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WIMAX LINK PERFORMANCE ANALYSIS FOR WIRELESS AUTOMATION APPLICATIONS

Master's thesis for the degree of Master of Science in Technology, submitted for inspection, Vaasa, 2 April, 2012.

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Vaasa, Finland, 2nd of April 2012

Samuel Olusegun Ailen-Ubhi

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ABBREVIATIONS

ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BS	Base Station
BTC	Block Turbo Coding
BWA	Broadband Wireless Access
CP	Cyclic Prefix
CTC	Convolutional Turbo Coding
DFT	Discrete Fourier Transform
DL	Downlink
DSCP	Differentiated Services Code Point
DSL	Digital Subscriber Line
FCH	Frame Control Header
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FFQ	fluid-flow fair queuing
FTP	Foiled Twisted Pair
FUSC	Fully Used Subcarrier
HTTP	The Hypertext Transfer Protocol
ICI	Inter-Channel Interference
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
LOS	Line of Sight
MAC	Medium Access Control

MBS	Micro BS
MIMO	Multiple Input Multiple Output
MS	Mobile Station
MSB	Most Significant Bit
NIC	Network Interface Card
NLOS	Non Line of Sight
OFDM	Orthogonal Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PER	Packet Error Rate
PRBS	Pseudorandom Binary Sequence
PUSC	Partially Used Subcarrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SINR	Signal-to-interference and noise ratio
SNR	Signal-to- noise ratio
SS	Subscriber Station
STC	Space Time Coding
UL	Uplink
VOIP	Voice over IP
VPN	Virtual Private Network
WiMAX	Worldwide Interoperability for Microwave Access

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ABSTRACT

Wireless broadband access technologies are rapidly growing and a corresponding growth in the demand of its applicability transcends faster internet access, high speed file download and different multimedia applications such as voice calls, video streaming, teleconferencing etc, to industrial operations and automation. Industrial and automation systems perform operations that requires the transmission of real time information from one end to another through high-performance wireless broadband communication links. WiMAX, based on IEEE 802.16 standard is one of the wireless broadband access technologies that has overcome location, speed, and access limitations of the traditional Digital Subscriber Line and Wireless Fidelity, and offers high efficient data rates.

This thesis presents detailed analysis of operational WiMAX link performance parameters such as throughput, latency, jitter, and packet loss for suitable applicability in wireless automation applications. The theoretical background of components and functionalities of WiMAX physical and MAC layers as well as the network performance features are presented. The equipment deployed for this field experiment are Alvarion BreeZeMAX 3000 fixed WiMAX equipment operating in the 3.5 GHz licensed band with channel bandwidth of 3.5 MHz. The deployed equipment consisting of MBSE and CPE are installed and commissioned prior to field tests. Several measurements are made in three link quality scenarios (*sufficient, good* and *excellent*) in the University of Vaasa campus. Observations and results obtained are discussed and analyzed.

KEYWORDS: WiMAX, Physical Layer, MAC Layer, Performance, Analysis, Automation

1. INTRODUCTION

Communication is regarded as one of the key basic needs of man outside shelter, food and clothing. A basic communication system consists mainly of three components namely- the sender (transmitter), the transmitting medium (channel) and the recipient (receiver). The quest for reliable means of transferring information from one point to another has brought a revolution in the telecommunication field with great impact on how we source and share information nowadays. This advancement has witnessed the development and deployment of several technologies in wired, cellular and data communications networks.

Global development as well as technology advancement has increased the demand for more radio resource (e.g. bandwidth) capacity in the telecommunication networks. International Telecommunication Union (2011) has shown that internet users has increased from 18% of the world population (6.5 billion) in 2006 to 35% of 7 billion people in 2011. Individuals, business organisations and governmental bodies require faster internet access, high speed file download and different multimedia applications such as voice calls, video streaming, teleconferencing etc, and also the availability of these services at any time and at any location for effective and efficient communication. These needs necessitate a broadband wireless technology that offers high efficient data rates with target quality of service (QoS) as against the traditional wired counterpart (e.g Digital Subscriber Line) and Wireless Fidelity (Wi-Fi) which have limitations as regard location, speed, access etc.

Worldwide Interoperability for Microwave Access (WiMAX) is one of the broadband wireless technologies designed to bring a last mile solution. WiMAX is based on IEEE 802.16 standards developed for broadband Wireless Metropolitan Area Networks (WMAN), by the Institute of Electrical and Electronics Engineers (IEEE). IEEE 802.16d standard known as fixed WiMAX was published in 2004 (IEEE Std 802.16™-2004 2004) to provide broadband services through point-to-point applications such as connecting buildings at a site or point-to-multipoint for example backhaul for Wi-Fi hotspots. WiMAX technology has diverse applications as shown in Figure 1, and its interoperability solution facilitates integration into different or existing network infrastructure. Rabbani, Kamruzzaman, Gondal and Ahmad (2011) recent research found out that QoS is improved in an integrated WiMAX/Wi-Fi architecture. To enable full mobility support, IEEE 802.16e standard also known as mobile WiMAX was introduced in December 2005 with some enhancement to fixed WiMAX (IEEE Std 802.16e™-2005 2006). For certified based product of this technology, a non-profit organization called WiMAX Forum was formed to develop, specify and conduct different interoperability testing in order to promote established conformance and compatibility of the broadband wireless services.

1.1. The WiMAX Standard

In 1998, a working group called IEEE 802.16 group was formed and was saddled with the responsibility of developing an air interface standard for wireless broadband. The operating frequency band specified for the earlier version of IEEE 802.16 standard was in the range of

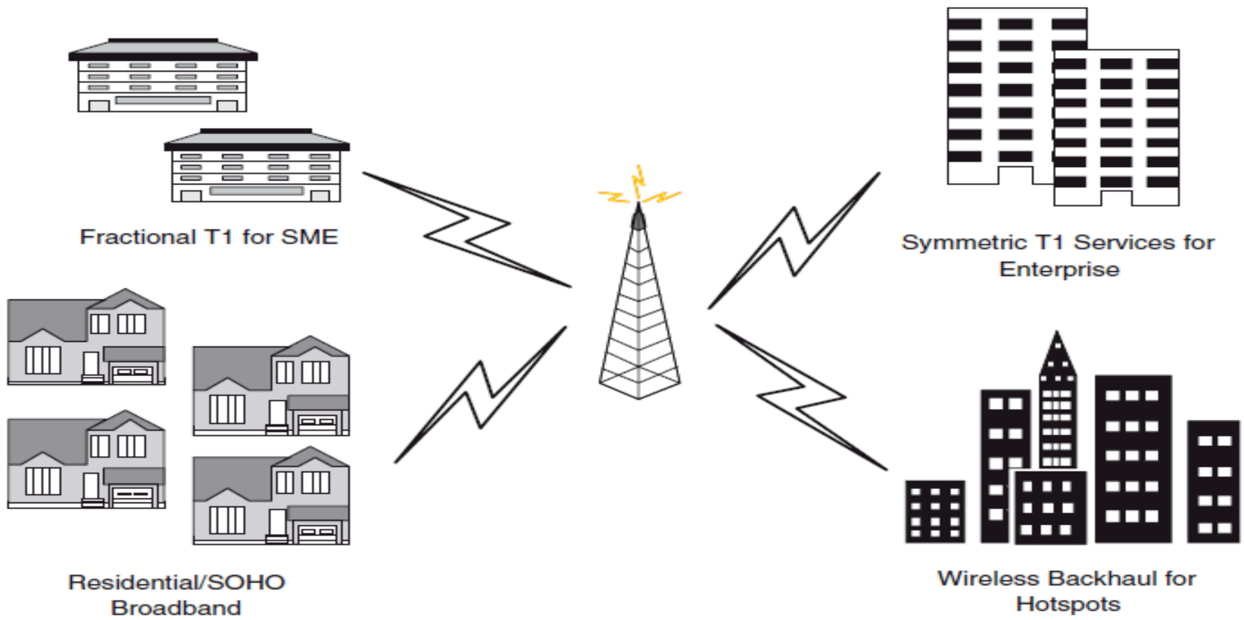

Figure 1. WiMAX point-to-multipoint applications (Andrews, Ghosh & Muhamed 2007: 11).

10GHz and 66 GHz which is suitable for line of sight (LOS) operations. Though more bandwidth are available with less risk of interference in this range of high frequency band, the standard lacks suitability for lower frequencies applications and non line-of-sight (NLOS) operations. This standard was revised and amended to accommodate (NLOS)

Table 1. Further IEEE 802.16 Standards and Amendments (Scarfone et al. 2007: 2-7).

Name	Standard or Amendment	Status	Purpose
802.16h	Amendment	Current Draft: 3/2010	Develops method to improve WiMAX coexistence over licence-exempt spectrum.
802.16k-2007	Standard	Active: Published 8/2007	Defines procedures to support bridge functionality in IEEE 802.16-2004
802.16m	Standard	Current Draft : 4/2010	Enhances the IEEE 802.16 air interface to support speeds up to 1 gigabit/seconds (Gbps) for fixed operations and 100 megabit/seconds (Mbps) for mobile operations.

operations in the 2GHz-11GHz licensed and license-exempt frequency spectrum. Based on the revision of the previous versions (IEEE 802.16 in 2001, IEEE 802.16c in 2002 and IEEE 802.16a in 2003), IEEE 802.16d was established which defines the physical (PHY) and the medium access control (MAC) layers features in the 2GHz-11GHz spectrum for fixed NLOS transmission. Additional support for mobile applications in the 2GHz-6GHz band was implemented in IEEE 802.16e which consolidates 802.16d to support both fixed and mobile operations. IEEE 802.16d and IEEE 802.16e form the bedrock of WiMAX operations and several further amendments/Standards (some relevant ones shown in Table 1) has been published afterwards for better speed and performance enhancement. (Scarfone, Tibbs & Sexton 2010: 2-6; Abichar, Yanlin & Chang 2006).

1.2. WiMAX Protocol Architecture

The WiMAX protocol architecture shown in Figure 2 is made up of two main layers: the Physical layer and the Medium Access Control layer. The physical layer covers the physical interface as well as the transmission medium and maintains a two-way mapping between MAC Protocol Data Units (PDUs) and Physical layer frames. The MAC layer is made up of three sub-layers: the Service Specific Convergence Sub-layer (CS), Common Part Sub-layer (CPS) and the Security Sub-layer (SS). Interface communications between layers as defined by the standard is done through the Service Access Points (SAPs). The CS is responsible for the classification of different MAC Service Data Units (SDUs) formats in the MAC layer connections and also does the mapping between the higher level protocols data units and the

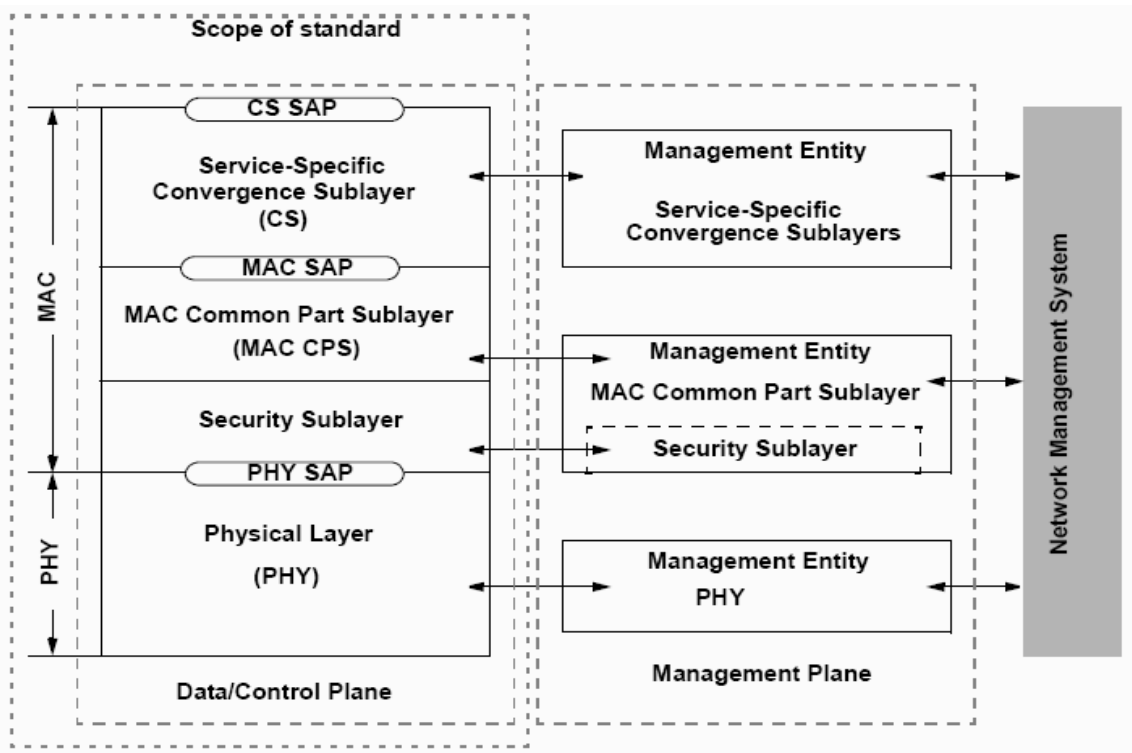

Figure 2. IEEE Std 802.16 protocol layering (IEEE Std 802.16^{TM}-2004 2004: 3).

MAC SDUs format. The CPS is tightly integrated to the SS and forms the central part of the layered structure. The CPS handles effective bandwidth management, connections set up and (PDUs) construction. The SS lies between the MAC CPS and the PHY layer and switches MAC PDUs with the PHY layer. The SS addresses the authentication, establishes key and also handles key exchange, encryption and decryption of exchanged data between MAC and PHY layers. (Barbeau 2005)

1.3. WiMAX Network Architecture

In order to establish the WiMAX End-to-End Network Architecture that provides platform for cooperative support for network deployments and services for fixed, nomadic and mobile users, the WiMAX Forum defined the WiMAX Network Reference Model (NRM) that represents the structure of the network architecture. The NRM shown in Figure 3 describes the operational entities and network reference points through which entities interoperability is achieved. The NRM consists of the Mobile/Subscriber (either mobile or fixed) Station (MS), Access Service Network (ASN) and Connectivity Service Network (CSN) which constitute the logical entities. The MS is the functional entities through which Subscribers access the network. The ASN is made up of one or more Base Stations and also, one or more ASN

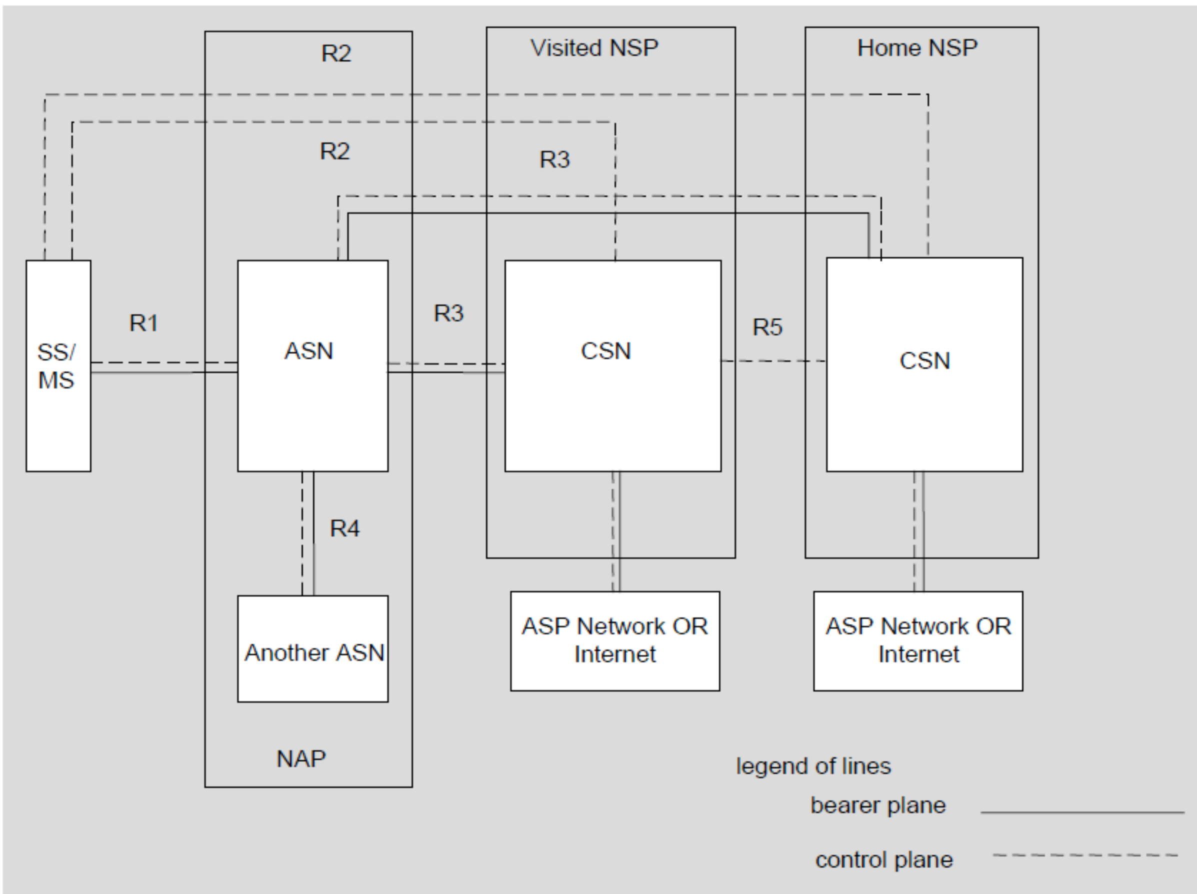

Figure 3. Network Reference Model (WiMAX Forum 2009: 24).

Gateway (ASN-GW). The ASN is acquired by Network Access Provider (NAP) and defines different message communications for various services and operational functionalities between WiMAX subscribers and CSN. The CNS is deployed by Network Service Provider (NSP) and specifies the operational entities that ensure the availability and provision of Internet Protocol (IP) access to WiMAX subscribers. The Reference Points (R1-R5) consist of protocols (control plane and bearer plane) and procedures that represent an imaginary point between various functional and logical entities. The implementation choice of the NRM in physical devices depends on the manufacturer provided the design implementation comply with the requirements for full operation and interoperability. (WiMAX Forum 2009: 23-32.)

WiMAX network involves communication link between the MSs and BSs. Each MS and BS embodies the WiMAX protocol architecture and maintains a duplex link. Uplink (UL) is the communication from MSs to BSs and the one from BSs to MSs is the downlink (DL). BS is the medium through which the MS accesses the network.

1.4. Motivation for the Thesis

The evolution and growing rate of wireless technologies with diverse range of applications has found significant use in various sectors of life such as industries and automation. The impact of wireless technologies through innovative applications in industrial environments and automated systems cannot be undermined as compared to wired technologies. For effective and efficient operations, the transmission of information bits between machinery, monitoring, and control devices as well as periodic updates in wireless automation systems require a communication link with reliable data flow. (Ahmad, Heiss & Meier 2008: 6.)

One key success factor in wireless automation applications is the delivery of real-time information through a broadband wireless access technology with good coverage and high-performance capacity, and also with flexible interoperability and integration to other existing networks. WiMAX is one of the wireless broadband access technologies that is considered to meet these requirements.

One of the wireless automation applications that significantly requires WiMAX broadband wireless access solutions is the smart grid. Smart grid constitutes an intelligence system that averts energy leaks and enhances efficient energy consumption through monitoring operations of all home utilities such as gas, water and power. The system installed at customer premise takes real time updates of ongoing process and consumption of every appliance and also assists in control activities of the home utilities by regulating consumption during peak periods. It facilitates efficient monitoring, accurate consumption billing, and uninterrupted services by transmitting the updates to a remote control center through wireless network. (Linsey, Nalweyiso, Srinivasan, Stroup & Vasudevan 2010: 6.)

The requirements for real time information transmission access of wireless automation applications necessitate the need to analyze practical WiMAX network link operational capabilities and performance for suitable applicability. Availability of such data will give first hand information on the deployment of WiMAX broadband technology for wireless automation applications.

1.5. Objectives of the Thesis

This thesis is target to achieve three goals. The first aim is to provide an improved comprehension and knowledge of the actual operational performance (Latency, data throughput, link stability, jitter, packet loss etc.) of the WiMAX link in the University of Vaasa campus at different link quality scenarios. The second goal is to study the behaviour of the link when a Customer Premise Equipment (MS) is place in the presence of a Wi-Fi source. The third objective is to analyze the network performance based on the measured field experimental data for wireless automation applications.

1.6. Scope of the Thesis

The thesis work covers the installation and commissioning of a WiMAX Micros Base station and Customer Premise Equipment. The test equipment are WiMAX compliant equipment operating in the 3.5GHz licence band with channel bandwidth of 3.5MHz. Furthermore, the experimental field tests and measurements will be carried out to evaluate link performance as follows:

I. The link quality and throughput will be examined in different signal-to-noise (SNR) grouped into three scenarios.

II. The link behaviour will be evaluated using TCP and UDP data traffic in both uplink and downlink at different distances of the Link Under Test (LUT).

III. Focus will be on data throughput, latency, link stability, jitter, and packet loss.

IV. The behaviour of the WiMAX CPE in the presence of a Wi-Fi source will be examined in order evaluate effect of strong interference source.

