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A Quantitative Performance Analysis of 2.5 GHz and 3.65 GHz Mobile WiMAX

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A QUANTITATIVE PERFORMANCE ANALYSIS OF 2.5 GHZ AND 3.65 GHZ MOBILE WIMAX

by

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Mobile WiMAX has emerged as a prime contender for the de-facto ITU's 4G standard. It provides high data rate with large coverage and vehicular mobility support. It has been, and is being, widely deployed in diverse applications like video streaming, broadcasting and data service. The FCC (Federal Communications Commission) issues licenses to operate Mobile WiMAX services in several spectrums, among which 2.5 GHz and 3.65 GHz are the most common. Because the 2.5 GHz spectrum suffers the least propagation losses, it has been widely applied commercially. For this reason, academic and industrial researchers have given it particular attention. However, in some cases, the 3.65 GHz is often a better choice, in spite of having a lower coverage, particularly due to its favorable licensing requirements. Due to limited amount of work published in the 3.65 GHz spectrum, the concerned parties do not have sufficient data to reliably select the spectrum.

In this research work, a thorough quantitative analysis of the two Mobile WiMAX spectrums, 2.5 GHz and 3.65 GHz, are presented and compared. Actual physical testing of commercial equipment in real-world settings has been done to provide a generic overview of the performance of the two spectrums. The results presented serve multiple purposes. First, they provide reliable technical data for decision-making. Second, they

can be used for link budget analysis. Finally, they can be utilized as benchmarks for future testing and quality control of equipment production. It is shown that the maximum achievable downlink throughput for the 2.5 GHz and the 3.65 GHz systems is around 22 Mbps and 21 Mbps respectively. Assuming an average user bandwidth demand of Mbps, they can both reliably serve 40 to 45 users within a coverage radius of 12 km and 8 km respectively. Other than the lower coverage, opting for the 3.65 GHz spectrum over the 2.5 GHz spectrum will cause no significant performance loss and should be preferred if the loss of coverage can be tolerated.

Dedicated to my parents

Acknowledgements

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List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AMPS	Advanced Mobile Phone System
BS	Base Station
CC	Convolutional Coding
CDM	Code Division Multiple Access
CPE	Customer Premises Equipment
CTC	Convolutional Turbo Coding
DL	Downlink
EDG	Enhanced Data Rates for GSM evolution
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiple Access
FEC	Forward Error Correction
FUSC	Full Usage of Subcarriers
GPR	General Packet Radio Service
GSM	Global System for Mobile
HAR	Hybrid Automatic Repeat Request
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union

LTE	Long Term Evolution
MAC	Media Access control
MIMO	Multiple Input Multiple Output
ODU	OutDoor Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing Access
PUSC	Partial Usage of Subcarriers
SS	Subscriber Station
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VOIP	Voice Over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1. INTRODUCTION TO WIRELESS COMMUNICATIONS

1.1. History of Communications

The history of communication is as old as the history of human civilization itself. The human need to communicate was the most motivating factor for all inventions in communication engineering in ancient times and, to some extent, in the modern age as well.

Communication, in simple words, is relaying information. The earliest form of communications can be traced back to around 3000 BC when the ancient civilizations used carving of symbols on stones and rocks to communicate and leave messages. Transmission of information over long distances began around 1000 BC. Ancient Greeks have been reported to use fire as means of signaling in annals and historical stories. The very first postal service was introduced for government use in China in 900 BC. The first recorded archive of using pigeons to carry information is traced back to 776 BC. Around 500 BC and later, papyrus rolls and early parchments made of dried reeds came into use, which provided lighter and portable surfaces to write on. This made communicating over large distances easier. Between 200 BC to 100 BC, messenger relay stations were built in Egypt and China, which facilitated safer communication over long distances.

In 14 AD, Romans built post offices in Europe. The foundation of medieval communication was laid in 105 AD when Tsai Lun of China invented paper, as we know

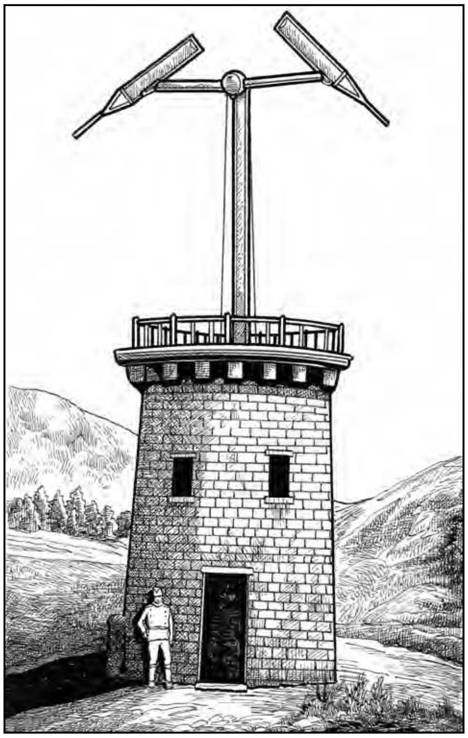


Figure 1.1: Chappe's Optical Telegraph [1]

Figure 1.2: Morse's Telegraph [2]

it. The invention of paper facilitated widespread use of books and newspapers in Asia and became an effective means of message transmission. In the mid-15th century, newspapers appeared in Europe.

