarriers. This PHY specifies three types of subcarriers:

- Data subcarriers: for data transmission
- Pilot subcariers : for various estimation purposes
- Null subcarriers: no transmission at all, for guard bands, non active subcarriers and DC subcarriers

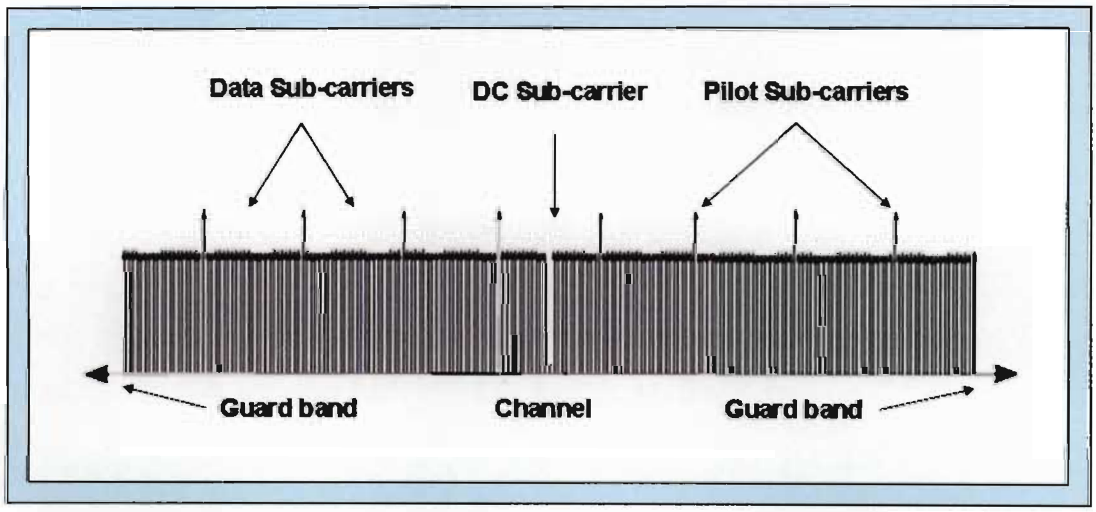

Figure 4.3: OFDM frequency description [17]

The purpose of the guard bands is to enable the signal to naturally decay and create the FFT "brick wall" shaping. Subcarriers are non-active only in the case of subchannelized transmission by a subscriber station (SS).

Equation (4.1) specifies the transmitted signal voltage to the antenna, as a function of time, during any OFDM symbol [12].

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{k=-N_{used/2}}^{N_{used/2}} c_k . e^{j2\pi k \Delta f (t - T_g)} \right\} \qquad (4.1)$$

Where:

c_k is a complex number; the data to be transmitted on the subcarrier whose frequency offset index is k, during the subject OFDM symbol. It specifies a point in a QAM constellation. In subchannelized transmissions, C_k is zero for all unallocated subcarriers.

N_{used} is the number of used subcarriers

t is the time, elapsed since the beginning of the subject OFDM symbol, with $0 < t < T_s$,

T_s is the OFDM symbol time;

$$T_s = T_b + T_g \qquad (4.2)$$

T_g is the CP time;

$$T_g = G.T_b \qquad (4.3)$$

G This is the ratio of CP time to "useful" time. Required values of this parameter are specified in Table 4.1.

T_b is the useful symbol time;

$$T_b = \frac{1}{\Delta f} \qquad (4.4)$$

Δf is the subcarrier spacing, given by:

$$\Delta f = \frac{F_s}{N_{fft}} \qquad (4.5)$$

N_{fft} is the smallest power of two greater than N_{used}

F_s is the sampling frequency, given by:

$$F_s = floor(n.BW / 8000)x8000 \qquad (4.6)$$

BW this is the nominal channel bandwidth

n is the sampling factor. This parameter, in conjunction with BW and N_{used} determines the subscriber spacing, and the useful symbol time. Required values for this parameter can be found in Table 4.1, which provides a brief description of each of the OFDM PHY layer Parameters.

PARAMETER	VALUE
NFFT	256
N_{used}	192
n	For channel bandwidths that are a multiple of 1.75MHz then n =8/7 Else for channel bandwidths that are a multiple of 1.5MHz then n=86/75 Else for channel bandwidths that are multiple of 1.25MHz then n=144/25 Else for channel bandwidths that are a multiple of 2.75MHz then n=316/275 Else for channel bandwidths that are a multiple of 2.0MHz then n=57/50 Else for channel bandwidths not otherwise specified then n =8/7
G	1/4, 1/8, 1/16, 1/32
Number of lower frequency guards	28
Number of higher frequency guards	27

Table 4.1: 256- OFDM PHY Layer Parameters [17]

4.1.3 Subchannelization

Subchannelization is the process of selecting only a subset of available sub-channels for transmission. The IEEE 802.16 wirelessMAN OFDM PHY specifies a subchannelization technique for the uplink (data transmission from SS to BS) only. There are sixteen sub-channels available for transmission of data in the uplink. When subchannelization is enabled, a SS can use one, two, four or eight of the sixteen available sub-channels to transmit data to the BS. If subchannelization is disabled a default value of sixteen sub-channels is used.

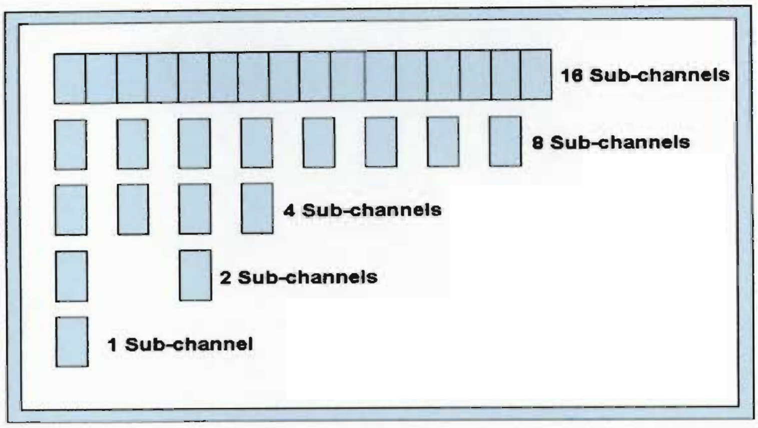

Figure 4.4: Subchannelization in the IEEE 802.16 OFDM **PHY**

4.2 Structure of 802.16-2004 OFDM PHY Layer

The IEEE 802.16-2004 wirelessMAN OFDM PHY is made up of two parts, the RF band and baseband. After baseband processing the digital data stream is passed to the RF band where it is separated into real and imaginary parts and converted to analogue stream. The real and imaginary data are then converted to in-phase and quadrature waves. The in-phase wave multiplies a sinusoidal IF waveform; the quadrature wave multiplies with a cosinusoidal waveform. These two waveforms are summed together to form a modulated intermediate frequency (IF) carrier. This is then multiplied with the RF carrier and after power amplification the electromagnetic signal is sent into the antenna. At the receiver, complimentary operations are performed in the reverse order [19].

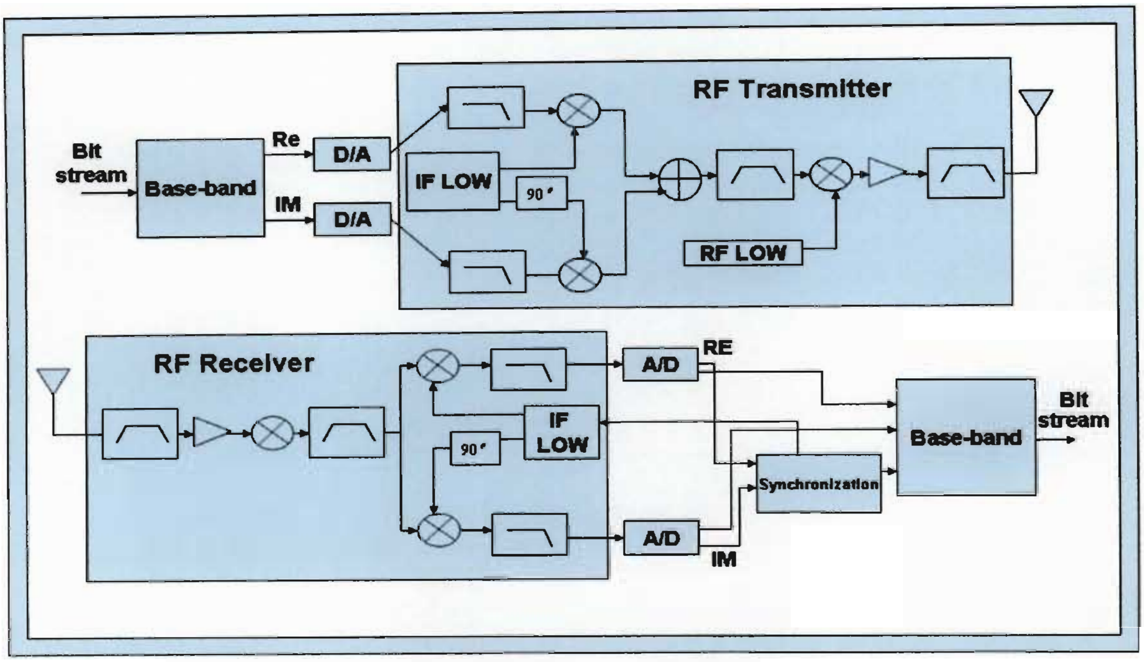

Figure 4.5: OFDM Transceiver [19]

4.2.1 OFDM Baseband Processing

During baseband processing the high bit rate serial data stream entering the PHY layer is formatted into N parallel low bit rate data sub-streams (see Figure 4.6). Each data sub-stream is mapped to a subcarrier at a unique frequency depending on the spectrum range being used, to ensure the orthogonality of the subcarriers. The data is subsequently passed through a channel coding block. The channel coding comprises three steps: randomization, forward error correction (FEC) and interleaving. The next stage in the baseband processing is modulation.

During modulation the data is differentially encoded and mapped with the proper amplitude and phase requirements depending on the modulation type. An inverse Fourier Transform (IFFT) is then used to convert the spectrum being used back into its time domain signal. The output of the IFFT is given by [20]:

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{l=0}^{N-1} d_l(k) \exp(j2\pi) f_i(t - kT_b)) f(t - kT_b) \qquad (4.7)$$

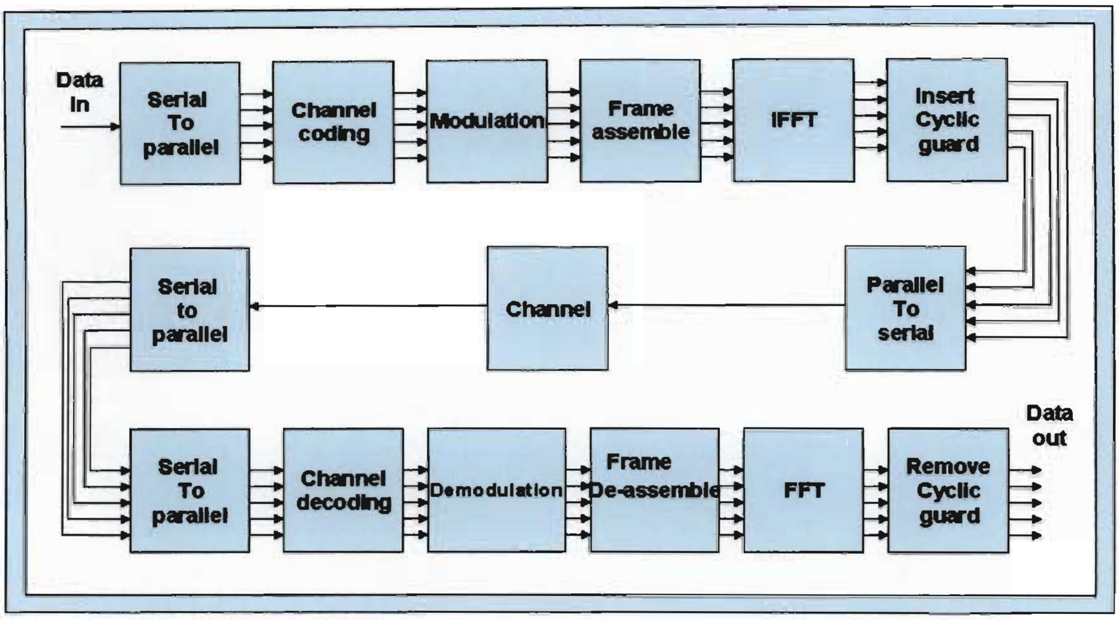

Figure 4.6: OFDM Baseband Structure

Where:

- T_b is the symbol duration of the OFDM signal and $f_i(i = 0,1,2,3...)$ is the frequency of the ith sub-carrier and is given by:

$$f_i = f_o + \frac{1}{T_b} \tag{4.8}$$

Where:

- f_o is the operating frequency
- $f(t)$ the pulse waveform of each symbol is defined as:

$$f(t) = \begin{cases} 1 & 0 < t \leq T_b \\ 0 & otherwise \end{cases} \tag{4.9}$$

A guard period is then added to the OFDM symbol period. The guard period used is the cyclic extension of the OFDM symbols. Cyclic extension is the periodic lengthening of the symbol duration by appending to the symbols a copy of the last part of the OFDM signal. This makes the transmitted signal periodic and helps to avoid ISI and inter-carrier interference (ICI). The symbol duration is increased by T_g, where T_g is the guard interval. The new symbol duration can be expressed as:

$$T_s = T_g + T_b \qquad (4.10)$$

It is important to note that as the length of the cyclic prefix increases the transmitted energy increases and this in turn causes deterioration in the signal-to-noise ratio (SNR) of the system. The SNR loss can be expressed as [21]:

$$SNR_{Loss} = -10\log_{10}(1-\gamma) \qquad (4.11)$$

Where:

$$\gamma = T_g / T_{tot} \qquad (4.12)$$

Typically, the relative length of the cyclic prefix is small and the ICI and ISI free transmission motivates the SNR loss (less than 1dB for γ<0.2 [21]). Once the guard period has been added to the OFDM signal, it is given by [21]:

$$s'(t) = \sum_{k=-\infty}^{\infty}\sum_{i=0}^{N-1} d_i(k)\exp(2j\pi f_i(t-kT_{tot}))f'(t-kT_{tot}) \qquad (4.13)$$

Where:

$$f'(t) = \begin{cases} 1 & T_g \geq t \geq T_b \\ 0 & t < -T_g, t > T_b \end{cases} \tag{4.14}$$

The OFDM signal is then transmitted to the receiver through a fading channel. At the receiver the received signal is expressed as [19]:

$$r(t) = \int_0^\infty h(\tau;t)s(t-\tau)d\tau + n(t) \tag{4.15}$$

Here $h(\tau;t)$ is the impulse response of the channel at time t, and *n(t)* is the complex AWGN. The receiver performs the inverse operations to the transmitter beginning with removing the cyclic extension guard period as illustrated in the block diagram in Figure 4.6. FFT (fast Fourier transform) is used to obtain the original transmitted spectrum.

4.2.1.1 Channel Coding

In order to ensure error free communication, channel coding is added to the PHY. Channel coding refers to a class of signal transformations designed to improve communications performance by enabling the transmitted signal to better withstand the effects of various channel impairments such as noise, fading, and jamming. The goal of channel coding is to improve the bit error rate (BER) performance of power-limited and bandwidth-limited channels by adding structured redundancy to the transmitted data [22]. In this PHY specification channel coding is accomplished in three steps:

- Step 1: Randomization - Ensures that data is provided with a high level of entropy
- Step 2: Forward Error Correction – Corrects most of the transmission errors
- Step 3: Interleaving – Ensures the correct mapping of data bits

At the receiver the complementary operations occur in reverse order.

a) Randomization

Randomization is implemented using a Pseudo random binary sequence generator (PBRS). The PBRS uses 2 XOR gates and a 15 bit shift register, with a generator polynomial of [17]:

$$1 + x^{14} + x^{15} \tag{4.16}$$

Each data byte to be transmitted is fed into the randomizer serially, with the most significant bit (MSB) first. The serialized bit stream is then combined in an XOR operation with the randomized bits that are calculated using the seed value.

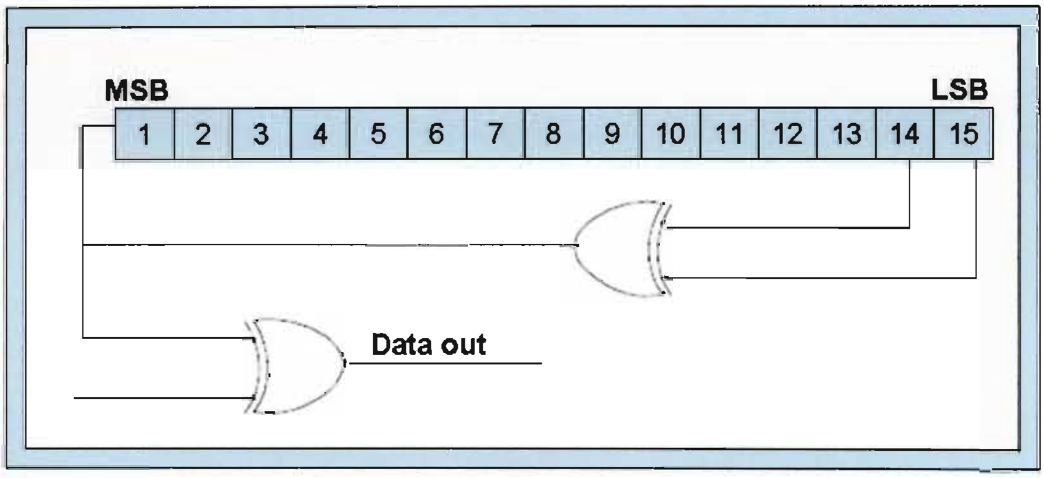

Figure 4.7: PRBS for data Randomization [17]

For the downlink the randomizer is reset at the beginning of each frame with the initial vector 100101010000000. The output of the randomizer is fed into the FEC.

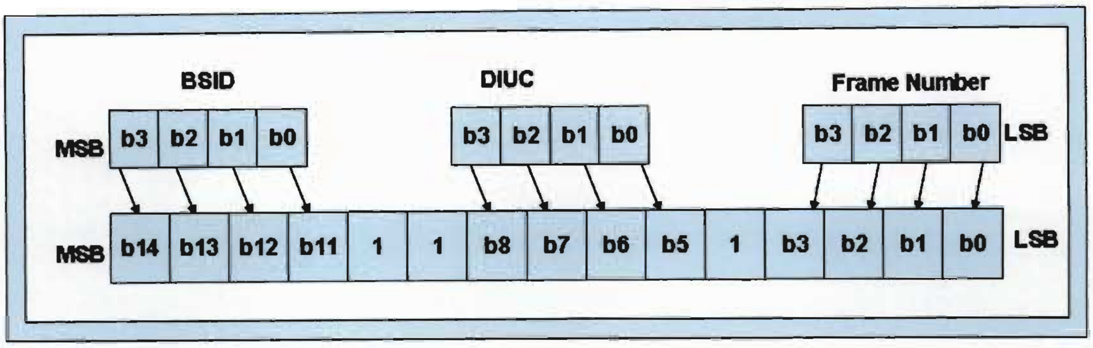

Figure 4.8: OFDM randomizer DL initialization vector [17, 22]

b) Forward Error Correction (FEC)

FEC is made up of two parts: the outer Reed - Solomon (RS) encoder and an inner convolutional encoder (CE). The purpose of the FEC is to add redundancy to the data i.e. redundant data is sent along with the original data during transmission so that it can be used by the receiver to check the symbols. The encoding is carried out by first passing the data in block format through the RS encoder and then passing it through a zero-terminating convolutional encoder [17].

b (i) Reed - Solomon Encoder (RS-Encoder)

The Reed – Solomon encoder uses block codes, which makes it the perfect tool for correcting burst errors. The RS encoding is derived from a systematic RS (N=255, K=239, T=8) code using a generating function $GF(2^{T})$, where:

- N is the number of overall bytes after encoding,
- K is the number of data bytes before encoding,
- T is the number of data bytes which can be corrected

The systematic code uses two polynomials;

Code Generator Polynomial [17]:

$$g(x) = (x+\lambda^{0})(x+\lambda^{1})(x+\lambda^{2})...(x+\lambda^{2T-1}), \lambda = 0.2_{HEX} \qquad (4.17)$$

Field Generator Polynomial [17]:

$$p(x) = x^8 + x^4 + x^3 + x^2 + 1 \quad (4.18)$$

The code is generated in such a way that the first K bits output from the RS-encoder are information bits and remainder of the bits (N-K) are check bits, which are used to correct errors.

b (ii) Convolutional Encoder

The Convolutional encoder is used to correct random errors. It uses a coding rate of half, constraint length of 7, and the following generator polynomial codes to derive its code bits [17]:

$$G_1 = 171_{OCT} \quad \text{FOR X} \quad (4.19)$$

$$G_2 = 133_{OCT} \quad \text{FOR Y} \quad (4.20)$$

The generator is shown in Figure 4.11.

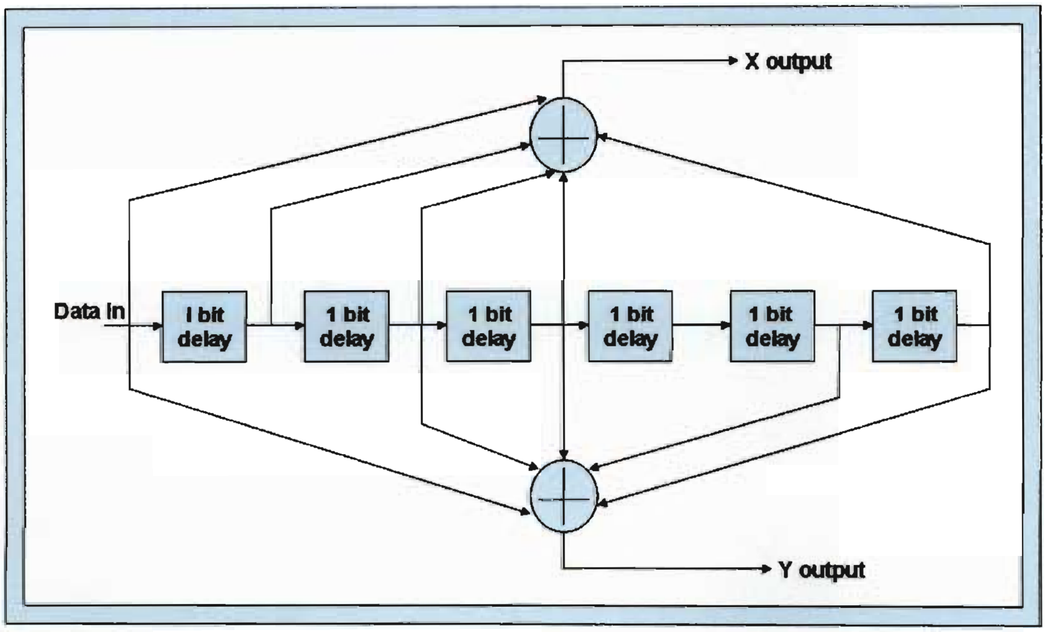

Figure 4.9: Convolutional Encoder of rate ½ [17]

c) Interleaving

The output of the RS-CC encoder is passed through an interleaver. The RS-C encoded data is then passed through a block interleaver with a block size corresponding to the number of coded bits per the specified allocation, *Ncbps*. The value of *Ncbps* differs depending on the modulation scheme being used. Table 22 below shows the block sizes of the interleaver as a function of modulation and coding [17].

	Default (16 Subchannels)	**8 subchannels**	**4 subchannels**	**2 subchannels**	**1 subchannel**
	N_{cbps}	N_{cbps}	N_{cbps}	N_{cbps}	N_{cbps}
BPSK	192	96	48	24	12
QPSK	384	192	96	48	24
16-QAM	768	34	192	96	48
64-QAM	1152	576	288	144	72

Table 4.2: Block sizes of Interleaver [17]

The interleaver is defined by a two-step permutation.
Let *Ncpc* be the number of coded bits per carrier [17], then:

$$N_{cpc} = \begin{cases} 2 & for \quad QPSK \\ 4 & for \quad 16-QAM \\ 6 & for \quad 64-QAM \end{cases} \qquad (4.21)$$

Let $s = ceil(\frac{N_{cpc}}{2})$. Within a block of N_{cpc} bits at transmission, let k be the index of the coded bit before the first permutation at transmission; m_k be the index after the first and before the second permutation; and j_k be the index after the second permutation, just prior to modulation mapping.