1.7. Contributions

Few related research works on performance analysis of WiMAX link have been published. This thesis is based on the same objective and further considers the lack (Yousaf, Daniel & Wietfeld 2007, Durantini & Petracca 2008, Westall & Martin 2011) of WiMAX link operational capabilities and performance experimental data by providing further data that show the operational link performance when an MS is under the influence of a strong Wi-Fi source. Sector antenna and Transport Control Protocol (TCP) window size of 64Kbyte are used as well in the field measurements.

1.8. Outline of the Thesis

Chapter two presents details of the theoretical background, components and functional stages of WiMAX PHY layer. Diverse constituents and functionalities of the WiMAX MAC layer are explained in Chapter three. WiMAX link and system performance features are presented in Chapter four. Chapter five discusses various aspects of the field experimental test bed setup and measurement methodology. Results and analysis are presented in Chapter six. Finally, Chapter seven comprises thesis conclusions and proposed future work.

2. PHYSICAL LAYER OF WIMAX

The PHY layer is responsible for the successful transmission and reception of information bits through a physical medium and is based on IEEE 802.16d and IEEE 802.16e standards. The PHY layer operational principles is based on a multicarrier modulation technique called orthogonal frequency division multiplexing (OFDM). In this chapter, OFDM basics is introduced and thereafter, details and functional stages of WiMAX PHY layer are explained.

2.1. OFDM and OFDMA Basics

In OFDM, the bandwidth available for transmission is divided into multiple subcarrier frequencies. A basic OFDM system is shown in Figure 4. An input data stream into the system is modulated by dividing the data stream into several sub-streams, each having lower data rate and as a result increases the symbol duration. These sub-streams are parallel and modulation operation is performed on each sub-stream. Each modulated sub-stream is then transmitted on individual subcarrier which are orthogonal to one another. The lower data rate increases its effectiveness against multipath effects. Additionally, a cyclic prefix (CP) is inserted to remove Inter-Symbol Interference (ISI) and Inter-Channel Interference (ICI). The CP forms the origin of a data payload and comprises duplicated last segment of the data part of the block. As long as the channel delay spread is less than its duration, the CP proves very effective but lowers the bandwidth efficiency. OFDM takes advantage of the multipath channel frequency diversity by performing coding and interleaving operations on the transmitted data in various subcarriers before transmission. The use of Inverse Fast Fourier Transform (IFFT) facilitates modulation with large number of subcarriers. OFDM resources are available in both frequency and time domain. Subcarriers are the medium for resource availability in frequency domain while the means for resource availability in time domain is

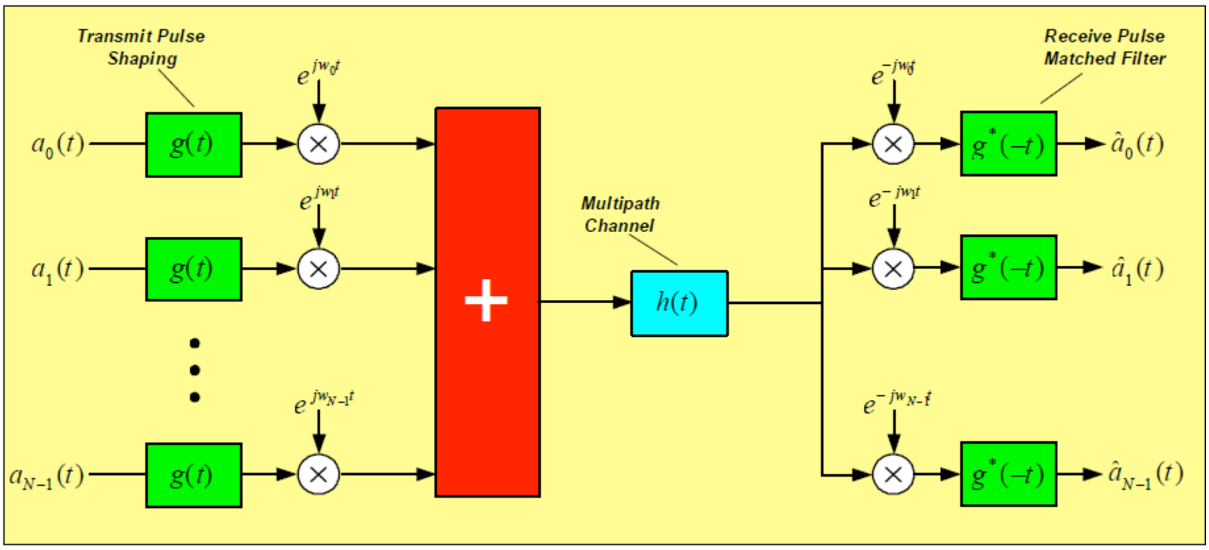

Figure 4. Basic Architecture of an OFDM System (WiMAX Forum 2006: 12).

through OFDM symbols and these resources are arranged in sub-channels and are assigned to each user. The allocation of a set of subcarriers and time slots to each user in the uplink and downlink sub-channels yields a multiple-access system known as orthogonal frequency division multiplexing access (OFDMA). (WiMAX Forum 2006: 11-12.)

Four PHY layers are specified by the IEEE 802.16 standards (IEEE Std 802.16^{TM}-2004 2004; IEEE Std 802.16e^{TM}-2005 2006), and these layers are:

- WirelessMAN-SC, PHY layer established on single-carrier technology and designed to operate in the frequency spectrum of 10-66GHz with LOS transmission.
- WirelessMAN-SCa, a single-carrier PHY layer designated for NLOS transmission in the 2-11GHz frequency bands.
- WirelessMAN-OFDM, PHY layer constructed on OFDM modulation and operated below 11GHz frequency bands in the NLOS conditions.
- WirelessMAN-OFDMA, OFDM modulation PHY layer with modification that includes scalability of operations in the 2-11GHz frequency spectrum for NLOS nomadic and mobile transmissions.

2.2. Components and Functional Block of the Physical Layer

The WiMAX PHY layer consists of components at the transmitter and at the receiver. The successive operations performed on a transmitted data at the transmitter is repeated in the reverse order at the receiver in retrieving the original information from the received data. IEEE 802.16 standards only define the PHY layer components and functionalities of the transmitter and assign the responsibility of the receiver implementation to equipment manufacturers (Andrews et al. 2007: 272.). Figure 5 shows the WiMAX PHY layer transmitter functional blocks in succession. The MAC PDUs data constitute the input to the Randomizer. These data are randomized and are transferred to the channel encoder for coding (Reed Solomon coding and Convolutional coding), puncturing and interleaving operations. The output coded data from the channel encoder is then mapped onto QAM symbols through modulation mapping actions performed on the data. Thereafter, the symbols undergo OFDM modulation which consist of assembling, IFFT and cyclic prefix (CP) insertion processes, and are finally transmitted through the radio frequency channel.

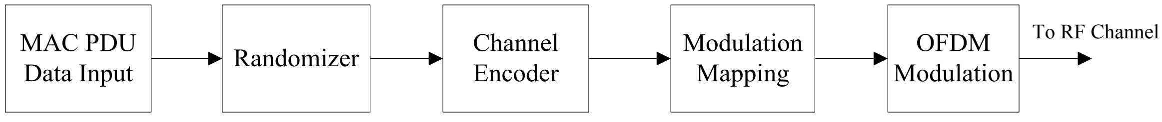

Figure 5. Block diagram of WiMAX PHY layer transmitter.

2.3. Randomization

Data burst are randomised in the downlink and uplink and the randomization operation is carried out independently on each distribution of data block. The randomizer shown in Figure 6 is composed of a pseudorandom binary sequence (PRBS) generator consisting of 15 bits shift register and two XOR operators. The PRBS generations is based on equation 1 which is initialized for each fresh allocation, and at the origin of each FEC block. The PRBS is

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

successively XORed beginning with the most significant bit (MSB) and its corresponding output is XORed with the data sequence to produce a randomized data. During each

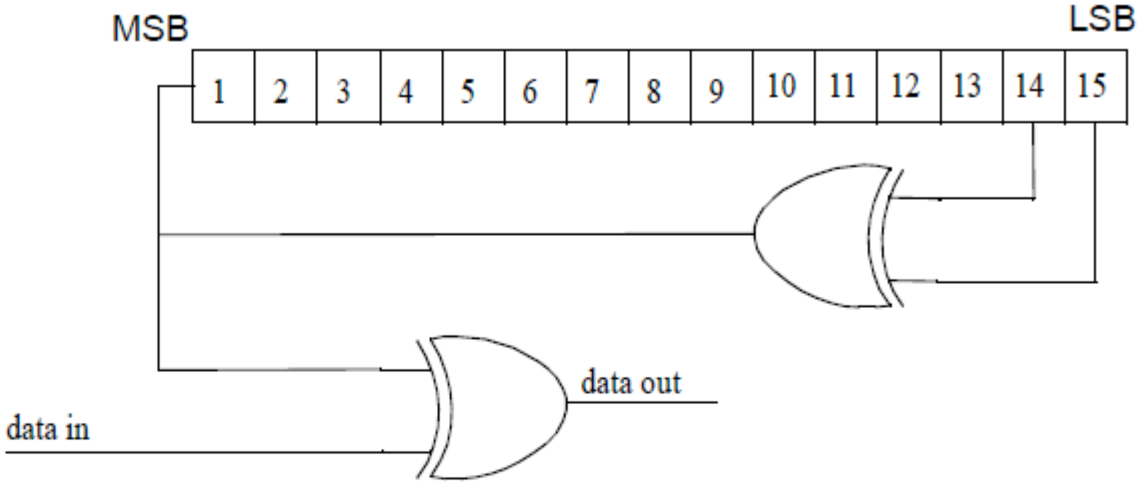

Figure 6. PRBS for data randomization (IEEE Std 802.16™-2004 2004: 431).

randomization, the last portion of the transmission block is padded with 0xFF ("1" only) if the data processed for transmission is less than the allocated data. (IEEE Std 802.16™-2004 2004: 430-431.)

2.4. Channel Encoder

The randomized data is fed into a channel encoder which houses the FEC encoder, puncturing and interleaving units. The IEEE 802.16 standards specification for the FEC encoder in both downlink and uplink transmissions is the concatenated Reed-Solomon Convolutional Code (RS-CC) encoder. An outer RS encoder and inner convolutional encoder constitute the RS-CC encoder that is employed for error detection and error correction. The encoding process involves the passage of data through RS encoder and thereafter through the

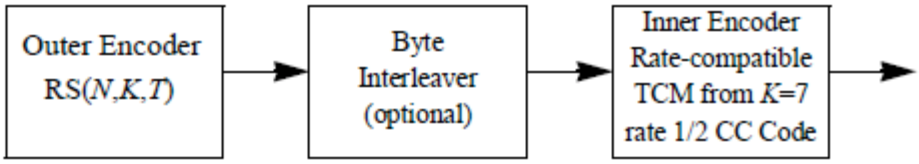

Figure 7. Concatenated FEC Encoder Block (IEEE Std 802.16™-2004 2004: 357).

convolutional encoder. A coding mode of RS-CC with rate of ½ must be constructed for all network access and FCH burst requests. (IEEE Std 802.16™-2004 2004: 432.)

2.4.1. Reed-Solomon Encoder

Reed-Solomon codes are a subset of linear, non-binary, cyclic BCH codes with burst error correction applications in digital communication and also in diverse digital storage devices. Several two information symbols can be added in a given code length without reduction in the minimum distance in Reed-Solomon codes and this effective property enhances its usefulness in channels comprising lots of large input symbols. The Reed-Solomon encoder takes a digital data to be transmitted and construct a polynomial over Galois Fields (GF). The codes divide the information stream into data blocks and add redundant bits to each block depending on their respective input. GF is a finite field and its components constitute the Reed-Solomon coding symbols. GF polynomial is divided by executing a computational Linear Feedback Shift Register (LFSR) and the remainder from this division is appended to the information thereby accomplishing the encoding process. The structure of a systematic code word is shown in Figure 8. Reed-Solomon codes are generally represented as RS (n, k, t) with specification of the GF(q), where "t" represents the maximum number of data in error that can be corrected and "k" the number of data bytes before encoding. Other defined parameters are given as follows (Ardalan, Raahemifar, Yuag & Geurkov 2003; Moreira & Farrell 2006: 115-116; Sklar 2001: 438):

Total number of bytes (Code length)	$n = q - 1$
Redundant (Parity check) bits	$n - k = 2t$
Minimum distance	$d_{min} = 2t - 1$

$\alpha^{q-1} = q - 1$, provided that α is a primitive component of GF(q). The polynomial that generates the linear, cyclic, block RS (n, k, t) with code length $n = q - 1$ with data size k is given as (Moreira et al. 2006: 116)

$$g(x) = (x - \alpha)(x - \alpha^2) \ldots (x - \alpha^{n-k})$$

$$= (x - \alpha)(x - \alpha^2) \ldots (x - \alpha^{2t})$$

$$= g_o + g_1 x + g_2 x^2 + \ldots + g_{2t-1} x^{2t-1} + g_{2t} x^{2t} \quad (2)$$

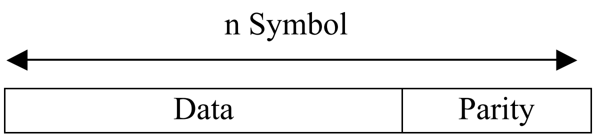

Figure 8. Reed-Solomon code word.

The WiMAX standard specifies a systematic RS (N = 255, K = 239, T = 8) code with GF(2^8) for constructing the Reed-Solomon encoding. The parameters are as defined in the previous page. The systematic code polynomials are:

Code Generator Polynomial: $g(x) = (x + \lambda^0)(x + \lambda^1)(x + \lambda^2)\ldots(x + \lambda^{2T-1})$ (3)

Field Generator Polynomial: $p(x) = x^8 + x^4 + x^3 + x^2 + 1$ (4)

where λ represents the primitive element of the GF. Furthermore, WiMAX standard defines code shortening and puncturing format for Reed-Solomon code to facilitate its flexibility. This increases the potency of the code with various implementation of its block sizes and error correcting strength. Variable shortened and punctured Reed-Solomon codes are significantly useful in packet loss recovery and protection (Xu & Zhang 2002). A prefix of 239-K zero bytes is added to any block shortened to K data bytes and the added 239-K zero bytes are discarded after encoding. The puncturing scheme specifies the usage of only the first 2*t* out of the entire 26 parity bytes for any codeword, punctured to yield error correction of *t* bytes. Reed-Solomon encoding shortening and puncturing process is shown in Figure 9. (IEEE Std 802.16™-2004 2004: 432.)

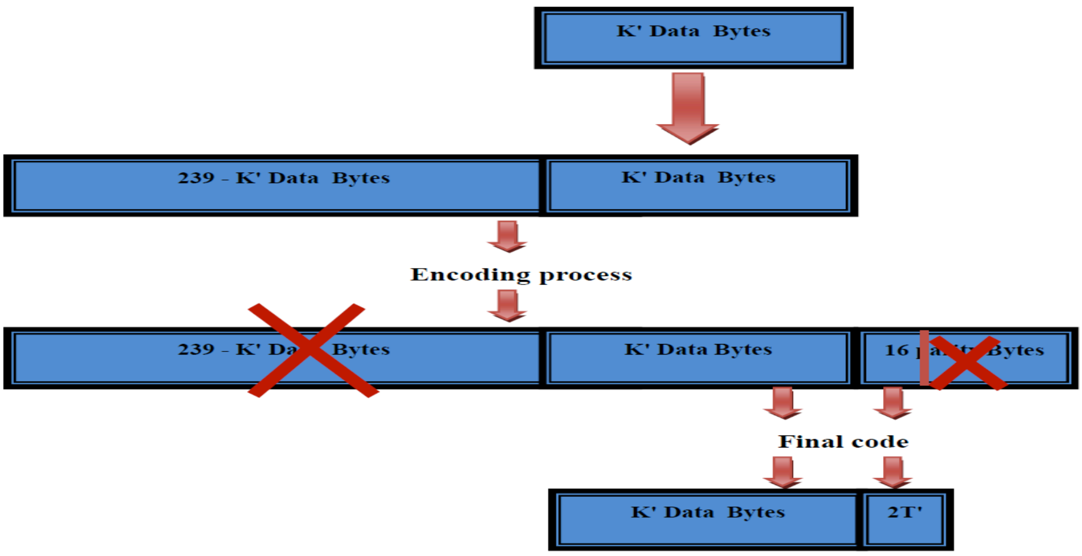

Figure 9. Reed-Solomon code shortening and puncturing process (Al-Hussaini 2009: 15).

2.4.2. Convolutional Encoder

The coded output data from the Reed-Solomon encoder goes directly into the inner Convolutional encoder for further coding processing. At a given instant *i,* a Convolutional encoder reproduces an output of *n*-tuple c_i coded data from *k*-tuple m_i input message data. The instant *i* depends on both the *k*-tuple m_i input message data instant and the preceding *k*-tuples m_j, available at instants *j* less than *i.* The WiMAX PHY uses a binary Convolutional encoder with a native rate of ½ and a constraint length of 7. Figure 10 shows a Convolutional encoder with the generator polynomial implementation codes defined by equations 5 & 6 to give the coded output X & Y. (IEEE Std 802.16^{TM}-2004 2004: 432; Moreira et al. 2006: 158.)

$$G1 = 171_{OCT} \text{ for X} \quad (5)$$

$$G2 = 133_{OCT} \text{ for Y} \quad (6)$$

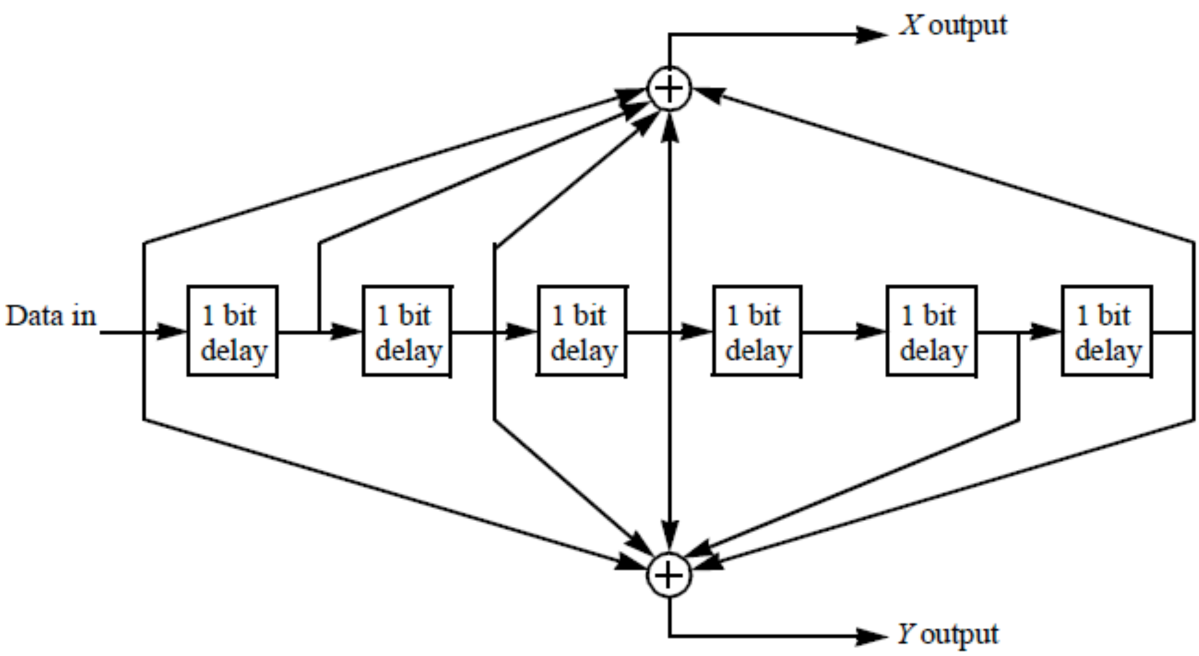

Figure 10. Convolutional encoder of rate 1/2 (IEEE Std 802.16^{TM}-2004 2004: 433).

Different block sizes and code rates are employed for different modulation and coding rate schemes. Table 2 shows the WiMAX PHY layer mandatory Reed-Solomon codes, Convolutional code rates and the overall coding rate for different modulation schemes.

Table 2. Channel coding per modulation (IEEE Std 802.16^{TM}-2004 2004: 434).

Modulation	Uncoded block size (bytes)	Coded block size (bytes)	Overall coding rate	RS code	CC code rate
BPSK	12	24	1/2	(12,12,0)	1/2
QPSK	24	48	1/2	(32,24,4)	2/3
QPSK	36	48	3/4	(40,36,2)	5/6
16-QAM	48	96	1/2	(64,48,8)	2/3
16-QAM	72	96	3/4	(80,72,4)	5/6
64-QAM	96	144	2/3	(108,96,6)	3/4
64-QAM	108	144	3/4	(120,108,6)	5/6

2.4.3. Puncturing

Puncturing is the removal of bits from the output stream of an encoder having low data rate in order to achieve a high code rate. This process reduces the amount of data the encoder transmits based on defined sets of operational specifications. This increases the coding flexibility and hence produces variable code rates with diverse error protection capabilities. The defined configuration and the supported code rates are shown in Table 3 with transmitted output bit denoted with "1" and discarded output bit indicated with "0". X and Y are as defined in the previous section. (IEEE Std 802.16^{TM}-2004 2004: 433.).

Table 3. Puncturing scheme for Convolutional codes (IEEE Std 802.16^{TM}-2004 2004: 433).