The foundation of modern communications was laid by a French inventor named Claude Chappe in 1792 when he demonstrated a practical visual semaphore system that transmitted coded information between Paris and Lille. This was the first practical telecommunication system of the industrial era and was used by Napoleon to organize his army. The idea to use electricity to transmit information was first successfully demonstrated by an American physicist, Joseph Henry, in 1830. In 1837, British physicists William Cooke and Charles Wheatstone patented the first telegraph using the principles of electromagnetism. However, the most successful and widely used implementation of this principle is credited to Samuel Morse. In 1844, the first experimental electrical telegraph line between Baltimore and Washington D.C. was completed and successfully demonstrated. Telegraph lines dominated as the means of communication for most of the 19th century. Guglielmo Marconi, in 1897, demonstrated the possibility of transmitting electrical signals over wireless links for communication. On December 12, 1901 he successfully transmitted the first transatlantic radio signal using Morse code and thus ushered in the new era of radio communications.

With the invention of the first triode in 1906 and then transistors in 1948, radio communications started becoming cheap and popular. Radio communications was widely used in both world wars. With the age of computing processing power beginning in the mid-20th century, wireless communications was widely adopted as a powerful communication standard in many applications including military and entertainment.

1.2. History of Wireless Communications in the United States

Public radio broadcasting in the United States can be traced back to October 1920 when KDKA in Pittsburgh received its license as the first commercial broadcasting station. Radio broadcasting boomed in the first half of the 20th century. By 1940, commercial FM (Frequency Modulation) and Single Side Band (SSB) radios were commercially available. The great potential of wireless communication was realized in World War II where they were extensively used for co-ordination, spying and tactical purposes.

Wireless telephony was used in the United States with much success as early as 1930 but the cost was expensive and the technology was primitive. In the 1940s, Motorola developed the hand-held two-way communication radio for the U.S. military. In 1946, the mobile telephone system was introduced in St. Louis. Despite its commercial success, the technology was not advanced enough to support many users simultaneously.

The concepts of cellular planning, that would later prove to be the backbone of modern wireless communications, were proposed in Bell Labs as early as 1947. By the 1960s, the technology was advanced enough to produce electronics for these concepts. In 1970, Amos E. Joel, Jr. from Bell Labs invented “call handoff” technology that allowed cellular phones to move from one cell to another without loss of connection. In 1971, AT&T, who then owned Bell Labs, submitted a proposal for providing cellular service to the Federal Communications Commission (FCC). Unfortunately, it required years of hearings. The FCC finally approved the proposal in 1982 and AMPS (Advanced Mobile Phone System) was borne. AMPS is regarded as the first generation (1G) mobile network. It is an FDMA-based analog network operating in the band of 824-849 MHz for

Figure 1.3: Martin Cooper with portable cell phone [3]

uplink and 869-894 MHz for downlink. It was popular through most of the 1980s. Meanwhile, on April 3, 1973, Martin Cooper, from Motorola, made the first analog handheld mobile phone prototype, although it was not portable.

Due to inherent capacity and security problems of analog systems, it became necessary to adopt a new system to cater to growing mobile telephony needs. To meet these requirements, IS-54 standard, popularly known as digital AMPS, was introduced in March 1990. IS-54 used the TDMA scheme for multiplexing, which effectively tripled the user capacity per cell and had features for authentication. Because of the huge user base of AMPS, backward compatibility was maintained. However, the number of wireless telephony users had exploded from 2 million to over 16 million in the five years between 1988 and 1993 [4]. Further improvements to IS-54 gave rise to IS-136. Unlike IS-54, IS-136 used TDMA for both voice and control channels. It provided higher capacity and improved battery life.

Despite improvements in cell capacity provided by IS-54 and IS-136, they were unable to meet the growing need to support an ever-increasing number of mobile users, since the resources of time and bandwidth are limited. In 1995, Qualcomm proposed a revolutionary digital cellular standard IS-95 under the brand name cdmaOne. Unlike older systems that used time or frequency division for multiple access, IS-95 used pseudo-random codes called PN sequences for multiplexing. The multiple access was appropriately named Code Division Multiple Access (CDMA). CDMA has its roots as far back as during World War II and is believed to be method of communication for the U.S. military post-war era before it was declassified in the mid-1980s. CDMA had the distinct advantage of having a very low power spectral density, which makes it possible for the same cell to support multiple users without having them interfere with each other. The CDMA standard is widely acknowledged as the second generation (2G) mobile standard.

As technology advanced, the use of mobile phones was no longer limited to voice communication and simple text messaging. Service providers also had to support internet and multimedia services. The traditional 2G networks could no longer support the tremendous boom in high resource demand of the internet and multimedia services. The third generation (3G) mobile networks have been designed to address the concerns of effective utilization of limited resources and support for mobility. CDMA2000, also known as IMT-Multi Carrier, is a popular 3G standard.

1.3. History of wireless communications in the rest of the world

While mobile radio communication was evolving in the United States, the rest of the world, particularly Europe and Japan, was also developing its own standards.