First step permutation [17]:

$$m_k = \left(\frac{N_{cbps}}{12}\right) \times k_{\text{mod}12} + floor\left(\frac{k}{12}\right) \quad k = 0,1,\ldots\ldots\ldots N_{cbps} - 1 \tag{4.22}$$

Second step permutation [17]:

$$j_k = s \times floor\left(\frac{m_k}{s}\right) + \left(m_k + N_{cbps} - floor\left(12 \times \frac{m_j}{Ncbps}\right)\right)_{\text{mod}(s)} \quad k = 0,1,\ldots\ldots N_{cbps-1} \tag{4.23}$$

The first permutation ensures that adjacent coded bits are mapped onto nonadjacent carriers. This ensures that if a deep fade affects a bit, its neighboring bits are likely to remain unaffected by the fade, and therefore is sufficient to correct the effects of the fade. The second permutation insures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation. This makes detection accurate and long runs of low reliability bits are avoided [22]. The inverse operation is performed at the receiver.

4.2.2 Modulation

After bit interleaving the data bits are sent through a modulator where they are mapped to analogue form so that they can be transmitted over the channel. The IEEE802.16-2004 supports four modulation types: namely BPSK, Gray-mapped QPSK, 16-QAM, and 64-QAM. It operates on an adaptive modulation basis.

4.2.2.1 Adaptive Modulation

In a typical wireless network different order modulations allow more bits to be transmitted per symbol thus achieving higher throughputs, that is, better spectral efficiencies. However when a higher modulation type is used such as 64-QAM, better signal-to-noise ratios (SNRs) are required to overcome any interference and maintain a certain bit error ratio (BER). The use of adaptive modulation allows a wireless system to choose the highest order modulation depending on the signal to noise ratios at the receiver. Figure 4.10 provides a general estimate of the channel conditions needed for the different modulation techniques. As the distance from the BS is increased the modulation type is stepped down to a lower modulation such as QPSK; while as the distance from the BS is decreased, the modulation type is stepped up to a higher modulation scheme such as 64-QAM for increased throughput. In addition, adaptive modulation allows the system to overcome fading and other interference. The use of adaptive modulation allows wireless technologies to optimize throughput, yielding higher throughputs while also covering long distances [23].

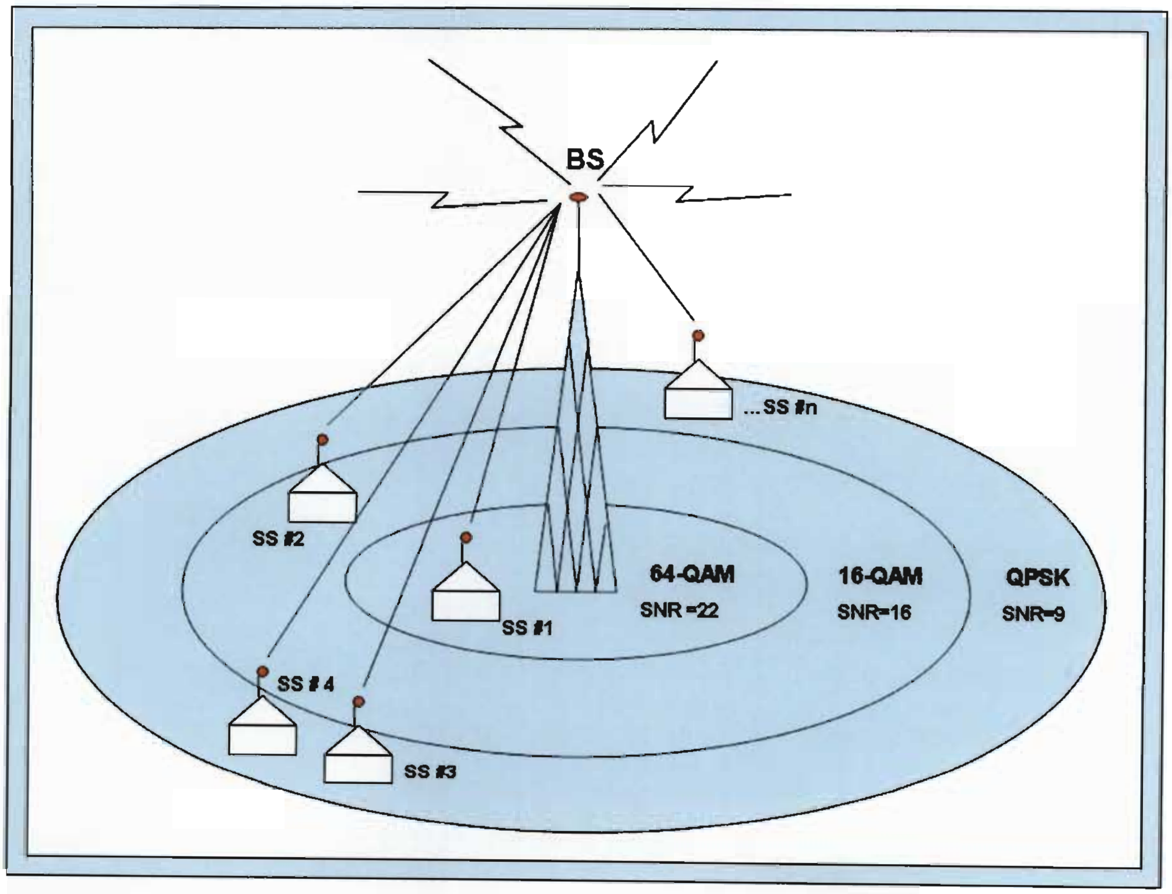

Figure 4.10: Adaptive Modulation

4.2.3 IEEE 802.16 OFDM WirelessMAN Framing

The IEEE 802.16 WirelessMAN OFDM PHY supports a frame-based transmission. A frame consists of a downlink sub-frame and an uplink sub-frame. In an FDD system the uplink and downlink sub-frames are transmitted on separate channels while in a TDD system the uplink and downlink sub-frames share a common channel. In TDD mode the uplink and downlink on air transmission times can vary on a frame by frame basis. Figure 4.11 illustrates the frame structure for a TDD system. The frame is divided into downlink (DL) and uplink (UL) sub-frames.

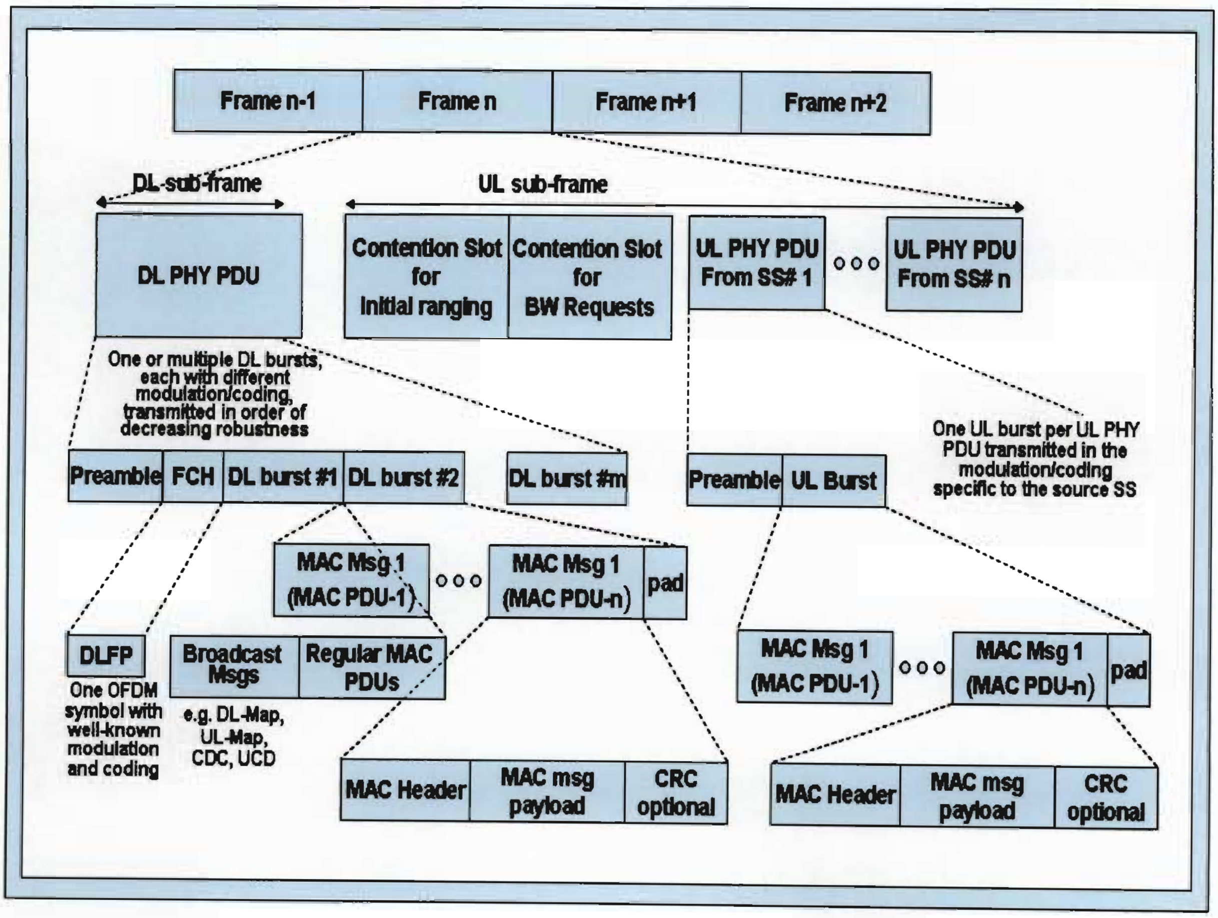

Figure 4.11: Frame structure (TDD) [17]

The DL sub-frame consists of one downlink PHY PDU. The downlink PHY PDU starts with a long preamble. The long preamble consists of 2 consecutive OFDM symbols, and is used for synchronization purposes. The preamble is followed by a frame control header (FCH) burst. The FCH burst is one OFDM symbol long. It consists of a DL-frame prefix that specifies the burst profile and the length of the DL bursts that immediately follow the FCH. The DL-MAP, UL-MAP, DL Channel Descriptor (DCD), UL Channel Descriptor (UCD), and other broadcast messages that describe the content of the frame are sent at the beginning of these first bursts. The remainder of the DL sub frame is made up of data bursts to individual SS's. Each data burst consists of an integer number of OFDM symbols and is assigned a burst profile that specifies the code algorithm, code rate, and modulation level that are used for those data transmitted within the burst.

The UL sub frame contains a contention interval for initial ranging and bandwidth allocation purposes and UL PHY PDUs from different SS's. The initial ranging contention slot is used during the network entry process. The bandwidth request contention slot is used by SS's to request bandwidth. The DL-MAP and UL-MAP completely describe the contents of the DL and UL sub frames. They specify the SS's that are receiving and/or transmitting in each burst, the sub channels on which each SS is transmitting (in the UL), and the coding and modulation used in each burst and in each sub channel.

If transmit diversity is used, a portion of the DL frame can be designated to be a transmit diversity zone; this portion is referred to as a STC zone. All data bursts within the transmit diversity zone are transmitted using space time coding (STC). STC coding is optional for the IEEE 802.16 standard, and is not considered in this thesis.

If an adaptive antenna system (AAS) is used, a portion of the DL sub frame can be designated as the AAS zone. AAS is used in the 802.16 specification to describe beam forming techniques, where an array of antennas is used at the BS to increase gain to the intended SS, while nulling out interference to and from other SS's and interference sources. AAS techniques can be used to enable SDMA, where multiple SS's that are separated in space can receive and transmit on the same sub-channel at the same time. By using beam forming, the BS is able to direct the desired signal to the different SS's and can distinguish between the signals of different SS's even though they are operating on the same sub-channel(s). Within this part of the sub frame, AAS is used to communicate to AAS-capable SS's. AAS is also supported in the UL, [13, 17, 24].

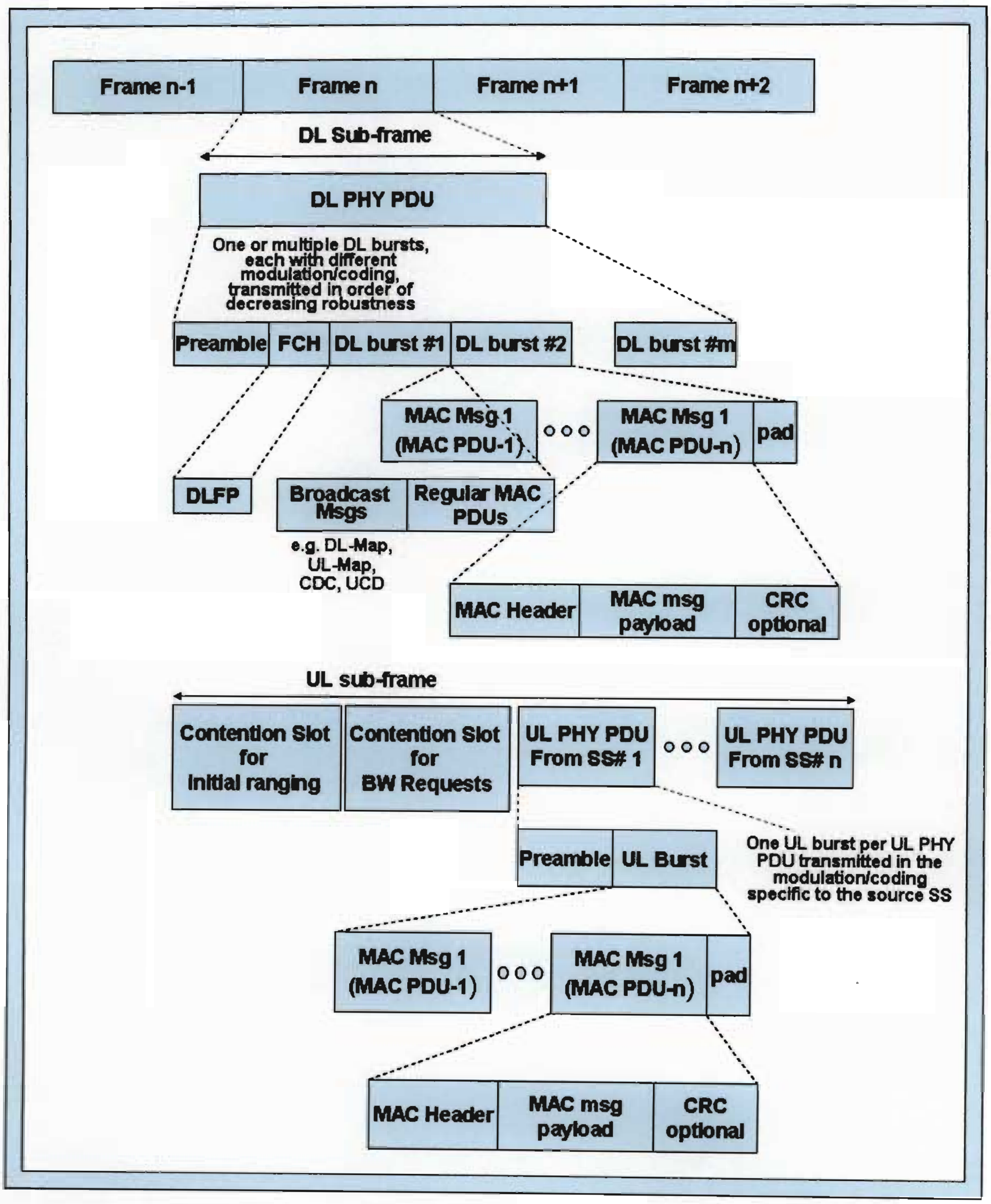

Figure 4.12: Frame structure for an FDD system [17]

4.3 Chapter Summary

One of the most interesting aspects concerning the IEEE 802.16-2004 standard is its ability to provide NLOS coverage. In order to understand how this is achieved one has to focus special attention on the IEEE 802.16-2004 WirelessMAN OFDM PHY layer. This physical layer is designed to provide NLOS in the frequency band between 2.5-11GHz. It is based on OFDM modulation. This chapter therefore starts by providing an overview of OFDM modulation. It then moves on to discuss some of the other features of the IEEE 802.16-2004 WirelessMAN OFDM PHY that makes it ideal for rural areas.

5. THE MEDIUM ACCESS CONTROL LAYER

In this chapter the architecture of the IEEE 802.16 MAC layer is discussed in detail and an overview of each of its functions are provided. The network entry process, PDU creation, and service classes are discussed in detail.

The IEEE MAC layer performs the standard Medium Access Control (MAC) layer functions of providing a medium-independent interface to the 802.16 Physical (PHY) layer. Because the 802.16 PHY is a wireless PHY layer, the main focus of the MAC is to manage the resources of the airlink in an efficient manner. The 806.16 MAC is designed to support mesh and point-to-multipoint (PMP) network models. In this thesis only the PMP network model is considered. The 802.16 MAC protocol is connection oriented. Upon entering the network, each subscriber station (SS) creates one or more connections over which their data are transmitted to and from the base station (BS). The MAC layer schedules the usage of the airlink resources and provides Quality of Service (QoS) differentiation. It handles network entry for SS's that enter and leave the network, and perform standard Protocol Data Unit (PDU) creation tasks. Finally, the MAC layer provides a convergence sub layer that supports Asynchronous Transfer Mode (ATM) cell- and packet-based network layers. [24]

5.1 The MAC Architecture

The MAC layer is subdivided into three parts as illustrated in Figure 5.1;

- Service-Specific Convergence Sublayer (CS) – Classifies MAC PDU's to the appropriate connection and performs packet header suppression (PHS) if necessary.
- Common Part Sublayer (CPS) – Performs the core functions of the MAC layer such as network entry, PDU creation and bandwidth allocation.
- Security Sublayer – Performs secure key exchange and authentication of SS's and authentication.

The sublayers interact with each other through the service access points (SAPs).

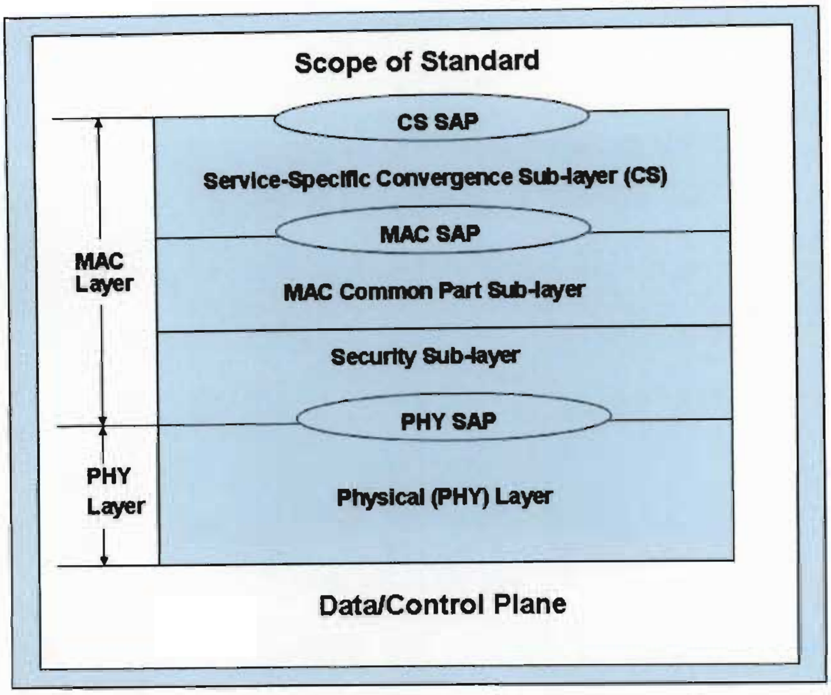

Figure 5.1: Scope of the IEEE 802.16-2004 standard

5.1.1 Service Specific CS

The Service Specific Convergence Sub-layer (CS) maps services to and from MAC connections. The IEEE 802.16 Standard specifies 2 service specific CS sub-layers:

- The ATM CS Sublayer – for ATM services
- The Packet CS Sublayer – for packets based services such as IPv4 or IPv6.

The main function of the service specific CS is the classification of MAC service data units (SDU's) to the appropriate MAC connections. SDU's are data units exchanged between two adjacent protocol layers. On the downward direction, it is the data unit received from the previous higher layer. On the upward direction, it is a data unit sent to the next higher layer (see Figure 5.2). Classification is the process of mapping MAC SDU's that enter the CS to the appropriate connection for transmission between MAC peers. If necessary the service specific CS is also able to perform packet header suppression and reconstruction.

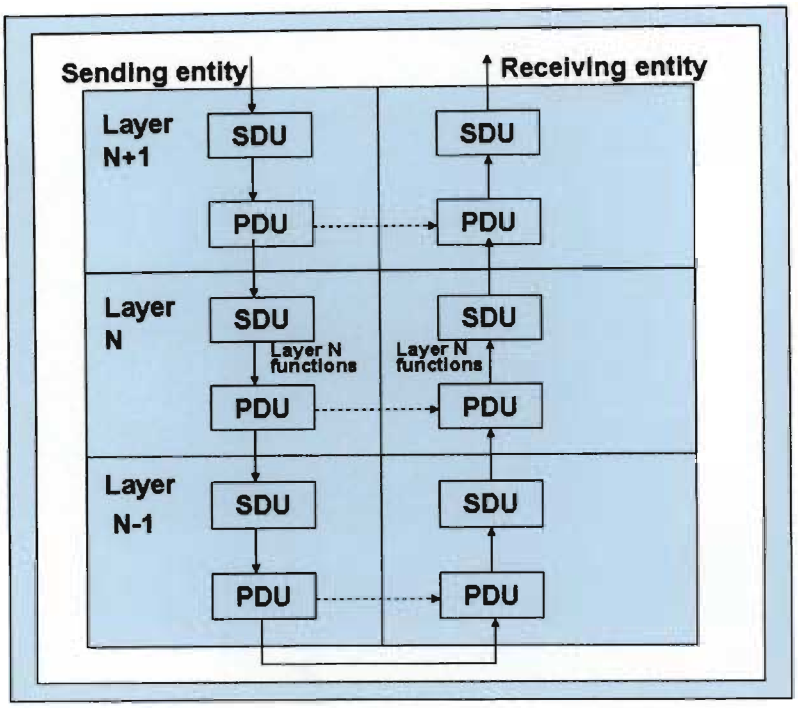

Figure 5.2: SDU and PDU in a Protocol Stack [17]

5.1.2 Common Part Sub-layer (CPS)

The Medium Access Control (MAC) layer operates on a point-to-multipoint basis, with a central base station and sectorized antenna capable of handling multiple independent sectors simultaneously [17]. Since transmissions made by the BS are generally broadcast, all SSs within the same antenna sector and frequency channel receive the same transmissions or parts thereof. In cases when the BS does not explicitly indicate that a portion of the DL sub-frame is intended for a particular SS all SS's capable of listening to that portion of the DL sub-frame may do so. The SS's identify the MAC PDUs intended for them by checking the connection identifier (CID) in the received PDU header. The CID is a 16 bit value that points to the destination and context information of the connection. By using a 16-bit CID each uplink and downlink channel is able handle up to 64K connections at any given time.

In addition to the CID each SS has a 48-bit universal MAC, which uniquely identifies each SS in terms of its vendor specifications and equipment type. When a SS enters a network the BS uses the information provided by the SS's 48-bit MAC address during the authentication process.

Once the SS is successfully authenticated, the BS sets up the appropriate management connection between them. Up to three pairs of management connections are established each associated with a different level of quality of service. Two pairs of connections are set up between the SS and the BS for uplink and downlink transmissions while the third is optionally generated. The three types of MAC management connections are as follows [24]:

- Basic Connection – is used by the SS MAC and the BS MAC to exchange short, time urgent MAC Management messages.
- Primary Connection - is used by the SS MAC and the BS MAC to exchange longer, more delay tolerant MAC Management messages
- Secondary Connection – used by the BS and SS to transfer delay tolerant standards based messages such as Trivial File Transfer (TFTP) and Dynamic Host Configuration Exchange (DHCP).