	Code rates			
Rate	1/2	2/3	3/4	5/6
d_{free}	10	6	5	4
X	1	10	101	10101
Y	1	11	110	11010
XY	X_1Y_1	$X_1Y_1Y_2$	$X_1Y_1Y_2X_3$	$X_1Y_1Y_2X_3Y_4X_5$

2.4.4. Interleaver

Interleavers are of diverse significant use in digital communication. Interleaving is a technique that involves the permutation of the positions of sequential data to yield a provisional arranged different format of the same data. They are basically used for data sequence randomization. In burst error application, data interleaving distributes error bursts among several code blocks in order to avoid error concentration at a particular spot thereby increasing the FEC encoder performance. Burst errors occur in wireless channels as well as in concatenated codes and interleaving proves invaluable in this regard. There are mainly four categories of data interleavers, these are: block, linear, random, and convolutional interleavers. Block interleavers initially write the data in the row layout in the permutation design and thereafter reads the data in column layout. Linear interleavers are class of block interleavers in which data permutation operations are based on linear law. Pseudo-random interleavers are flexible block interleavers that store data in a randomly selected location. In convolutional interleavers, interleaving is achieved by a constant and incremental data shift. (Moreira et al. 2006: 249.)

The output data bits of the RS-CC encoder are fed into the interleaving unit which constitute the channel encoding final operation. The WiMAX standard specifies two permutation steps for a block interleaver whose block size is dependent on the number of coded bits per the allocated subchannels per OFDM symbol, (N_{cbps}). The first permutation step establishes mapping between neighbouring coded bits and distant subcarriers as defined by equation 7. The second step secures the periodic mapping of the neighbouring coded bits unto less or significant bits of the constellation as represented in equation 8. The respective equations are:

$$m_k = \left(\frac{N_{cbps}}{12}\right).k_{mod12} + floor\left(\frac{k}{12}\right) \qquad k = 0, 1, \ldots, N_{cbps} - 1 \qquad (7)$$

$$j_k = s.floor\left(\frac{m_k}{s}\right) + (m_k + N_{cbps} - floor\left(12.\frac{m_k}{N_{cbps}}\right))_{mod(s)} \quad k = 0, 1, \ldots N_{cbps} - 1 \qquad (8)$$

given N_{cpc} as the number of coded bits per subcarrier, and $s = ceil\left(\frac{N_{cpc}}{2}\right)$. k represents the index of the previous coded bits to the first permutation, m_k the index of the code bits subsequent to the first and prior to the second permutation while j_k denotes the index that precedes the second permutation and before the modulation mapping. (IEEE Std 802.16™-2004 2004: 440-441.)

Table 4. Block sizes of the bit interleaver (IEEE Std 802.16™-2004 2004: 441).

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

2.5. Modulation Mapping

Modulation mapping is the translation of data to complex valued modulation symbols. The interleaved data goes into the modulation mapper where necessary conversion operations take place to generate its equivalent output of amplitude and phase modulation. The amplitude and phase modulation are defined by points in the complex vector space in the in-phase (I) and quadrature-phase (Q) components. Various forms of the modulation schemes are shown using the IQ plot. Modulation mapping process involves the use of Grade coding thereby reducing the possibility of several errors occurrence in each symbol error. (Roca 2007: 22.)

The WiMAX standards support the use of BPSK, QPSK, 16-QAM and 64-QAM modulation constellations in the PHY layer operations. Equal average power is accomplished by normalizing the constellations through the multiplication of both the indicated factor c and the constellation point, where b_0 represents LSB for every modulation. The constellations and the respective values of each parameter are shown in Figure 11. (IEEE Std 802.16^{TM}-2004 2004: 441.)

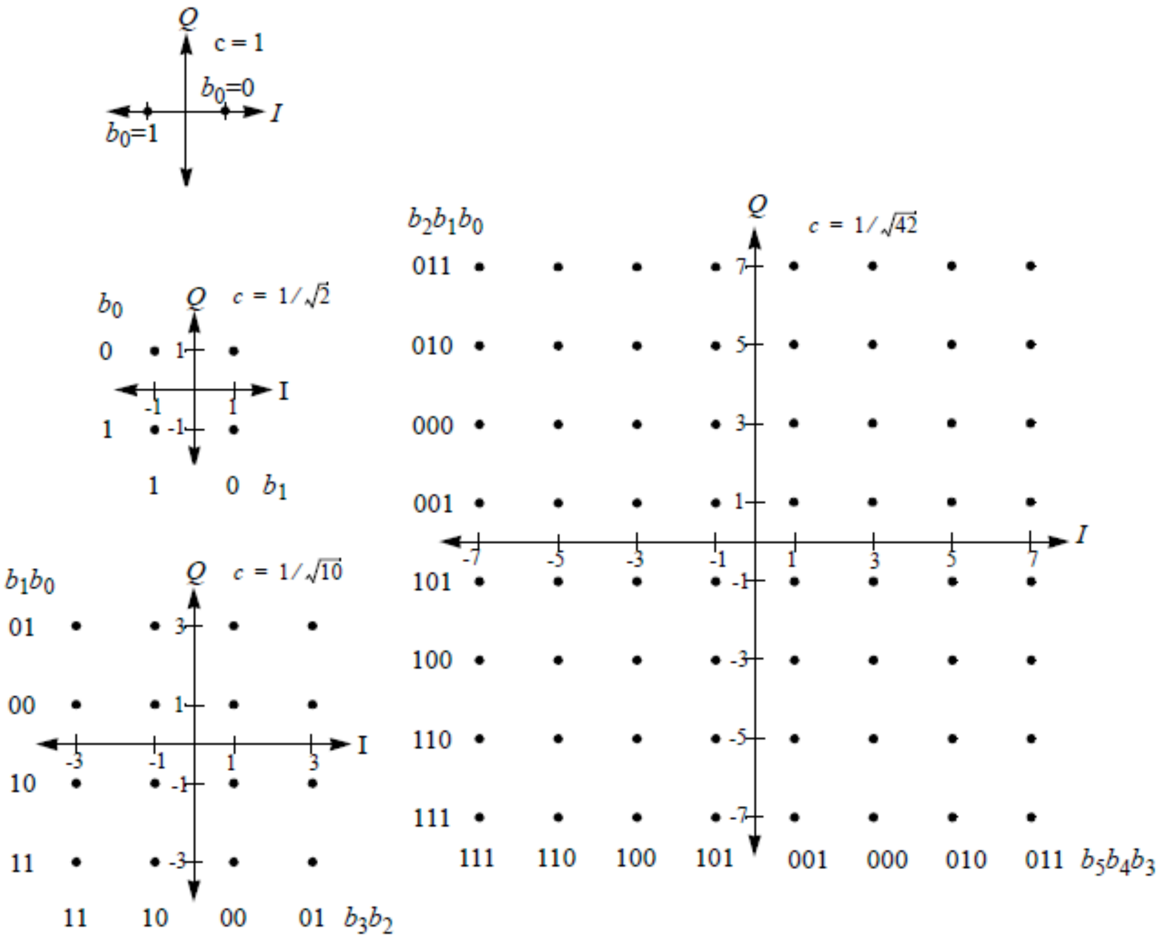

Figure 11. BPSK, QPSK, 16-QAM, and 64-QAM constellations (IEEE Std 802.16^{TM}-2004 2004: 441).

2.6. OFDM Modulation

OFDM modulation begins with the construction of a complete OFDM signal in the frequency domain, followed by the corresponding signal conversion to time domain using IFFT. Multiple oscillators are not required for OFDM signal transmission and reception in IFFT design, this feature of simple implementation strengthens its suitability in this regard. The construction of every OFDM symbol in the frequency domain is achieved through mapping between sequence of symbols and subcarriers. There are three categories of subcarriers in WiMAX.

- *Data subcarriers* are employed for transporting data symbols.

- *Pilot subcarriers* are responsible for conveying pilot symbols. The pilot symbols are deduced theoretically and can be utilized in channel estimation and tracking.

- *Null subcarriers* have no power allotment, and this includes the guard subcarriers located near the boundary and the DC subcarriers as well. There is no power allocation for the guard subcarriers at the boundary to ensure the OFDM symbol spectrum perfectly occupies the allotted bandwidth thereby reducing the adjacent channels interference. The effects of saturation or plethora power draw at the amplifying unit is averted by not modulating the DC subcarrier. According to (IEEE Std 802.16™-2004 2004: 428), the function of the guard band is to facilitate the natural decay of the signal thereby giving rise to the shaping of the FFT "brick Wall".

Every OFDM symbol in WiMAX comprises these three categories making a total of 256 subcarriers. 192 subcarriers are used for carrying data symbols, 8 subcarriers are used for pilot symbols distributed over the OFDM symbol, 1 subcarrier is utilized as DC subcarrier and the remaining 55 subcarriers as guard subcarriers. Figure 12 shows an OFDM symbol consisting of the data subcarriers, pilot subcarrier and null subcarriers representation in the frequency domain. (Andrews et al. 2007: 282&285.)

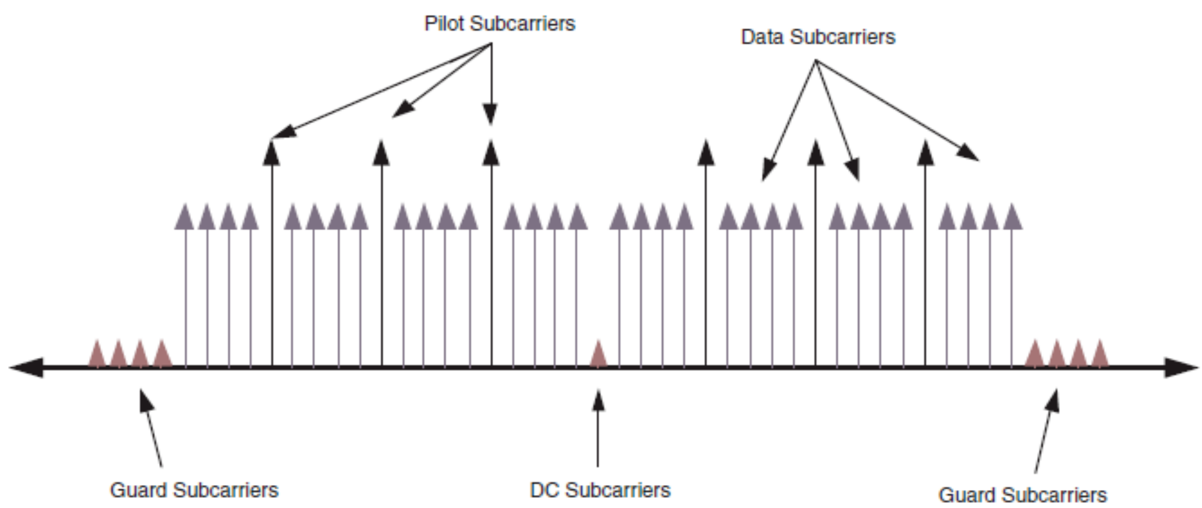

Figure 11. OFDM symbol structure in the frequency domain (Andrews et al. 2007: 283).

2.6.1. Pilot Modulation

An OFDM symbol is constructed by implanting pilot subcarriers into each data burst. The modulation of the pilot subcarriers is based on their respective positions in the OFDM symbol. The PRBS generator whose polynomial is given in equation 9 is used to create a

$$x^{11} + x^{9} + 1 \qquad (9)$$

sequence w_k from which the pilot modulation value of OFDM symbol k is obtained. The index k denotes the symbol index with respect to the origin of the downlink subframe in the downlink and also signifies the symbol index in relation to the origin of the burst in the uplink. Figure 12 shows a PRBS for pilot modulation and the initialization sequences for both the downlink and uplink operations. The BPSK modulation for every pilot subcarrier (marked by frequency offset index) is obtained through equations (10) and (11). (IEEE Std 802.16TM-2004 2004: 443.)

DL: $c_{-88} = c_{-38} = c_{63} = c_{88} = 1 - 2w_k$ and $c_{-63} = c_{-13} = c_{13} = c_{38} = 1 - 2\overline{w_k}$ (10)

UL: $c_{-88} = c_{-38} = c_{13} = c_{38} = c_{63} = c_{88} = 1 - 2w_k$ and $c_{-63} = c_{-13} = 1 - 2\overline{w_k}$ (11)

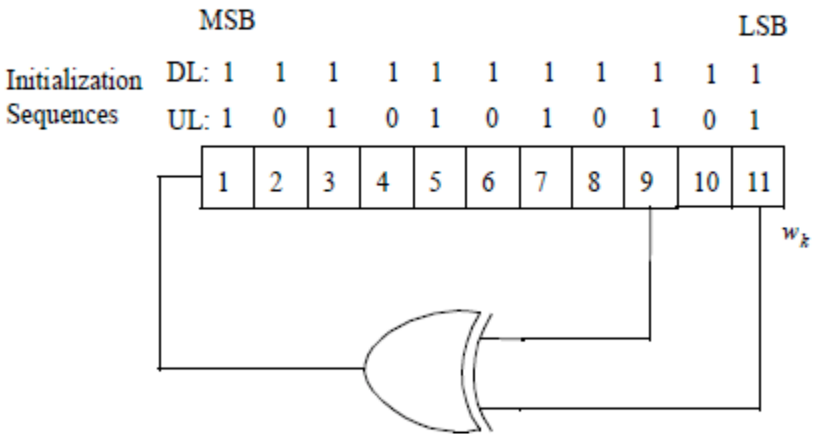

Figure 12. PRBS for pilot modulation (IEEE Std 802.16TM-2004 2004: 443).

2.6.2. Inverse Fast Fourier Transform

The IFFT block takes OFDM symbols in the frequency domain as input and gives an output of the corresponding symbols in time domain. At a time, N symbols each having a period of t seconds are fed into the IFFT block. N denotes the number of the system's subcarriers and N orthogonal sinusoids constitute the foundation on which the IFFT function is based. All the sinusoids have distinctive frequencies and the DC subcarrier represents the lowest frequency. At the input, every symbol correlates individual subcarrier which undergo the IFFT process to give a summation of all N sinusoids at the output. This output constitutes a single OFDM symbol of length Nt that is transmitted after further processing. (Litwin & Pugel 2001: 34.)

2.7. Cyclic Prefix Insertion

Cyclic Prefix insertion is one of the important features of the OFDM system and plays a significant role in the elimination of ICI and ISI. The CP technique copies the end part of an OFDM symbol in time domain, appends it to the beginning to yield a symbol with long symbol period as shown in Figure 13. The time duration required for the conversion of OFDM symbols in frequency domain to time domain using IFFT is known as the useful symbol time T_b. The CP is the replicate of the last portion (denoted as T_g) of the useful symbol period. A combination of T_g and T_b constitute the total symbol period indicated as T_s. The CP eliminates effects of multipath delay spread in wireless channels and maintains the orthogonality between subchannels. The use of CP insertion comes with cost of some radio

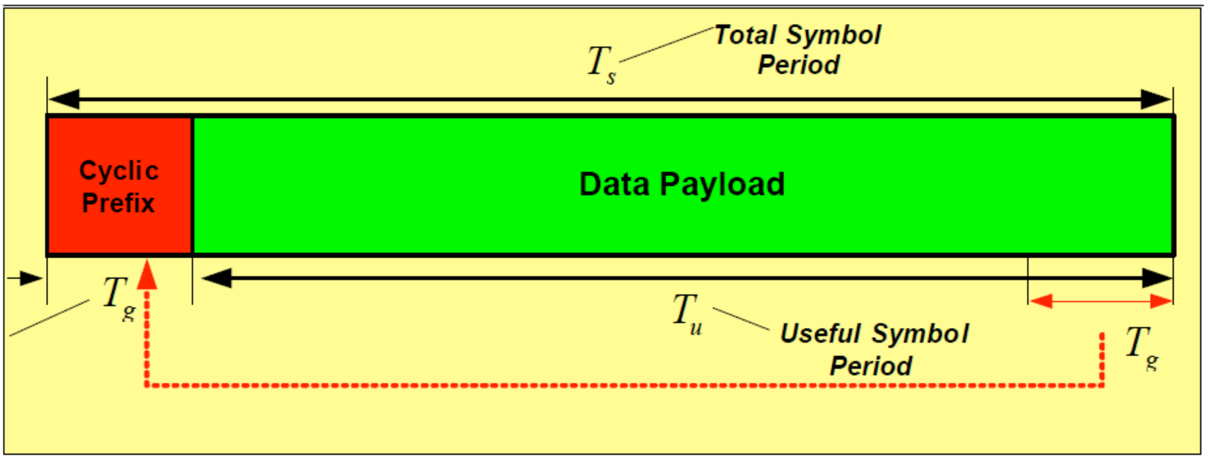

Figure 13. Insertion of Cyclic Prefix (CP) (WiMAX Forum 2006: 12).

resources. Apart from reduction in bandwidth efficiency as stated earlier, CP insertion also incur power loss. Additional bandwidth and transmit power is utilized in the transmission of the redundant part of the symbols. The transmitter energy is directly proportional to the length of the guard time. The receiver energy is constant irrespective of the variation in the length of the guard time. As the length increases, the corresponding increase in the transmitter energy leads to a loss of $10log(1 - T_g/(T_b+T_g))/log(10)$ dB in E_b/N_0. Increasing the size of the FFT could cut down the fraction of the CP overhead and the total SNR loss, though the oscillators sensitivity of the system to phase noise could be critically affected. For FFT operation at the receiver, the application of CP extension in this regard enables the flexibility of the samples required with respect to the length of the extended symbol. This proffers tolerance in the synchronization errors of the symbol time and also ensures freedom from multipath effects. During initialization, the MS scans all available values of the CP in search of the BS CP. When detected, the MS uses BS CP for uplink. For downlink operation, the BS selects the CP duration and must remain constant in order to avoid forced resynchronization of all MSs to the BS. (IEEE Std 802.16TM-2004 2004: 427.)

2.8. OFDM symbol parameters and transmitted signal

This section gives details of OFDM symbol parameters and the transmitted signal voltage input to the antenna. Basically, there are four fundamental parameters from which others are derived. The four parameters are: the nominal channel bandwidth BW, number of subcarrier used N_{used}, sampling factor n, and the proportion of the CP time to the useful OFDM symbol time. The distribution of the subcarrier and the useful time of the symbol is jointly controlled by the sampling factor, BW and N_{used}. The derived parameters as defined by the WiMAX standard are given as follows:

- The number of used subcarrier N_{used} less than the least power of two is denoted as N_{FFT}.
- The sampling frequency is denoted as F_s = floor(n $\cdot BW/8000) \times 8000$
- Subcarrier spacing is given as $\Delta f = F_s / N_{FFT}$.
- The useful symbol time is represented as $T_b = 1/\Delta f$
- Cyclic Prefix time is designated as $T_g = G \cdot T_b$
- OFDM Symbol Time is denote as $T_s = T_g + T_b$
- The sampling time is given as T_b / N_{FFT}

and each parameter is allocated an operational value by system designers. The antenna is the last interface between the transmission block and the wireless channel. The signal voltage (as a function of time) of any OFDM symbol transmitted to the antenna is defined by equation (12),

$$s(t) = Re\left\{ e^{j2\Pi f_c t} \sum_{\substack{k=-\frac{N_{used}}{2} \\ k\neq 0}}^{\frac{N_{used}}{2}} c_k \cdot e^{j2\pi k\Delta f/(t-Tg)} \right\} \tag{12}$$

t in the above equation represents the time spent from the start of the subject OFDM symbol while $c_k$denotes the complex number, and the frequency offset index is given as k. The values of the OFDM parameters are shown in Table 5. (IEEE Std 802.16^{TM}-2004 2004: 428-429.)

Table 5. Parameters of OFDM symbol (IEEE Std 802.16TM-2004 2004: 429).

Parameter	Value
N_{FFT}	256
N_{used}	200
n	For channel bandwidths that are a multiple of 1.75 MHz then $n = 8/7$ else for channel bandwidths that are a multiple of 1.5 MHz then $n = 86/75$ else for channel bandwidths that are a multiple of 1.25 MHz then $n = 144/125$ else for channel bandwidths that are a multiple of 2.75 MHz then $n = 316/275$ else for channel bandwidths that are a multiple of 2.0 MHz 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 guard subcarriers	28
Number of higher frequency guard subcarriers	27

2.9. PHY layer data rate

The flexibility of the WiMAX PHY layer data rate performance is dependent on the operating parameters. Parameters such as the modulation and coding scheme utilized, and the channel bandwidth have considerable impact on the data rate compared to the impacts of the OFDM guard time, oversampling rate, and number of subchannels. These parameters with some assumed values and factors as well as their corresponding calculated PHY layer data rates are shown in Table 6. (Andrews et al. 2007: 46.)

Table 6. PHY layer data rate at different channel bandwidth (Andrews et al. 2007: 47).

Channel bandwidth	3.5MHz		1.25MHz		5MHz		10MHz		**8.75MHz[a]**	
PHY mode	256 OFDM		128 OFDMA		512 OFDMA		1,024 OFDMA		1,024 OFDMA	
Oversampling	8/7		28/25		28/25		28/25		28/25	
Modulation and Code Rate	**PHY-Layer Data Rate (kbps)**									
	DL	UL	DL	UL	DL	UL	DL	UL	DL	UL
BPSK, 1/2	946	326	**Not applicable**							
QPSK, 1/2	1,882	653	504	154	2,520	653	5,040	1,344	4,464	1,120
QPSK, 3/4	2,822	979	756	230	3,780	979	7,560	2,016	6,696	1,680
16 QAM, 1/2	3,763	1,306	1,008	307	5,040	1,306	10,080	2,688	8,928	2,240
16 QAM, 3/4	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 1/2	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 2/3	7,526	2,611	2,016	614	10,080	2,611	20,160	5,376	17,856	4,480
64 QAM, 3/4	8,467	2,938	2,268	691	11,340	2,938	22,680	6,048	20,088	5,040
64 QAM, 5/6	9,408	3,264	2,520	768	12,600	3,264	25,200	6,720	22,320	**5,600**

a. The deployed WiBro version in South Korea.