The history of wireless radio communications in Europe developed in parallel with the U.S., both using radio links for public broadcasting, entertainment and research. Europe, too, heavily utilized radio communications during World War I and II. The first generation mobile telephony in Europe started with the introduction of Nordic Mobile Telephony (NMT) in 1981, operating in Sweden and Norway. It later spread to other Nordic countries. The transmitted signal was analog and frequency- modulated. NMT was a huge commercial success, laying the foundation for the later prominence of Nokia and Ericsson. Other lesser known 1G standards were Total Access Communications Systems (TACS) in the UK; C-450 in West Germany, Portugal and South Africa; Radio Telefono Mobile Integrato (RTMI) in Italy and JTACS (Japan TACS) in Japan. The other

1G standards all over the world had the same problems of capacity and security as with AMPS.

The second generation of mobile telephony in Europe began with the launching of the GSM (Global System for Mobiles) standard in Finland by Radiolinja in 1991. GSM enjoyed worldwide success; to this day, more than 80% of worldwide mobile phone users use GSM or a technology derived from it. GSM also enjoyed tremendous success in the U.S., where major carriers such as AT&T opted for GSM over CDMA technology. GSM is a digital technology which uses a hybrid of TDMA and FDMA for multiple accesses. It provides sophisticated security mechanisms via the famous A5 algorithms. To address the requirements of internet and mobile services, GSM was extended to first GPRS (General Packet Radio Service) and later EDGE (Enhanced Data Rates for GSM evolution) by the 3GPP (3rd Generation Partnership Project) committee. They are sometimes referred to as 2.5G and 2.75G, respectively. Meanwhile, Japan had developed its own 2G standard called Personal Digital Cellular (PDC), which was extensively used in Japan.

The era of third generation mobile networks began in Europe with 3GPP specified the first UMTS (Universal Mobile Telecommunications System) in 2000. UMTS, unlike GPRS and EDGE, was not intended to extend GSM, but rather to replace it. It had superior performance in high speed data transmission, resource usage and mobilization, and mobility support and security compared to 2G standards. 3GPP later introduced IMS (IP Multimedia Subsystem), for delivering IP-based multimedia services over mobile networks and HSPDA (High Speed Downlink Packet Access), sometimes known as 3.5G, for improved high speed data communication. These standards have also been widely adopted in the U.S.

1.4. The fourth generation mobile standards

The human means to communicate has evolved from prehistoric semaphores to modern smart phones. The information to be transmitted has expanded exponentially and the technology has adapted accordingly. Modern mobile user demand has far exceeded the requirements of voice, text and multimedia transmissions. Mobile TV, live broadcasting, mobile shopping and other services have emerged as a great source of revenue for service providers. Providing these services is beyond the capacity of 2G and 3G networks from the point of view of resource utilization and security. The International Telecommunication Union-RadioCommunication Section (ITU-R) specified the International Mobile Telecommunications Advanced (IMT-Advanced) requirements, which are popularly called the 4G network requirements. The 4G networks will be based on an all-IP packet switched network, and must provide peak data rates up to 100 Mbps for high mobility and 1 Gbps for low mobility among others. Although a standard that totally complies with the ideal 4G network is still evolving and a matter of research, two popular technologies have emerged as candidates.

i) Mobile WiMAX

In 1999, the IEEE 802 LAN/MAN Standards Committee developed standards for global deployment of broadband wireless solutions for metropolitan area networks. The standard was called 802.16. In 2001, the commercial name WiMAX (Worldwide Interoperability for Microwave Access) was coined and WiMAX forum was established to market and promote the standard.

In 2004, IEEE 802.16-2004, or more popularly known as Fixed WiMAX, was proposed, which defined the air interface for a fixed broadband wireless access system. Although Fixed WiMAX introduced the realm of broadband access with superior performance over older technologies in terms of throughput and coverage, it did not address the problem of mobility.

With the introduction of the 802.16e-2005 standard, WiMAX started supporting mobility. IEEE 802.16e-2005 standardizes the physical and the media access control layer of the air interface. Mobile WiMAX uses advanced physical layer techniques for superior throughput, coverage and mobility support. Newer technologies like scalable orthogonal frequency division multiplexing, adaptive modulation and coding, multiple-input-multiple-output (MIMO) antenna support better non-line of sight performance and hybrid automatic repeat request for better error performance. Similarly, the media access layer defines how different wireline technologies like Internet Protocol are encapsulated in the air interface. It defines provisions for security, power saving mechanisms, handovers and packet fragmentation and reassembly. Most commercially available Mobile WiMAX devices conform to the 802.16e-2005 standard.

The next major WiMAX release was IEEE 802.16-2009, which standardizes the physical and the media access control layers for the air interface for fixed and mobile broadband wireless access systems.

The latest version of WiMAX is 802.16m, also known as Mobile WiMAX Release 2. It was approved by the IEEE Standards Association in early 2011. It is expected to address ITU's 4G standard requirements for worldwide deployment. It includes recent innovative communication technologies such as multi-user MIMO, multicarrier operation, and cooperative communications. It also incorporates femto-cells, self-organizing networks, and relays for more efficient communication.

The development works for 802.16n and 802.16p are under progress. IEEE 802.16n is expected to address the issue of higher reliability networks. On the other hand, the IEEE 802.16p will have enhancements to support machine-to-machine applications.

ii) LTE-Advanced

The 3GPP LTE (Long Term Evolution) was first proposed by NTT DoCoMo in Japan as the international standard in 2004. It was based on previous 2G and 3G wireless communication standards. LTE was introduced to address the high speed communications requirements of modern end user devices under significant mobility. LTE arrived with new cutting-edge hardware technology, digital signal processing techniques, and significantly newer features compared to the older 2G and 3G technologies such as an all-IP flat network architecture and end-to-end QoS including provisions for low-latency communications. The maximum achievable download and upload throughputs speed were about 300 Mbps and 75 Mbps, respectively. It had a large capacity that exceeded 200 active users per cell.