The IEEE MAC layer is connection oriented; that is almost all services, even connectionless services such as IP traffic, are mapped to a connection. The SS's share the uplink on a TDMA basis and data is multiplexed to the SS's in the downlink on a TDM basis.

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5.1.2.1 Network Entry Process

In order for an SS to become an active member in a network, it must first successfully complete a network entry process. The network entry process is divided into several stages; downlink channel synchronization, initial ranging, capabilities negotiation, authentication message exchange, registration, and IP connectivity stages (refer to Figure 5.3). If the SS fails to complete any stage it will not be allowed to communicate with the BS. The network entry process aims at ensuring that the connection between the SS and the BS is of the highest quality.

a) Downlink Channel Synchronization

When a SS wants to join a network, it scans for a channel within the interested frequency range. When a channel is detected the SS can synchronize to it by detecting the periodic frame preambles (PHY synchronization). In order to achieve MAC synchronization the SS must receive atleast one MAC management message from the BS. The SS uses the MAC management messages to obtain Uplink and downlink transmission parameters such as modulation and Forward Error Correction (FEC) schemes used by the BS. The SS will remain synchronized to the BS as long as it continues to receive MAC management messages from the BS.

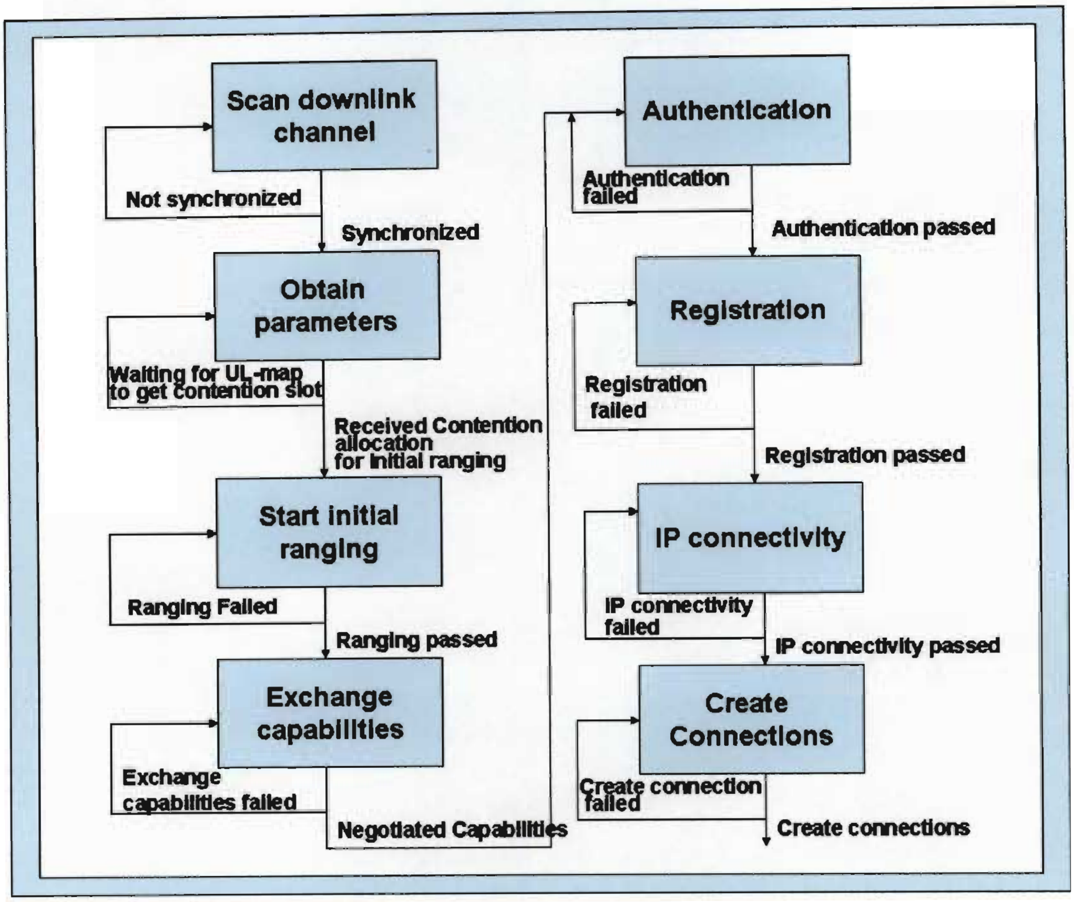

Figure 5.3: Flow diagram of the Network Entry Process [24]

b) Initial Ranging

Once synchronized with the DL channel the SS scans the DL-MAP and UL-MAP messages in every frame for ranging information. The DL-MAP defines the information required to access the downlink and the UL-MAP allocates access to the uplink channel. A back-off algorithm is used by the SS to determine which initial ranging slot to transmit the SS ranging request (RNG-REQ) message. Once the slot is determined the SS begins the initial ranging process by sending its burst on the initial ranging interval using the minimum transmission power. If it does not receive a response, the SS will repeat the process in the subsequent frames, using higher transmission powers each time until it receives a ranging response. The BS adjusts its timing advance and power to the SS with the ranging response (RNG-RSP) based on the time of arrival of the RNG-REQ. The response provides the SS with CIDs for the basic and primary management connections together with power and timing corrections that the SS must make. Once the corrections are complete the SS sends another ranging request. The SS is ready to transmit data on the UL as soon as it receives a successful response.

c) Capabilities Negotiation

At this stage the SS sends the BS a capability request message. Within this message the SS provides the BS with a description of its capabilities in terms of the modulation schemes, coding schemes and rates, and duplexing methods supported. Based on this information the BS permits or denies the SS entry into the network.

d) Authentication

Each SS contains both a manufacturer-issued factory-installed X.509 digital certificate and the certificate of the manufacturer. The SS in the Authorization Request (AR) and Authentication Information (AI) messages sends these certificates together with a description of the cryptographic algorithms it supports to the BS. Using this information the BS is able to validate the SS and check the level of authorization the SS has. If the SS is usefully authorized the BS determines the cipher algorithm and protocol that should be used and sends an authorization reply to the SS containing an authorization key (AK) encrypted with the SS's public key. The SS must periodically refresh its keying material.

e) Registration

Once a SS is authenticated, it registers with the network by sending a registration request message to the BS and receiving registration from the BS. [19] The registration determines the capabilities related to connection setup and MAC operation of the SS and establishes the SS's secondary management connection.

f) IP Connectivity

Once registered on the network the SS attains an IP address through the DHCP (IETF RFC 2131) and establishes the time of day using the Internet time protocol (IETF RFC868). The SS also uses the DHCP to get the address of the TFTP (IETF RFC 1350) from which it downloads operational parameters such as vendor-specific configuration information.

g) Connection Setup

Connection setup is the part of the network entry process where data actually flows. In the IEEE 802.16 MAC layer one way transmissions are defined is in terms of service flows. Service flows are characterized by a set of quality-of-service parameters, such as those for latency and jitter. To most efficiently utilize network resources, such as bandwidth and memory, the IEEE 802.16 MAC adapts a two-phase activation model in which resources assigned to a particular admitted service flow may not be actually committed until the service flow is activated. Each admitted or active service flow is mapped to a MAC connection with a unique CID. In the general, the service flows are provisioned, and the BS initiates the setup of the service flows during SS initialization. Each service flow is associated with a different service class.

5.1.2.2 Service Classes

The 802.16 MAC provides different levels of QoS differentiation for different types of applications that might operate over 802.16 networks [24]. The 802.16 standard defines the following types of services [13, 17, and 24]:

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

- **Real-Time Polling Services (rtPS):** rtPS is designed to support real-time services that generate variable size data packets on a periodic basis, such as MPEG video or VoIP with silence suppression.
- **Non-Real-Time Polling Services (nrtPS):** nrtPS is designed to support non-real-time services that require variable size data grant burst types on a regular basis.
- **Best Effort (BE) Services:** BE services are typically provided by the Internet today for Web surfing. Each SS to BS connection is assigned a service class as part of the creation of the connection. When packets are classified in the convergence sublayer, the connection into which they are placed is chosen based on the type of QoS guarantees that are required by the application.

5.1.2.3 Protocol Data Unit Creation [17, 22, 24]

MAC protocol data units (MPDUs) are the data units exchanged between the MAC layers of the BS and the corresponding SS's. The 802.16 MAC performs the standard PDU creation functions; it applies the MAC header, and if necessary calculates the cyclic redundancy check (CRC). If necessary the 802.16 MAC layer is able to perform both fragmentation of MAC SDUs and packing of MAC SDUs. Small SDUs are packed to fill up airlink allocations and large SDUs are fragmented when they do not fit into an airlink allocation [24]. In this way air link resources are efficiently managed. MAC PDUs may also be concatenated into bursts having the same modulation and coding.

a) MAC PDU Formats

Each MAC PDU (MPDU) consists of a fixed-length generic MAC header, a variable length payload which may contain zero or more MAC sub-headers and an optional (CRC) as illustrated in Figure 5.4.

Two generic MAC header formats are defined, namely:

- Generic MAC header – The generic MAC header is attached to the beginning of each MAC PDU that contains MAC management messages or CS data

- Bandwidth Request Header – When additional bandwidth is required by a SS, the SS sends a bandwidth request PDU to the BS. The bandwidth request PDU consists of a bandwidth request header only and does not contain any payload.

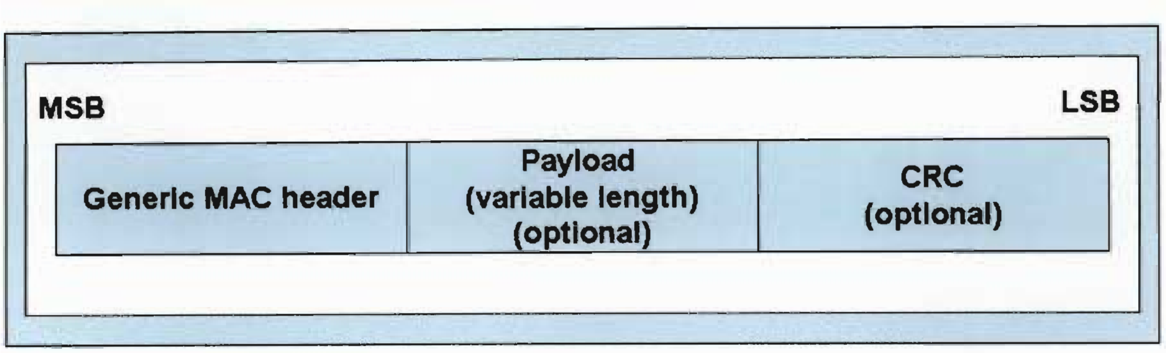

Figure 5.4: MAC PDU Format [12]

a (i) Bandwidth Request Header

To request changes to the granted characteristics of a connection, a 6-byte bandwidth request header is transmitted in place of the Generic MAC Header (GHM). The header type (HT) bit is set to 1 to indicate that the header is a bandwidth request header and not a GMH. The contents of bandwidth request header are as shown in Figure 5.5.

The HT and encryption control (EC) bits must be set to 1 and 0 respectively. The 6-bit type field can take the value 0 to indicate an incremental bandwidth request or a value of 1 to indicate an aggregate request.

The CID field indicates the connection for which the bandwidth request is being made. Thus the bandwidth request does not need to be only for a connection that is specified in the GMH. It can apply to any connection specific to the requesting SS.

The BR field indicates the number of uplink bytes of bandwidth being requested. The HCS field, on the other hand, is an 8-bit cyclic redundancy check (CRC) of the first 5 bytes of the bandwidth request header.

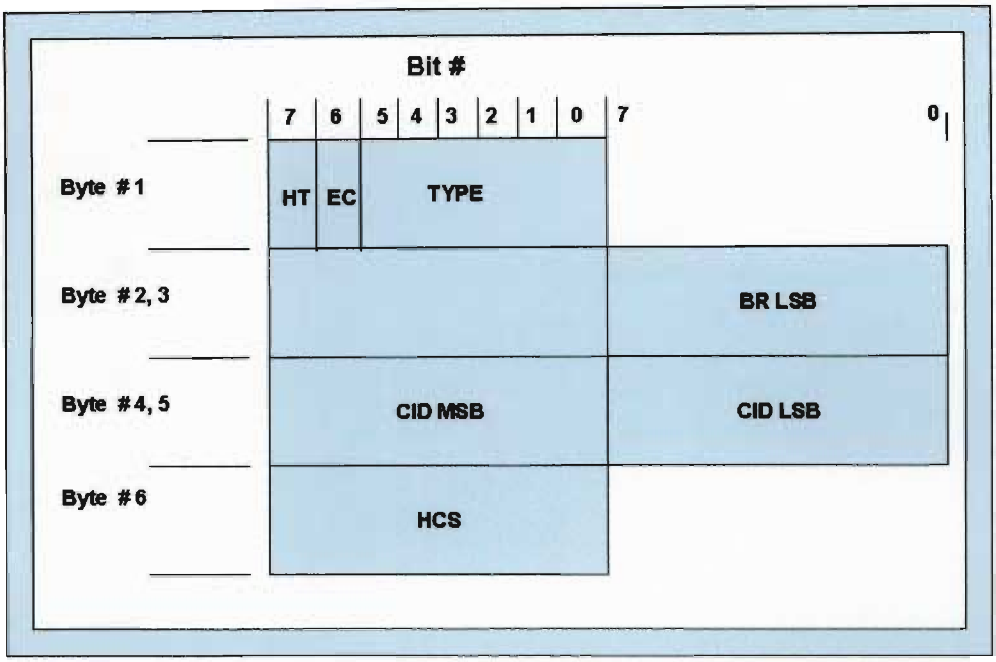

Figure5.5: Contents of the bandwidth request header

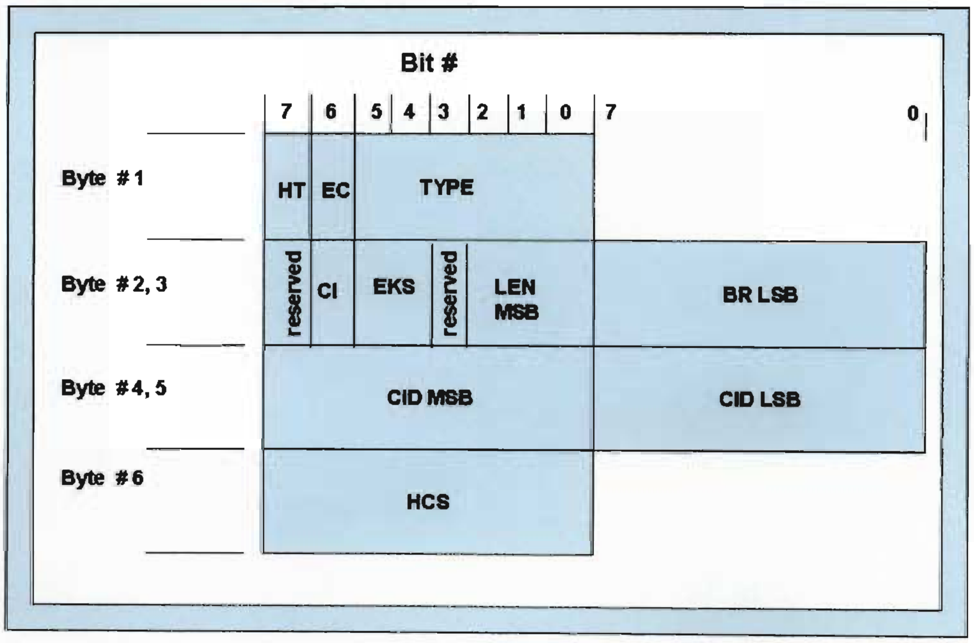

Figure5.6: Generic MAC header for the generic MPDU

a (ii) Generic MPDUs

Generic MPDUs carry transport and management information to the connection identified by the CID in the header. Each generic MAC PDU (MPDU) begins with a general MAC header (GMH), which is show in Figure 5.6.

The HT bit is set to 0 to indicate a GMH is being transmitted. The EC bit indicates whether or not the frame is encrypted while the CRC indicator (CI) indicates the presence of the optional CRC at the end of the MPDU.

The encryption key sequence (EKS) bits indicate which key was used to encrypt the frame. The privacy sub layer allows overlapping keys so that keys can be updated without interrupting the flow of data. The EKS differentiates between old and new keys during an update.

The 11 bits of the LEN field indicate the number of bytes in the MPDU including the header and the CRC. This limits the frame length to a total of 2047 bytes.

The CID indicates which connection the MPDU is servicing. The HCS, on the other hand, is a 8-byte CRC of the first 5 bytes of the GMH. Finally, the type field contains 6 bits that indicate what is present in the payload:

- Bit 0 is set when a grant management sub-header is present in the payload.
- Bit 1 is set when a packing sub-header is present in the payload.
- Bit 2 is set when a fragmentation sub-header is present in the payload
- Bit 3 is set when the fragmentation or packing headers are extended
- Bit 4 is set when the frame contains an ARQ feedback payload
- Bit 5 is set when a mesh sub-header is present

b) The MAC Sub-Headers

The sub headers are used to implement the signaling necessary for the fragmentation, packing, ARQ and optional mesh features of the MAC.

b (i) Grant Management Sub-Header

The grant management sub-header is a lightweight way to attach a request uplink bandwidth without having to create and transmit a complete MPDU with the overhead of MAC headers and CRCs. Each connection (identified by the 16 bit CID) has a particular class of scheduling service assigned to it. If the CID in the GMH indicates a channel that is using the unsolicited grant service (UGS) then the following grant management sub-header format is used (Figure 5.7).

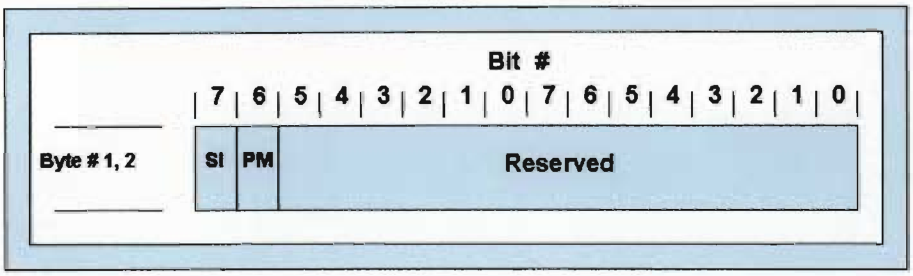

Figure 5.7: Grant management sub-header format used for connections using UGS scheduling service.

The slip indicator (SI) bit is used by the SS to inform the BS that the uplink buffer servicing a flow has filled up, generally due to the rate of arrival of the data to be sent being slightly faster than the granted uplink rate. It acts as a request to the BS to make additional uplink grants. . The poll me (PM) bit is used to request that the BS sends a bandwidth poll. In the case of any of the other scheduling services (rtPS, nrtPS or BE), the format in Figure 5.8:

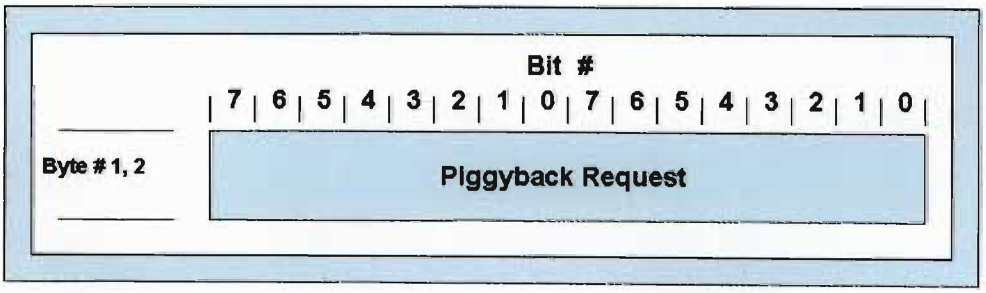

Figure 5.8: Grant management sub-header format used for connections using the rtPS, nrtPS, or BE scheduling service.

In Figure 5.8, the piggyback request is a 16-bit number that represent the number of uplink bytes of bandwidth being requested for the connection. The piggyback request of Figure 5.8 is used to explicitly indicate the amount of uplink bandwidth that the SS requires. The format in Figure 5.7 applies to unsolicited grant service (UGS) connections, where the grants are implicit and regular and the rate of data over a connection is assumed to be approximately synchronized with the data rate needs of the flow being transported. The two bits are used to occasionally request a bit more bandwidth to keep the connection rate synchronized with the data rate.

b (ii) Fragmentation Sub Header

An MSDU may be divided into fragments that are transmitted independently. To signal this, a fragment sub-header (FSH) is included at the start of the payload, as shown in Figure 5.9.

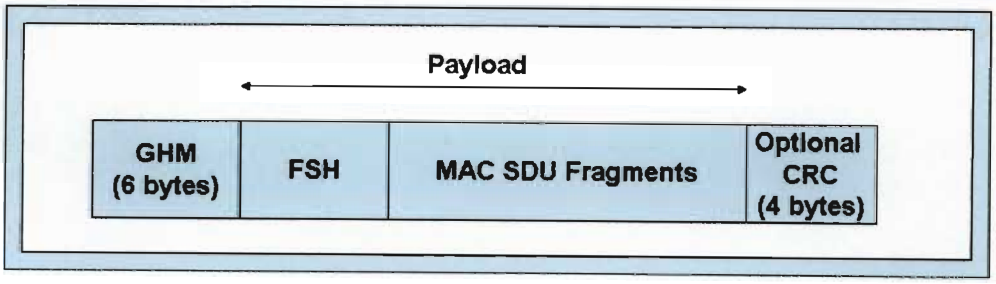

Figure 5.9: Fragment Sub-header

A fragment sub-header is added at the start of a payload to indicate to the system that the MSDU must be divided into fragments.

The FSH describes a fragment of an MSDU. The normal FSH is as shown in Figure 5.10. The fragment control (FC) bits indicate whether the fragment is the first fragment of an MSDU (10), the last fragment (01) or a fragment somewhere in the middle (11). When set to 00 the MSDU is not fragmented. The fragment sequence number (FSN) increases by 1 for each fragment of an MSDU so the receiver can reassemble fragments appropriately.

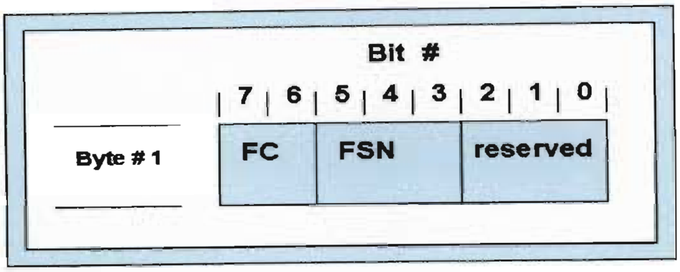

Figure 5.10: Diagram of a typical fragment sub-header (FSH)

b (iii) Packing

Multiple MSDUs or multiple MSDU fragments can be packet into a single MSDU. This is sometimes referred to as MAC-level packet aggregation.

To indicate that packing is used in an MPDU, a bit in the GMH indicates the presence of a packing sub-header (Figure 5.11). An MPDU can contain multiple packing sub-headers, each followed by either an MSDU or a fragment of an MSDU.

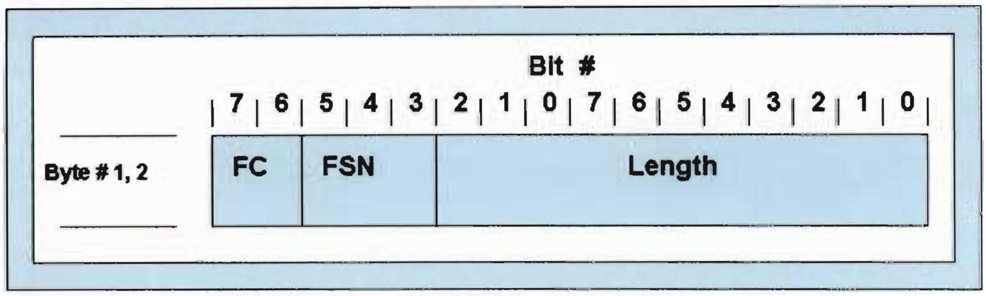

Figure 5.11: Diagram of the packing sub-header (PSH)

Since an MSDU can be broken into fragments and transmitted in packed frames, this enables the BS to make better use of the available slots and the channel. For instance an MSDU that does not fit into the remainder of an MPDU can be allocated to occupy the remainder of the current MPDU and the rest will be sent in the subsequent MPDUs.