3. MAC LAYER OF WIMAX

The WiMAX Media Access Control (MAC) layer constitute the other part of the WiMAX protocol architecture. The MAC layer shares a common boundary with the PHY layer and is located just above the PHY in the reference model. The MAC layer performs several mapping, management, scheduling, transmission and access definition functions in the network operations. In this chapter, the components of the MAC layer and detail operational features are explained.

The WiMAX MAC layer specifies two types of access for transmission and resource sharing operations: point-to-multipoint (PMP) access and mesh access. PMP access defines the DL broadcast communication from a BS to several MSs in a network and an UL unicast communication from individual MS to the serving BS. The BS represents the access point for all the MSs and broadcast a DL-MAP which specifies the allocated subframe for each MS in the network. Each MS translates the DL-MAP to extract its designated subframe defining the allotted burst region for DL and also the on demand allocated region required for UL transmission. The Mesh access involves transmission between MSs and also from one MS through other MSs. This facilitates effective communication among MSs that are in locations of more than one hop distance from the BS. Nodes represent the mesh network systems and are used to differentiate the three mesh network terminologies: neighbors, neighborhood and extended neighborhood. Neighbors describes stations that are one hop distance from each other while neighbourhood defines all neighbours attached to a node. An extended neighborhood comprises all neighbors attached to a neighborhood. Transmission collision is avoided in mesh network through coordinated transmission between the mesh BS and other stations in their two-hop neighborhood. Omnidirectional antennas are used in mesh network transmission while sector antennas are employed in PMP communication. (Ergen 2009: 309)

3.1. Components of the MAC layer

As mentioned in section 1.2, The MAC layer comprises three sublayers: the Service Specific Convergence sublayer, Common Part sublayer and the Security sublayer. Each sub-layer is saddled with diverse responsibilities, executed during operations. The following subsection considers each of these Sub-layers.

3.1.1. Service Specific Convergence Sublayer

The CS is located above the MAC CPS and is responsible for higher-layer address mapping and packet header suppression. The CS receives and accepts higher-layer protocol data units (PDUs) transmitted from the higher-layer, classifies and thereafter processes the higher-layer PDUs, depending on the classification. The CS employs the services of the CPS through the use of MAC SAP. The CS delivers CS PDUs to the desired MAC SAP and also receives PDUs from the associate entity. This operation is significantly useful in enabling the compatibility of the higher-layer protocol, the MAC and PHY layers required for transmissions. The WiMAX standard defines two types of CS: the asynchronous transfer mode (ATM) CS and the packet CS, though the WiMAX Forum implementation of CS is based on IP and Ethernet (802.3). (Andrews et al. 2007: 309; IEEE Std 802.16^{TM}-2004 2004: 17.)

3.1.2. MAC Common Part Sublayer

The operation of the MAC CPS is based on the PMP network structure. Time Division Multiplexing (TDM) is used for data transmission for DL while the MSs UL transmissions are accomplished using Time Division Multiplexing Access (TDMA). Every service is mapped to a connection to ensure successful communication in the connection-oriented MAC layer. The CPS constitutes the central part of the MAC layer that implements an effective and efficient sharing mechanism of resources and service profiles in the network. The CPS is responsible for several operations such as communication addressing and connections, construction and transmission of MAC PDUs, bandwidth allocation and request mechanism, network entry and initialization, ARQ mechanism, and scheduling services. (Eklund, Marks, Stanwood & Wang 2002)

3.1.3. Security Sublayer

The SS directly shares boundary with PHY layer and is responsible for authentication and encryption operations. Authentication between two communication parties is essential in order to avoid the use of network resources with an attacker or an illegal third party. The SS functions are composed of two components protocols: an encapsulation protocol and a key management protocol (PKM). An encapsulation protocol specifies a set of sequence based on cryptography and the stated conditions for the execution of the algorithms on MAC PDU payload. It is used for packet data encryption in a fixed broadband wireless access (BWA) network. The PKM is employed for network access operation. In WiMAX network, the BS encrypts the associated service flow to avert the use of data transport services by unauthorized MSs. The MS authentication is based on the client/server KMP whereby the allocation of authentication keys to every MS required for network access is done by the BS. The MS authentication potency for access is further increased through combine application of PKM and digital certificate. (IEEE Std 802.16^{TM}-2004 2004: 271.)

3.2. Packet Header Suppression

Packet header suppression (PHS) is the removal of the repetitive part of every SDU header. This operation is performed at the transmitter by the CS in order to reduce the overhead. For instance, in the transmission of SDUs IP packets, the header of each IP packet comprises the source and destination IP addresses which remains the same for all the packets. This repetitive part is discarded at the transmitter prior to transmission and is then reinserted back into the SDU at the receiver. To achieve a successful PHS operation, the CS at the transmitter is synchronised with the receiver CS using PHS protocols. The application of PHS increases packet transmission efficiency such as voice over internet protocol though the implementation is optional in WiMAX. The application of PHS is guided by already laid out PHS rule that defines the framework of the SDU header suppression, and the rule to be utilized is determined by the CS depending on the defined parameters or the form of service, such as VOIP or HTTP. The CS generates the required connection identifier (CID), service flow ID (SFID) and PHS for the SDU operation, immediately a matching rule is established. WiMAX PHS procedure is illustrated in Figure 14. When the SDU packet is received for PHS operation, the CS determines the existence of a PHS rule that matches the SDU and thereafter determines the part of the header (PHS field) that requires suppression operation and the other part (PHS mask) that does not require suppression operation, after a matching PHS rule has been established. In occasion that employs the application of PHS verify

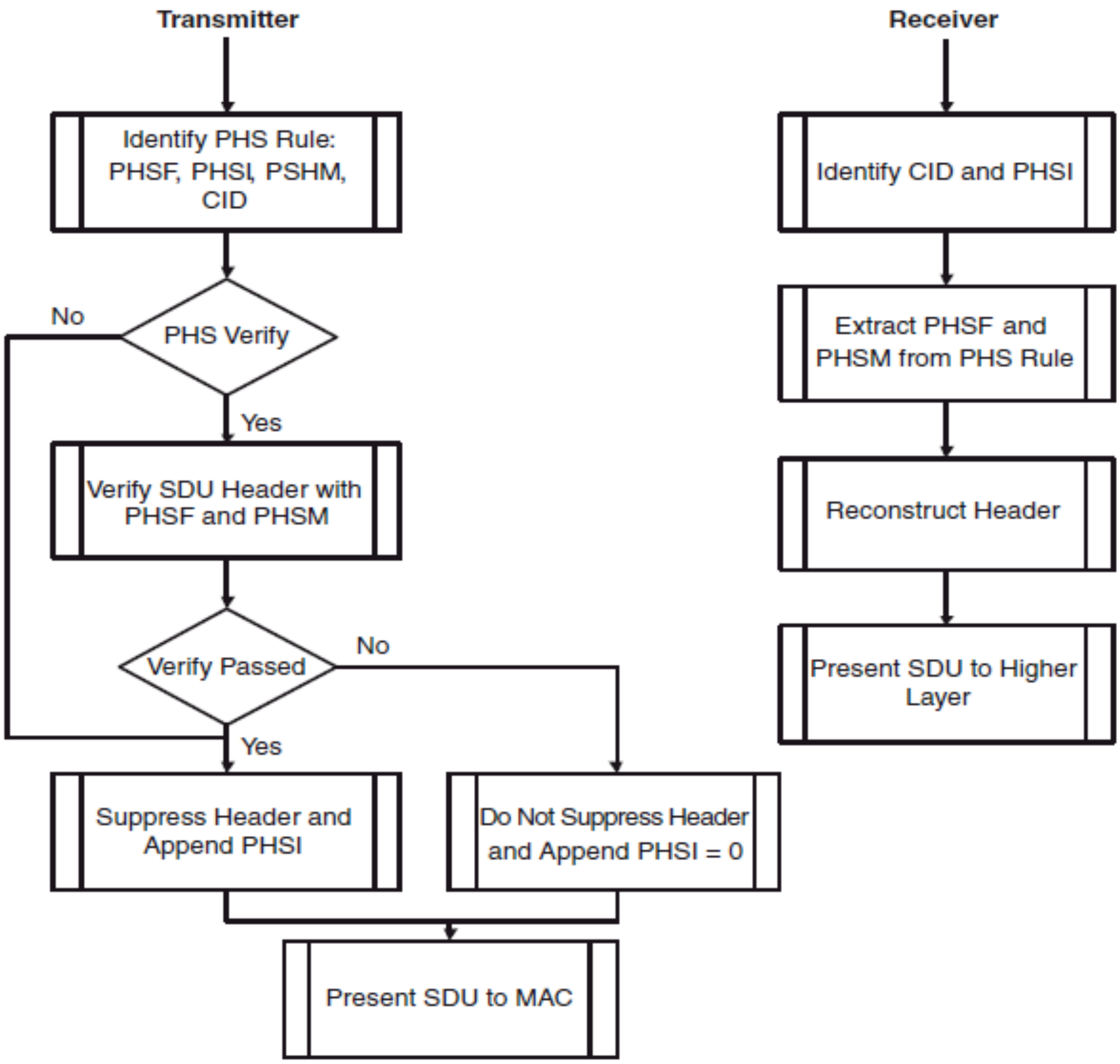

Figure 14. WiMAX PHS operation (Andrews et al. 2007: 311).

(PHSV), the received PHS field (PHSF) bits are examined against the expected bits, using the PHS rule. If the SDU PHSF and cache PHSF match, the SDU PHSF bytes are discarded and a PHS index (PHSI) is appended on the SDU based on the matching rule. Furthermore, if the SDU PHSF and cache PHSF do not match, the suppression operation is not executed on the SDU PHSF and a PHSI value of 0 is therefore appended. (Andrews et al. 2007: 309-310.)

3.3. Data/Control Plain

The connections of the data and control plane modules are distinguished through the application identifier on each connection. Each MS possesses a unique MAC address of 48 bits, used for connection registration with a BS. The connection is identified with a 16 bit CID assigned by the BS. During the MS initial network entry, the BS creates two pairs of management CIDs and also creates an optional third pair for MS that permits network control. Two directional CIDs (one for DL and the other for UL) constitute a CID pair for every connection. Based on applicability, there are three classification of management CIDs: basic management connection, primary management connection and secondary management connection CIDs. The basic management connection CID is employed in the transfer of brief immediate MAC management messages between BS and MS, while primary management connection CID is used for lengthy and delay flexible MAC management messages. Secondary management connection CID is used in the exchange of standards-based messages for example DHCP. (Ergen 2009: 312-313.)

3.4. MAC PDU Format

Data are transported as MAC PDU in the WiMAX network. The MAC PDU structure shown in Figure 15 comprises a fixed length MAC header, a payload with flexible length and a Cyclic Redundancy Check (CRC). The 48 bits length MAC header houses information contents, such as the user ID and the instructions regarding the length of the header. The optional MAC PDU payload is composed of a complete or fragment segment of the MAC SDUs. Fragmentation is the splitting of MAC SDU into more fragments (Fragment Sub-header) which are transmitted in different SDUs thus enhancing the flexibility of the MAC PDU size. A Fragment Sub-header (FSH) is made up of 16 bits components appended to every MAC PDU that carries the SDU fragment. The FSH components are :

- Fragmentation Control (FC) containing 2 bits.
- Fragment Sequence Number (FSN) having allocated 11 bits required for non-ARQ connections.
- Block Sequence Number (BSN) consisting allotted 11 bits used for ARQ connections.
- Reserved 3 bits utilized for rounding purpose.

The payload fragmentation state is denoted by FC (00, 10,01 and 11). Non-fragmentation is

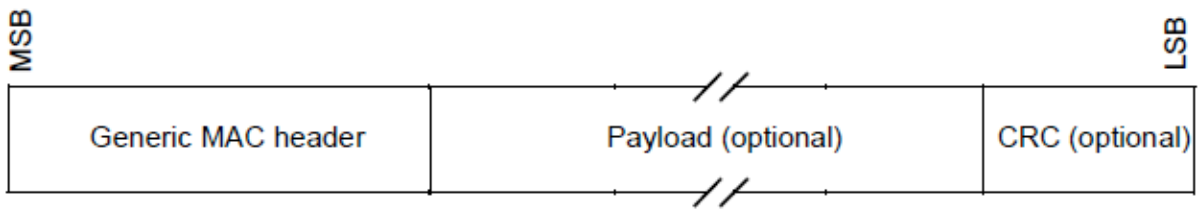

Figure 15. MAC PDU formats (IEEE Std 802.16™-2004 2004: 35).

denoted by 00, while first fragmentation is indicated by 10, last fragmentation by 01 and continue fragmentation by 11. The immediate SDU fragment sequence number is designated by FSN. The length of the header is not always an integer number bytes, the standard utilizes the reserve bits to accomplish integer number of bytes length for all the headers. This implies that, for a 16 bits CRC, an overhead of 80 bits (48 bits MAC header, 16 bits FSH and 16 bits CRC) is joined to every payload. (Can, Vannithamby, Lee & Koc 2008.)

3.4.1. MAC Header Formats

The WiMAX standards define two types of MAC header formats: the generic MAC header and the bandwidth request MAC header. A MAC header whose origin comprises CS data or MAC management messages is known as the generic MAC header and is used to convey data

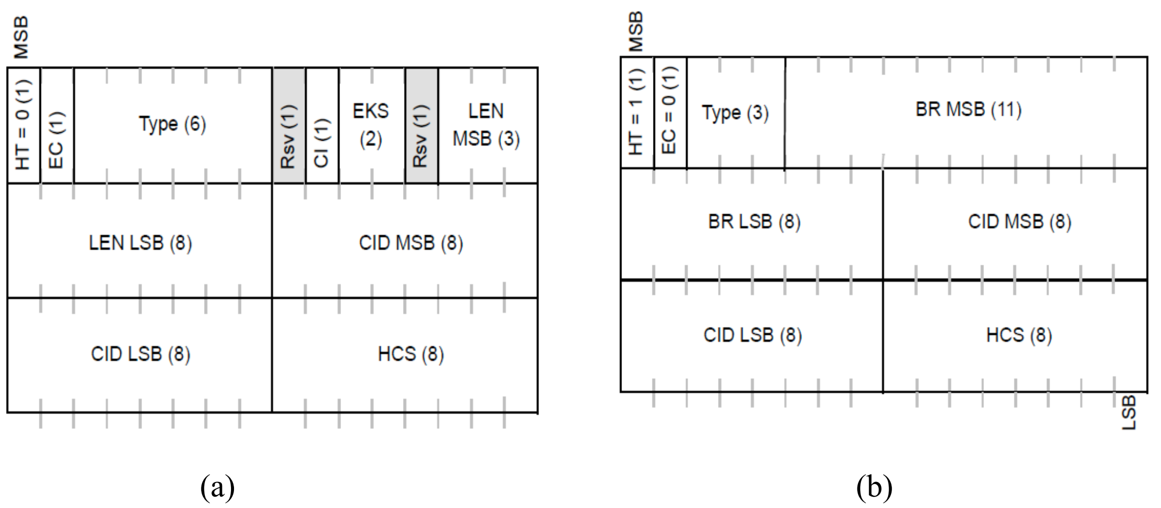

Figure 16. WiMAX MAC PDU headers: (a) generic; (b)bandwidth request (IEEE Std 802.16™-2004 2004: 36 & 38).

and management messages while the bandwidth request header is utilized by the MS to request for additional bandwidth. The generic MAC header is differentiated from the bandwidth request header by the single-bit Header Type (HT) field. A zero HT field indicates a generic MAC header and a HT field of value one represents a bandwidth request header. The generic MAC header, bandwidth request MAC header, and the values of each parameter are shown in Figure 16 and in Tables 7 & 8. (IEEE Std 802.16^{TM}-2004 2004: 35.)

Table 7. Generic MAC header fields (Andrews et al. 2007: 314).

Field	Length (bits)	Description
HT	1	Header type (set to 0 for such header)
EC	1	Encryption control (0 = payload not encrypted; 1 = payload encrypted)
Type	6	Type
ESF	1	Extended subheader field (1 = ES present; 0 = ES not present)
CI	1	CRC indicator (1 = CRC included; 0 = CRC not included)
EKS	2	Encryption key sequence (index of the traffic encryption key and the initialization vector used to encrypt the payload)
Rsv	1	Reserved
LEN	11	Length of MAC PDU in bytes, including the header
CID	16	Connection identifier on which the payload is to be sent
HCS	8	Header check sequence; generating polynomial $D^8 + D^2 + D + 1$

Table 8. Bandwidth request MAC header fields (Andrews et al. 2007: 315).

Field	Length (bits)	Description
HT	1	Header type (set to 1 for such header)
EC	1	Encryption control (set to 0 for such header)
Type	3	Type
BR	19	Bandwidth request (the number of bytes of uplink bandwidth requested by the SS for the given CID)
CID	16	Connection indentifier
HCS	8	Header check sequence

3.4.1. MAC Subheader

The WiMAX standards define five types of subheader that are placed next to the generic MAC header in a MAC PDU structure if utilized. Four out of the five subheaders are per-PDU subheaders and the other one belongs to per-SDU subheader. The four per-PDU subheaders indicated in the order of precedence when utilized are Mesh, Fragmentation, Grant management and Fast-feedback allocation, while the last, Packing subheader is the per-SDU subheader. Two or more subheaders can be used and the per-PDU subheaders always precedes the per-SDU subheader whenever both subheaders are utilized, the only exception is the Fragmentation subheader due to the mutually exclusive nature when used with per-SDU subheader. The Mesh subheader is used alongside the generic MAC header when a mesh mode operation is employed. The Fragmentation subheader is used to denote the fragmented SDU in the MAC PDUs. The Grant management subheader is utilized by the MS to transmit bandwidth information to the BS while the Fast-feedback allocation subheader is used to denote the presence of feedback in a MAC PDU. The MS uses the Fast-feedback allocation subheader to update BS on information regarding the DL channel state. The Packing subheader is employed to give details of packed multiple SDUs in a single MAC PDU. (IEEE Std 802.16^{TM}-2004 2004: 39- 42.)

3.5. MAC PDU Construction and Transmission

The construction and transmission of MAC PDU process is accomplished through one of these three operations: fragmentation, concatenation, and parking which are performed on data packets and management messages. Fragmentation operation involves the division of each MAC SDU into one or several MAC PDUs and this facilitates performance readiness and improves the QoS scheduling and frame efficiency. The transmission of the fragments is dependent on the mode of the ARQ which is either *enabled* or *disabled*. The *enabled* mode activates the retransmission of the fragments, while a single transmission in sequence is executed whenever the ARQ in *disabled*. The receiver uses sequence number to retrieve the transmitted MAC PDU. Concatenation is an operation in which several MAC PDUs are combined into a single transmission. Each MAC PDU has its unique CID and this enables the receiver to disintegrate the received MAC PDU. Packing is a procedure that yields a single MAC PDU containing pack of several MAC SDUs. The MAC header length field can be employed to identify the packed SDU only when a fixed size of SDU is used. (Ergen 2009: 320.)

3.6. Quality of Service Support

The WiMAX standards define the QoS requirements for WiMAX network design in order to facilitate the provision of various types of data services and applications. This is reflected in the design features such as speedy air interface, pliable proficiency in the DL and UL, flexibility in resource distribution structure, and fine-grained resource capacity. QoS in

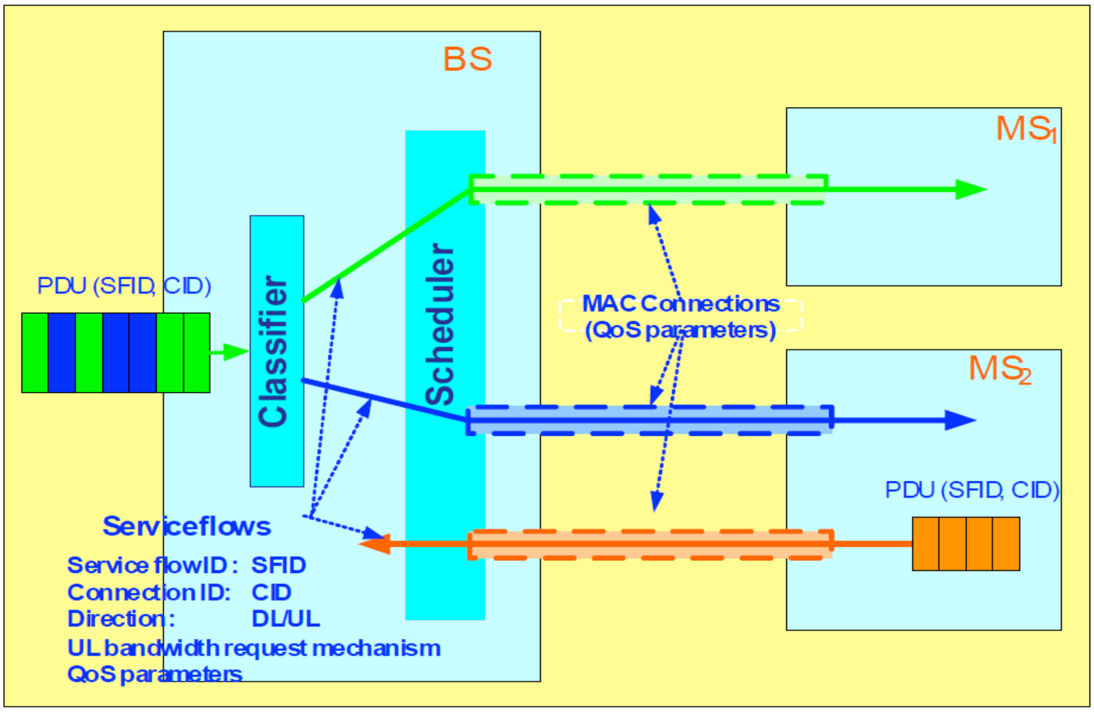

Figure 17. QoS support in mobile WiMAX (WiMAX Forum 2006: 20).