Its advanced form, appropriately named LTE-Advanced, was submitted to ITU as a candidate for 4G standard in late 2009. LTE-Advanced, also referred to as 3GPP Release 10, was designed to meet and surpass the ITU’s 4G worldwide standard requirements. It was released in early 2011, with features such as worldwide functionality and roaming capability, service compatibility, internetworking to other radio access systems and enhanced peak data rates. 3GPP is further working on Releases 11 and 12 for better performance with added features. 3GPP Release 11 is scheduled to be released in late 2012.

Even though the goals of fulfilling the ITU's 4G requirements for a worldwide deployment standard have been fulfilled to a great extent, researchers and scientists are continuously striving to improve performance of the system by using newer innovations in different layers and cross-layer designs.

Chapter 2. BACKGROUND OF THE PHYSICAL LAYER OF MOBILE WIMAX

In this chapter, a technical level introduction to the physical layer of Mobile WiMAX is presented. First, an introduction to the carrier modulation scheme is presented, which forms a significant building block of the system. Next, the functional overview of the physical layer of WiMAX is discussed in brief, with the purpose of introducing different sections of the system. Finally, the fundamental blocks of the overall system are discussed in detail.

2.1. OFDM (Orthogonal Frequency Division Multiplexing) and OFDMA (OFDM Access)

OFDM is based on the concept of dividing a high rate single carrier data stream into

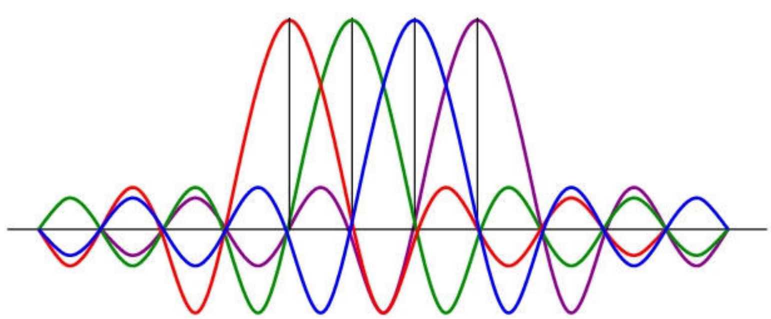


Figure 2.2.1: OFDM carriers in time domain.

parallel multicarrier modulation schemes. These multiple carriers are often called subcarriers. The subcarriers are selected such that each of them are orthogonal to each other over the symbol duration. This eliminates any form of intercarrier interference (ICI), as individual carriers are clearly separable at the receiver. FFT and IFFT blocks are

$X_{N-k}\ X_{N-k+1}\ldots\ldots X_{N-1}$	$X_0\ X_1 X_2\ X_3\ \ldots\ldots\ldots\ldots X_{N-k-1}$	$X_{N-k}\ X_{N-k+1}\ldots\ldots X_{N-1}$

Figure 2.2: Last k symbols copied to form cyclic prefix.

used in practical implementation of OFDM systems since they can generate orthogonal frequencies.

OFDM utilizes the concept of cyclic prefix to counter delay spread, which results in intersymbol interference (ISI) which is a common problem in digital communication systems. Consider N samples of an OFDM symbol that are passed through a channel with maximum channel delay spread of k+1 samples. To apply the cyclic prefix, k samples are copied as shown in Figure 2.2. After passing through the channel, the output will have N+2k samples. The first k samples contain interference from the preceding OFDM symbol and are discarded. The last k samples disperse into the following OFDM symbol and are also discarded. This leaves exactly N samples of the OFDM symbol which is the desired channel output. However, the use of cyclic prefix comes with bandwidth and power penalty. Figure 2.3 shows a simplified conceptual block diagram of OFDM.