The packing sub header is identical to the fragment sub-header. The length field identifies the start of the next PSH within the MSDU payload.

b (iv) ARQ

The automatic retransmission request (ARQ) is the process of retransmitting MAC SDU blocks ("ARQ blocks") that have been lost or distorted. The 802.16 MAC uses a simple sliding window based approach, where the transmitter can transmit up to a negotiated number of blocks without receiving an acknowledgement. The receiver sends acknowledgement or negative acknowledgement messages to indicate to the transmitter which SDU blocks have successfully been received and which have been lost. The transmitter retransmits blocks that were lost and moves the sliding window forward when SDU blocks are acknowledged to have been received.

A system parameter block size is defined. MSDUs are considered to be made from a number of blocks of the same size, except for the final block which may be smaller.

In systems with ARQ enabled, the extended FSH and expended PSH is used (indicated by the extended bit in the GMH type field) in place of the FSH. This is shown in Figure 5.12.

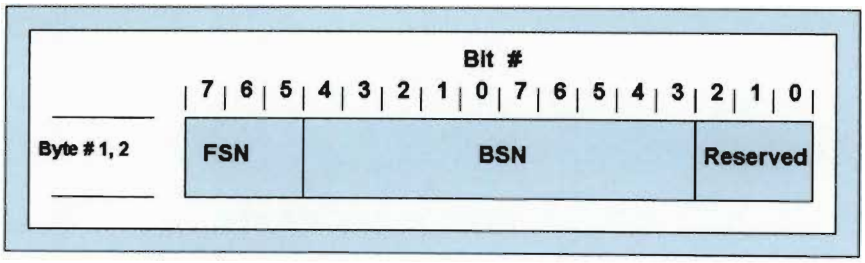

Figure 5.12: Format of the packing sub-header that precedes each packed MSDU or fragment.

In the case shown in Figure 5.12, a block sequence number (BSN) is used in place of the FSN, for the purposes of ARQ. When an ARQ request is made, the request is made to retransmit blocks by identifying them with the BSN. In the extended FSH, the BSN indicates the first block in the fragment. In ARQ-enabled connections, a fragment is built from an integral number of blocks of an MSDU so the first block in a fragment will align with the start of a fragment. Similarly to the FSH, the PSH is extended when used in an ARQ capable connection so that a 11-bit BSN is used in place of the 3-bit FSN (Figure 5.13).

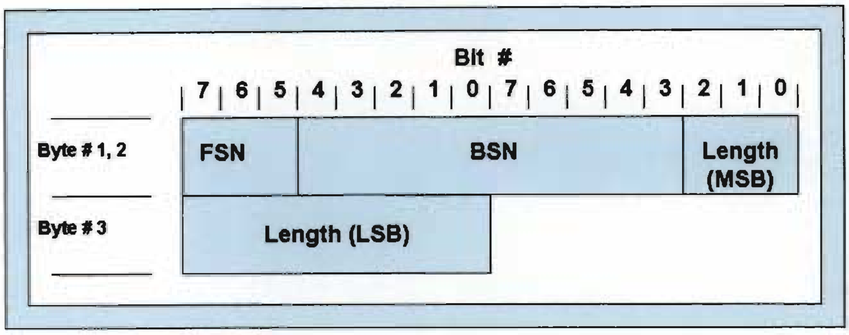

Figure 5.13: Extended fragmentation sub-header that is used when ARQ is enabled.

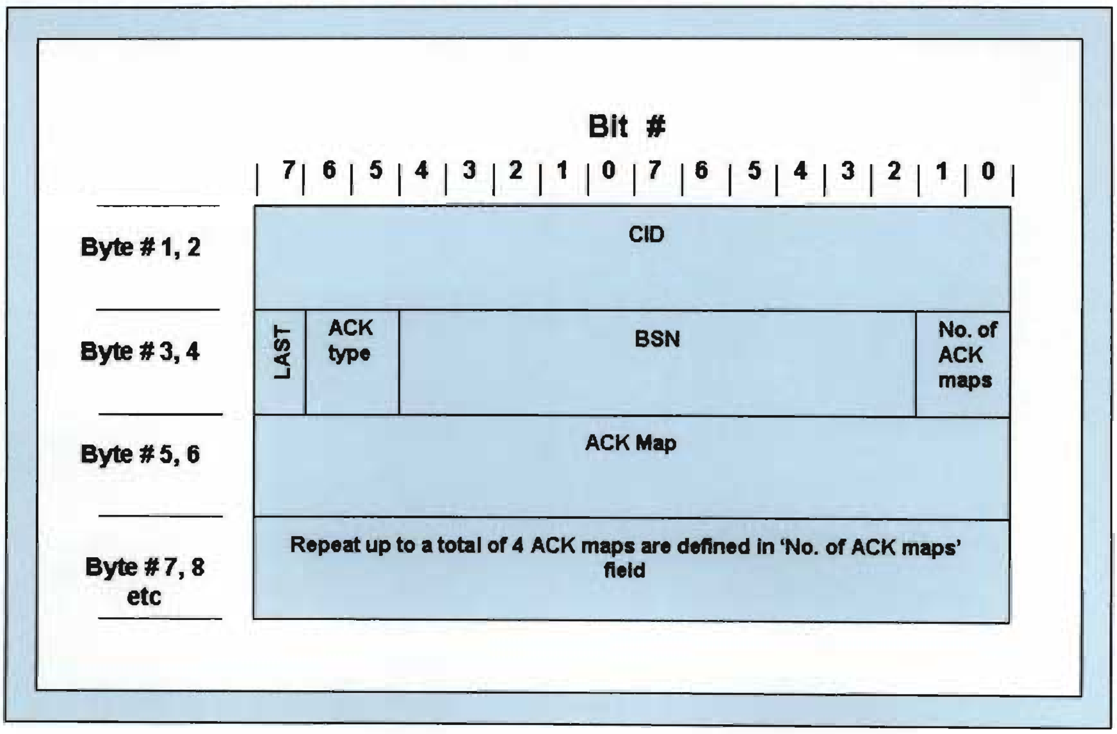

Figure 5.14: Extended packing sub-header that is used when ARQ is enabled

To request the retransmission of blocks (NACK) or to indicate the successful reception of blocks (ACK), the ARQ feedback payload is included in the payload. The ARQ feedback payload is structured as shown in Figure 5.14.

The ACK maps are a bitmap of the successfully received blocks. From this, the sender of the data can distinguish what blocks were received successfully and what blocks require retransmission.

Once all the management connections are established, an SS can set up transport connections. Service flows attached to transport connections call also join multicast groups and so will listen to multicast polling channels that are assigned to those groups.

The IEEE 802.16-2004 MAC layer supports two types of polling:

- **Unicast:** When an SS is polled individually, it is allocated bandwidth to send bandwidth request messages.
- **Contention-based:** Contention-based bandwidth request is used when insufficient bandwidth is available to individually poll many inactive SS's. The allocation is multicast or broadcast to a group of SS's that have to contend for the opportunity to send bandwidth requests.

Figure 5.15 illustrates the 802.16 QoS mechanism in supporting multimedia services, including TDM voice, VoIP, video streaming, TFTP, HTTP, and e-mail.

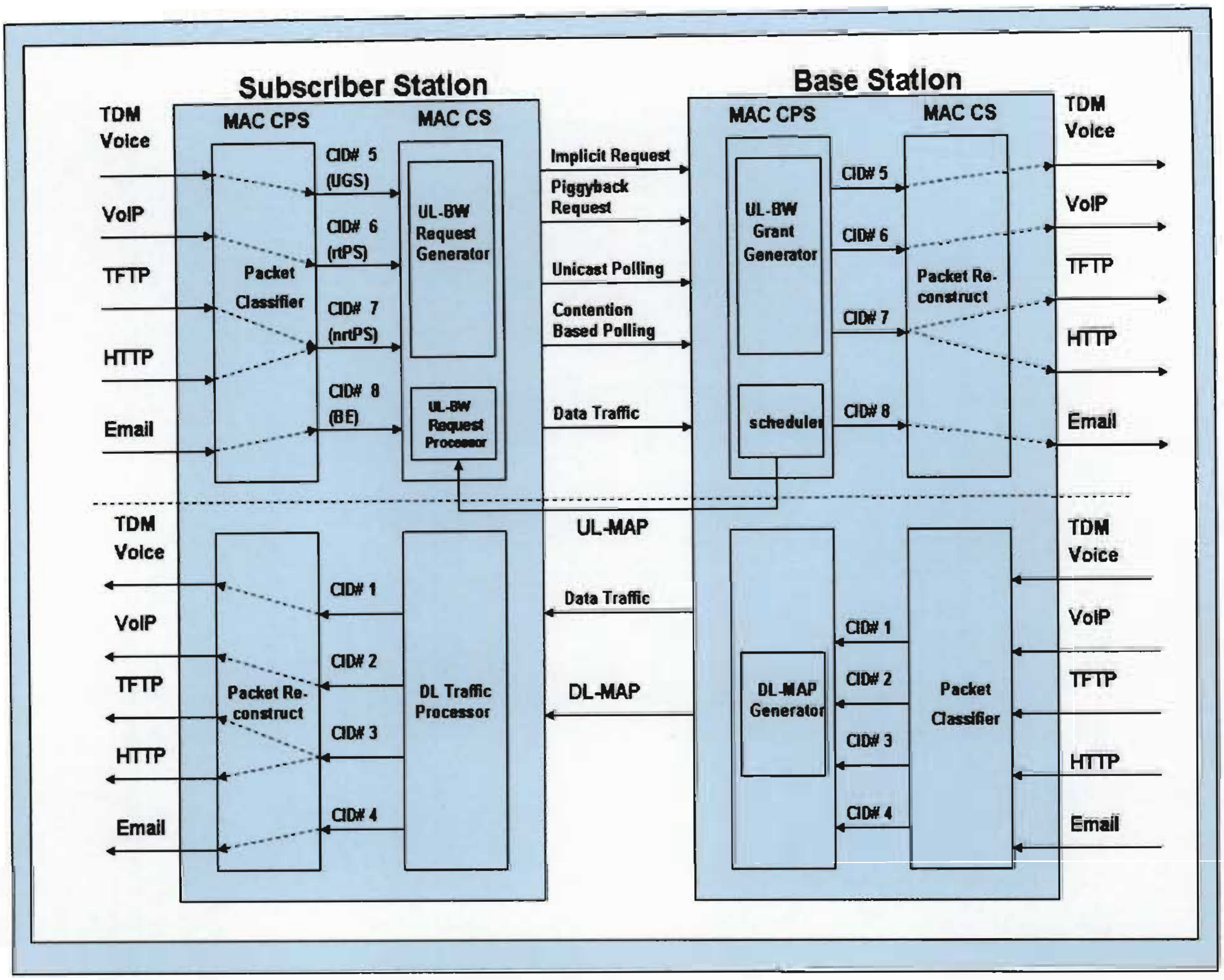

Figure 5.15: QoS mechanism for multimedia services

5.2 Chapter Summary

The MAC layer plays a vital role in determining the capacity of the network. In a typical WiMAX network an increase in the MAC overhead results in a decrease in the average capacity of the network. It is therefore of utmost importance to fully understand the architecture and operations of the MAC. The IEEE MAC layer performs the standard Medium Access Control (MAC) layer functions of providing a medium-independent interface to the 802.16 Physical (PHY) layer. Because the 802.16 PHY is a wireless PHY layer, the main focus of the MAC is to manage the resources of the airlink in an efficient manner.

This chapter focuses on the architecture and functionality of the IEEE 802.16- 2004 MAC layer. It explains the relevance of each of the MAC header formats supported by the standard and then moves on to explain the different technologies that make it possible for the IEEE 802.16-2004 standard to support so many users simultaneously.

6. PERFORMANCE EVALUATION OF WiMAX

In this chapter the performance of a WiMAX network deployed in rural South Africa is evaluated. The capabilities of WiMAX networks in terms of coverage and capacity are evaluated in two ways: firstly by means of an analytical model and secondly by simulating a WiMAX network in a typical rural area. The results obtained from the simulation are compared with the analytical results to ascertain which path loss model provides a better coverage prediction for rural areas.

6.1 Case Study

In order to evaluate the performance of a WiMAX network deployed in rural South Africa as accurately as possible, a simulation of a WiMAX network is set up using ATDI software for Nkandla, a typical rural area in South Africa. Nkandla is situated on outskirts of Kwa-Zulu Natal in Zulu-land.

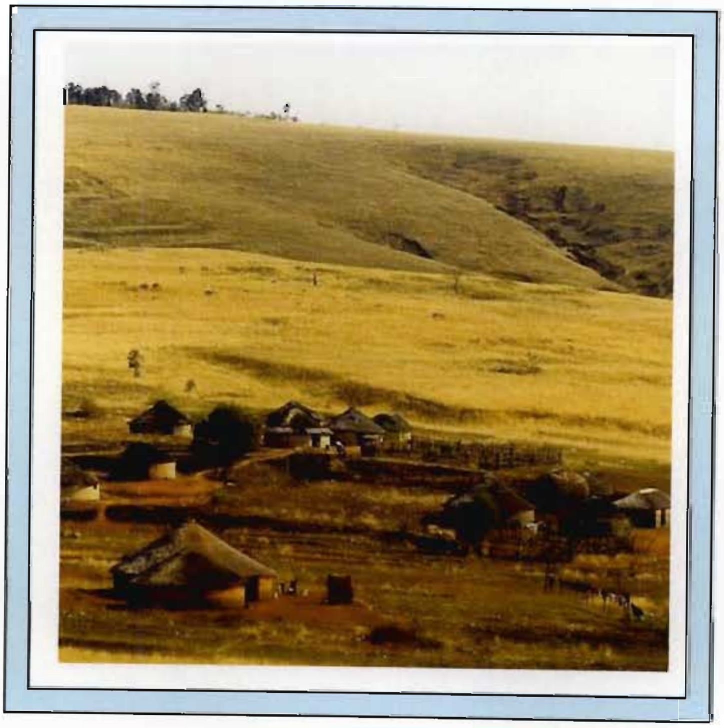

Figure 6.1: Nkandla: a typical rural area in South Africa

Nkandla is approximately $35 \times 40 km^2$ and has a population of about 250000 people. The terrain characteristics of Nkandla are hilly with both light and thick distribution of vegetation in some areas (see Figures 6.1 and 6.2). The hilly nature of Nkandla makes it the perfect area to evaluate the NLOS performance of WiMAX base stations. The Nkandla Forest is one of the most outstanding examples of surviving mist belt forest in South Africa (see Figure 6.3). The forest covers the crown and south-western slopes of the ridge which lies above the Mhlatuze and Thukela rivers at a height of between 1100 and 1300 m above sea level. Streams rising in the forest form deep gorges leading into the Nsuze River which runs along the base of the ridge. Apart from being an area of great, often pristine, natural beauty, the Nkandla Forest represents a rare relict type of high wet rain forest, of which very few examples survive. They are relicts of times in the distant past when the climate was wetter, and even colder. The forest has an exceptionally high species diversity with many species that are associated with scarp forest occurring. The tree heights on average are about 15-20 m, as seen at the site [http://www.kznwildlife.com/nkandla_dest.htm].

Apart from the simulations, an analytical model is also used to analyze the performance of the network. The analytic model is written in Matlab and can be found in appendix A1.

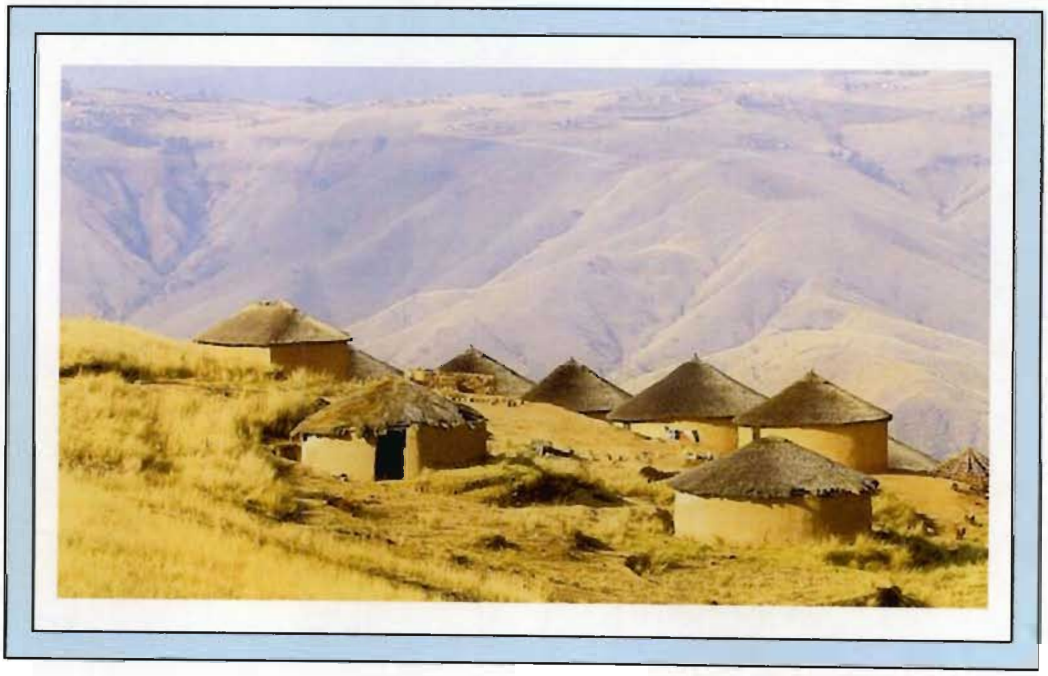

Figure 6.2: The hilly nature of Nkandla

Figure 6.3: The Nkandla Forest (see: http://www.zbr.co.za/sz/nkandla.htm)

6.2 WiMAX System Profiles

The network operates using a centralized base station and a sectorized antenna on a point-to-multipoint basis. The uplink is shared on a TDMA basis and the downlink on a TDM basis.

The maximum transmitter output power depends on the regional regulations. In Europe, the maximum peak transmission power for TDMA Base Stations in the 3.5 GHz frequency range is 35 dBm, while in the 5.8 GHz frequency range, the power is 24 dBm [14, 25]. The Subscriber station transmit power is limited to about 25% of the base station power.

The gain of an antenna is dependant on the antenna beam width. Base station sector antennas with beam widths of 60, 90, and 120 degrees have gains of 17 dBi, 15 dBi and 14 dBi respectively. Subscriber stations can use either directional outdoor antennas with large beam widths or omni-directional indoor antennas.

The BS uses a sectorized antenna with a beam width of 90^o (i.e. four sectors). Each sector operates independently of the other. The subscriber stations use directional antennas with beam widths of 177 degrees and gains of 18 dBi.

Table 6.1 provides a summary of the system profiles used to set up the WiMAX network. Two scenarios are evaluated:

- Scenario A - system operates in the licensed spectrum with a frequency of 3.5 GHz.
- Scenario B – system operates in the unlicensed spectrum with a frequency of 5.8 GHz.

	Scenario A	**Scenario B**
Operating Frequency	3.5 GHz	5.8 GHz
Transmit Power (BS)	33 dBm	22 dBm
Transmit Power (SS)	8 dBm	5 dBm
Gain (Downlink)	14 dBi	14 dBi
Gain (Uplink)	18 dBi	18 dBi

Table 6.1: System profiles

6.3 Coverage Analysis

6.3.1 Analytical Approach

The analytical approach is based on empirical channel models for frequencies above 2 GHz. Empirical channel models make it possible to predict the behavior of radio signals as they propagate from the transmitter to the receiver without having to know specific characteristics of the site such as trees and building heights. This is a very useful tool in wireless network design.

6.3.2 Channel Model

One of the most important things to consider when designing a wireless network is the losses experienced by the signal as it traverses between the transmitter and the receiver since an increase in losses implies a decrease in the signal coverage. The maximum propagation loss tolerated by the system in a specific scenario is determined according to a well-known link budget calculation, which is represented by [26]:

$$P_{rec} = P_t + G_t - L_t \qquad (6.1)$$

Where;

- P_{rec} is the receiver sensitivity
- P_t is the transmission power
- G_t is the total system gain – comprises all the system contributions to enhance signal level at reception
- L_t is the total system loss – corresponds to all the losses in the system.

The receiver sensitivity P_{rec} in dBm is given by [26]:

$$P_{rec} = SNR_{rx} + 10\log(W) + F + N_o \qquad (6.2)$$

Where,

- SNR_{rx} is the required signal-to-noise ratio in dB
- W is the effective channel bandwidth
- F is the noise figure
- N_o is the thermal noise level in dBm, given by:

$$N_o = 10\log(\frac{kT}{10^{-3}}) \qquad (6.3)$$

With

- $k = 1.38 * 10^{-23} J/K$ (Boltzmann's constant)
- T being the temperature in Kelvin

WiMAX technology is capable of providing LOS and NLOS coverage, so in order to evaluate the performance of WiMAX as accurately as possible both LOS and NLOS channel models will be considered.

The LOS model consists of the free space loss in dB [26]:

$$L_o = 32.45 + 20\log(f_c) + 20\log(d) \tag{6.4}$$

Where,

- d is the distance between the transmitter and the receiver in km,
- f_c is the operating frequency in MHz.

However this formula does not include ground reflections and is therefore inappropriate for our studies.

The dual slope path model includes ground reflections. The model is described by the following equations [27]:

$$L = \begin{cases} 26.44 + 20\log(f_c) + 26\log(d) & for \quad d < d_c \\ 26.44 + 20\log(f_c) + 20\log(d_c) + 40\log(\frac{d}{d_c}) & for \quad d > d_c \end{cases} \tag{6.5}$$

Where,

- d_c is the breakpoint distance and is calculated from the equation,

$$d_c = {4h_t h_r}/{\lambda} \tag{6.6}$$

- λ is the wavelength in meters
- h_t, h_r are the transmit and receive antenna heights, respectively.

The Cost 231 propagation model is adopted in several real world applications, since it provides accurate estimates for NLOS propagation. Within COST 231 specifications, the Walfisch-Ikegami (street Canayon-SC) model is more appropriate for frequencies up to 6 GHz, since climate impacts can be neglected for frequencies between 2 and 6 GHz. [26]. The following expression describes the model [26]:

$$L = \begin{cases} 42.64 + 20\log(f_c) + 26\log(d) & for \quad d < d_c \\ 42.64 + 20\log(f_c) + 26\log(d_c) + 40\log(\frac{d}{d_c}) & for \quad d > d_c \end{cases} \qquad (6.7)$$

In a rural environment the RF signal experiences additional attenuation as a result of excess vegetation present in the area (see Figure 6.4). So an additional attenuation term is added to the path loss models mentioned above to appropriately model a rural environment. This additional attenuation is expressed as follows [14]:

$$A_{ev} = A_m[1 - e^{(-d\gamma/A_m)}] \qquad (6.8)$$

Where,

- d is the length of the path within the woodland,
- γ is the specific attenuation for very short vegetation paths(dB/m), and
- A_m is the maximum attenuation for one terminal within a specific type and depth of vegetation (dB).

The value of γ depends on the species and densities of the vegetation, and the frequency band of operation. Based on measurements, an approximate value 0.7 dB/km is given in the recommendation for systems operating at 3.5 GHz [14].

The maximum attenuation A_m depends on the species and density of the vegetation, the antenna pattern of the terminal within the vegetation, and the vertical distance between the antenna and the top of the vegetation. The frequency dependency of A_m is of the following form [14]:

$$A_m = A_1 f^{\alpha} \quad (6.9)$$

Where,

- A_1 and the α are coefficients derived from various experiments
- f is the operating frequency in MHz.