WiMAX shown in Figure 17, is made available through service flows. Service flow is the provision of a unidirectional transfer of packets, based on a distinct set of QoS parameters. The connection between the BS and MS is established first before transmission of any form of data services can be achieved. During the connection process, a unidirectional logical link is created through which the MS associates its MAC address details with the BS MAC address. At the outbound MAC, the required service flow for the transferred packets are combined with the packets at the MAC interface and is then transmitted over the connection. The air interface transmission sequence and scheduling is specified by the service flow based on the incorporated QoS parameters. The air interface constitutes a challenge in wireless transmissions. The QoS is connection-oriented and can be employed in regulating the air interface operations thereby facilitating QoS control from one end of the network to the other. MAC massages serve as a medium for dynamically controlling the parameters of the service flow in providing dynamic service need. Service flow enhances QoS in a communication network and is utilized in both DL and UL. Table 9 shows various types of data services and applications with different QoS requirements supported in WiMAX. (WiMAX Forum 2006: 19-20.)

Table 9. Mobile WiWAX applications and QoS (WiMAX Forum 2006: 21).

QoS Category	Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP	• Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance
rtPS Real-Time Polling Service	Streaming Audio or Video	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Traffic Priority
ErtPS Extended Real-Time Polling Service	Voice with Activity Detection (VoIP)	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance • Traffic Priority
nrtPS Non-Real-Time Polling Service	File Transfer Protocol (FTP)	• Minimum Reserved Rate • Maximum Sustained Rate • Traffic Priority
BE Best-Effort Service	Data Transfer, Web Browsing, etc.	• Maximum Sustained Rate • Traffic Priority

3.7. MAC Scheduling Services

The successful transmission of data services over a connection depends on the structure of data administration, designated as the service flow and is established by the MAC scheduler. Every data service is attached to a connection based on the associated set of QoS parameters. The dynamic service addition (DSA) and dynamic service change (DSC) message dialogs are utilized to manage these parameters. Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Extended real-time Polling Service (ErtPS), Non-real-time Polling Service (nrtPS), and Best Effort (BE) constitute the five services applied in WiMAX as shown in Table 9. The UGS construction targets real-time data traffic at periodic intervals. The Voice over IP (VOIP) and T1/E1 fall in the category of constant size data packets with defined mandatory QoS specifications of tolerated maximum latency, maximum sustained rate, and maximum jitter tolerance. The design of rtPS is identical to UGS except that the traffic comprises data packets of varying sizes. The moving pictures experts group (MPEG) video represent the type of data packets supported in this service class with QoS requirements such as traffic priority, minimum reserved rate, maximum latency tolerance, and maximum sustained rate. The ErtPS takes advantage of UGS and rtPS, and improves the efficiency with additional QoS specification of delay tolerance. The nrtPS applies to dynamic size data transmissions that accommodate delay such as FTP while the design of BE focuses on the data traffic such as data transfer and web browsing that do not specify a minimum service criteria requirement for transmission. (IEEE Std 802.16^{TM}-2004 2004: 138- 139; IEEE Std 802.16e^{TM}-2005 2006: 183.)

The MAC scheduler possesses properties that are exhibited in the efficient execution of scheduling functions while delivery data services and applications over wireless networks. These properties (WiMAX Forum 2006: 21-22.) are:

- **Fast Data Scheduler**
  The MAC scheduler operates at optimal resource distribution level in order to efficiently meet the dynamic demands of both the channel states and transmitted data burst. The design of every BS requires a strategic scheduler mechanism to facilitate prompt response to these demands. The QoS parameters are specified, the service flows attached to the data packets are well arranged and this ensures speedy scheduling of the right sequence of the data packets transmission over the air interface. The MS through feedback update the scheduler on the channel state information and the scheduler in response to the provided information selects a suitable modulation and coding scheme in order to maintain an efficient transmission.
- **Scheduling for both DL and UL**
  The scheduler performs scheduling tasks for both DL and UL. The distribution of resources and scheduling efficiency is dependent on the timing and accuracy of the channel state information feedback from the UL. The UL supports different mechanism of requesting bandwidth in the UL and specifies distinct feedback mechanism for each link which enhances anticipated scheduler response.
- **Dynamic Resource Allocation**
  The MAC scheduler allocates resources in frequency and time domain on each frame for both DL and UL, which are distributed as MAP messages at the start of every frame and this enables resource distribution flexibility depending on the received feedback.
- **QoS Oriented**
  The MAC scheduler is responsible for data transfer scheduling and the task is executed from one connection to the other, based on the QoS requirements of individual service data attached to the connection. The scheduler is capable of effective resource distribution required for both DL and UL, and thus guarantees the provision of excellent QoS required for data transmission for the DL and UL.
- **Frequency Selective Scheduling**
  A transmission link may consists of various types of sub-channels, the MAC scheduler has the ability to efficiently execute several scheduling tasks on these sub-channels. The PUSC permutation is an example of frequency-diverse sub-channels in which there is pseudo-random distribution of subcarriers over the bandwidth. These sub-channels have distinct frequencies and posses identical features. Frequency-diversity scheduling allows fine-grained QoS and also dynamic resource distribution in frequency and time domain. The AMC permutation belongs to the contiguous permutation in which the quality of one sub-channel is different from the other, the frequency-selective scheduling thus allots the best sub-channel to the user.

3.8. Network Entry and Initialization

An MS seeking an access to a WiMAX network must undergo network entry operations in order to establish communication with the network. At the onset of the entry operation, the MS scans for the availability of a DL channel of the intended WiMAX network. Once the network presence is confirmed, the MS thereafter synchronizes itself with the DL channel of the chosen network BS. On completion of synchronization, the MS procures transmission parameters from different control messages received from the BS and performs ranging afterwards. Furthermore, the MS negotiates basic capabilities to ensure efficient network communication, and subsequently undergo authentication and registration operations. Finally, the MS acquires an IP address which completes the network entry procedure and prepares the MS to begin dynamic or provisioned service flows set up prior to transmission of data and management messages. (Ergen 2009: 325.)

3.9. Bandwidth Request and Request Mechanism

In WiMAX network, dedicated CIDs ranging from one to three are allocated to each MS to transmit and receive control messages during network entry and initialization. The purpose of the link pairs justifies the application of distinct sets of QoS on MAC management traffic links. Bandwidth usage flexibility is imperative in all services besides incompressible UGS connections characterized with constant bit rate, whose demands for example channelized T1 may vary based on the traffic. Resources are allotted for Demand Assignment Multiple Access (DAMA) services based on demand and the time of need. BS is responsible for bandwidth allocation to MSs. MS requires bandwidth for successful transmission and the request message is communicated to BS through the following methods:

- **Requests**
  Requests are UL messages through which the MS informs the BS to assign UL bandwidth. There are two forms of requests: stand-alone bandwidth request header and the piggyback bandwidth request. Due to the dynamic variability of the UL burst profile, the UL bandwidth requests comprises the required number of bytes for the transportation of the MAC header and payload excluding the PHY header. The request for bandwidth can either be cumulative or aggregate and is designated in the bandwidth request header Type field. The BS responds to these two request types in two different ways. In cumulative bandwidth request, a given amount of bandwidth is added to the existing MS bandwidth of the link while in aggregate bandwidth request, the existing MS bandwidth is completely replaced with the quantity of the requested bandwidth.

- **Grants**
  Grants are messages through which the BS informs the MS on the allocation of the requested bandwidth. These messages are delivered to the MS basic CID since the BS does not know the connection CIDs that is in need of the allocated bandwidth. The

distribution of the allotted bandwidth to the actual CID connection is done by the MS. In conditions where the received allocated bandwidth is less than the requested bandwidth, the MS may withdraw for a while and request again or determine the connection(s) that will utilize the bandwidth, otherwise the MS deletes the SDU based on the received BS information.

- **Polling**
  Every connection in a network requires resources (e.g bandwidth) for transmission. The mechanism of MS bandwidth requests also requires bandwidth allocation for operation. This mechanism through which an MS is specifically allocated bandwidth for bandwidth request purpose is known as polling. A single MS or groups of MSs may be recipient(s) of these allocations. The allocation of a single MS is accomplished through the basic CID and that of groups of MSs is through UL-MAP and special CID. (IEEE Std 802.16^{TM}-2004 2004: 141- 142.)

3.10. Mobility Management

Mobility management was defined in the IEEE 802.16e standard following the amendment of IEEE 802.16d standard to support mobile applications. There are basically two points in question as regards mobility in wireless networks. They are power and handoff management. These issues are addressed in mobile WiMAX (WiMAX Forum 2006: 22) through specification that employs Sleep Mode and Idle Mode operations to facilitate the efficient use of power resources and also, a consistent handoff scheme that ensures uninterrupted communication of the MS when moving from one BS to another at vehicular speeds.

3.10.1. Power Management

As stated in the previous section, the Sleep Mode and Idle mode are the two modes utilized in WiMAX network for MS power management. In sleep mode, the MS pre-negotiates with the serving BS on the time intervals it will be unavailable to the BS air interface. During these time intervals, there will not be traffic in both DL and UL, thus reducing the MS power consumption as well as the air interface resources of the serving BS. Furthermore, the Sleep Mode supports MS scanning operation of neighbouring BSs for information, utilized for handoff purpose in the course of Sleep Mode. In Idle Mode, the MS at periodic time intervals accesses the broadcast traffic messages of a BS and travels across an air link of several BSs without registration. The Idle Mode operation discards the handoff requirements and other routine procedures, these features in this regard favour the MS. The Idle Mode also favours the BS. Here, the operation deletes the network handoff traffic and the air interface of MSs that are not in active communication and maintains DL traffic paging with the MSs. (WiMAX Forum 2006: 23.)

3.10.2. Handoff

The handoff mechanism is of paramount importance in WiMAX network and ensures an ongoing connection is maintained as an MS migrate from one BS to another. The WiMAX IEEE 802.16e standard supports three methods of performing handoff operation. These methods are: Fast Base Station Switching (FBSS), Hard Handoff (HHO) and Macro Diversity Handover (MDHO). The standard specifies a mandatory method of HHO while FBSS and MDHO are optional. Diverse HHO optimization techniques have been developed by WiMAX Forum to enhance performance that ensures the handoff delays of Layer 2 is kept below 50 milliseconds. In FBSS method, a list consisting of the MS FBSS associated BSs known as Active Set is preserved by the MS and BS. The BSs in the active set are constantly observed, among which the MS selects one as the Anchor BS. The MS exclusively maintains a DL and UL communication with this Anchor BS during the FBSS operation, and switching to a different Anchor BS does not require the use of specific HO signalling commands. The signal quality (power) of the serving BS is conveyed through the Channel Quality Indicator (CQI) channel to facilitate the Anchor update scheme. The MS starts the FBSS handover process by scanning the BS of the neighbouring cells, chooses the BSs with satisfactory quality, and executes an active set update with the BS. The MS picks one of the BSs in active set as the Anchor BS after constantly observing their respective signal strengths and thereafter begin the HO request message. The FBSS operation requires concurrent data transmission between the MS and active set BSs. In MDHO, the same procedure of selecting an Anchor BS among the BSs in active set is performed except for a special case (regular mode of operation) in which the active set comprises only one BS. During the MDHO operation, communication between the MS and the BSs in the active set is achieved through unicast messages and traffic. The transmission and reception of unicast messages and traffic, between MS and several BSs at the same period signifies the commencement of the MDHO. The DL transmission of two or more BSs are synchronized and the MS executes diversity combining for successful reception of the synchronized transmission, while selective diversity is performed on the UL transmission received by the BSs. (WiMAX Forum 2006: 23-24.)

4. WIMAX PERFORMANCE FEATURES

The WiMAX network supports several features that enhance performance and efficient network resources usage. This chapter exploits the properties of these features as defined by WiMAX standard as well as their enhancement functionalities in the successful transmission of information bits from the transmitter to the receiver.

4.1. Adaptive Modulation and Coding

Adaptive modulation and coding (AMC) is significantly useful in wireless network and is employed in WiMAX to capitalize the variations in the channel. The concept of AMC involves the application of a suitable transmission rate depending on the channel conditions. At good channel condition, data are transmitted at high rate as possible and otherwise at poor channel condition. The MS communicates the DL channel quality to the BS through a channel feedback indicator while the UL channel quality is evaluated from the signal quality received from the MS. The BS scheduler accesses the DL and UL channel qualities and then administers a corresponding AMC scheme in order to maximize the throughput based on the channel's current signal-to-noise ratio. Small constellation for example QPSK and error-correcting codes such as Turbo or Convolutional codes of low rate (1/2) are utilized to accomplish low data rate, while large constellations (64 QAM) and less robust error-correcting codes, such as Turbo, Convolutional, or low-density parity check (LDPC) of code rate, like 3/4 are used to achieve high data rate. On every link, WiMAX AMC accommodates compromise between throughput and robustness, and thus boost the total system capacity in a considerable manner. WiMAX defines 52 different AMC schemes though the implemented burst profiles (shown in Table 10) constitute a fraction of the total number. The application of these bursts profiles procures the provision of wide range of spectral efficiencies, and this necessitates the increase of throughput as the SNR increases in accordance to Shannon formula $C = log_2(1 + SNR)$. Equation 13 defines the bandwidth normalized throughput that

$$T = (1 - BLER) r log_2(M) \text{ bps/Hz} \tag{13}$$

Table 10. Modulation and Coding schemes supported in WiMAX (Andrews et al. 2007: 47).

	Downlink	Uplink
Modulation	BPSK, QPSK, 16 QAM, 64 QAM; BPSK optional for OFDMA-PHY	BPSK, QPSK, 16 QAM; 64 QAM optional
Coding	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, LDPC, RS-Codes for OFDM-PHY	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, LDPC

can be realized, where the block error rate is denoted by BLER, the coding rate, $r \leq 1$ and M represents the constellation points. The efficient control of the coding rate, transmit rate, and transmit power at the same time is one main issue in AMC which is considered and resolved by system Engineers. The distribution of each scheme in a cell is shown in Figure 19. (Andrews et al. 2007: 47, 206 &208.)

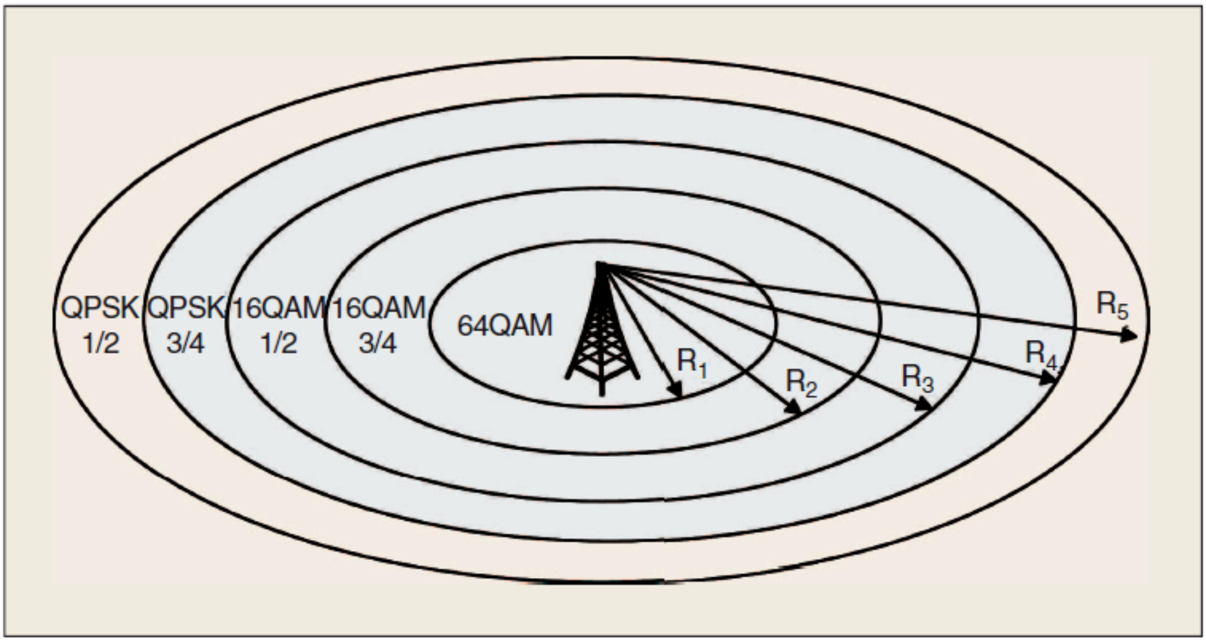

Figure 18. A multirate cell of AMC scheme (Kolios, Friderikos, & Papadaki 2011).

4.2. Channel Performance

Channel represents the transmission medium between a transmitter and a receiver. In practical wireless communication, the signal received at the receiver cannot be the exact copy of the transmitted signal due to fading (multipath effects, channel variation, reflections, scatters, etc.) experienced in the wireless channel. According to (Tse & Viswanath 2004: 166), Channel performance evaluation is based on its capacity, and thus defines the maximum transmission rate a wireless channel can achieve with relatively little error probability. The capacity of fading channels are examined based on the foundation of the Addictive White Gaussian Noise (AWGN) channel.

4.2.1. AWGN Channel Performance

Shannon capacity gives the theoretical limit that can be achieved by communication systems. The real world communication system cannot operate beyond this limit due to bandwidth and signal-to-noise ratio (SNR) limitations, hence the efficiency of the real world communication system is evaluated based on the degree at which its operation approaches this limit. The utilized modulation and coding serves as the only performance evaluator since channel effects are not present in AWGN channels. The AWGN channel performance with respect to Shannon capacity is therefore employed as a reference point in tackling channel effects in WiMAX communication systems. The AWGN performance is also utilized in deriving the SNR thresholds for different AMC schemes that are exploited by communication systems in selecting a suitable AMC that matches the fading channel SNR. (Andrews et al. 2007: 370.)

4.2.2. Fading Channel Performance

The real world communication of WiMAX systems involves the challenges of multipath fading channels. Travelling signals encounter various kinds of fading based on the signals parameters and channel parameters, and these effects are taken into consideration in WiMAX networks. Several copies of a transmitted signal may be formed as a result of scattering, reflection, diffraction, etc, experienced in wireless channels. These signals travel through different paths and suffer individual delay, distortion, phase shift etc, and arrive at the receiver as a constructive or destructive signal. These effects could result in network performance degradation and are therefore addressed in wireless communication networks through channel models. The practical channel fading effects are modelled as Rayleigh fading channel and Ricean fading channel, through which the real world WiMAX network performance is measured since multipath propagation is not considered in AWGN channel. (Kaarthick, Yeshwenth, Nagarajan & Rajeev 2009.)

4.2.3. Channel Estimation and Equalization

As stated in the previous section, transmitted signals experience different channel effects such as attenuation, time dispersion, and phase shift prior to reception at the receiver. Time dispersion effect is alleviated through the application of OFDM and cyclic prefix while the amplitude and phase shift effect is mitigated by channel estimation and equalization. Estimate of the wireless channel amplitude and phase shift is extracted from the pilot signal information through channel estimation operation followed by the elimination of the wireless channel effect via equalization operation before symbol demodulation. Multiple user receiver houses the channel estimation and equalization module that distinctively operates for every user since each user possesses different fading and noise characteristics for the assigned radio channel. During transmission, the receiver uses the channel state information modulated on the transmitted pilot subcarriers to calculate the encountered distortion of the transmitted data subcarriers. Each user can be allotted multiple subchannels, and linear interpolation in frequency and time, based on a tile-to-tile for every subchannel, is utilized to estimate the channel frequency response. Once the whole estimates of the channel have be derived, the channel distortion is eliminated with a single-tap zero forcing equalizer through the division of the received signal with estimated frequency response of the channel. One single-tap equalizer is employed since the application of OFDM and cyclic prefix has gotten rid of the channel time dispersion. (Altera 2007: 3-6.)

4.3. Hybrid-ARQ

The application of Hybrid-ARQ enhances wireless link performance compared to the traditional ARQ though this improvement comes at the expense of more complex implementation. The implementation of an ARQ system with FEC at the physical layer produces an H-ARQ system. Two types of H-ARQ: type I H-ARQ and type II H-ARQ are supported in WiMAX standard. In type I H-ARQ also known as type I *chase combining*, the combination of ARQ and FEC involves the execution of an FEC encoding operation on blocks of data and CRC code prior to transmission, and the decoder at the receiver requests for retransmission if the received block cannot be successfully decoded. The receiver combines the coded block that was previously decoded with the received retransmitted coded block and the resulting output is fed into the FEC decoder input thereby increasing the probability of accurate decoding. In WiMAX, collections of supported FEC codes are combined with an N-channel *stop and wait* ARQ and this enhances throughput, since the operational channel can be utilized by another H-ARQ process for more data transmission during the acknowledgment waiting period of one H-ARQ process. The WiMAX signalling structure supports an asynchronous H-ARQ operation that accommodates flexible delay in retransmission intervals and enhances adaptable scheduling operations. The type II H-ARQ also known as *incremental redundancy* involves the distinctive coding of every (re)transmission in order to acquire more performance enhancement. This magnifies the retransmission reliability though the code rate decreases in every retransmission since each retransmission includes additional parity bits. (Andrews et al. 2007: 56.)