Mobile WiMAX used OFDMA as the multi-access strategy to share subcarriers and

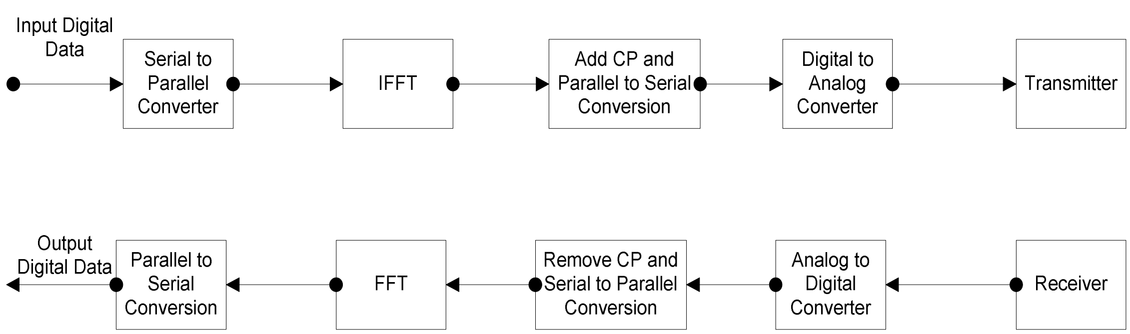


Figure 2.3: Simplified Block Diagram of OFDM

time among users. OFDMA is a hybrid of TDMA and FDMA. Different users are assigned different subcarriers dynamically in different time slots. There are two main principles that provide the high performance in OFDMA—multiuser diversity and adaptive modulation and coding. Multiuser diversity is implemented in OFDMA by adaptive subcarrier allocation. It provides large gains by directing subcarriers to users to good channel conditions. Adaptive modulation and coding is implemented to take advantage of the fluctuating channel conditions. The principle is to transmit signal at a high data rate when channel conditions are good and gradually decrease the rate as the channel condition worsens or vice versa. The data rate is controlled by baseband modulation and channel coding schemes. For poorer channels, smaller constellations like QPSK and low-rate channel encoder like ½ convolutional or turbo coders is used. For better channels, a higher data rate is achieved by using larger constellations like 64QAM and higher rate channel coders.

The standard does not specify the implementation of resource allocation in OFDMA. It involves developing algorithms for user selection, subcarrier allocation and power level specification. Nonetheless, some important aspects of OFDMA like sub-channelization, mapping messages and ranging are standardized.

2.2. The Physical Layer of Mobile WiMAX

The physical (PHY) layer of Mobile WiMAX is based on the IEEE 802.16e-2005 standard [5]. In this chapter, much of the focus will be centered on WirelessMAN OFDMA PHY. It is based on OFDM modulation and is designed for NLOS communications below frequencies of 11 GHz. It supports at least one of the FFT sizes of 2048, 1024, 512 and 128. This enables the use of various channel bandwidths.

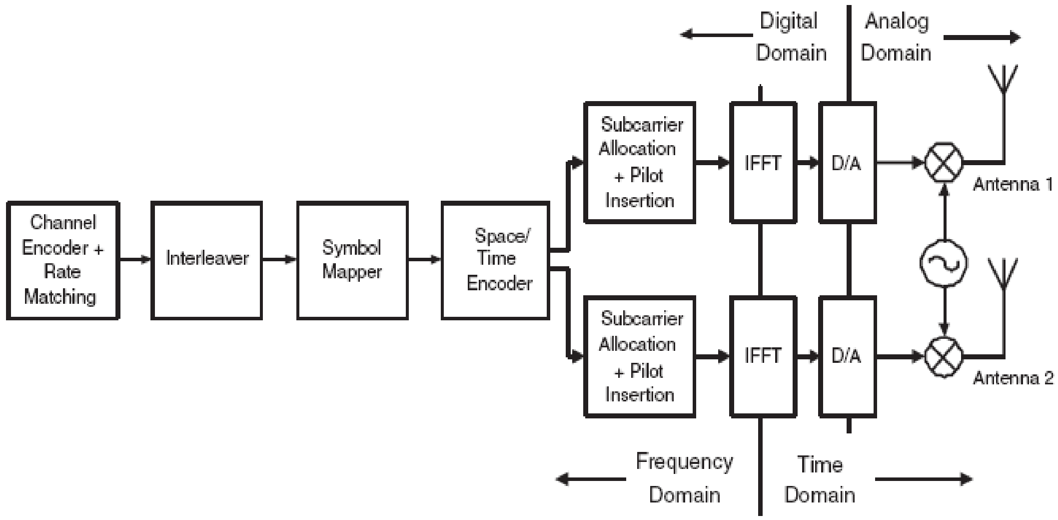


Figure 2.4: Functional Stages of the WiMAX Physical Layer.

Figure 2.4[6] shows the functional stages of the WiMAX physical layer on the transmitter side. The initial stages of the system are concerned with protecting the baseband binary data from channel noise and interference. Channel encoding, rate matching and interleaving processes are involved in this stage. The encoded binary data are then mapped to appropriate symbols based on the modulation scheme to increase throughput. The modulated symbols are space-time coded for diversity and better performance. The symbols are then allocated to data subcarriers based on the permutation scheme and pilot symbols are also inserted. The signal is then passed through an IFFT block for orthogonal modulation. Finally, this digital signal is converted to analog signal, carrier-modulated and then transmitted. All these processes are explained in the following subsections in detail. The receiver side works in the reverse fashion.

2.2.1. OFDMA symbols descriptions and parameters

2.2.1.1. Time Domain Description

IFFT is performed on the high data rate baseband modulated signal to create the OFDMA waveform. This time is called useful symbol duration. A copy of the last few samples of the useful symbol duration is appended to the symbol to collect multipath, as explained in earlier section. On initialization the subscriber unit searches all possible values of CP until it finds the CP being used by the base station. The subscriber uses the same CP in uplink; once selected, the CP is not changed.

2.2.1.2. Frequency Domain Description

An OFDMA symbol is made up of subcarriers whose number is determined by the size of FFT used. There are several types of subcarriers—data subcarriers for data transmission, pilot subcarriers for various estimation purposes and null carrier which contains no transmission at all for guard bands and DC carrier. The active subcarriers are divided into subsets of subcarriers called sub-channels. The subcarriers forming the sub-channel may not be adjacent.

2.2.2. Sub-channel and Subcarrier Permutations

A sub-channel is a logical collection of subcarriers. The number and exact distribution of the subcarriers depend on the subcarrier permutation mode. The number of sub-channels allocated to transmit a block of data depends on several parameters such as size of data block, modulation scheme and coding rate. The contiguous set of sub-channels allocated to a user is called the data region of the user. It is always transmitted on the same burst profile.