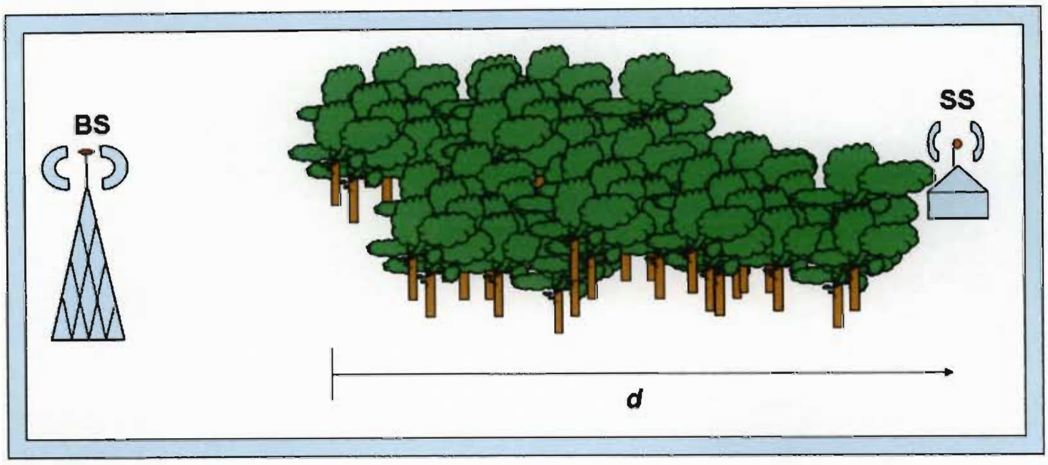

Figure 6.4: Representative radio path in woodland

According to the recommendation, measurements in the frequency range 900-2200MHz carried out in a French forest on paths varying in length from a few hundred meters to 6 km with various species of trees of mean height 15 m have yielded A_1 = 1.15dB and α = 0.43. In these measurements, receiving antenna height of 1.6 m and transmitting antenna height of 25 m were used. The standard deviation of the measurements was 8.7 dB, and seasonal variation of 2 dB at 900 MHz and 8.5 dB at 2200 MHz were observed [14].

6.3.3 Determining the Receiver Sensitivity in WiMAX systems

When calculating the sensitivity of the receiver it is important to bear in mind that the entire channel BW is not used for transmitting data. Firstly part of the channel BW is consumed by the FFT during sampling. This reduces the effective bandwidth by a factor [26]:

$$F_s / BW \qquad (6.10)$$

Where,

- F_s is the sampling frequency in MHz, as seen in chapter 5,
- BW is the channel BW in Hz.

Secondly, part of the channel bandwidth is also used by the DC and guard subcarriers, leaving only N_{used} out of the N_{FFT} subcarriers available for transmitting data. Thus the bandwidth efficiency is defined in the IEE 802.16 standard as [26]:

$$BW_{efficiency} = \frac{F_s N_{used}}{BW(N_{FFT})} \qquad (6.11)$$

Where,

- N_{used} is the number of subcarriers used to transmit data
- N_{FFT} is the length of the FFT

The bandwidth is further reduced as a result of subchannelization and is given by [26]:

$$BW_{efficiency} = \frac{F_s N_{used}}{BW(N_{FFT})} \frac{N_{subchannels}}{16} \qquad (6.12)$$

The effective bandwidth, W, of the system can now be calculated as [26]:

$$W = BW_{efficiency} BW = \frac{F_s N_{used}}{N_{FFT}} \frac{N_{subchannels}}{16} \qquad (6.13)$$

The IEEE 802.16-2004 OFDM PHY specifies a noise figure of 5 dB and an implementation margin of 7dB; this implies that the resulting effective noise figure of the system is 12dB. Using a temperature of 290°K the thermal noise becomes *No* =-174dBm. Substituting these vales into the receiver sensitivity equation the receiver sensitivity of an OFDM PHY is given [26]:

$$P_{r,\min} = -174 + 12 + SNR_{rx} + 10\log(\frac{F_s N_{used}}{N_{FFT}} \frac{N_{subchannels}}{16}) \qquad (6.14)$$

6.4 Simulations

6.4.1 ATDI Software

ATDI Software is a radio network planning and modeling tool. It provides for the regulation, modeling, planning and measurement of all network types that use the radio spectrum [28].

The ATDI software calculates the coverage of WiMAX base stations using site specific information gathered from the Nkandla region, such as tree and building heights. The coverage analysis calculates the total propagation losses experienced by the network and displays the resulting receiver sensitivity and signal field strength experienced at each location in the area. Based on these it then calculates the corresponding coverage of the BS. The path loss models used in the simulation are provided in the following subsections.

6.4.1.1 Path loss Models

The propagation of radio waves is characterizes by several factors [19]:

- Signal power is diminished by geometric spreading of the wave front, commonly referred to as free space loss.
- Signal power is attenuated as the wave passes through solid objects such as trees, walls and buildings.
- The signal is scattered and can interfere with itself if there are objects in the beam of the transmit antenna even if these objects are not on the direct path between the transmitter and the receiver.

a) Free Space Loss

The free space loss of the signal results from the expanding of the radiated signal energy as the distance from the transmitter increases. It is calculated as [29]:

$$L_{fs} = -32 + 20\log D + 20\log f \qquad (6.15)$$

Where,

- f = frequency (GHz)
- D = distance from transmitter (km)

b) Diffraction attenuation

Diffraction attenuation occurs when the direct path between a transmitter and a receiver is obstructed by one or several obstacles. In Fresnel theory, the attenuation brought by one single knife-edge located in free space can be derived using Fresnel integrals. Since those integrals have no explicit solution, a good approximation to this knife-edge diffraction loss is used [29]:

$$L_d = 6.9 + 20\log[(v-0.1) + \sqrt{(1+(v-0.1)^2})], \qquad (6.16)$$

Where the Fresnel parameter v is given by:

$$v = \sqrt{2}\frac{h}{r}, \qquad (6.17)$$

The fraction $\frac{h}{r}$ is known as the clearance ratio, it is the ratio of the algebraic height (positive upward) of the edge above the line of sight over the radius of the Fresnel ellipsoid at distance *d* from the transmitter (Tx), as can be seen in Figure 6.5 below.

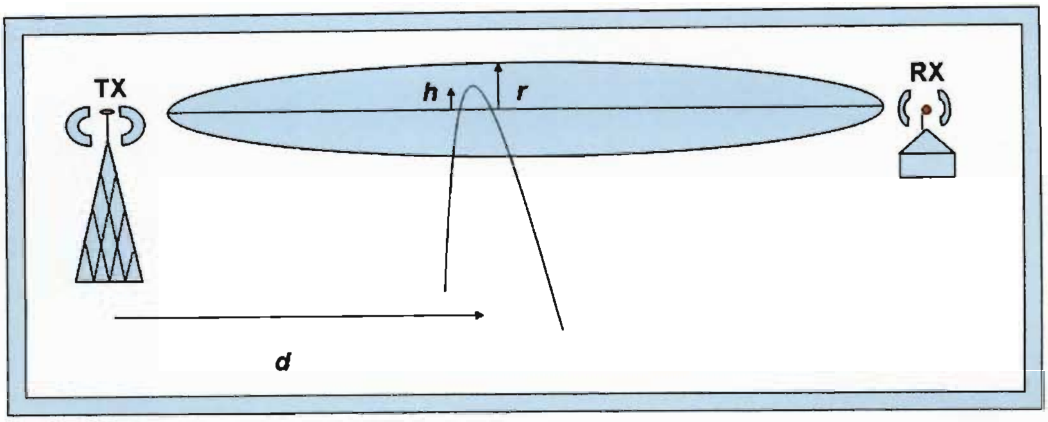

Figure 6.5: Diffraction attenuation Model

The radius of the Fresnel Ellipsoid, *r* is calculated as follows [29]:

$$r = 17.32\sqrt{\frac{D}{4f}}, \qquad (6.18)$$

Where,

- r = radius in meters
- D = total distance between transmitter and receiver in kilometres
- F = frequency transmitted in Gigahertz

c) Standard Sub-path Attenuation

When using geometrical models, one often finds that the predicted values for field strength and power received are too optimistic. In an attempt to correct this, J Deygout proposed the introduction of a correction term [29]:

$$L_{gr} = 20\log(75000d) - 20\log(\pi h_1 h_2 f) \qquad (6.19)$$

Where:

- d = distance to Tx (km),

- h_1, h_2 = respectively the Tx and Rx height (m),
- f = the frequency (MHz).

This correction term is derived from surface reflective modelling and is referred to as the ground reflection attenuation. Based on this ground reflection attenuation, the standard subpath attenuation, L_{sp}, of the signal can be calculated as follows:

$$L_{sp} = FZ\rho L_{gr} \quad (6.20)$$

Where:

- FZ is a coefficient of reduction of this virtual ellipsoid:
  - FZ=1 means that the whole ellipsoid is considered
  - FZ=0 means that the virtual ellipsoid reduces to the straight line of sight segment, refer to Figure 6.6.
- ρ is the portion of the total path that is located above the first Fresnel virtual ellipsoid.

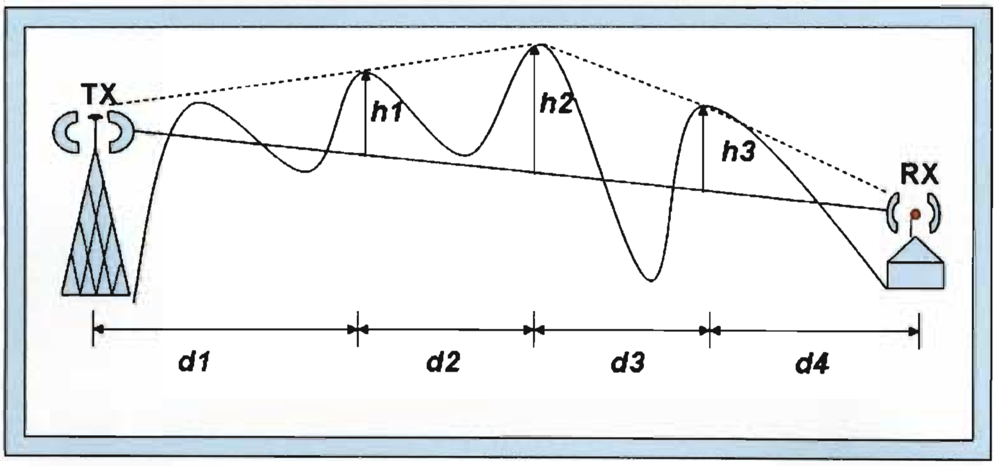

Figure 6.6: Sub-path attenuation

From Figure 6.6 above ρ is calculated as follows [29]:

$$\rho = (\frac{d_1 + d_2 + d_3 + d_4}{d}) \tag{6.21}$$

Using the above mentioned attenuation terms the coverage of the network can be analyzed in terms of field strength and receiver sensitivities experienced at each location on the map. The power received (dBm) is calculated as follows [29]:

$$P_{rec} = P_{rad} + G_{rx} - L_{prop} \tag{6.22}$$

Where,

- G_{rx} is the receiver antenna gain
- P_{rad} is the radiated power in dBm
- $L_{prop} = L_{fs} + L_d + L_{sp} + L_{clu} + L_{rain}$ (6.23)

The field strength (dBuV/m) is calculated as follows [29]:

$$F_{rec} = P_{rec} - G_{rx} + L_{prop} \tag{6.24}$$

6.5 Coverage Analysis Results

a. Effects of vegetation density on coverage

In this evaluation the Walfisch-Ikegami (street Canayon-SC) model and the excess attenuation model are combined to predict the coverage of the BS in a rural environment. In this simulation a QPSK1/2 modulation is used (since it has the highest range for data transmissions). The plot is shown in Figure 6.7. As expected, the variation is a logarithmic function of distance, d, through the vegetation.

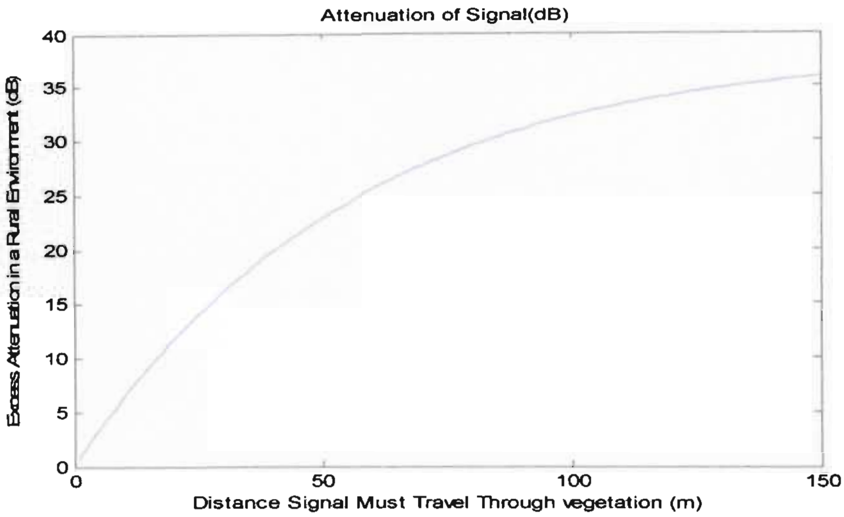

Figure 6.7: Excess Attenuation vs. Distance through Vegetation

From the analytical results it is found that the greater the distance the signal travels through vegetation the lower the coverage of the base station. Figure 6.8 and Figure 6.9 provides the analytical results obtained for downlink coverage in a rural environment. Again, it shows that the denser the vegetation, the much smaller the coverage range of the BS.

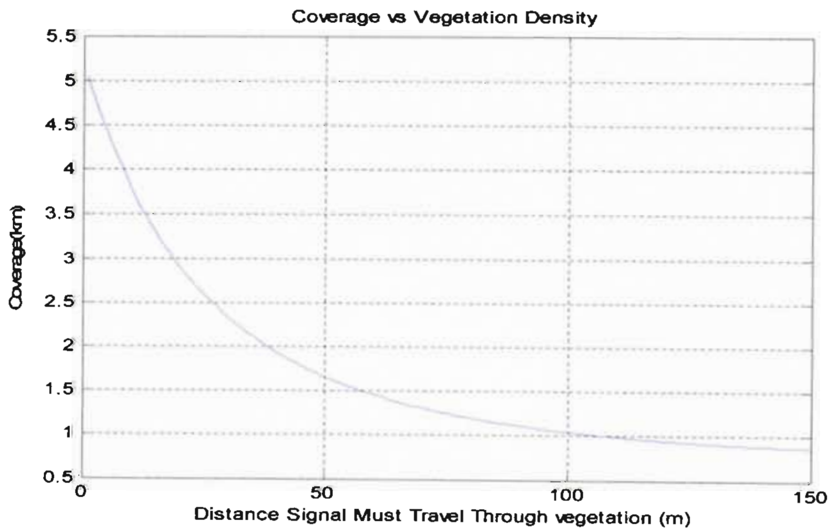

Figure 6.8: Downlink Coverage using QPSK modulation at a coding rate of ½ (scenario A)

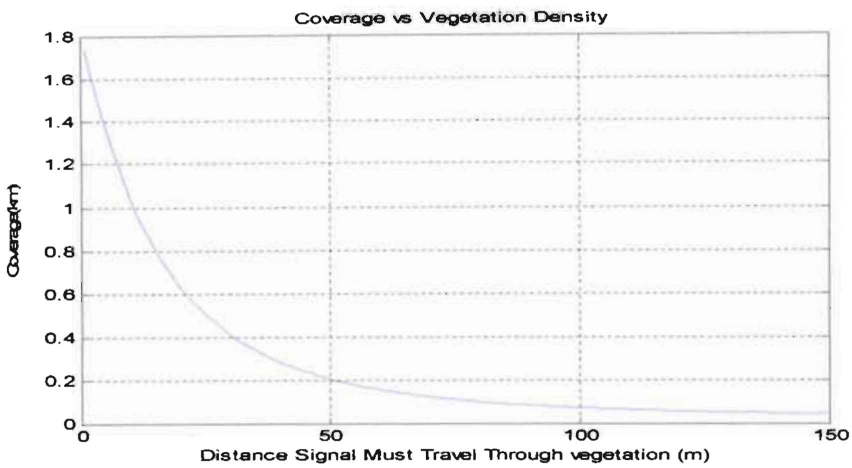

Figure 6.9: Downlink Coverage using QPSK modulation at a coding rate of ½ (scenario B)

b. Effects of Modulation Type and Coding Rate on Coverage

For the remainder of the simulations it is assumed that the signal has to travel through an average 3 m of vegetation before it reaches the receiver. This is based on the reality in Nkandla, where the shrubs and trees may not be densely placed, unless the entire propagation is through the forest.

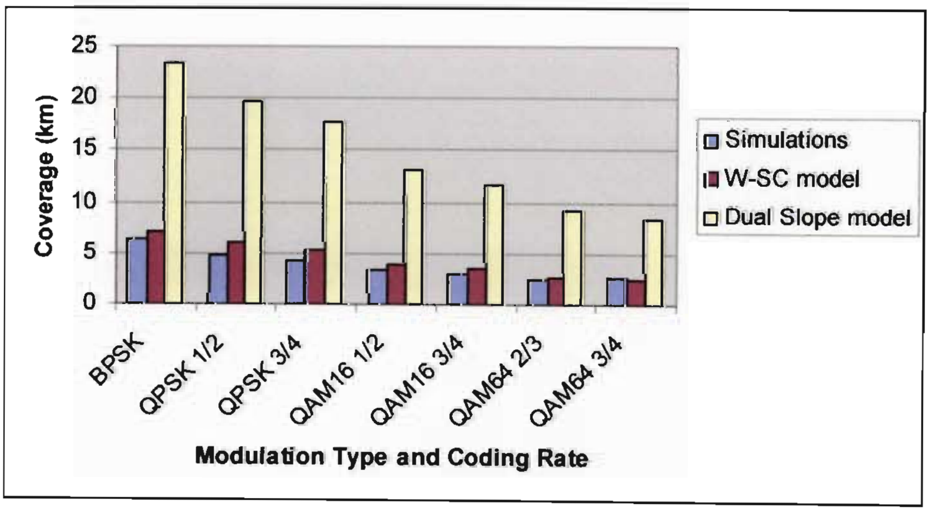

Figure 6.10: Effects of Modulation and coding on downlink Coverage (Scenario A)

In Figure 6.10 and subsequent simulations, we have:

- W-SC model represents the analytical results obtained using the Walfisch-Ikegami (street Canayon-SC) model
- Dual slope model represents the analytical results obtained using the Dual Slope Path Loss model
- Simulations represent the simulated results obtained using the ATDI software package

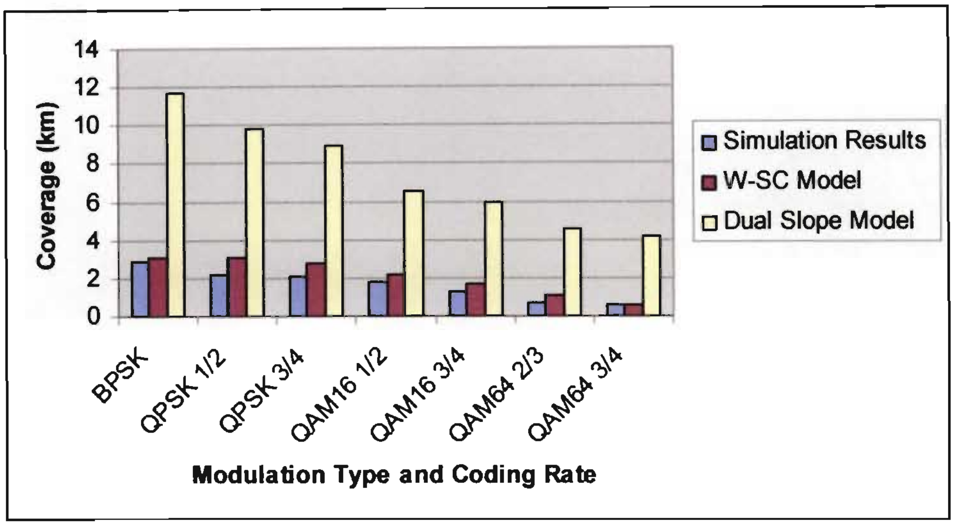

Figure 6.11: Effects of Modulation and coding on Uplink Coverage (Scenario A)

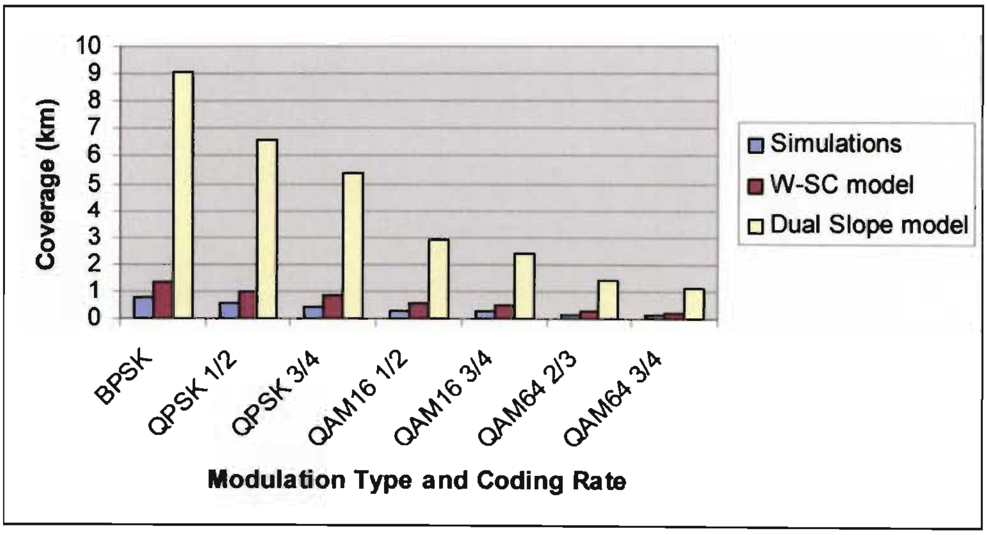

Figure 6.12 Effects of Modulation and coding on Uplink Coverage (Scenario B)

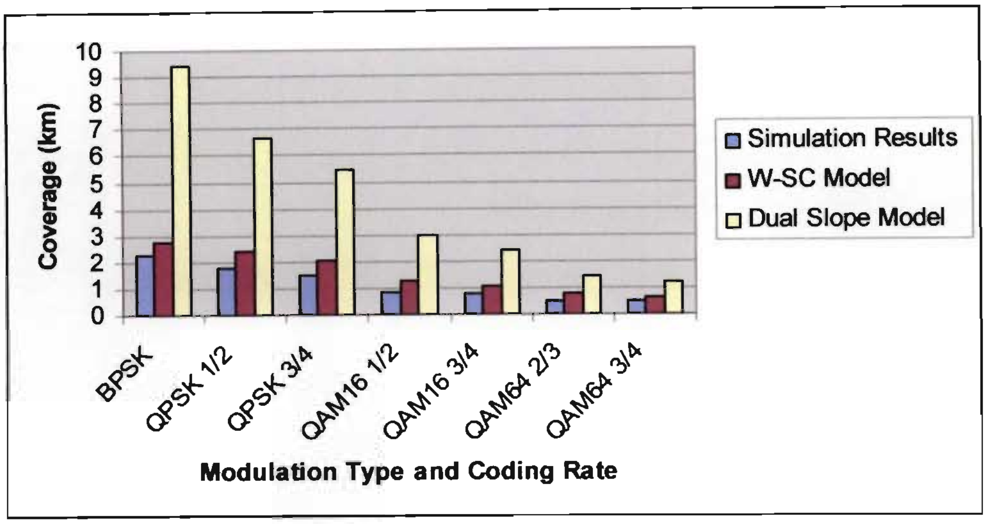

Figure 6.13 Effects of Modulation and coding on Uplink Coverage (Scenario B)

Figures 6.8 - 6.13 illustrate the fact that the higher modulation type and coding rate the lower the coverage of the BS. This is the case since the higher the modulation type the higher the receiver sensitivity and hence the smaller the coverage. Using the results obtained, one is now able to see to what extent the coverage of a network is decreased by stepping up the modulation type. This information will help network planners obtain a balance between the capacity and coverage demands of an area. Also from the simulation results it can be seen that the W-SC model is most appropriate for a rural environment; the dual slope model overestimates the coverage capabilities of the network. The results also reveal the fact that coverage in the licensed spectrum is almost 5 times more than the unlicensed spectrum. This means that using the unlicensed spectrum to roll out WiMAX in a rural environment would be an unattractive option since more WiMAX base stations would have to be used, which would then raise the cost. The unlicensed spectrum would probably be of better use in providing coverage to population centers or small suburban areas rather than rural connectivity.

c. Effects of Subchannelization on Uplink Coverage

Subchannelization is the technique of using only a subset of the available channels to transmit data. The IEEE802.16-2004 OFDM wirelessMAN specifies subchannelization capabilities only for transmissions in the uplink (transmission from BS to SS) direction. The standard specifies that from the 16 available channels, 1, 2, 4, 8 or 16 of them can be used at any given time to transmit data. In Figures 6.14 and 6.15 the effect that subchannelization has on the uplink coverage is investigated. From the graph it can be seen that the fewer active subchannels the higher the coverage. By using 1 subchannel instead of the default sixteen, an SS can increase its coverage from 2.6 km to 4.8 km, almost doubling its coverage capabilities. This increase in coverage occurs since by decreasing the number of used subchannels the power concentrated in each subchannel is increased; that is when there are sixteen active subchannels each subchannel has a power of P/16, and when the number of active subchannels is decreased to four the power of each subchannel becomes of P/4. Again the W-SC model proves to be the more relevant for rural conditions, compared to the Dual-slope model.