4.4. Improved Frequency Reuse

Frequency reuse enhances network capacity as well as spectral efficiency. WiMAX systems operated on a frequency reuse 1 could experience significant outage especially at the inter-sector and inter-cell edges due to interference. This significant outage is reduced in WiMAX through the application of coordinated sub-channel allocation to users located at the cell edges, thus providing dynamic frequency distribution over sectors depending on the interference level and loading situation, as against the conventional fixed frequency planning. Frequency reuse factor of 1 is known as the universal frequency reuse plan and the frequency reuse factor in which a user can successfully operate depends on the condition of their SINR. Users with good SINR status operates on frequency reuse of 1 with maximum channel bandwidth at their disposal while non-overlapping subchannels are assigned to users with poor SINR status to facilitate operation on frequency reuse of 2, 3, or 4, based on the number of distributed non-overlapping channels. This method of assigning sub-channel facilitates active fractional frequency reuse of value higher than 1. WiMAX supports wide range of sub-channelization schemes and this feature enhances operational flexibility though cell edge-users experience reduced peak rate due to inadequate access to full channel bandwidth. This flexibility in sub-channel reuse in Mobile WiMAX is exploited through sub-channel segmentation and permutation zone to enhance the cell edge-users access to full channel bandwidth. The sub-divided part of the allocated OFDMA sub-channels constitutes a segment and is utilized in a single MAC deployment, while a number of adjacent OFDMA symbols that utilize the same permutation either in DL or UL constitute a Permutation Zone. Figure 19

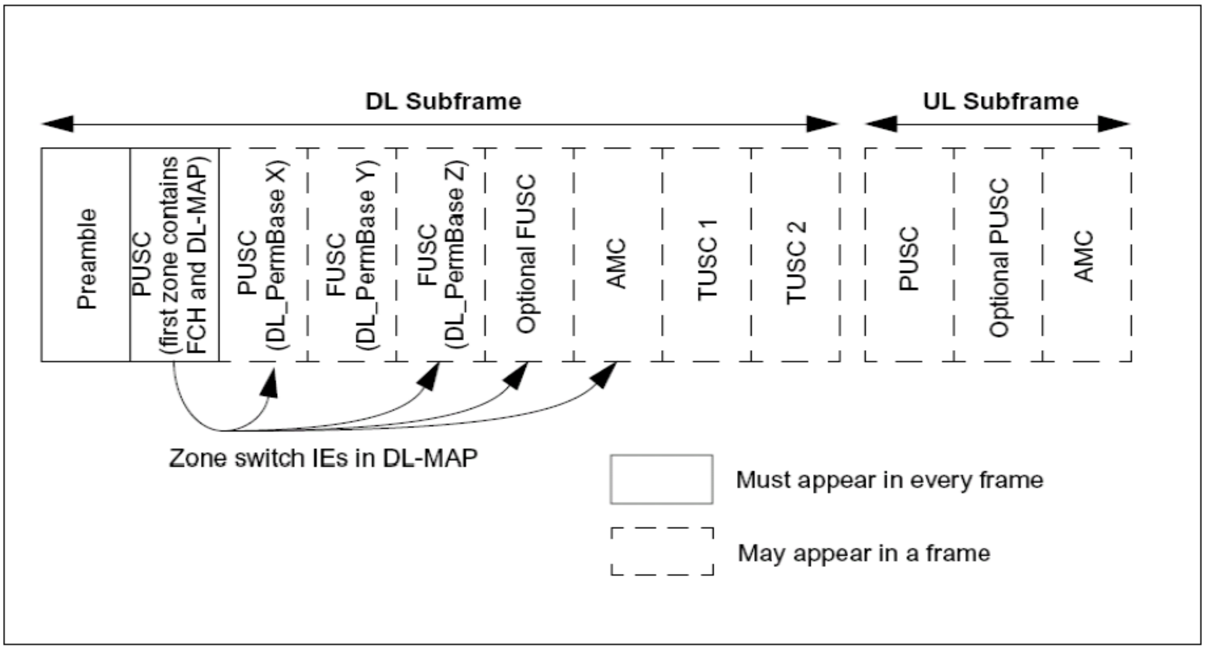

Figure 19. Multi-zone frame structure (WiMAX Forum 2006: 28).

shows a DL or UL sub-frame which can made up of one or more permutation zones. The configuration of the sub-channel reuse pattern is performed to aid the operation of all cells and sectors on the same frequency channel. (Andrews et al. 2007: 56; WiMAX Forum 2006: 27- 28.)

4.5. Scheduling Algorithm

The design and type of scheduling algorithm utilized in WiMAX network have a significant impact on the network performance. The effectiveness and efficiency of any scheduling algorithm is dependent on the design with respect to implementation structure, fairness, and supported different levels of service. Several scheduling algorithms are available in WiMAX network, out of which the following: Round-Robin (RR), Diffserv-Enabled (Diffserv), Strict-Priority (SP), Self-clocked-Fair (SCF), Weighted Round Robin (WRR) and Weighted-Fair Queuing (WFQ) are acknowledged to be the prevailing and paramount ones and are examined in this subsection. The RR algorithm implements equal proportion sharing of system resources irrespective of the channel quality. The same amount of resources is allocated to each queue without regards to inherent priority of the packets in the queue. One packet in each queue is serviced, starting from queue with the highest priority to the lowest priority queue until every queue that has packets in that particular round is attended to. As a result, different QoS specifications defined for every queue cannot be guaranteed. The Diffserv algorithm provides an evaluation structure for network traffic classification and management, though its performance in non-critical services and critical network traffic yields low latency. It employs traffic classification principles for packet classification and per-hop behaviour (PHB) indication through the engagement of the 6-bit Differentiated Services Code Point (DSCP) field located in IP packets header. In order to distinctively manage and prioritize every traffic class, each traffic is differentiated depending on the class and this task is executed by the configured network routers. Strict-Priority (SP) algorithm operation is established on weight order priority. The scheduler at the beginning evaluates the packets QoS classes, assembles the packets and thereafter assigns them into queue of different priorities. The prioritized queues are then serviced by the algorithm starting with the highest priority queue. The highest priority queue is serviced until is exhausted before servicing the next highest priority queue and this operation continues in that direction until the lowest priority queue is serviced. This algorithm may result in low network performance due to deprivation of bandwidth of QoS classes with low priority, and may not be satisfactorily employed in WiMAX network. In SCF algorithm, the order of servicing a packet is controlled by a virtual time that is internally generated as the packet servicing operation is in progress. The work progress in fluid-flow fair queuing (FFQ) is correlated with the virtual time by the SCF algorithm. The internal generation of the virtual time requires a negligible overhead and this algorithm approach proves efficient in broadband implementation and QoS satisfaction. WRR algorithm is an extended version of RR algorithm that implements a resource sharing scheme based on weights. At the start of operation, the packets are distinguished and distributed into various service classes, and are subsequently allocated queues based on computation of different bandwidth percentages. The RR operation is then applied to service each queue which marks the final end of the operation. The WRR algorithm implements a computer or network resource sharing structure that prevents bandwidth starvation for any service classes though it yields poor performance in operations that involve packets of variable sizes. WFQ algorithm is utilized in WiMAX for UL transmission of packets of various sizes. It accommodates the transfer of diverse size packets and the packets are allocated finish times to ensure different flows receive fair scheduling. The finish times are allocated depending on the packets weights and sizes, and this makes WFQ algorithm have better performance than the WRR algorithm. Each packet start time is neglected in the WFQ algorithm and this can reduce the capability of the scheduler system in a situation of several packets occurrence in the priority zone. (Arhaif 2011.)

4.6. Subcarrier Permutation

Subchannels are made up of subsets of data and pilot subcarriers. Sub-channelization is supported in WiMAX PHY for both DL and UL with a minimum frequency-time resource unit of one slot (48 data tones). The two types of subcarriers permutations employed in sub-channelization are diversity permutation and contiguous permutation. In diversity permutation, subcarriers are pseudo-randomly drawn to produce a subchannel. Its benefits include provision of frequency diversity and ICI averaging. The diversity permutations types consist of DL PUSC (Partially Used Subcarrier), UL PUSC, DL FUSC (Fully Used Subcarrier), and other optional permutations. In DL PUSC, clusters comprising 14 contiguous subcarriers per symbol period are created for every pair of OFDM symbols. Each cluster is assigned pilot and data subcarriers in both even and odd symbols as shown in Figure 20. Groups of clusters are created through the application of a re-arrangement mechanism in a way that ensures even distribution of each group clusters across the subcarrier space. Each subchannel in a group is made up of 2 clusters and comprises 8 pilot subcarriers and 48 data

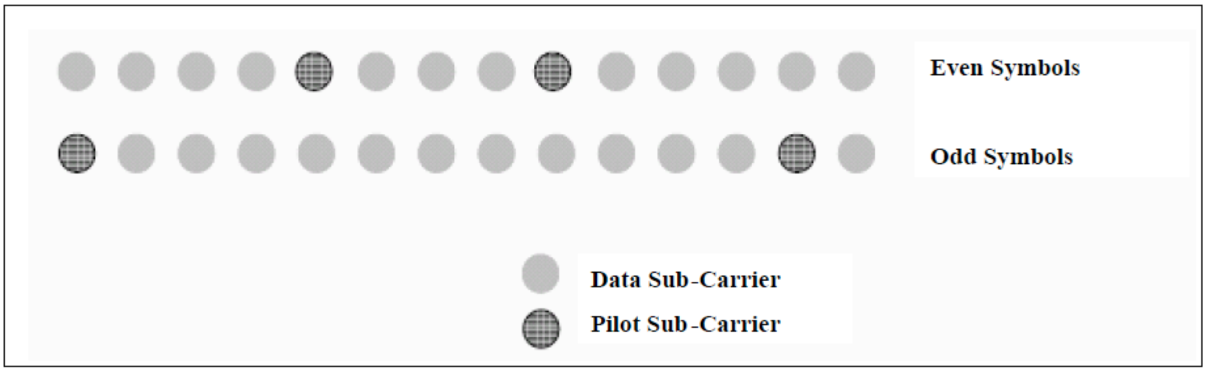

Figure 20. DL frequency diverse subchannel (WiMAX Forum 2006: 14).

subcarriers. Subchannels in the group are produced by additional permutation operation performed on the data subcarriers. A cluster structure for DL PUSC is analogous to a *tile* structure for UL PUSC as shown in Figure 21. *Tiles* are created by splitting a usable subcarrier space followed by a re-arranging/permutation scheme employed to select 6 *tiles*

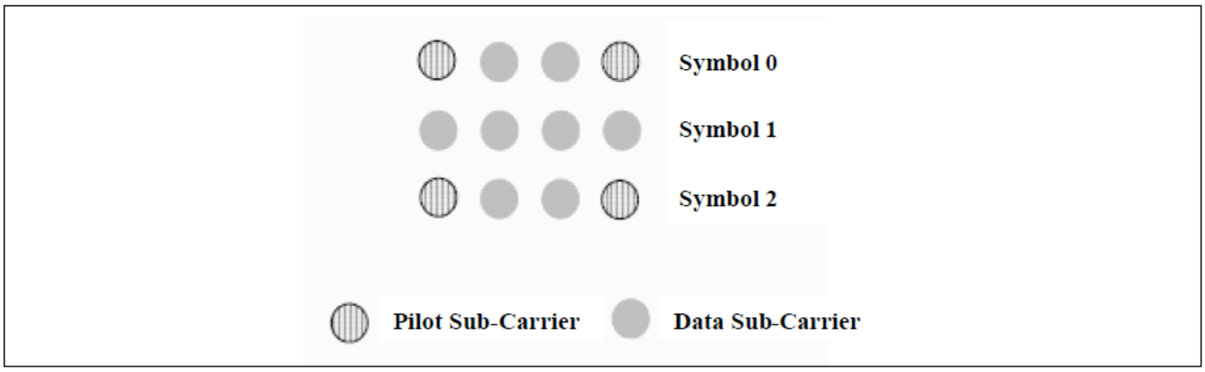

Figure 21. Tile structure for UL PUSC (WiMAX Forum 2006: 14.).

which are assembled to create a slot. A slot in 3 OFDM symbols is made up of 24 pilot subcarriers and 48 data subcarriers. In contiguous permutation, a subchannel is created by combining blocks of contiguous subcarriers. DL AMC and UL AMC constitute the families of contiguous permutation and both types share the same structure. A *bin* is made up of 9 contiguous subcarriers per symbol, 1 is allocated for pilot while the other 8 are allocated for data. A group of *bins* specified with type (N x M = 6) represents a slot in AMC, where the number of contiguous *bins* is denoted as N and the number of contiguous symbols designated as M. Multi-user diversity is facilitated in AMC permutation through the selection of the subchannel having the best frequency response. Basically, diversity subcarrier permutations have good performance in mobile operations while the performance of contiguous subcarrier permutations are suitable for fixed or portable applications. (WiMAX Forum 2006: 13-15.)

4.7. Multiple Antenna Techniques

Multiple antenna techniques are operations of complex vector or matrix performed on signals to enhance communication capacity and efficiency. Multiple antenna operations executed on vector-flat carriers are supported in WiMAX and the techniques prove a promising features that will be exploited in the next generation broadband communication systems. The supported multiple antenna techniques are:

- **Space-Time Coding (STC):** Alamounti code is a transmit diversity scheme that finds its use in STC employed to support spatial diversity and also minimise fade margin. WiMAX defines STC for one or more antennas at both transmitter and receiver .
- **Beamforming:** Beamforming involves the transmission of weighted signals through the application of multiple antennas. This technique improves the SNR by concentrating the transmitted beam in the receiver direction, thereby eliminating interference. Beamforming is utilized to mitigate outage probability as well as enhance coverage and system capacity.
- **Spatial multiplexing (SM):** Higher throughput and improved peak rates are exploited through spatial multiplexing. SM is a transmission technique in which multiple antennas are utilized to transmit multiple streams of a signal. Multiple antennas are employed at the receiver as well to separate the streams. Multiple antenna systems have better performance (for example higher throughput) than single antenna systems. The peak data rate of a 2x2 MIMO is increased through the transmission of two data streams.

Adaptive switching is supported in WiMAX and is utilized to yield optimal multiple antenna techniques performance under various channel conditions. The supported multiple antenna techniques architecture is shown in Figure 22. The performances of some of the techniques are affected by channel conditions. For example, SM enhances peak throughput though poor channel conditions could increase the Packet Error Rate (PER) and may limit the affected coverage area. STC coverage performance is not dependent on channel condition though it has no effect on the peak data rate. (Andrews et al. 2007: 56; WiMAX Forum 2006: 25-26)

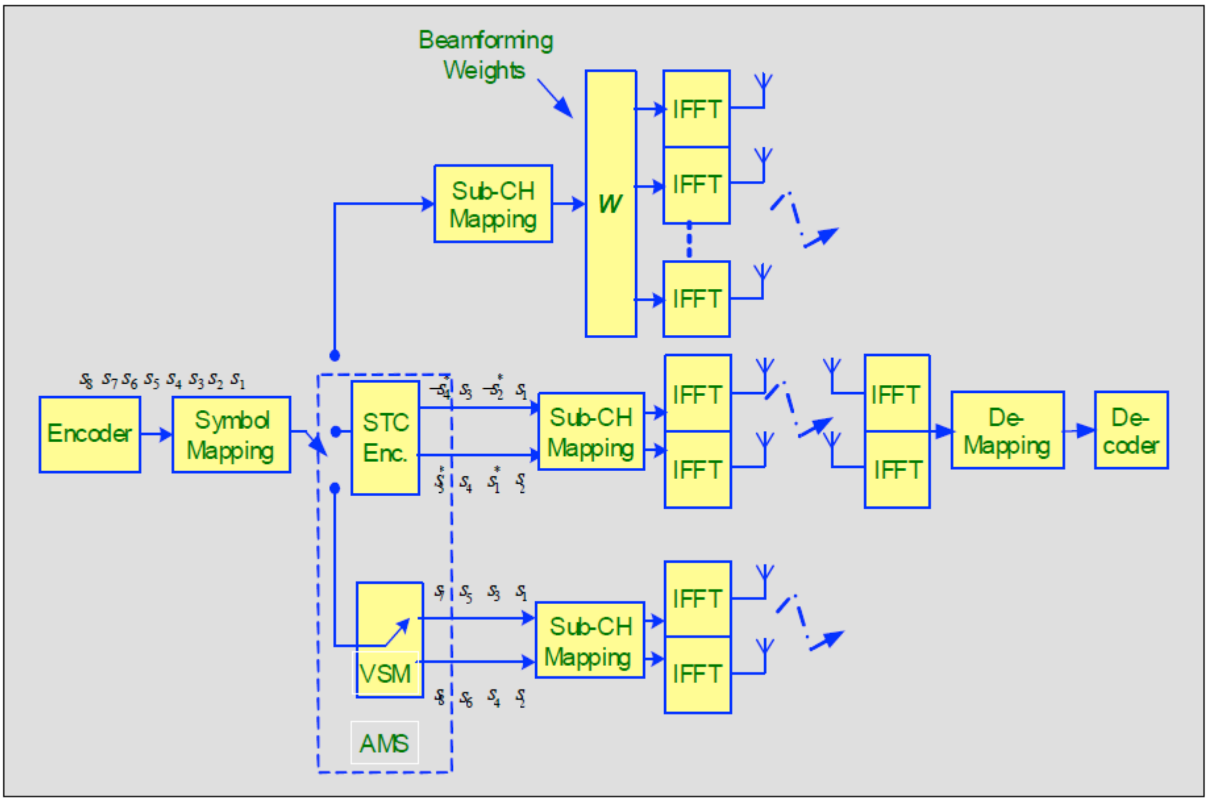

Figure 22. Adaptive Switching for smart antennas (WiMAX Forum 2006: 27).

5. TEST BED DEPLOYMENT AND TESTING

IEEE 802.16d compliant equipment were deployed for the field experiment. These equipment operate in the 3.5 GHz licensed band with channel bandwidth of 3.5 MHz. This section presents the description of the test equipment, network testing tools employed, installation and commissioning of the utilized Micro Base Station Equipment (MBSE) and Customer Premise Equipment (CPE).

5.1. Test Equipment

There are diverse brands of WiMAX equipment with different operating frequencies. The equipment employed for this field experiment is the Alvarion BreezMAX 3000. BreezeMAX 3000 takes advantage of the proven field experience, industrial leadership, core technologies, and BWA market-leading knowledge of Alvarion and supports variety of broadband access services to customers. Hundreds of subscriber units (SUs) per channel with different QoS is supported in the system's access and bandwidth assignment structures. The system employs and exhibits all the operating characteristics of OFDM radio technology including NLOS links and AMC per burst operations. Diverse range of network services such as internet access (via IP or PPPoE tunneling), Voice over IP, and VPNs are offered by BreezeMAX products and are currently available in the frequency bands: 3.3 GHz, 3.5 GHz and 3.8 GHz. A BreezeMAX system consists of Base Station Equipment (BSE), CPE, Network Equipment (NE) and management systems. NE (Standard switches/router) and management systems (billing and operation support systems) were not used in this field experiment. Furthermore, the BSE could either be a stand-alone MBSE or a modular BSE with large coverage capacity of up to six sectors and are installed at the network sites while the CPE are installed at the customers' sites. (BreezeMAX 2008: 2-3.)

5.2. Test Features

This section examines some of the primary features of BreezeMAX systems that define the modes of subscribers connectivity as well as the service types offered. Prior to testing, the network connectivity mode and the service type were selected and configured on the MBS.

5.2.1. Service Modes

The two modes of service provisioning in the BreezeMAX MBS are the *Advanced* mode and *Quick* mode. The SU has two Status: *Temporary* and *Permanent* that must be set to the corresponding MBS mode. The *Advanced* mode provides a structure in which SUs that are not defined in the operator system are completely denied services. This mode enhances the system's security though it makes the SU installation process slightly difficult since SU cannot be registered and receive any service if it is not defined in the system. In the *Advanced* mode, the SU status must be set to *Permanent* operation mode in order to receive required services from the BS. The *Quick* mode enables the provision of basic services to SUs that have not been defined in the system and are added to the MBS database as temporary. This mode does not enhance security of the system and is mainly utilized for temporary setup such as field experiment. In the *Quick* mode, the SUs are only allowed services based on the Default Service Profile(s). The corresponding SU status must be set to *Temporary* to receive MBS services. Whenever the SU status is changed, the SU must be reset since a new network entry process must be performed in order to receive correct default services. (BreezeMAX 2008: 133-134.)

5.2.2. Service Types

Both data and voice services are supported in BreezeMAX 3000. The supported service types are Layer 2 (L2), Point-to-Point Protocol over Ethernet (PPPoE), and Voice. L2 service conveys Layer 2 (Ethernet) frames from one subscriber's site to the other and also to network resource connected to the backbone of the provider. PPPoE allows connection between PPPoE enabled devices. PPPoE Access service connects a PPPoE aware Access Concentrator located behind the MBS and the subscribers' sites PPPoE enabled devices. The Voice service is responsible for the provision of telephony services over external Voice Gateway connected to the data port of the SU. L2 service among other services was utilized in this field experiment. (BreezeMAX 2008: 131.)