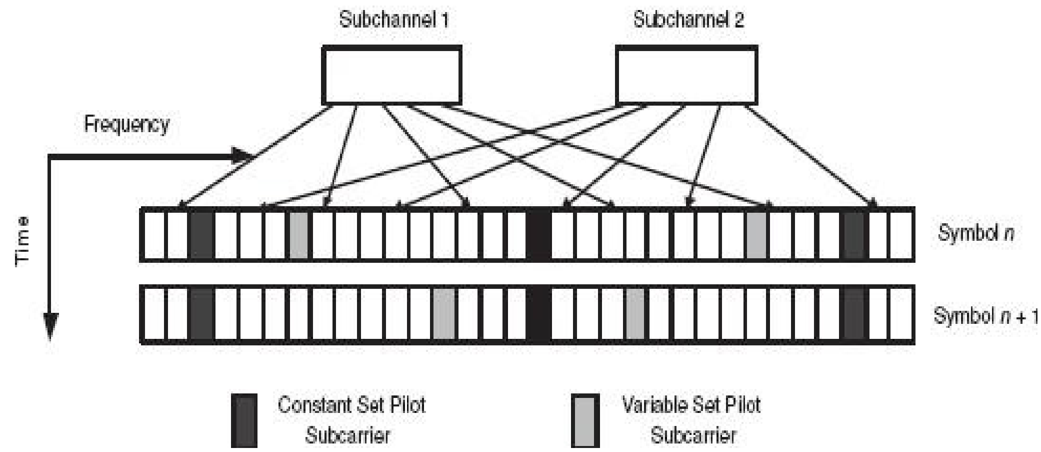


Figure 2.5: FUSC subcarrier permutation scheme.

The subcarriers forming the sub-channel can be either adjacent or distributed throughout the frequency band. An adjacent subcarrier distribution is better for beamforming and multiuser diversity. On the other hand, a distributed subcarrier permutation provides better frequency diversity. The scheme is determined by the subcarrier permutation mode. Different subcarrier permutation schemes are described in the following subsections.

2.2.2.1. Downlink Full Usage of Subcarriers (DL FUSC)

In DL FUSC, all data subcarriers are used to create sub-channels. Each sub-channel is made up of 48 data subcarriers, which are evenly distributed throughout the frequency spectrum as shown in Figure 2.5 [6].

In FUSC, the pilot subcarriers are allocated first. They are divided into two constant sets and two variable sets. The index of the variable sets varies from one OFDM symbol to another as shown by the *light gray blocks* in the figure. The variable set is used to estimate the channel response across the whole frequency band, which is important in the case of channels with smaller coherence bandwidth. The index of the constant sets,

Table 2.1: Parameters of FUSC Subcarrier Permutation

	FFT Size			
	128	512	1024	2048
Subcarrier per subchannel	48	48	48	48
Number of subchannels	2	8	16	32
Data subcarriers used	96	384	768	1536
Pilot subcarrier in constant set	1	6	11	24
Pilot subcarrier in variable set	9	36	71	142
Left-guard subcarriers	11	43	87	173
Right-guard subcarriers	10	42	86	172

shown by the *dark gray blocks* in the figure, does not change. After pilot subcarriers are allocated, the remaining subcarriers are mapped onto the various sub-channels. The parameters of FUSC Subcarrier Permutation are shown in Table 2.1[6].

2.2.2.2. Downlink Partial Usage of Subcarriers (DL PUSC)

The DL PUSC scheme is illustrated in Figure 2.6 [6]. First, all subcarriers except the null subcarrier are arranged into clusters. Each cluster is composed of 14 adjacent subcarriers over two OFDM symbols. Out of each set of 28 subcarriers, 24 are designated as data subcarriers and the remaining four as pilot subcarriers. Using a pseudorandom numbering scheme, the clusters are renumbered which redistributes the logical identity of the clusters. The clusters are then divided up among six groups. The first one-sixth of the clusters belongs to Group 0, the next one-sixth to Group 1, and so on. A sub-channel is

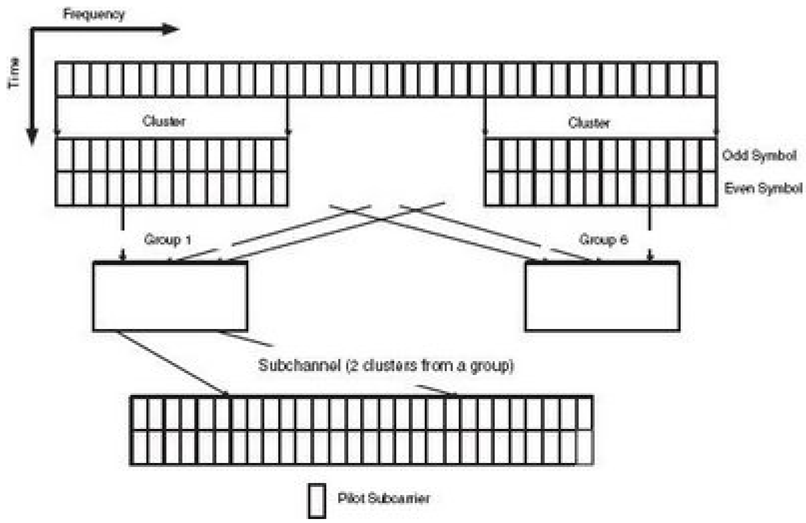


Figure 2.6: DL PUSC subcarrier permutation scheme.

created by using two clusters from the same group. The parameters of DL PUSC scheme is shown in Table 2.2[6].