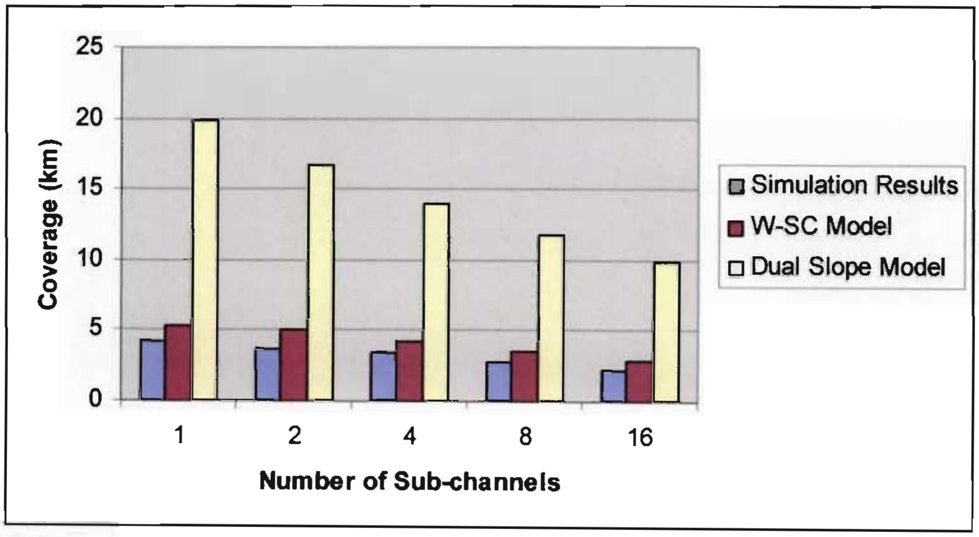

Figure 6.14: Subchannelization Effects on Uplink Coverage (Scenario A) using QPSK modulation at a coding rate of ½

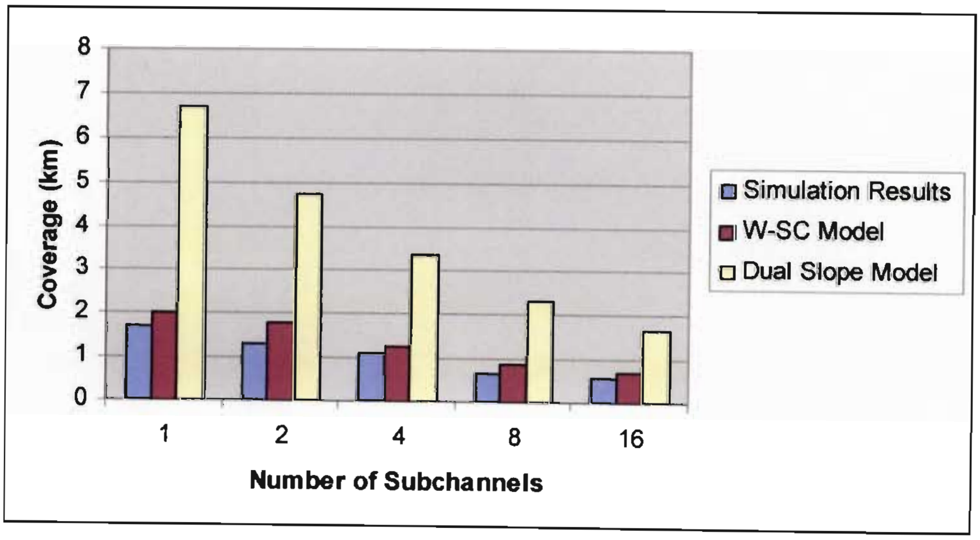

Figure 6.15: Subchannelization Effects on Uplink Coverage (Scenario B) using QPSK modulation at a coding rate of ½

d. Effects of Increasing Bandwidth on Coverage

From the analytical and simulated results it is found that an increase in the channel bandwidth reduces the BS coverage. This is the case since by increasing the channel bandwidth of the network the effective bandwidth is increased thereby causing degradation in the receiver sensitivity.

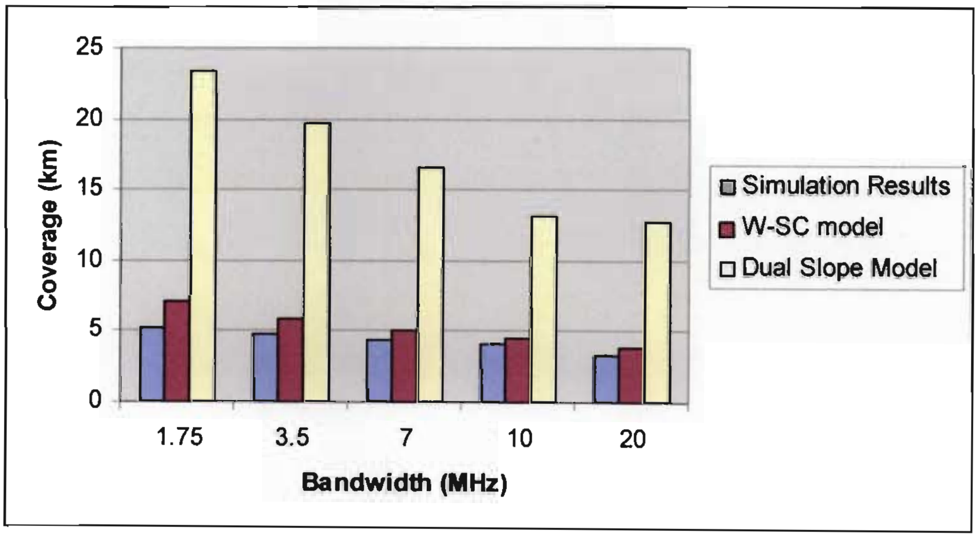

Figure 6.16: Increasing Bandwidth vs. Downlink Coverage (scenario A) using QPSK modulation at a coding rate of ½

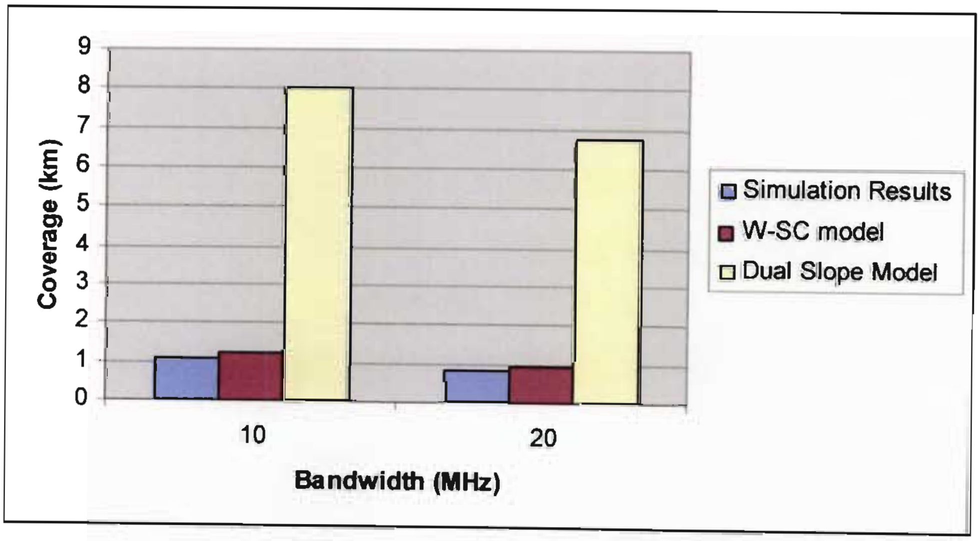

Figure 6.17: Increasing Bandwidth vs. Downlink Coverage (Scenario B) using QPSK modulation at a coding rate of ½

e. Effects of Adaptive Antenna Systems (AAS) on the coverage of a WiMAX Network

Adaptive antenna systems consist of multiple antenna elements at the transmitting and or receiving side of the communication link, whose signals are processed adaptively in order to exploit the spatial dimension of the channel [30]. Generally any combination of elements can form an array. The array or beam forming gain is the average increase in signal power at the receiver due to a coherent combination of the signal received at all antenna elements. The adaptive antenna gain compared by an amount equal to the number of array elements, e.g. an eight element array can provide a gain of eight (9dB) [30].

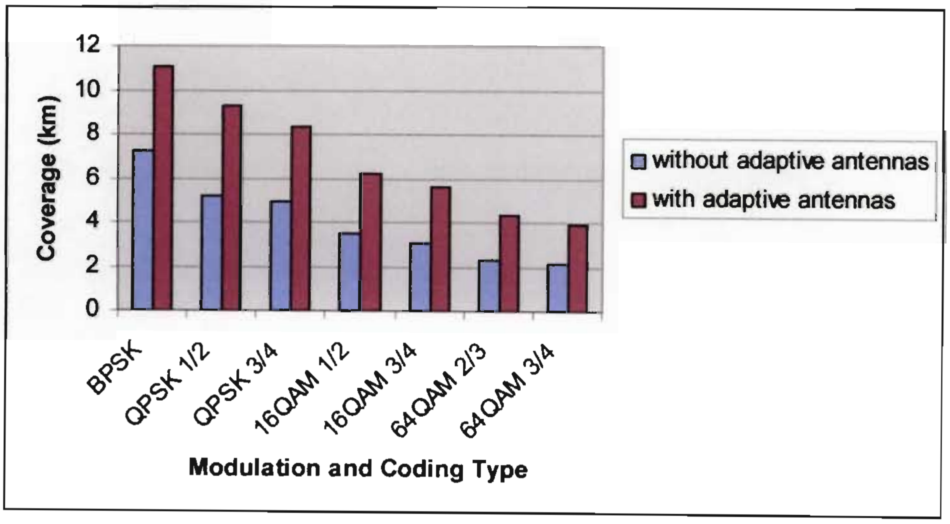

Figure 6.18: Analytical results for Coverage With and without Adaptive antenna systems

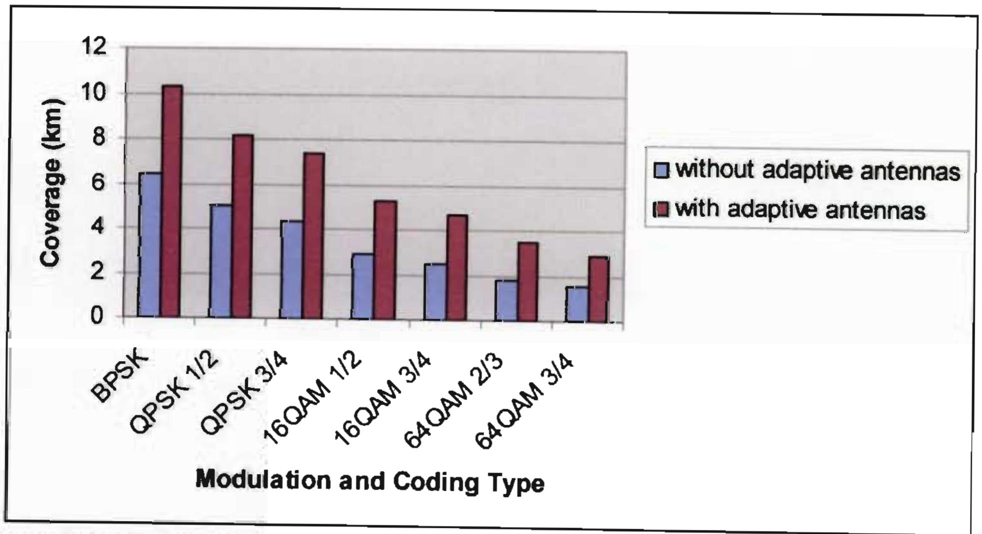

Figure 6.19: Simulation results for downlink Coverage with and without adaptive antennas

As expected from the simulation and analytical results, in Figure 6.18 and 6.19, the use of adaptive antenna systems results in better coverage.

6.6 Capacity Evaluation

6.6.1 Coverage Planning

The coverage planning is a key aspect of network design, it makes it possible for network designers to predict the number of base stations required to provide coverage in a region without having to gather site specific information. The best way to cover an area with equally sized cells is shown in Figure 6.20. The range of each base station, *r, can* be calculated from the equation below [14]:

$$r = \frac{1}{2n} \times \sqrt{2} \times L \qquad (6.24)$$

Where,

- n is the number of base stations
- r is the range of each base station
- L is the length of one of the sides of the area

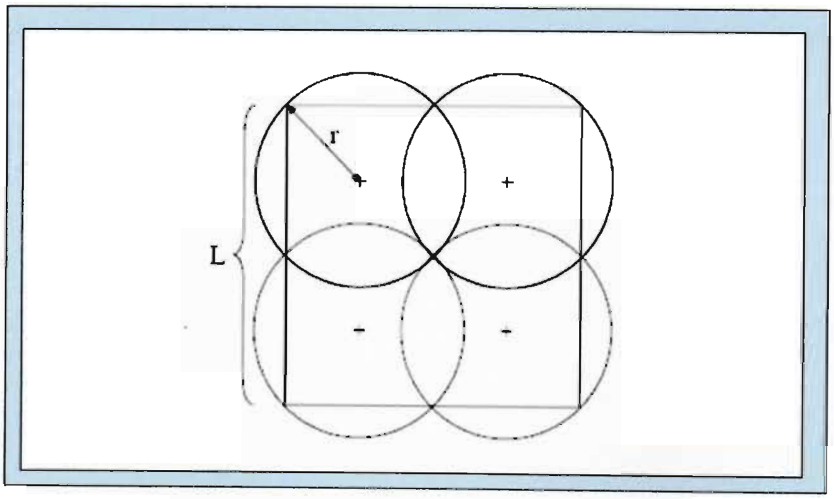

Figure 6.20: Four cells covering a square-shaped area [14]

From the results obtained from the coverage analysis we find that a WiMAX base station in the Nkandla area has coverage radius $r \approx 5km$ using QPSK ½ . Taking this into account and making n the subject of the equation, it is found that approximately 6 base stations are required to provide coverage for the entire Nkandla region.

6.6.2 Subscriber Density

Having completed the coverage analysis, we now move on to evaluate WiMAX in terms of capacity. From the coverage analysis, it was found that each base station has a coverage radius of approximately 5 km thereby implying that each BS provides coverage to an area of approximately $50km^2$. So in order to evaluate the performance of WiMAX in terms of capacity the subscriber density within this area must first be calculated.

The subscriber density within the simulation area is calculated as follows:

Nkandla has an area of approximately $35 \times 40km^2$ with a population of approximately 250000 people which implies that:

- Number of occupants per km^2 = $250000/(35 \times 40)$ $= 178.659$

- Occupants in a $50km^2$ area = 178.659×50 $= 8930$

Assuming an activity factor of 50 % , we obtain:

- Active Users in the $50km^2$ area = 8930×0.5 $= 4465$

Furthermore an oversubscription ratio of 1:4 is implemented since families in Nkandla have on average about 4-6 people per family.

- Subscriber Density = $4465/4$ = 1116.25

Thus each base station has approximately 1116 subscribers.

6.6.3 Analytic Model

a. Maximum Data Rate

The maximum transmission data rate R, that can be achieved in OFDM PHY is defined in the IEEE 802.16 standard as [17, 26]:

$$R = \frac{N_{used} b_m c_r}{T_s} \qquad (6.25)$$

Where:

- b_m is the number of bits per modulation symbol as follows;

$$\begin{aligned} b_m &= 1 \quad for \quad BPSK \\ b_m &= 2 \quad for \quad QPSK \\ b_m &= 4 \quad for \quad 16-QAM \\ b_m &= 6 \quad for \quad 64-QAM \end{aligned}$$

- c_r is the coding rate. Three possible values of c_r are 1/4, 2/3 or 3/4
- T_s is the symbol duration

b. Maximum Base Station Sector Throughput

The maximum throughput, τ of each base station sector can thus be calculated as follows:

$$\tau = ((R/W) * BW) - MAC_{overhead} \qquad (6.26)$$

Where,

- R/W = spectral efficiency

- BW is the bandwidth
- $MAC_{overhead}$ is the percent of MAC overhead
- W is the effective bandwidth in hertz

From [31] it is found that the overall MAC overhead of the 802.16-2004 OFDM system is approximately 10%, implying that about 90% of the raw bit rate is available to the upper layers.

c. Maximum Number of Subscribers per BS Sector

The maximum number of subscribers a base station sector can handle $SSs_{max/sect}$ is calculated as follows [14]:

$$SSs_{max/sect} = \left(\frac{\tau}{TD_{DL} + TD_{UL}}\right) \times C \qquad (6.27)$$

Where,

- τ is the max throughput of the base station sector
- TD_{DL} is the downlink traffic demand per SS
- TD_{UL} is the uplink traffic demand per SS
- C is the concentration factor

The capacity-based number of base-station sectors is the ratio between the expected number of customers in the service area and the maximum number of subscribers in one sector. The higher the traffic demands per SS the lower the concentration factor. The choice of a suitable concentration factor depends on the applications the subscribers are using. If the subscribers were only using the broadband connection to read their e-mails and browse the web, a high concentration factor could be used. New broadband services, such as video and music streaming have higher capacity demands and require constant throughput from the network. Some applications, such as peer-to-peer file sharing are even more problematic from the traffic concentration point of view. A subscriber sharing and downloading video files may be transmitting and receiving at maximum speed for many hours or even all the time [14].

6.6.4 Capacity Analysis Results

In the following sections the effects that the bandwidth, subchannelization and the different modulation types and coding rates have on the BS capacity is evaluated.

a. Effects that Modulation Type and Coding Rate have on the capacity of a WiMAX BS

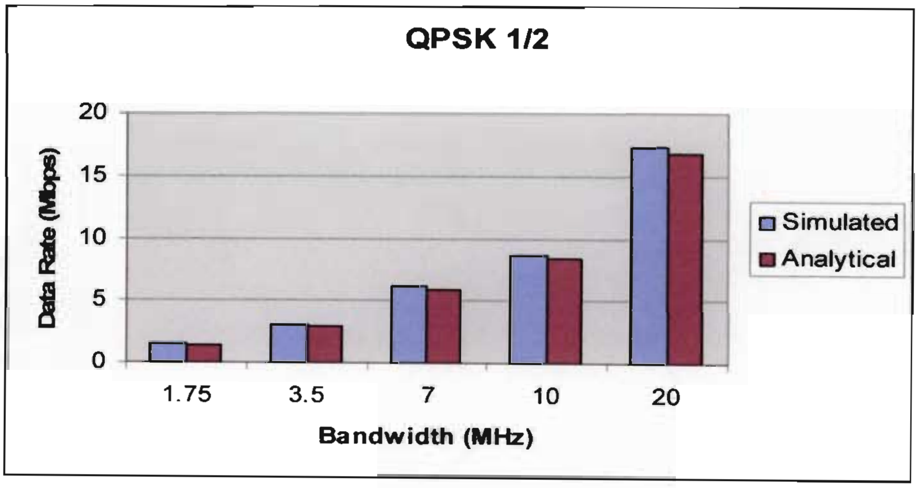

Figure 6.21 Increasing Bandwidth effects on Data rate for QPSK 1/2

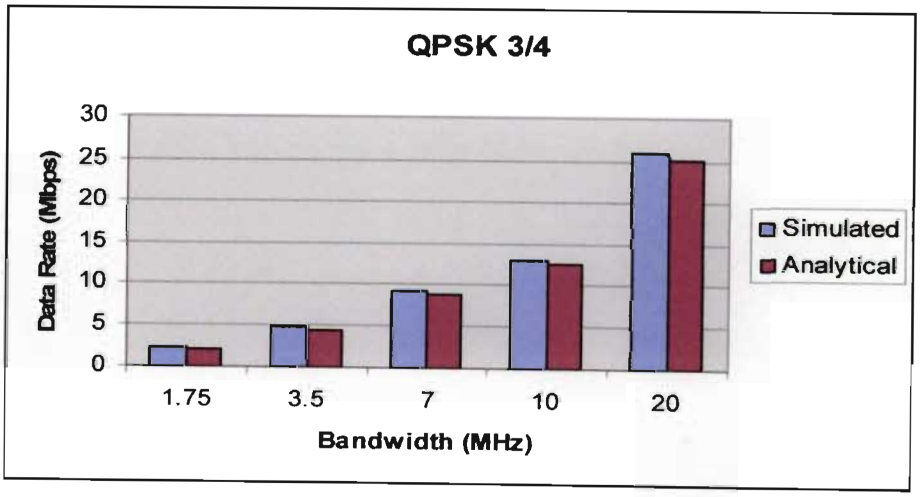

Figure 6.22 Increasing Bandwidth effects on Data rate For QPSK ¾

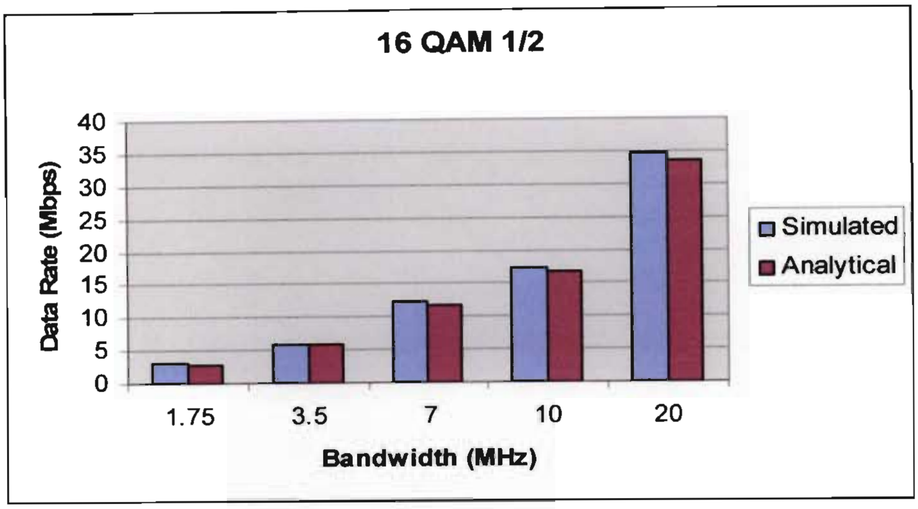

Figure 6.23 Increasing Bandwidth effects on Data rate For 16 QAM 1/2

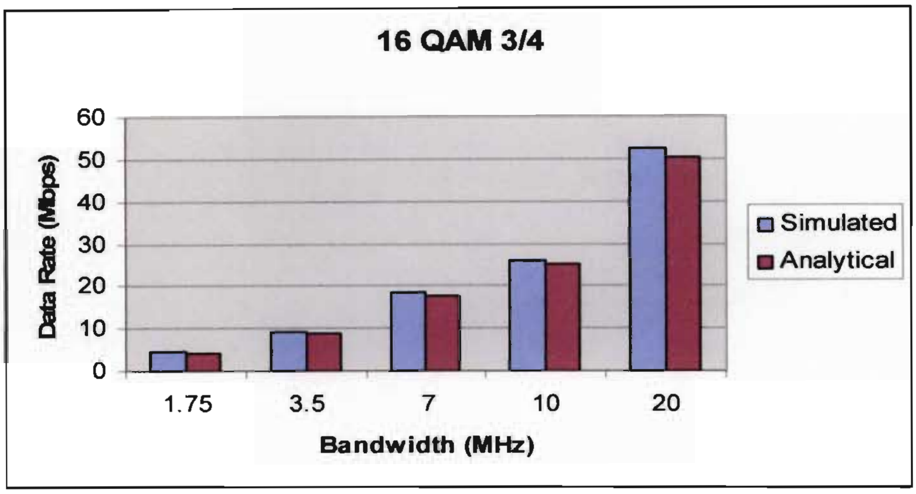

Figure 6.24 Increasing Bandwidth effects on Data rate For 16 QAM 3/4

From the results graphs in the Figures 6.21-6.26 it can be concluded that less robust the modulation type the higher the achievable data rates since higher modulation types provide better spectral efficiencies. The maximum data rate that a WiMAX BS can achieve is about 78Mbps, using 64-QAM with a coding rate of ¾.