5.3. Micro Base Station Equipment Installation

The MBSE comprises an Access Unit Indoor Unit (AU-IDU) also called the MBS, Access Unit Outdoor Unit (AU-ODU) and a sector antenna. The equipment were unpacked followed by verification of system configuration. The AU-IDU was installed on a movable rack while the AU-ODU and the sector antenna were mounted on a tripod. The AU-IDU was connected to the AU-ODU through an Intermediate Frequency (IF) cable and the connection between the AU-ODU and the antenna was made through a Radio Frequency (RF) cable. After the installation, the MBSE was powered with a -48v power source connected to the AU-IDU. The AU-IDU consists of a monitor port and two RJ45 ports (management port and data port). The AU-IDU is configured through the monitor port and the management port while data port is used for communication and was connected to the PC Network Interface Card through a crossed 10/100 Base-T Ethernet cable.

5.4. Customer Premise Equipment Installation

The CPE consists of SU-ODU and SU-IDU. The SU-ODU has an integral antenna which yields either vertical or horizontal polarization based on the mounting positioning (BreezeMAX 2006: 30). The SU-ODU was mounted on a tripod to yield vertical polarization as shown in Figure 23. For field measurement purpose, the SU-IDU was specially clipped towards the bottom end of the tripod. The SU-IDU comprises the SU Alignment Unit (SAU) connector and two RJ45 ports (RF port and Ethernet port). The SAU is attached to the connector to provide the SU-ODU status indications and is significantly useful during installation. The SAU is made up of link quality bar display that indicates the wireless link status and the quality of the received signal. The SU-IDU was connected to the SU-ODU through a Category 5E Ethernet 4x2x24# FTP outdoor cable and was also connected directly to a PC NIC via a straight 10/100 Base-T Ethernet cable. The CPE was power with an AC mains. Basically, CPEs are installed either at permanent sites or test sites depending on the installation purpose. The test site installation process was carried out in this field experiment.

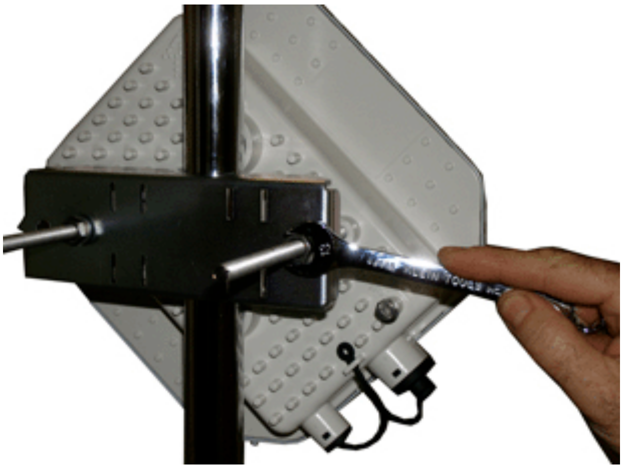

Figure 23. Vertical polarization SU-ODU installation (BreezeMAX 2006: 32).

5.5. Commissioning of the MBSE and CPE

The MBSE and CPE were subsequently commissioned via the monitor port of MBS (using Telnet program) and the Ethernet port of SU-IDU after successful installation to establish connectivity and provisioning of services. During the commissioning process, the basic parameters of both MBSE and CPE were configured to set up wireless communication link, and also to enable the correct operation of the units. Afterwards, the quality of the wireless link of the CPE was measured with SAU, during which the SU-ODU was panned to obtain an optimal link quality between the SU and MBS. Table 11 shows the respective range of values of SNR and RSSI that indicate the link quality. After proper verification of the link operation, static IP addresses were allocated to the MBS data port, SU Ethernet port as well as both PCs behind the equipment for data communication. Furthermore, the SU was pinged from the MBS end and there was reply which confirmed successful transmission and reception of data packets. The performance monitoring windows of both MBS and SU were examined to confirm the optimal performance of the wireless link, data port, and Ethernet port.

Table 11. SAU link quality bar LEDs functionality (BreezeMAX 2006: 57).

Bar LEDs	SNR
LED 1 (WLNK-orange) is On	The SU is connected with and receives services from AU/ MBS (Network Entry completed)
LED 2 (green) is On	5dB ≤ SNR < 10dB
LEDs 2-3 (green) are On	10dB ≤ SNR < 15dB
LEDs 2-4 (green) are On	15dB ≤ SNR < 20dB
LEDs 2-5 (green) are On	20dB ≤ SNR < 24dB
LEDs 2-6 (green) are On	SNR ≥ 24dB and RSSI < -75dBm
LEDs 2-7 (green) are On	SNR ≥ 24dB and RSSI ≥ -75dBm
LEDs 2-8 (green) are On	SNR ≥ 24dB and RSSI ≥ -70dBm
LEDs 2-9 (green) are On	SNR ≥ 24dB and RSSI ≥ -60dBm
LEDs 2-9 (green) and 10 (red) are On	RSSI ≥ -20dBm (saturation)

5.6. Network Testing Tools

There are several network testing tools designed for various network parameters measurements. Iperf (Iperf 2011), Jperf (Jperf 2011) and Qcheck (2011) were utilized in this field experiment to measure the WiMAX network performance parameters. The operation involves the creation of TCP and UDP data streams which are sent over the network. The network throughput, transmitted data time, jitter, and packet loss during transmission are evaluated and displayed on the Iperf window at both client and server. Iperf is capable of performing both unidirectional and bi-directional measurements and employs specifications of 1024*1024 for megabytes and 1000*1000 for megabits. Iperf commands are used to specify client/server status as well as TCP and UDP. Graphical representation of the measured parameters were provided with Jperf in association with Iperf. (Sehgal & Schönwälder 2010.)

5.7. Network Parameters Tests

The network performance parameters that were evaluated in this field experiment are throughput, latency, jitter, and packet loss. Furthermore, the effect of a strong interference source was also evaluated by examining the behaviour of the network parameters when the SU and a Wi-Fi modem were place at the same location.

5.8. Measurement Methodology

In order to analyze the WiMAX link performance, Iperf was used to generate and transmit TCP and UDP data traffic over the WiMAX network for both DL and UL, which also displays the network bandwidth, jitter, and packet (datagram) loss at the end of the transmission. Separate measurements were made for DL and UL as well. WiMAX has eight modulation schemes which are automatically adapted (AMC) by the MBS depending on the SU channel state information feedback. The multirate support in the AU responsible for the adaptive operation was *enabled* to ensure the utilization of the best AMC for any channel condition. The network link quality was grouped into three scenarios in which the link capacity was examined for both DL and UL. Scenarios 1, 2, and 3 represent *sufficient, good,*

Table 12. Classification of link SNR into Scenarios.

SNR	Scenario
The SU is connected with and receives services from AU/ μBST (Network Entry completed)	Not Applicable
5dB ≤ SNR < 10dB	1
10dB ≤ SNR < 15dB	
15dB ≤ SNR < 20dB	2
20dB ≤ SNR < 24dB	
SNR ≥ 24dB and RSSI < -75dBm	
SNR ≥ 24dB and RSSI ≥ -75dBm	3
SNR ≥ 24dB and RSSI ≥ -70dBm	
SNR ≥ 24dB and RSSI ≥ -60dBm	
RSSI ≥ -20dBm (saturation)	Saturation was avoided in compliance to system specifications

and *excellent* link qualities respectively as shown in Table 12. Depending on the sector antenna height, the MBS can cover a distance up to 20km radius in ideal situation though the coverage range is limited by obstacles such as tall buildings and trees. The link quality of SUs at different distances from the MBS in the coverage range are characterized by the link SNR values such that SUs located at close range to the MBS enjoy better (*excellent*) coverage than those located towards the cell edge with *sufficient* coverage. The MBS minimum transmit power (13dBm) was used virtually in all the measurements except when the effect of the transmit power on the performance was examined, while other link enhancing control parameters were set to their corresponding values to ensure the link under test was stressed. The QoS was set to BE since data traffic such as data transfer was employed in this field experiment. Furthermore, each measurement was repeated when a transmitting Wi-Fi modem was placed in the subscriber's location to ascertain interference effect on the link behaviour. Figures 24 and 25 show the test bed set up layout coupled with MBSE and CPE equipment installation at the University of Vaasa campus during field measurements. The gross capacity of each modulation scheme and radio specifications of the Alvarion test equipment utilized in this field measurements are shown in Tables 12 and 13.

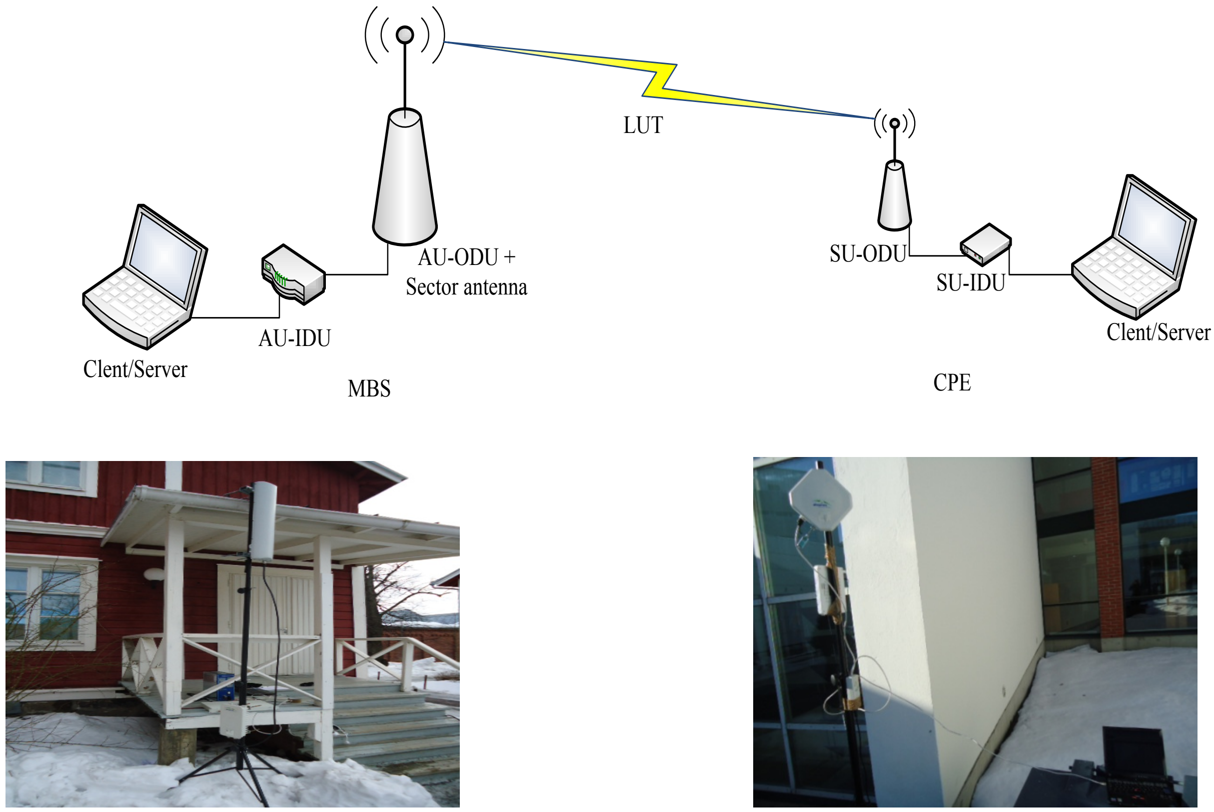

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Figure 24. Test bed setup layout with MBSE and CPE at test site (University of Vaasa).

Figure 25. CPE and a Wi-Fi modem.

Table 13. Test equipment gross capacity (BreezeMAX 2008: 13).

Modulation and Coding	Gross Capacity (Mbps)
BPSK 1/2	1.41
BPSK 3/4	2.12
QPSK 1/2	2.82
QPSK 3/4	4.23
QAM16 1/2	5.64
QAM16 3/4	8.47
QAM 64 2/3	11.29
QAM 64 3/4	12.71

Table 14. BreezeMAX 3000 equipment specification (BreezeMAX 2006: 5; BreezeMAX 2008: 12&14).

Item	Description		
Frequency	Unit/Band	Uplink (MHz)	Downlink (MHz)
	AU-ODU	3399.5-3453.5	3499.5-3553.5
	SU-ODU	3399.5- 500	3499.5-3600
Operation Mode	FDD, Full duplex		
Channel Bandwidth	3.5 MHz		
Central Frequency Resolution	0.125 MHz		
Antenna Port (AU-ODU)	N-Type, 50 Ohm		
BS ANT 60V/3.3-3.8	16.5 dBi minimum in the 3.3-3.8 GHz band, 60° AZ x 7° EL, vertical polarization, compliant with ETSI EN 302 326-3 V1.2.1 (2007-01)		
Max. Input Power (at AU-ODU antenna port)	-50 dBm before saturation, -17 dBm before damage		
Output Power (at AU-ODU antenna port)	AU-ODU: 13 to 28 dBm +/-1 dBm (excluding 3.6 GHz ODUs) 3.6 GHz AU-ODU: 18 to 28 dBm +/-1 dBm AU-ODU-HP: 24 to 34 dBm +/-1 dBm		
SU-ODU Integral Antenna (SA model)	17 dBi typical (16.5 dBi in the 3.3-3.4 GHz band), 20^0 AZ x 20^0 EL, vertical/horizontal polarization, compliant with EN 302 085, V1.2.2 (2003-08) Range 1		
Max. Input Power (at SU-ODU antenna port)	-20 dBm before saturation 0 dBm before damage		
Output Power (at SU-ODU antenna port)	20 dBm +/-1 dB maximum, ATPC Dynamic range: 46 dB		
Modulation	OFDM modulation, 256 FFT points; BPSK, QPSK, QAM16, QAM64		
FEC	Convolutional Coding: 1/2, 2/3, 3/4		

6. RESULTS AND ANALYSIS

This chapter presents the results obtained from the extensive field measurements of the WiMAX network link performance and the corresponding analysis. Trends and variations observed during the link performance measurements are explained together with the results. As explained in the measurement methodology subsection of chapter 5, the range of the available WiMAX network link SNRs and RSSIs which reflect the link qualities were group into three scenarios and examined for both DL and UL. *Sufficient, good,* and *excellent* link qualities are represented as scenarios 1, 2, and 3 respectively as depicted in Table 12. The following sub-sections explain details of the network parameters tests covered in this field measurements in evaluating the performance of the WiMAX link network.

6.1. Throughput Tests

The network throughput was measured in the three scenarios through the transmission of TCP and UDP. The duration of each test was exactly thirty (30) seconds and was conducted several times for both DL and UL. From several measurements, it was observed that the UDP throughput is more stable than TCP throughput in both DL and UL for all the eight modulation schemes as shown in Figures 26 and 27. TCP transmission has transmitted packet delivery checks with acknowledgement mechanism and is more reliable than UDP transmission. UDP transmission lacks mechanism of verifying correct reception of the transmitted packets, and thus transmits packets without any form of acknowledgement.

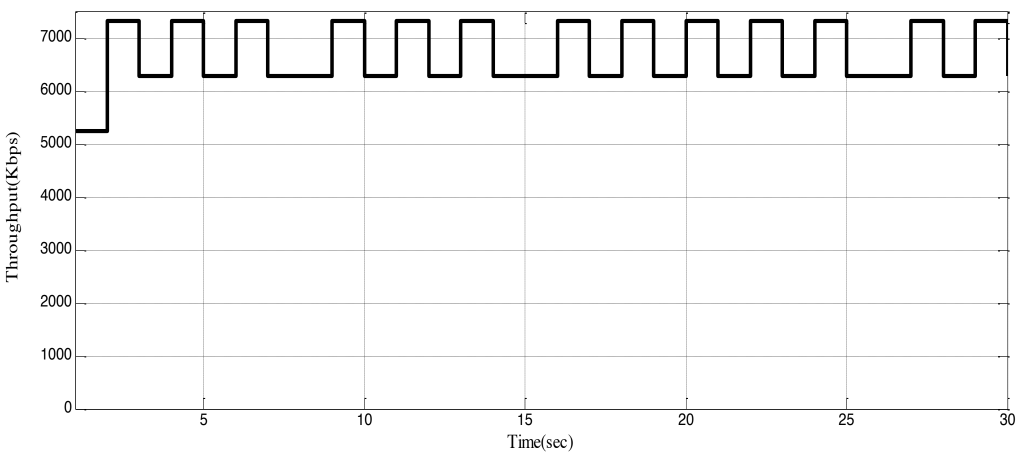

Figure 26. TCP Transmission stability.

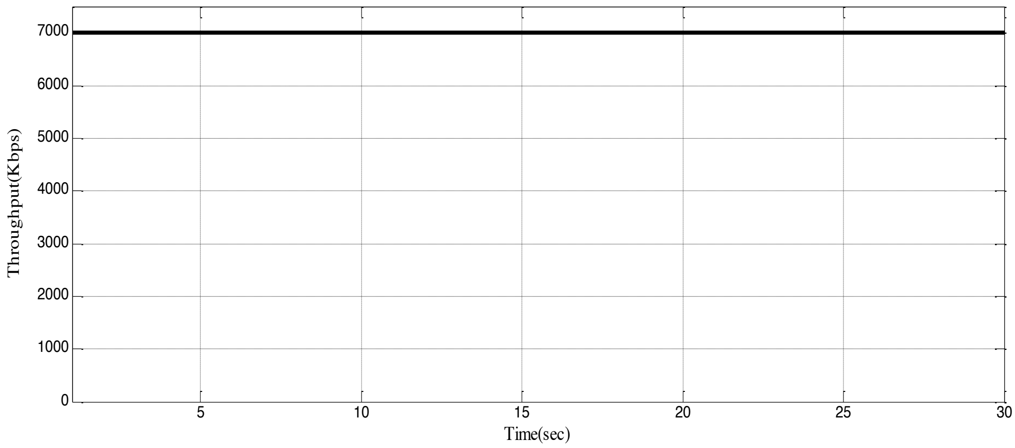

Figure 27. UDP Transmission stability.

It was also observed that TCP throughput has more stability in the UL than in the DL which supports the fact that the MBS receiver has more degree of signal processing capabilities than the SU receiver. When the network throughput in the three scenarios were measured, the results obtained betray the impact of link quality on throughput. It was observed that the network throughput increases as the link SNR increases from scenario 1 to scenario 2 and then finally to scenario 3 as shown in Figures 28, 29 and 30. The cumulative distribution function (CDF) for scenario 2 throughput is shown in Figure 31.

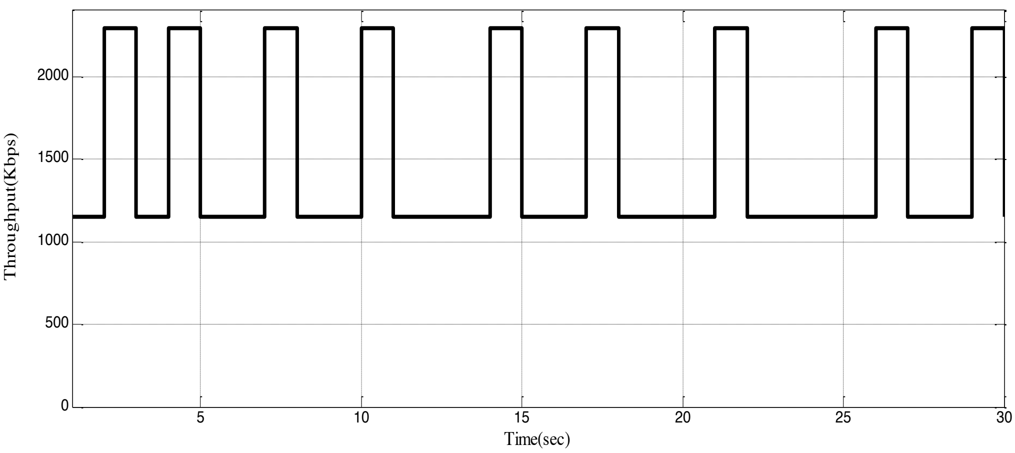

Figure 28. Scenario 1 DL throughput.

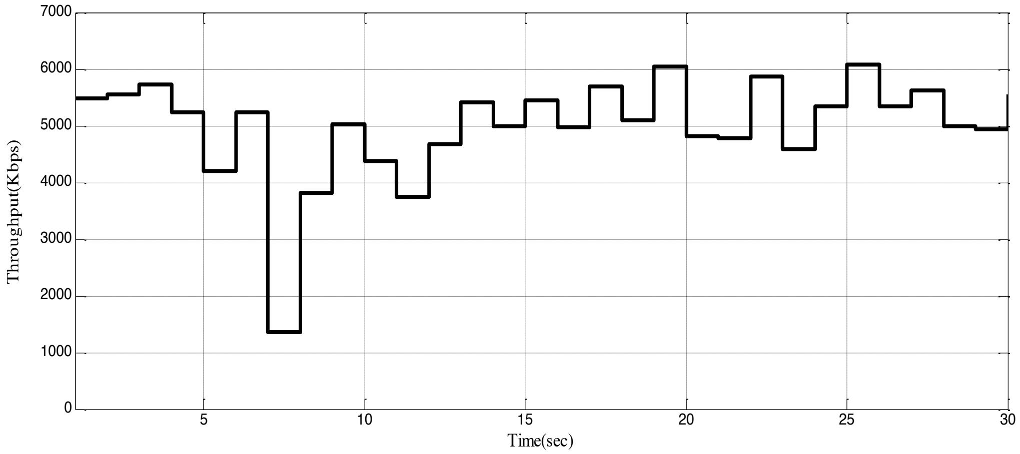

Figure 29. Scenario 2 DL throughput.