In PUSC, it is possible to allocate only a part of the six available groups to a particular transmitter, which effectively separates their signals in subcarrier space, which provides

Table 2.2: Parameters of DL PUSC Subcarrier Permutation

	FFT Size			
	128	512	1024	2048
Subcarriers per cluster	14	14	14	14
Number of subchannels	3	15	30	60
Data subcarriers used	72	360	720	1440
Pilot subcarriers	12	60	120	240
Left-guard subcarriers	22	46	92	184
Right-Guard Subcarreirs	21	45	91	183

tighter frequency reuse at the cost of data rate. Such a usage of subcarriers is called segmentation.

2.2.2.3. Uplink Partial Usage of Subcarriers (UL PUSC)

In UL PUSC, shown in Figure 2.7[6], the subcarriers are divided into tiles, each tile consisting of four subcarriers over three OFDM symbols. Among the 12 subcarriers, eight are designated as the data subcarriers and the remaining four as the pilot subcarriers. The tiles are then renumbered using a pseudorandom numbering sequence and divided up into six groups. Each sub-channel is created by using six tiles from a single group. An optional UL PUSC scheme is also allowed in the uplink in which three subcarriers over three OFDM symbols are used to form a tile. Among the nine subcarriers, eight are designated as the data subcarriers and the remaining one as the pilot subcarrier. This optional UL PUSC mode allows for a higher data rate at the expense of a

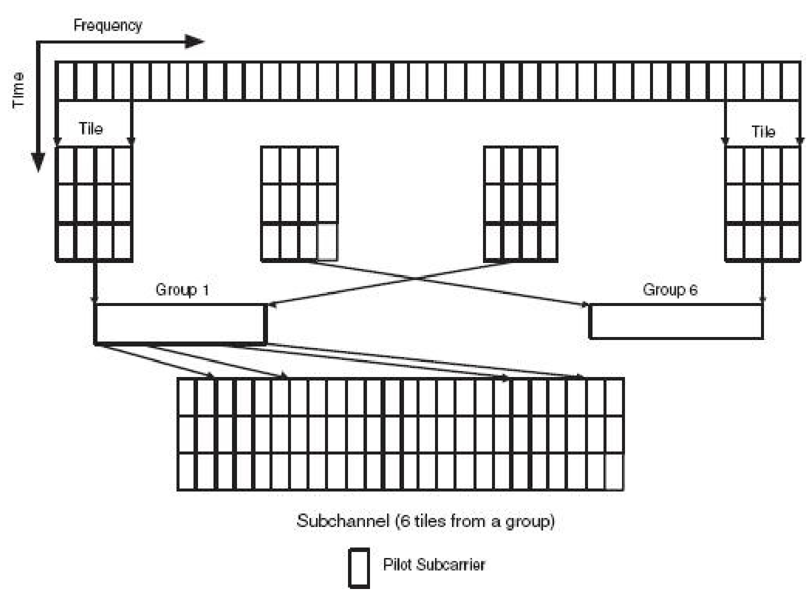


Figure 2.7: UL PUSC subcarrier permutation scheme

poorer channel tracking scheme. The two modes of UL PUSC allow the designer tradeoff between data rate and accurate channel tracking depending on the Doppler spread and coherence bandwidth.

2.2.3. Slot and Frame Structure

The MAC allocates physical resources to the users in units of *slots*, which is the smallest amount of time/frequency domain resources that can be allocated to a user. The size of the slot is dependent on the subcarrier permutation scheme. The contiguous collection of slots allocated to a single user is called the *data region* of the user.

In IEEE 802.16e-2005, both time division duplexing (TDD) and frequency division duplexing (FDD) is allowed for two-way communication. The frame structure for TDD is shown in Figure 2.8 [7]. The frame structure for FDD is identical, except that the uplink and downlink sub-frames are transmitted on different carrier frequencies.

As shown in the figure, each DL and UL sub-frame is divided into various zones, each using a different subcarrier permutation scheme. The first OFDM symbol in the DL sub-frame is the DL frame preamble. The preamble contains information for different physical layer procedures like time and frequency synchronization, initial channel estimation, and noise and interference estimation. The preamble is followed by the frame correction header (FCH). It is used for carrying system control information like subscribers used in segmentation, the ranging sub-channels, and the length of the DL MAP message. The FCH is followed by the DL MAP and the UL MAP messages, which consist of information on the data region of the various users in the DL and UL subframes, respectively, of the current frame. The base station also transmits the downlink channel descriptor (DCD) and the uplink channel descriptor (UCD) periodically which contains information about the channel structure and the various burst