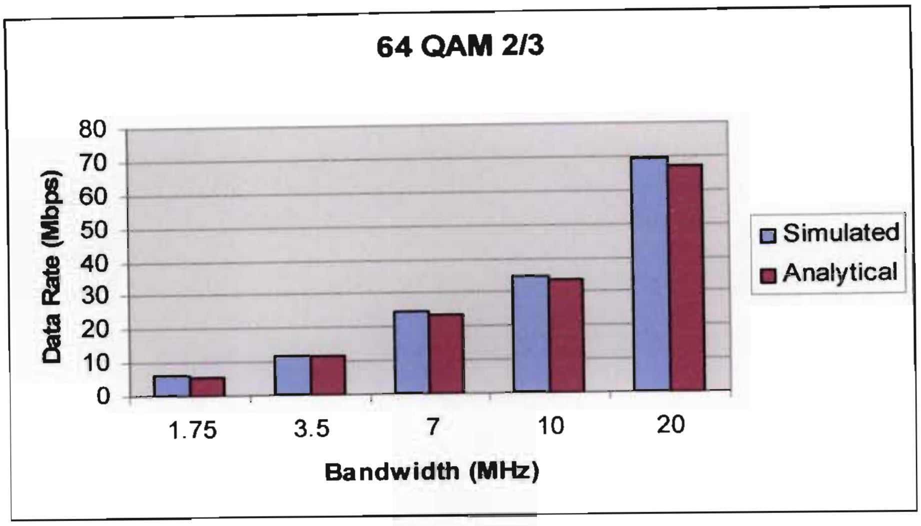

Figure 6.25 Increasing Bandwidth effects on Data rate For 64 QAM 2/3

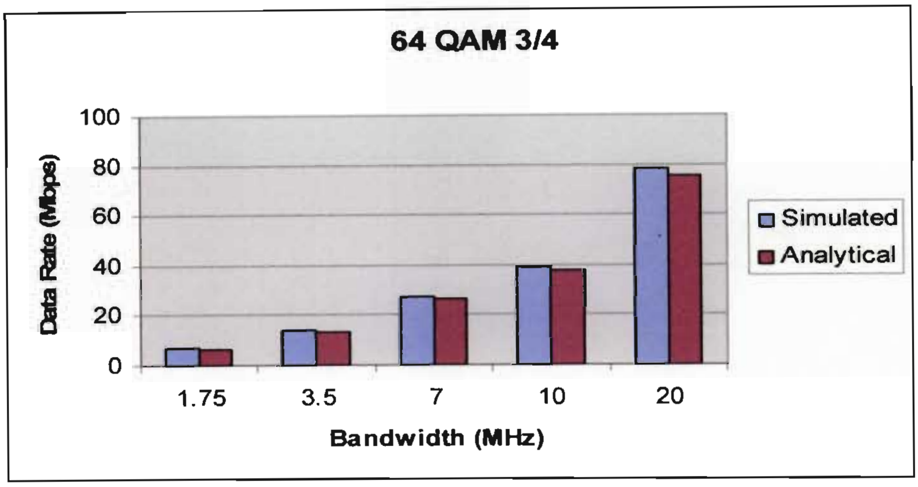

Figure 6.26 Increasing Bandwidth effects on Data rate For 64 QAM 3/4

b. Effects of Antenna Sectorization on the capacity of a WiMAX BS

The results In Figure 6.27 show that as the number of antenna sectors are increased the throughput of the network increases. A BS operating with six antenna sectors has a throughput three times higher than a BS using two antenna sectors. This is a very important result since in coverage limited networks; antenna sectorization provides a means of increasing BS capacity without reducing the coverage of the BS.

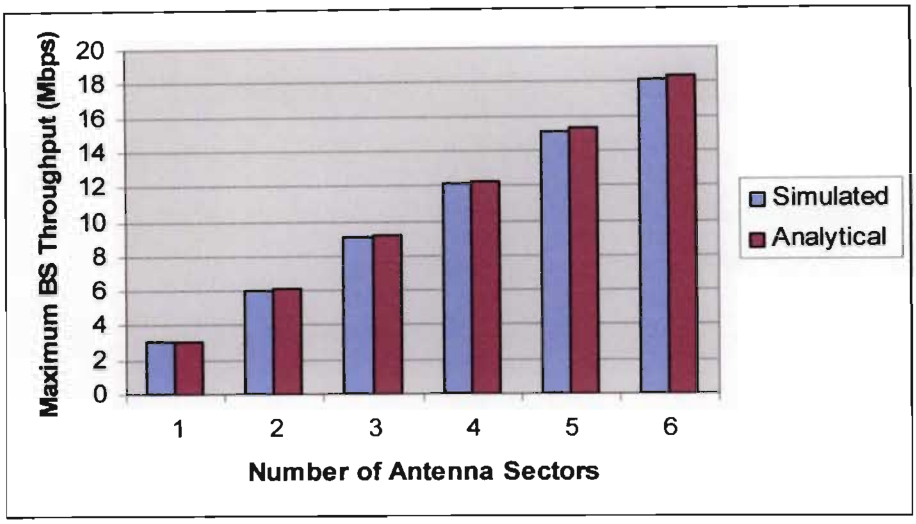

Figure 6.27: Effect of Antenna Sectorization on Throughput

c. Effects of Subchannelization on the capacity of a WiMAX network

The results obtained in Figures 6.28 show that as the number of sub-channels in the uplink are increased the data rate of the network increases, thus implying that subchannelization in the uplink is not the most feasible solution in capacity limited base stations since whilst it might increase the coverage it severely deteriorates the performance of the network in terms of capacity.

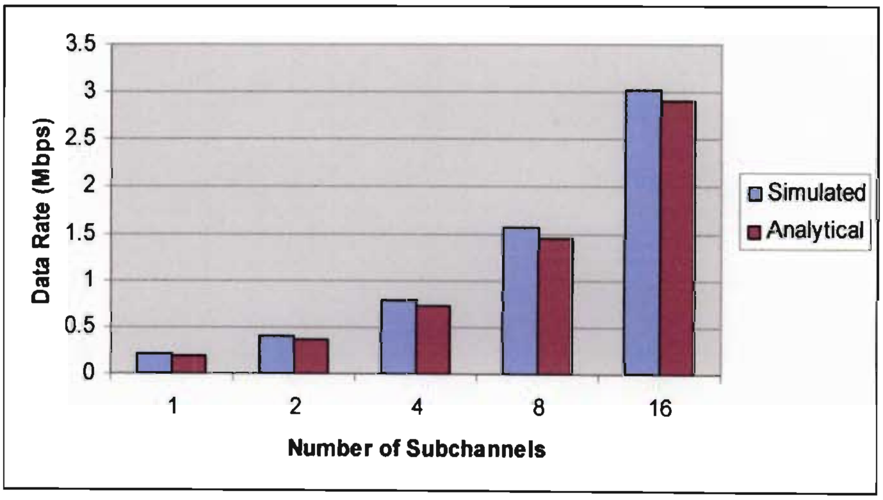

Figure 6.28: Effect of subchannelization on data rate of the network.

6.7 Feasibility Study

In order to ascertain whether or not WiMAX networks are a feasible solution for connecting rural areas, the traffic demand of the simulation area is projected over a 10 year period and simulations are run to evaluate whether or not WiMAX base stations can handle the growing traffic demand over the full projection period.

6.7.1 Traffic Projections

The voice traffic projections used in this simulation was obtained from Nkandla toward late 2005 from [12]. It consists of both GSM and non- GSM traffic. Based on the data traffic growth trends found in [32] the corresponding data traffic demand for the simulation area in Nkandla was calculated and projected over the next ten years. The simulations are run using a central base station and 4 antenna sectors each with an antenna beam width of 90 degrees. The operating frequency is 3.5 GHz and the bandwidth is 3.5 MHz.

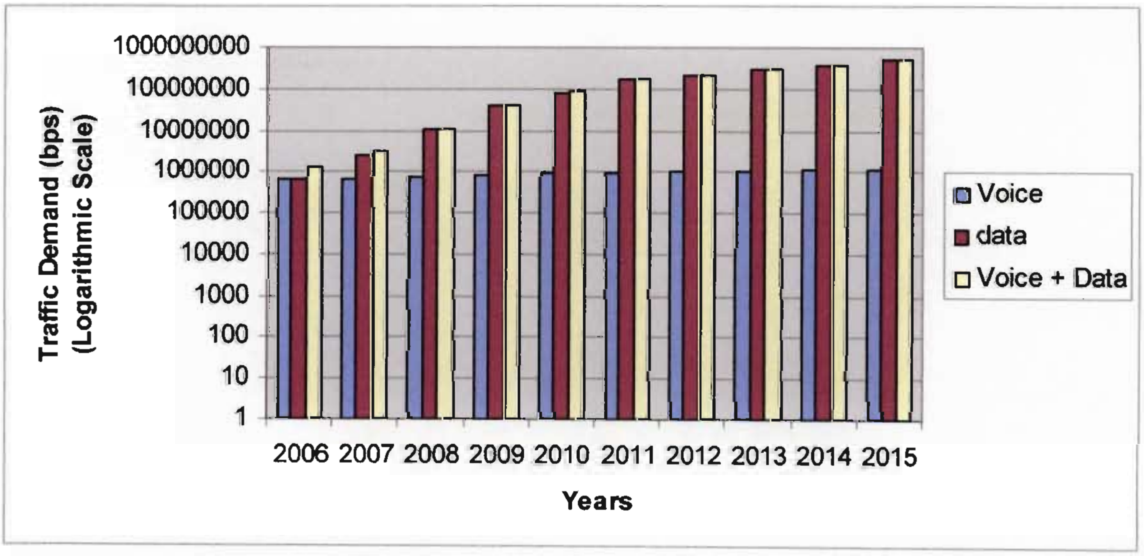

Figure 6.29: Voice and Data traffic projections over the next ten years for the simulation area in Nkandla [12, 32].

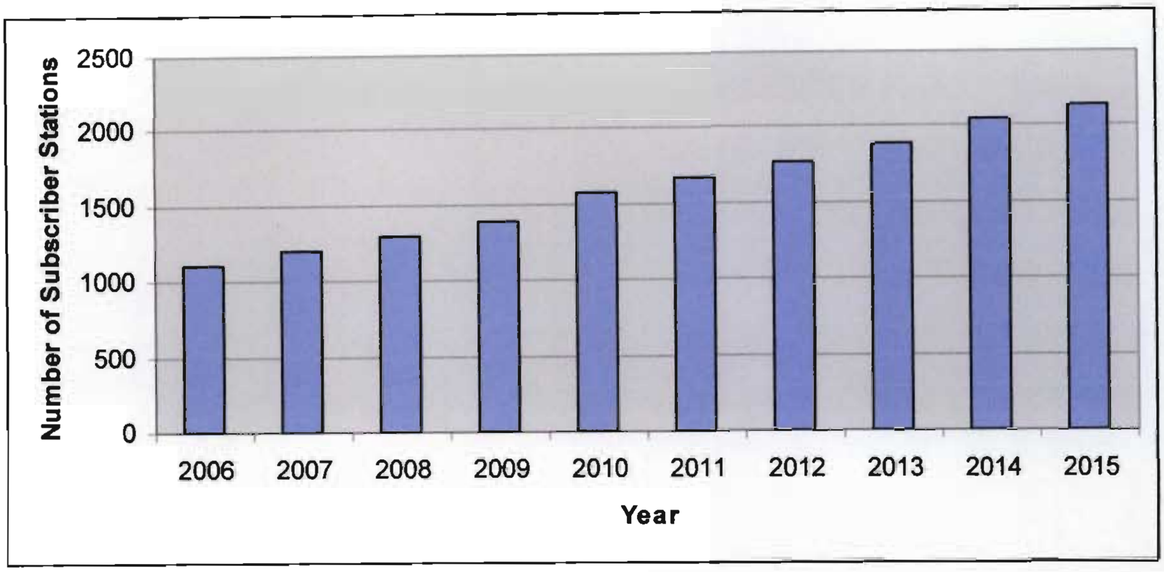

Figure 6.30: Projected growth in the number of SS's in the simulation area over the next ten years [12].

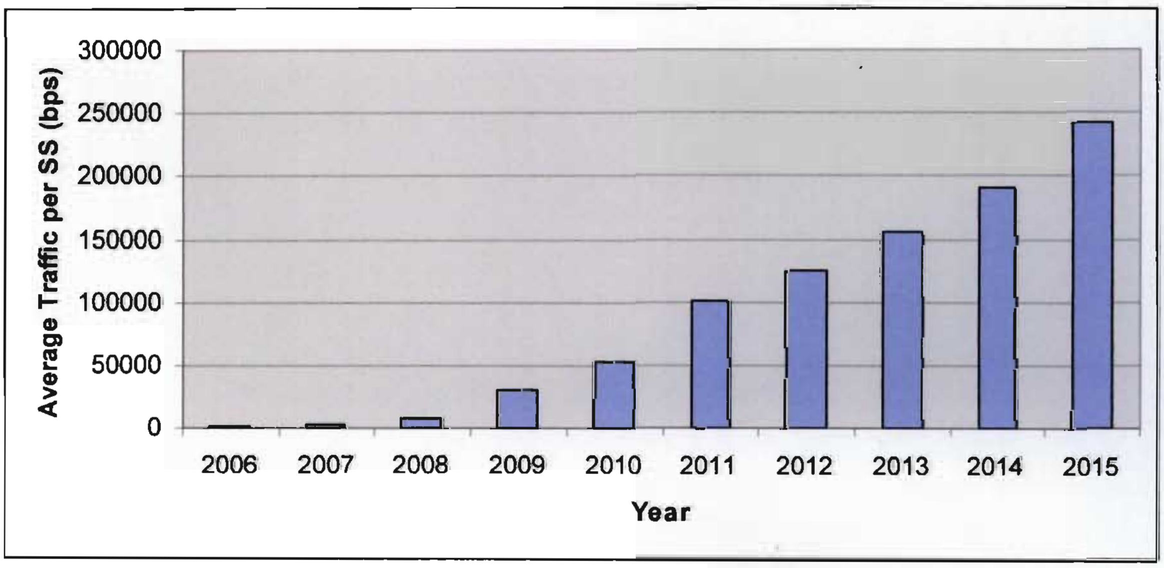

Figure 6.31: Average Traffic Demand per SS

From Figures 6.29 and 6.30, the traffic demand per subscriber station over the 10 year period is calculated, and the results are displayed in Figure 6.31.

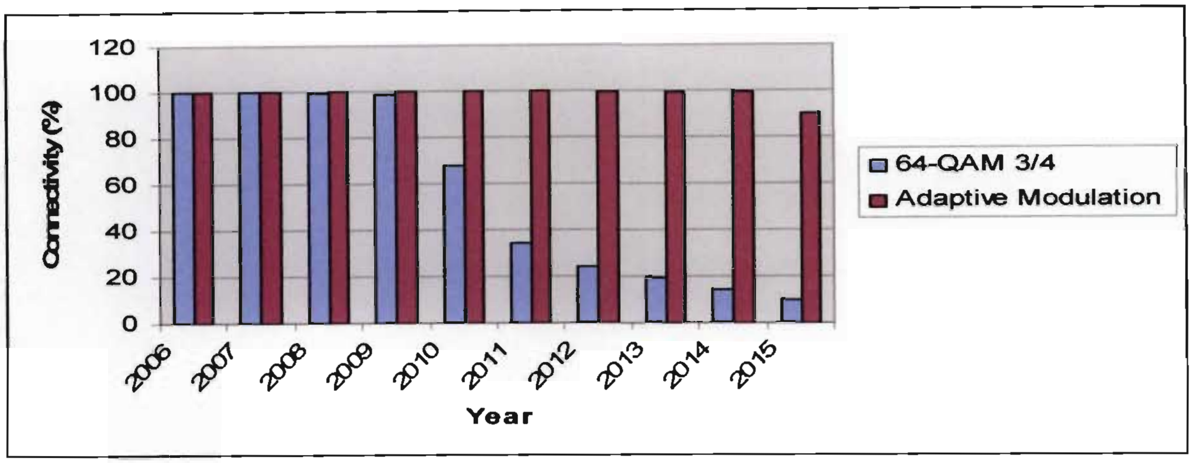

Figure 6.32: Maximum number of SSs the BS can handle.

From the simulation results we find that the single BS in Nkandla can only sustain the growing traffic demand over the first four years using 64-QAM modulation with a coding rate of ¾. Thereafter the BS begins to drop subscriber stations at a very high rate. However by using adaptive modulation the BS is able to sustain the growing traffic demand over the full ten year period. It is only towards the tenth year that the capacity of the BS is exceeded (see Figure 6.32). The benefits of adaptive modulation are also shown in Figures 6.33 and 6.34.

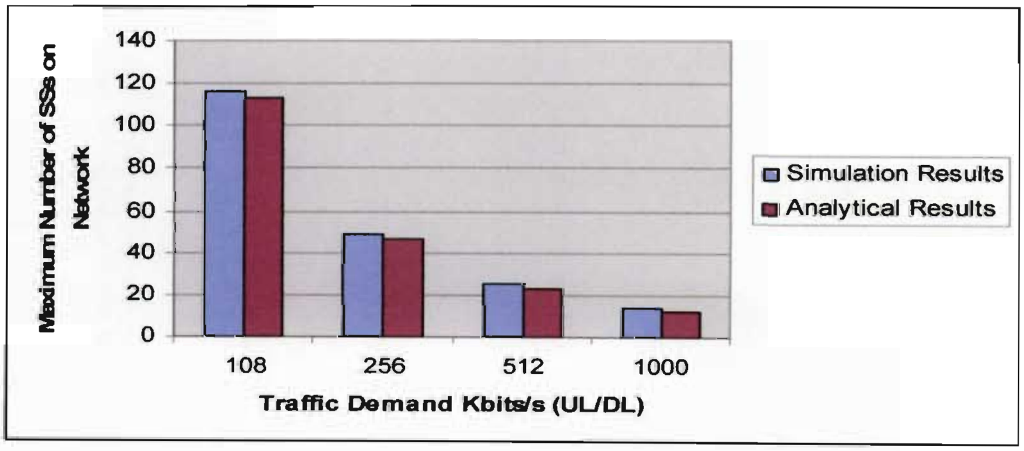

Figure 6.33: Maximum number of subscribers BS can handle as the traffic demand is increased (using adaptive modulation).

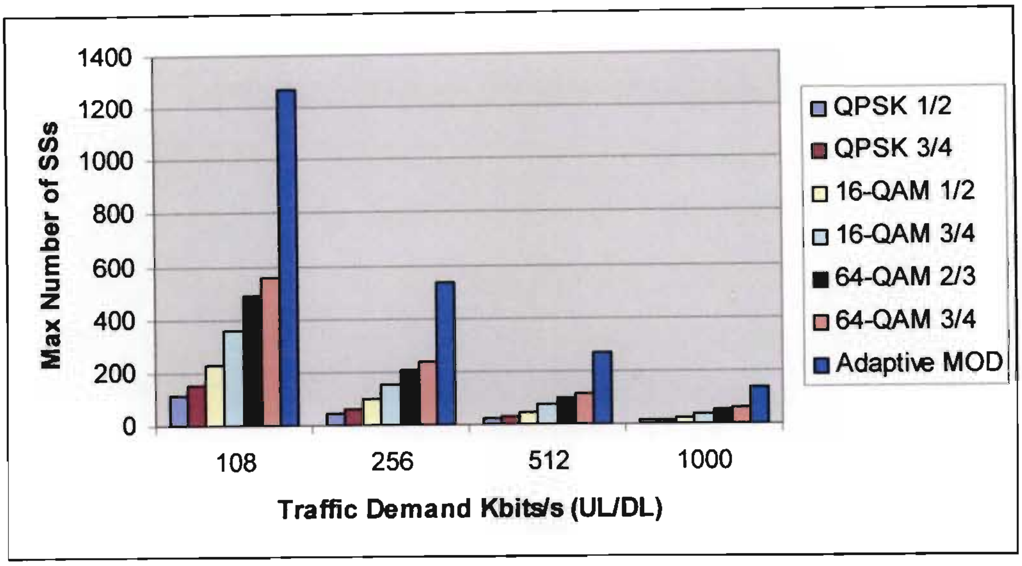

Figure 6.34: The effects of different modulation and coding schemes on capacity of the network (simulated results).

6.8 Channel Impairments

6.8.1 K-Factor Fading

The k-factor fading arises due to variations in atmospheric refractive conditions that occur as a result of changes in the normal conditions of the atmosphere. The normal conditions of the atmosphere are a temperature and pressure gradient with which is associated a gradient of refractive index. The varying index of refraction results in the bending of the propagating radio waves, with the sense of the gradient being such that the rays are bent towards the earth. This occurs since, changes in the temperature and the moisture content result in changes in the gradient of the refractive index, n. Conditions may result in an increase in the index with height and the bending of the rays away from the earth. The signal intensity at the receiver then fades markedly. Conversely meteorological conditions can result in a steeper gradient such that rays are bent towards the earth more strongly. Under such conditions the atmosphere forms a duct or wave guide that restricts the wave propagation over the earth's surface. Abnormally large ranges beyond line of sight are then obtained [33].

K- Factor fading causes a change in the k-factor from its median value. When the atmosphere is sufficiently sub-refractive (low k-Factor values), the ray path will be bent in such a way that the earth appears to obstruct the direct path between the transmitter and the receiver, giving rise to the kind of fading called diffraction fading. k values exceeded 99.9% of the time, suitable for Nkandkla region, were obtained from [33].

Table 6.2: k-factor values exceeded 99.9% of the time [33]

Period	**Nkandla**
February	0.2
May	0.3
August	0.9
November	0.5
Average for the Year	0.5

The k-factor values found in table 6.2 above represent the k factor values exceeded 99.9% of the time that are suitable for the Nkandla region. It is not simply the medium k factor values. The reason for this is that the system is being designed to provide 99.9 % link availability. The simulations are run using the ATDI software. The k-factor value is varied according the table 6.2, and the resulting k-factor fading experienced by each subscriber located at different distances from the BS and the receiver sensitivity of each SS are recorded and represented in Figures 6.35 to 6.38 below.