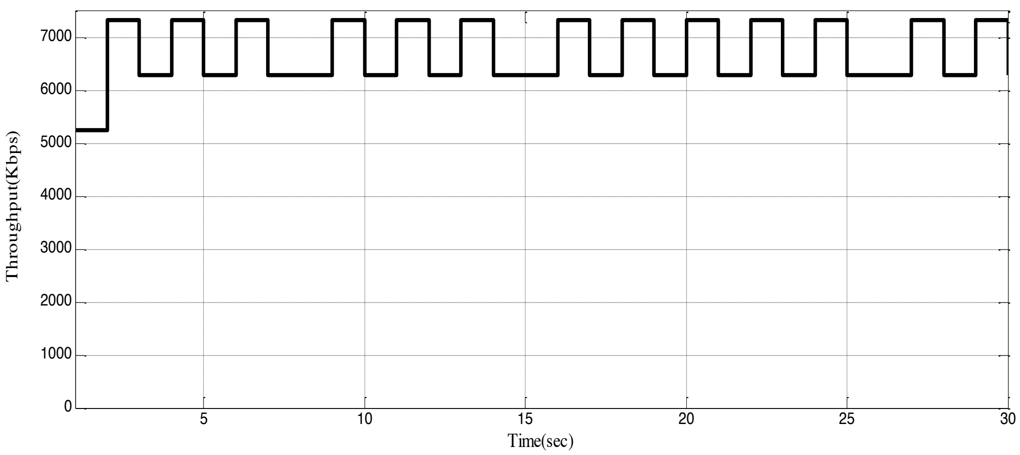

Figure 30. Scenario 3 DL throughput.

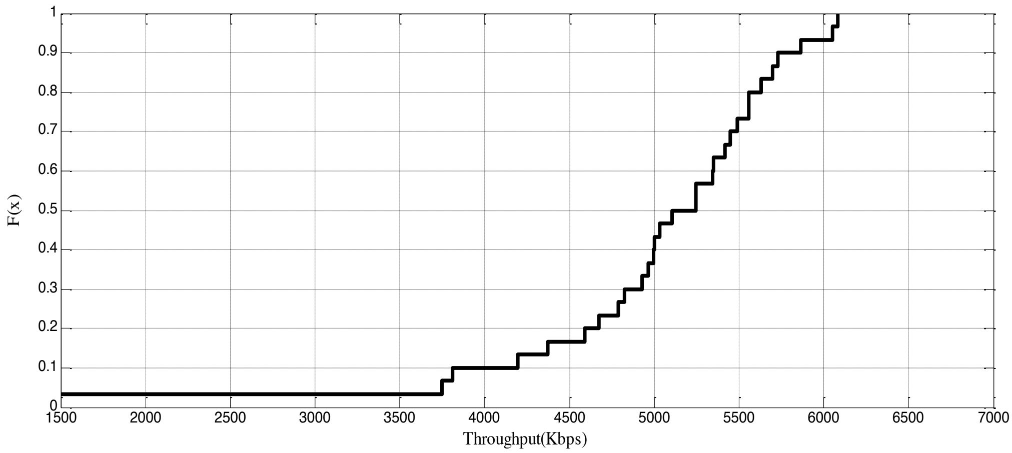

Figure 31. CDF for Scenario 2 DL throughput.

The effects of transmit power as well as the link layer ARQ on throughput was also examined. QAM64 ¾ modulation scheme was utilized for this evaluation. At first, the ARQ feature was *disabled* while the transmit power was increased from 13dBm to 25dBm to initially observe the transmit power effect and was thereafter *enabled*. The results obtained show that increasing the transmission power strengthens the link quality and improves throughput fluctuations while the ARQ feature stabilizes throughput which is in line with results obtained by (Yousaf et al 2007). It was also observed that the transmit power and link layer ARQ impact was not noticed in scenario 3 and this could be due to the fact that the link quality was in *excellent* state near saturation. The ARQ feature enables error detection and retransmission requests during link operation and is significantly utilized especially in the higher modulation schemes that are prone to errors due to relative short distances between the symbols. The transmit power and ARQ feature effects on DL TCP throughput performance for scenario 2 are shown in Figures 32, 33 and 34.

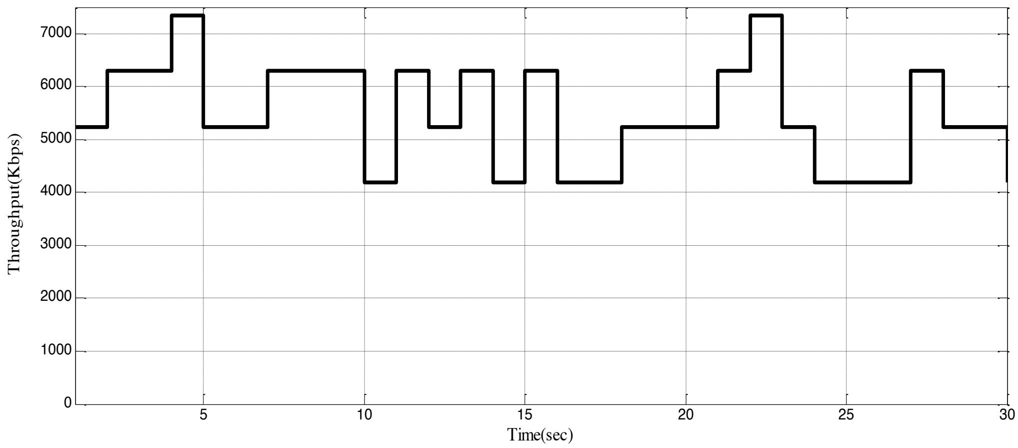

Figure 32. Scenario 2 QAM64 ¾ throughput.

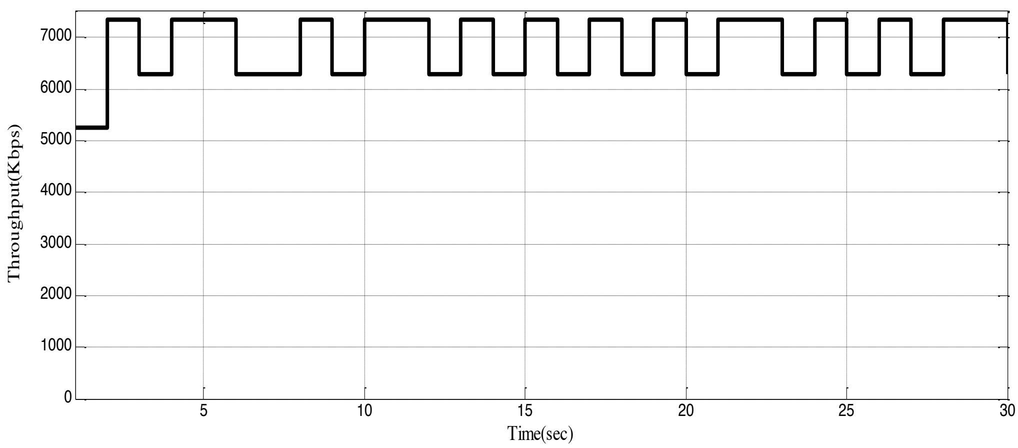

Figure 33. Scenario 2 QAM64 ¾ throughput at 25dBm.

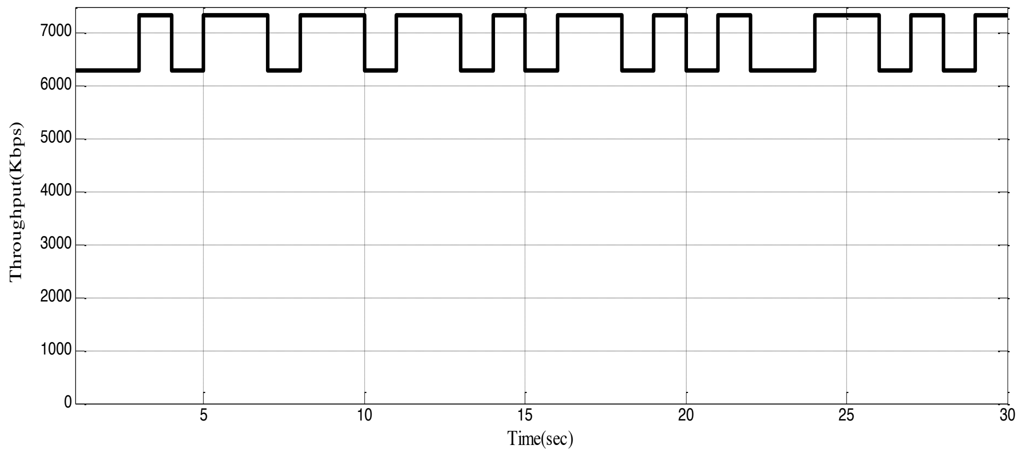

Figure 34. Scenario 2 QAM64 ¾ throughput at 25dBm with ARQ.

6.2. Latency Tests

The WiMAX network latency was examined with both ping test and Qcheck network test tools. During the field measurement, ping and Qcheck tests were simultaneously run to determine the round trip time values for each of the three scenarios. Table 15 shows the results of the average, standard deviation, minimum, and maximum latency values obtained for each scenario while the CDF of the measured values for scenario 3 is shown in Figure 35. It can be seen that latency decreases as the network link SNR increases. The link SNR is limited by network traffic loads and distance between SUs and the serving MBS. The increase of WiMAX network latency with distance could be due to signal propagation delay. Data streams undergo multipath fading when transmitted over wireless channels. As the transmission distance increases, the signals undergo additional multipath fading and thus yields additional delay in the network. Factors that may account for latency increase with network traffic loads are network processing delay, queuing delay, utilized scheduling algorithm, wired portion of the equipment etc. Without traffic prioritization, increase in network traffic loads increases latency since resource allocation of serviced SUs becomes smaller each time additional traffic load (e.g SU) is added to the network. Traffic prioritization salvages this challenge by defining different traffic class as well as allocating QoS profiles to each class as given in Table 9.

Table 15. Latency of WiMAX network link.

Scenario	Latency (ms)			
	Average	Standard Deviation	Minimum	Maximum
1	56.44	5.69	50	87
2	43.07	4.31	38	61
3	31.15	2.18	29	40

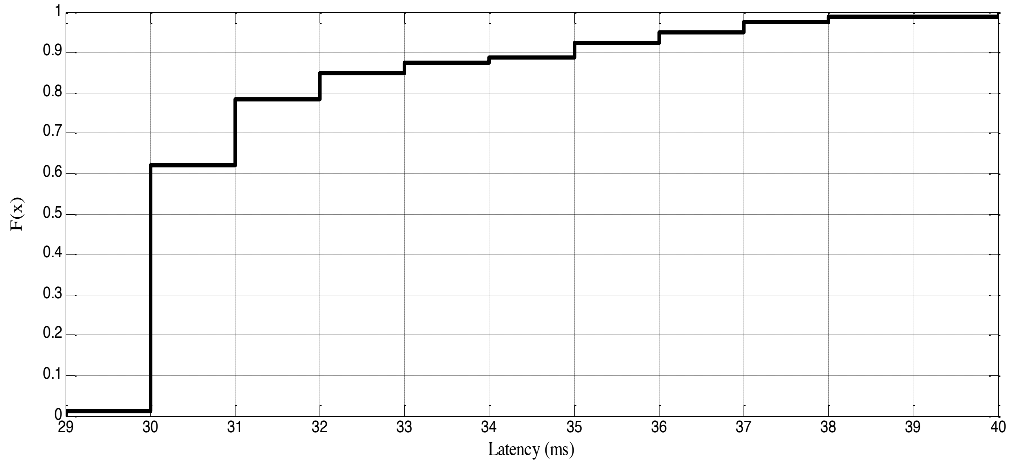

Figure 35. CDF of scenario 3 latency values.

6.3. Jitter Tests

The WiMAX network jitter was investigated in the three scenarios by sending UDP packet streams over the WiMAX link. Figures 36 shows network jitter performance for the three scenarios. A careful examination of the results obtained reveals that jitter increases as the link

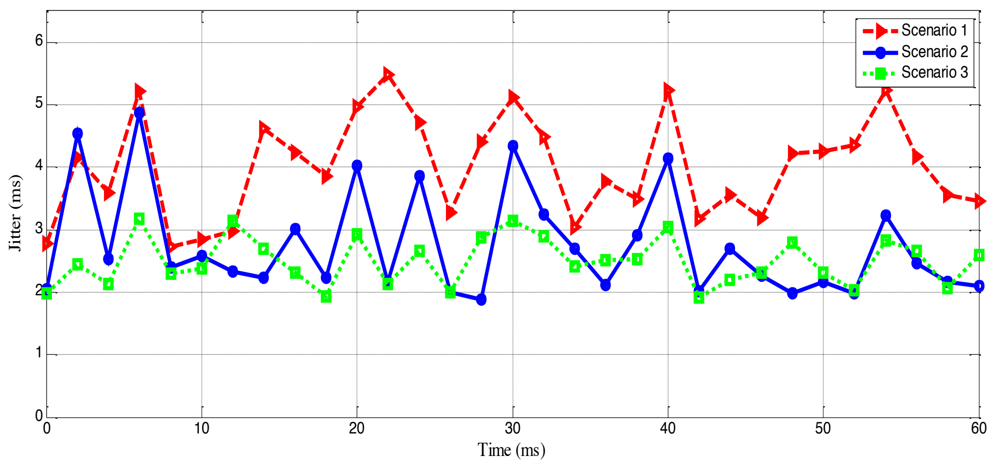

Figure 36. WiMAX link jitter.

SNR decreases. The increase of jitter with network load could be due to network processing delay as a result of queues and congestions in the network, while its significant increase with distance could be accounted for by fading effects due to obstacles created by trees and buildings.

6.4. Packet Loss Tests

Packet loss was examined for the three scenarios by transmitting UDP data streams through the WiMAX link using Iperf. There was significant packet loss for the least SNR value in scenario 1 and negligible packet loss in scenario 2 while there was no packet loss in scenario 3, though the measured values were inconsistent. Basically, faulty links as well as routers and switches congestions in any network may cause packet loss. In this field experiment, routers and switches were not utilized and the reliability of packet delivery was solely dependent on the WiMAX link.

6.5. Effect of interference on Throughput and Latency Tests

In addition to the previous measurements, a further step was taken to examine the effect of strong interference on network throughput and latency. A Wi-Fi modem was mounted few centimetres from the SU-ODU in order to ensure a significant interference impact on the directional integral antenna of the SU-ODU. At 13dBm, the interference impact of scenario 3 was not pronounced due to the robust nature of the link quality. However, the effect of the interference became evident in scenarios 1 and 2. As seen from Figures 37 and 38 for scenario 2, the Wi-Fi interference affects the link stability as well and latency through its effect on the SNR. To examine the effect of the MBS transmit power on interference, the transmit power was increase from 13dBm to 25dBm. The results obtained show an improvement on the link stability which supports previous observation on the impact of increasing transmit power on the wireless link quality.

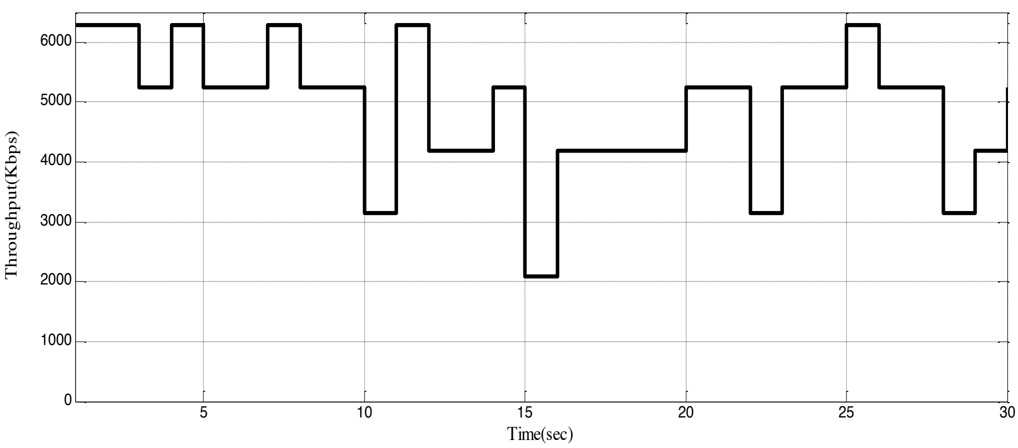

Figure 37. Scenario 2 throughput with interference.

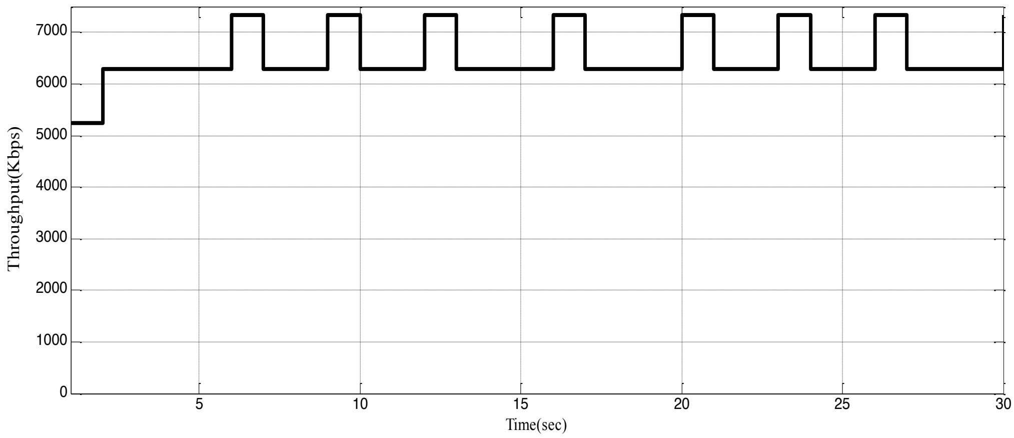

Figure 38. Scenario 2 throughput with interference at 25dBm.

7. CONCLUSIONS

Telecommunication field plays a fundamental role in the world and fits in all facets of life. There is and will always be a need to reliably transfer information from one location to another for various purposes. Statistics show global increasing growth rate of telecommunication services users as well as demand for faster internet access, high speed file download and different multimedia, and this necessitates the need for a wireless broadband technologies designed to bring a last mile solution. WiMAX based on IEEE 802.16 standards and offering interoperability solutions has proved to be one of the technologies designed to meet these needs. WiMAX protocol architecture comprises PHY layer and MAC layer with end-to-end network architecture for fixed and mobile applications. The successful transmission and reception of information bits through a physical medium is handled by the WiMAX PHY layer based on OFDM technique, and comprises functional components at the transmitter and receiver.

The link performance of WiMAX for wireless automation applications was investigated in this thesis through the use of Alvarion BreeZeMAX 3000 fixed WiMAX equipment operating in the 3.5 GHz licensed band with channel bandwidth of 3.5 MHz. The primary objective was to analyze the WiMAX network performance for suitability in wireless automation applications. Broadband wireless network performance parameters such as throughput, latency, jitter, and packet loss were investigated along with the impact of a strong interference source (Wi-Fi) on the network performance. Prior to field measurements and analysis, components and functionalities of the WiMAX PHY and MAC layers were presented to facilitate detailed understanding of the theoretical background. The successive operations and the functional stages of each block of PHY layer, undergone by transmitted data before finally transmitted through radio frequency channel were discussed. The operations involve data randomization, channel encoding (RS-CC coding, puncturing and interleaving), modulation mapping, IFFT and CP insertion. Various functions such as mapping, scheduling, management, transmission and access definition of the MAC layer were also presented. Furthermore, WiMAX performance features as well as their properties were equally examined to ensure comprehension of the operational performance capabilities of these features.

Before the experimental field measurements were made, the test equipment consisting of a MBSE and CPE were installed and commissioned to establish connectivity and provisioning of services. Various tests were carried out on the WiMAX network at the University of Vaasa campus in three different link quality scenarios: *sufficient, good,* and *excellent* using Iperf, Jperf and Qcheck network testing tools. Measurements of each network performance parameter for each of the three scenarios were performed for DL, UL and Wi-Fi interference effect. Results obtained as well as tests observations were discussed and analyzed to give details of the network performance.

From the results obtained, the average value of the fixed WiMAX network throughput increases from 1.49 to 5.00 and finally 6.71 Mbps while the average latency value decreases from 56.44 to 43.07 and finally to 31.15 ms for *sufficient, good,* and *excellent* link quality scenarios.

Given the project limitations of the fixed WiMAX field measurements and the results obtained, the network performance can be considered to satisfy wireless broadband network conditions and will be significantly useful in wireless automation applications that operate within the range of the operational WiMAX parameter values.

For future work, more field measurements should be investigated with additional SUs and also with rtPS such as streaming audio or video. Research work can be focused on the performance features such as:

- The use of optional Turbo codes in AMC for higher data rate.
- Scheduling algorithms for efficient network operation and resource allocation.
- Space-Time Coding for spatial diversity.
- Spatial multiplexing for higher throughput and improved peak rates.

Success made so far in these research fields especially in the area of higher throughput and improved peak rates are implemented in the current IEEE 802.16m standard also known as WiMAX 2 to support speeds up to 1Gbps for fixed operations and 100 Mbps for mobile operations.

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