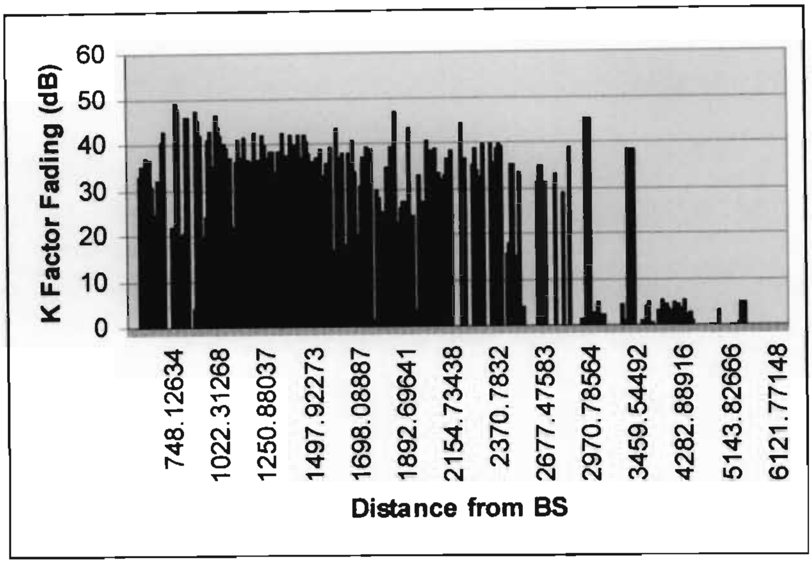

Figure 6.35: k-Factor Fading Depth for k=0.2

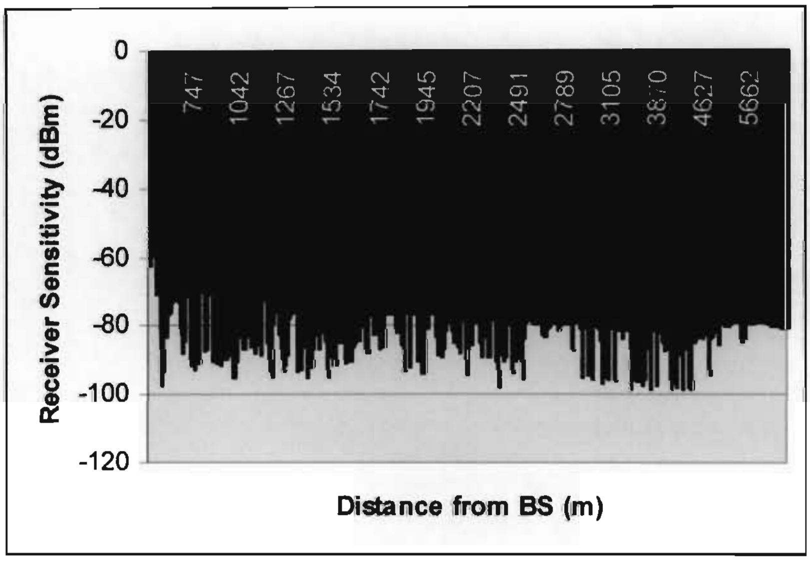

Figure 6.36: Receiver Sensitivity for k=0.2

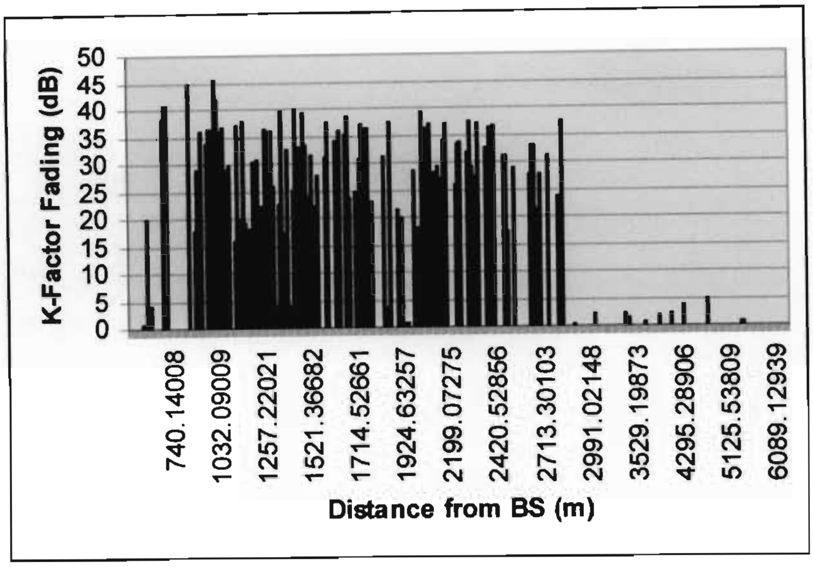

Figure 6.37: k-factor fading depth for k=0.9

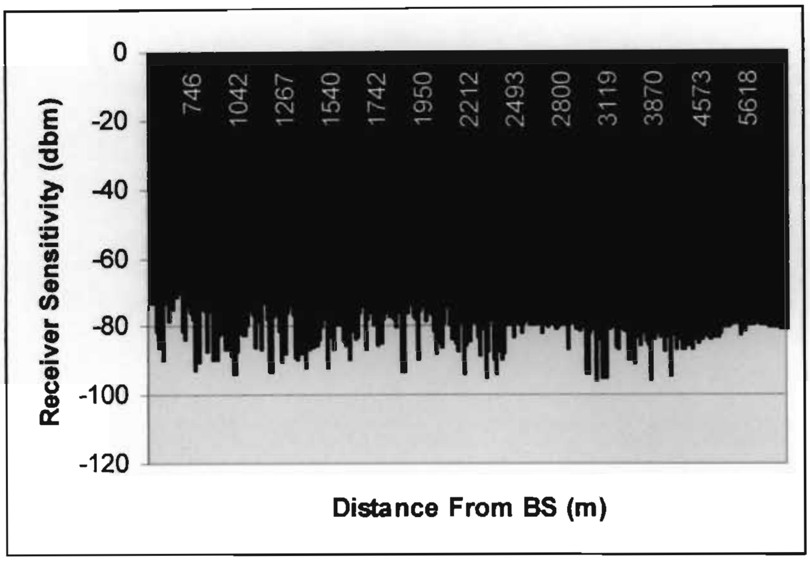

Figure 6.38: Receiver sensitivity for k=0.9

From the Figures 6.35 – 6.38 above, it is found that as the value of k (exceeded 99.9% of the time) increases, there is a corresponding improvement in the receiver sensitivity. Higher receiver sensitivities imply a higher modulation scheme may be used by the adaptive modulation algorithm; thereby increasing the capacity of the network (see Figure 6.39). The higher the modulation scheme the higher the spectral efficiency of the network.

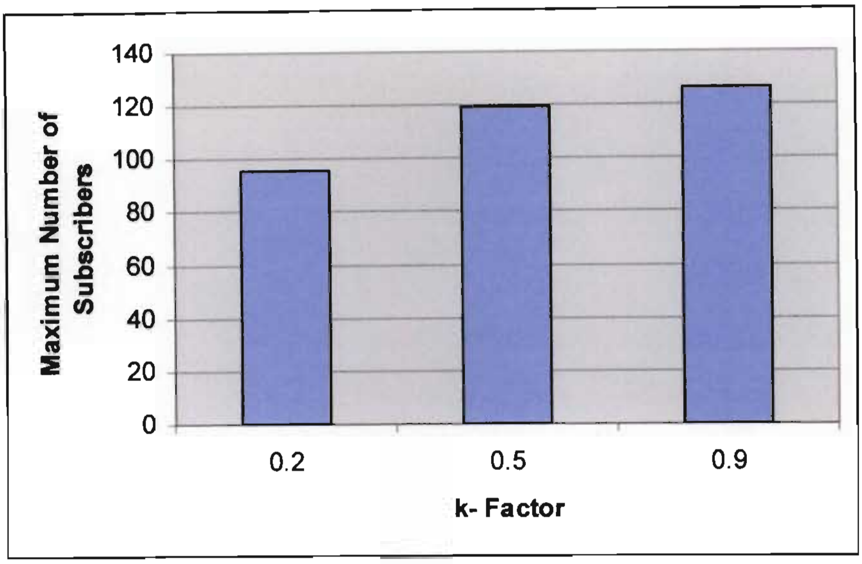

Figure 6.39: Effects of k- factor fading on the capacity of the network (traffic demand of each SS is set at 1Mbps) using adaptive modulation.

From Figure 6.39, it can be seen that an increase in k-factor causes a slight increase in the capacity of the network. The results show that a BS can handle at least 10 more subscribers with a k value of 0.9 than with a k value of 0.5. Thus in the months of February and May, the BS will support fewer subscribers than in the months of August and December.

6.8.2 Multipath Fading

Since multiple reflections of the transmitted signal may arrive at the receiver at different times, this can result in inter symbol interference (ISI), which the receiver cannot sort out. This time dispersion of the channel is called multipath delay spread, which is an important parameter used to assess the performance capabilities of wireless systems. A common measure of the multipath delay spread is the root mean square (rms) delay spread. The mean rms delay spread for N simulcasting signals is given by [34]:

$$\tau_{rms} = 2\sqrt{\frac{\sum_{i=1}^{N} P_i d_i^2}{\sum_{i=1}^{N} P_i} - \frac{(\sum_{i=1}^{N} P_i d_i)^2}{(\sum_{i=1}^{N} P_i)^2}} \quad (6.28)$$

Where:

- P_i and d_i are the power and delay of the i-th signal, respectively.

For reliable communications without adaptive equalization or other anti-multipath techniques, the transmitted data rate should be much smaller than the inverse of the RMS delay spread (called coherence bandwidth).

When the transmitted data rate is much smaller than the coherence bandwidth, the wireless channel is referred to as the flat channel or narrowband channel. When the transmitted data is closely equal to or larger than the coherence bandwidth, such a channel is called frequency-selective channel or wideband channel.

Using a bandwidth of 3.5 MHz and an operating frequency of 3.5 GHz the following OFDM parameters were calculated as shown in Table 6.3.

	Cyclic Prefix Ratios			
	1/4	**1/8**	**1/16**	**1/32**
Cyclic prefix (CP) T_g ***(us)***	16	8	4	2
Symbol time T_s ***(us)***	80	72	68	66

Table 6.3: Useful time and cyclic prefix times

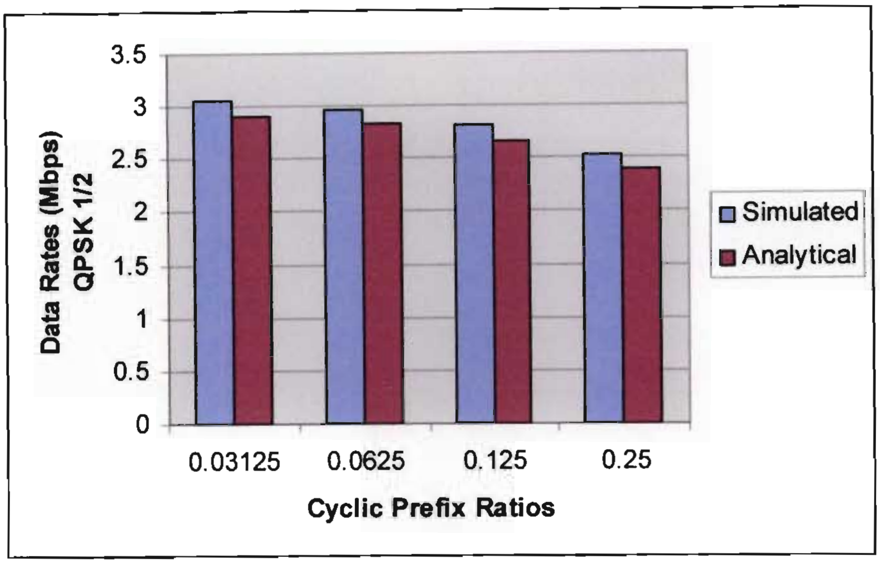

Figure 6.40: Effect of increasing CP on Data Rates

From Figure 6.40 above, it is found that by increasing the cyclic prefix ratios the data rate of the system is reduced since higher CP ratios reduce the spectral efficiency of the system. The implications of this is that in areas with large delay spreads, BS's will be forced to use a higher Cyclic Prefix (CP) ratio in order to prevent inter-symbol interference, thereby degrading the performance of the system in terms of capacity. Note that as long as the delay spread falls within the cyclic guard, no inter-symbol inference occurs. In the long run it is better for BS's to increase their CP ratio rather than risk Inter-symbol Inference.

A simulation was carried out to evaluate the performance of the WiMAX BS in the presence of multipath. The simulations are run in Lambertian mode [34]. The Lambertian mode takes into account the direct path, and all the reflections on obstruction sites. The reflected point radiates in all directions. The simulation results showing the RMS delay spread received at each antenna sector of the BS are shown in Table 6.3.

	SECTOR 1	SECTOR 2	SECTOR 3	SECTOR 4
RMS Delay Spread (*us*)	19.227	5.0	12.08	13.31
Coherence Bandwidth (*Mbps*)	0.0521	0.5	0.0827	0.03211

Table 6.4: Coherence bandwidth at each antenna sector

When using QPSK modulation at a coding rate of ½ the maximum achievable data rate is 2.4 Mbps which implies that the BS is experiencing frequency selective fading since this data rate is much higher than all the coherence bandwidths obtained from the simulations. Frequency selective fading introduces ISI to the network which results in higher bit error rates and reduced capacity.

6.9 Chapter Summary

In chapter six the performance of WiMAX, in a selected rural environment is carried out. The rural area of choice is Nkandla. The performance of WiMAX is evaluated in four parts: coverage, capacity, feasibility based on traffic projections and the influence of the refractivity (k) factor and multipath fading. The system is evaluated analytically using mathematical models written in Matlab and through simulations using ATDI software. From the results obtained it is found that from the two path loss models the Walsh-Ingen WS-C model is more appropriate in evaluating the coverage for rural environments.

7. CONCLUSION

The main focus of this thesis is to analyze the performance of WiMAX in a rural South Africa. The performance evaluation is approached from an analytical and a simulation perceptive. The BS is analyzed in terms of its coverage and capacity. The analytic model used in the coverage calculations is comprised of two path loss model, namely: the Walfisch-Ikegami (street Canayon-SC) path loss model with an added term to cater for the additional attenuation experienced in rural areas as a result of the excess vegetation present; and the dual slope path loss model also with an added attenuation factor. In terms of simulations, ATDI software is used to simulate a WiMAX network in a typical rural area in South Africa. In this thesis the simulations are run for the Nkandla area. Nkandla's hilly terrain characteristics, as well as possible vegetation cover due to the Nkandla forest, made it the perfect location to evaluate the NLOS capabilities of WiMAX.

The analytical and simulated results obtained from the analysis are presented in Chapter Six. The results show that the Walfisch-Ikegami (street Canyon-SC) path loss model provides a good approximation of the coverage capabilities of the base station whilst the dual slope model overestimates the coverage of the base station. This is a very important outcome since WiMAX coverage prediction in rural environments has not yet been covered in the literature. Coverage prediction is a very valuable key in wireless network design it makes it possible for network designers to predict the coverage of a BS without having to obtain site specific data such as tree and building heights. It simplifies the network planning process.

Another important aspect considered in the evaluation is the effects of system parameters on the coverage of the network. The system parameters used in the evaluation include: modulation type and coding rate, bandwidth, subchannelization, adaptive modulation and adaptive antennas. From the results one observes the extent to which variations of each of the different parameters affect the coverage and capacity of the WiMAX base station. This information will help network planners obtain a balance between the capacity and coverage demands of an area. For instance in a typical urban area, the capacity demand of the network is continuously growing at exponential rates, so in order to increase the range of a BS, network planners would have to use adaptive antenna systems with a large number of arrays. Subchannelization would not be an option in this scenario since from the results it is found that whilst subchannelization increases the range, it decreases the capacity of the network. By understanding the effects of system parameters on the performance of the network, network planners would be able to design optimal WiMAX networks for each area depending on the its characteristics and needs. Also from the simulation results it is found that k-factor fading and multipath fading play a significant role in the coverage and capacity performance of WiMAX base stations. Therefore they should be taken into account during the network planning/design process, in order to design optimal WiMAX networks, since each rural area has unique k-factor values and terrain characteristics.

In order to evaluate whether or not WiMAX is indeed a feasible option in bringing broadband to rural South Africa, a feasibility study was carried out. Traffic was projected over a ten year period to evaluate the sustainability of WiMAX base stations. From the simulation results, it is found that, in the Nkandla case, WiMAX is capable of sustaining the offered traffic over nine years using adaptive modulation. However using 64QAM ¾ modulation, the BS can only sustain the traffic over a four year period after which the demand would be too high for the BS to handle. In order to improve the quality of the network the number of antenna sectors should be increased to six. By increasing the number of antenna sectors the BS would be able to provide a hundred percent connectivity over the full ten year period with no problems.

Based on the simulation and analytical results, it is concluded that WiMAX is indeed a feasible solution to bring broadband to a typical region in rural South Africa.

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APPENDIX: A1

Coverage Analytical Model

```
f = input('Operating frequency(MHz) = ');
BW = input('Bandwidth(Hz) = ');
AGain= input('Antenna Gain (dBi) = ');
Nsubs= input('Number of subchannels(number subchannels=16 implies no subchannel = ');
Transmit_power = input('Transmit power (dBm) = ');
SNRx = input('The SNR of the system based on the modulation requirements = ')
HT= input('Transmit Antenna height (m)) = ');
HR= input('Receive Antenna height (m)) = ');
%calculating the effective Bandwidth
%AGain=[15 22.78 31.23 40.26 50.26 60.26]
BW=[1750000 3500000 7000000 10000000 20000000]
%SNRx = [6.4 9.4 11.2 16.4 18.2 22.7 24.4]
if rem(BW,7/8)== 0
   Sampling_freq =BW*(8/7)
   else if rem(BW,75/86)== 0
     Sampling_freq =BW*(86/75)
      else if rem(BW,125/144)== 0
        Sampling_freq =BW*(144/125)
           else if rem(BW,275/316)== 0
              Sampling_freq =BW*(316/275)
                else rem(BW,50/57)== 0
                       Sampling_freq =BW*(57/50)
                end
           end
     end
end


%Nsubs =[1 2 4 8 16];
BWeff = ((Sampling_freq/BW)*(192/256)*(Nsubs/16))
```

```
W = (BWeff*BW)

%calculating the receiver sensitivity
Receiver_sensitivity = -162 + SNRx + (10*log10(W))



    % in a Rural area the signal has to travel through vegetation inorder
    % to reach the SS, depending on how long the path through the
    % vegetation the signal travels throught , the corresponding
    % attenuation experienced by the signal is calculated

    d=3;
    %d=[1:1:150];
    Am=1.15*(f^0.43)

    Veg_attenuation = Am*(1-exp(-d*0.7/Am) )

   %plot (d,Veg_attenuation)
   %ylabel('Excess Attenuation in a Rural Environment (dB)')
  % xlabel('Distance Signal Must Travel Through vegetation (m)')
  % title('Attenuation of Signal(dB)')

   lamda=(3*(10 .^8)/(f*1000000))
   DC= ((4*HT*HR)/lamda)/1000;


    propagation_loss= -Receiver_sensitivity + AGain + Transmit_power - Veg_attenuation

    Coverage_W_SC=10 .^((propagation_loss - 42.64 -(20*log10(f)))/26)
     Coverage_W_SC2  =10  .^((propagation_loss  -  42.64  -(20*log10(f))+(40*log10(DC))-
(26*log10(DC)))/40)
    if Coverage_W_SC < DC
      D_cov=Coverage_W_SC
```

```
    %bar(SNRx, Coverage_W_SC)
    %grid on
    %ylabel('Coverage (km)')
    %xlabel('SNR (dB)')
    %title('Modulation and Coding rate vs Coverage')
   % bar(Nsubs, Coverage_W_SC)
    %grid on
    %ylabel('Coverage (km)')
    %xlabel('Number of subchannels')
    %title('Effects of Subchannelization on Coverage')
    %bar((BW/1000000), Coverage_W_SC)
    %grid on
    %ylabel('Coverage (km)')
    %xlabel('Bandwidth (MHz)')
    %title('Coverage vs bandwidth')
    %plot (d, Coverage_W_SC)
    %grid on
    %ylabel('Coverage(km)')
    %xlabel('Distance Signal Must Travel Through vegetation (m)')
    %title('Coverage vs Vegetation Density')
else

    D_cov=Coverage_W_SC2
  end
    %bar(SNRx, D_cov)
   % grid on
   % ylabel('Coverage (km)')
   % xlabel('SNR (dB)')
   % title('Modulation and Coding rate vs Coverage')
   %bar((BW/1000000),  D_cov)
    %grid on
    %ylabel('Coverage (km)')
  %xlabel('Bandwidth (MHz)')
   % title('Coverage vs bandwidth')
```

```
%bar(Nsubs, D_cov)
% grid on
% ylabel('Coverage (km)')
% xlabel('Number of subchannels')
% title('Effects of Subchannelization on Coverage')
%plot (d, D_cov)
%grid on
%ylabel('Coverage(km)')
%xlabel('Distance Signal Must Travel Through vegetation (m)')
%title('Coverage vs Vegetation Density')
Coverage_dual=10 .^((propagation_loss - 26.44 -(20*log10(f)))/20)
Coverage_dual_2 =10 .^((propagation_loss - 26.44 -(20*log10(f))+(40*log10(DC))-
(20*log10(DC)))/40)

if Coverage_dual < DC
D_cov2=Coverage_dual
else

D_cov2=Coverage_dual_2
end
```

APPENDIX: A2

Capacity Analytical Model

```
%Capacity Evaluation of WiMAX Base Stations

Coding_rate = input('Coding Rate (1/2, 2/3, 3/4) = ');
Bits_modulation = input('number of bits (1(BPSK) 2(QPSK) 4(16-QAM) 6(64-QAM)) = ');
Nused = 192
NFFT = 256
G = 1/32
%G = input('Guard ratio (1/4, 1/8, 1/16, 1/32) = ');
traffic_factor =1
c=1
%BW=3500000
Nsubs=16
%BW = input('Bandwidth (Hz) = ');
%Nsubs = input('Number of subchannels(16=no subchannel) = ');
%Spectral_efficiency = input('Spectral efficiency of system = ');
Uplink_traffic_demand = input('Uplink Traffic Demand per Subscriber (bits/s) = ');
Downlink_traffic_Demand = input('Downlink Traffic Demand per Subscriber (bits/s) = ');
traffic_factor = input('Traffic Factor = ');
c = input('Concentration factor = ');
Number_ant_sectors = input('Number of Antenna Sectors = ');
%G = [1/4 1/8 1/16 1/32]
%Nsubs = [1 2 4 8 16]
%Number_ant_sectors =[1:1:6]
BW=[1750000 3500000 7000000 10000000 20000000]
Number_ant_sectors=4
%x= [108000 256000 512000 1000000]

%Uplink_traffic_demand= x
%Downlink_traffic_Demand= x
```

```
if rem(BW,7/8)== 0
   Sampling_freq =BW*(8/7)
   else if rem(BW,75/86)== 0
     Sampling_freq =BW*(86/75)
      else if rem(BW,125/144)== 0
         Sampling_freq =BW*(144/125)
            else if rem(BW,275/316)== 0
               Sampling_freq =BW*(316/275)
                 else rem(BW,50/57)== 0
                       Sampling_freq =BW*(57/50)
                 end
            end
      end
end

   subcarrier_spacing=Sampling_freq/NFFT
   Useful_time = 1./subcarrier_spacing
   Symbol_time = (G+1)*Useful_time
   BWeff = ((Sampling_freq/BW)*(192/256)*(Nsubs/16))
   W = (BWeff.*BW)


   %The maximum data rate that the IEEE 802.16 WirelessMAN OFDM PHY can
   %achieve is defined as follows:

   data_rate = (((Nused*Bits_modulation*Coding_rate)./Symbol_time)*(Nsubs/16))
        Spectral_efficiency=  data_rate/W

  Throughput_per_sector = ((Spectral_efficiency*BW)-((Spectral_efficiency*BW)*0.10))
 Max_number_subs_per_sector=
((Throughput_per_sector/(Uplink_traffic_demand+Downlink_traffic_Demand))*c)
 %Max_number_subs_per_sector= ((Throughput_per_sector./(2*x))*c)
  Max_number_subs_network = (Number_ant_sectors * Max_number_subs_per_sector)
        %bar((Nsubs), (data_rate/1000000) )
```

```
% grid on
% ylabel('Data rate (Mbits/s)')
 %xlabel('Number of Subchannels')
 %title('Effects of Subchannelization on the Data Rate')



 %bar(G, (data_rate/1000000) )
 %grid on
 %ylabel('Data rate (Mbits/s)')
% xlabel('Cyclic Prefix')
% title('Cyclic Prefix Length vs Data Rate')

%bar(Number_ant_sectors, ((Throughput_per_sector*Number_ant_sectors)/1000000) )
%grid on
% ylabel('Maximum Througput of the BS')
% xlabel('Number of Antenna Sectors')
 %title('Effect Antenna Sectorization has on BS Thoughput')

%bar((BW/1000000), (data_rate/1000000) )
%grid on
%ylabel('Data rate (Mbits/s)')
%xlabel('Bandwitdh (MHz')
%title('Bandwidth vs Data Rate (64QAM 2/3)')
%bar( x/1000, Max_number_subs_network)
% grid on
% ylabel('Number of subscribers')
%  xlabel('Taffic demand (UL/DL) per subscriber (kBits)')
% title('Maximum Number of Subscriber BS can handle' )
```