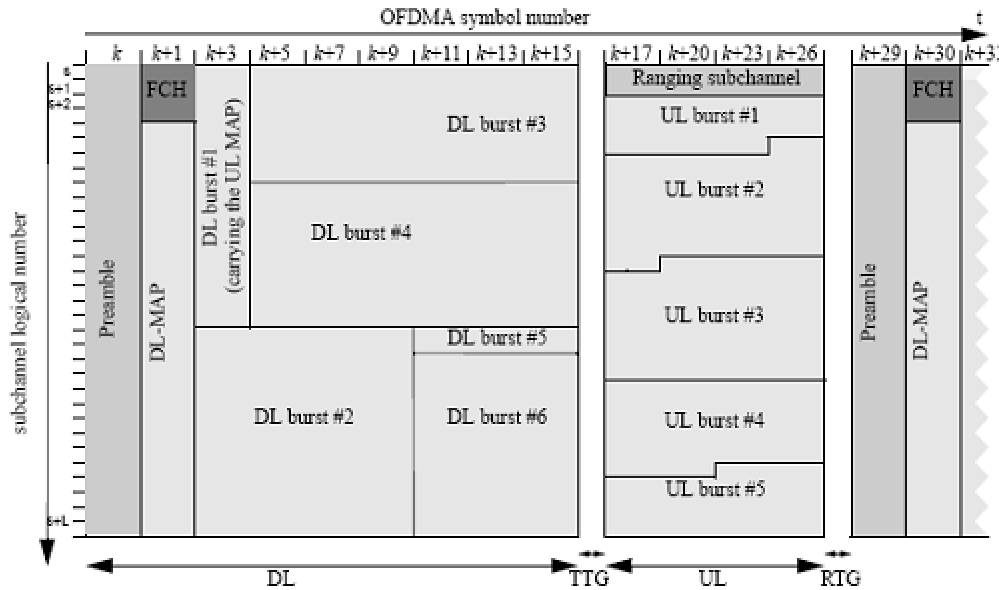


Figure 2.8: TDD frame structure.

profiles.

2.3. Forward Error Correction

Forward Error Correction (FEC) is an important stage of Mobile WiMAX. It allows the binary information to be resilient against channel noise and interference. In IEEE 802.16e-2005, it is implemented in five stages: (i) Data randomization, (ii) Channel coding, (iii) Rate matching, (iv) HARQ, if enabled and (v) Interleaving.

For data randomization, the binary data is modulo 2 added to the pseudorandom output of a maximum length shift register. This provides added security to the data via layer 1 encryption. After randomization, the FEC blocks are channel-coded and rate-matched. Two popular channel coding schemes are used in Mobile WiMAX as explained in the following sections.

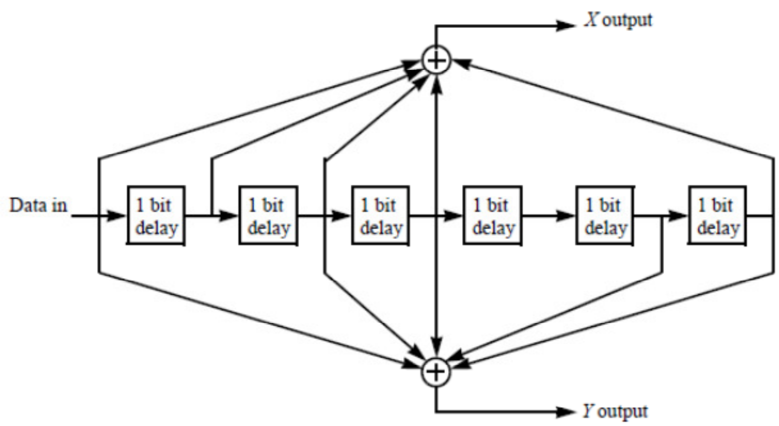


Figure 2.9: Convolutional Encoder rate 1/2, constraint length 7.

2.3.1. Channel Coding

2.3.1.1. Convolutional Coding

Convolution coding (CC) is the mandatory channel coding scheme in IEEE 802.16e-2005. The encoder, as shown in Figure 2.9 [5], is a constituent encoder with a constraint length of 7 and a code rate of ½.

The randomized data are fed into the encoder. In order to initialize the encoder to the zero state, each FEC block is padded with a byte of *'0's* at the end in the OFDM mode. In the OFDMA mode, tailbiting is used in which six bits from the end are appended to the beginning. These bits flush out the remnants of the encoding of the earlier FEC block. Tailbiting is more bandwidth efficient but it requires more complex decoding. To achieve code rates higher than ½, the output of the encoder is punctured, using the puncturing pattern shown in Table 2.3 [6].

Table 2.3: Puncturing for Convolutional Codes.

Code Rate	R 1/2	R 2/3	R 3/4	R 5/6
d_{free}	10	6	5	4
Parity 1 (X)	11	10	101	10101
Parity 2 (Y)	11	11	110	11010
Output	X1Y1	X1Y1Y2	X1Y1Y2X3	X1Y1Y2X3Y4X5

2.3.1.2. Turbo Coding

Besides the mandatory convolutional coding, several optional coding schemes including block turbo codes, convolutional turbo codes and low density parity check codes are defined in IEEE 802.16e-2005. Among these, convolutional turbo coding (CTC) is the most popular because of its superior performance. The turbo encoder used in Mobile WiMAX is shown in Figure 2.10 [5]. It is a duo-binary convolutional encoder with constraint length of 4. The polynomials for the feedback branch and the Y parity branch are $1+D+D^3$ and $1+D^2+D^3$ respectively.

The data bits to be encoded are fed to A and B alternatively, starting with the MSB of the first byte being fed to A. The data is encoded in blocks of k bits at a time, where k is a multiple of 8 and not 7. First, with the switch on position 1, data are fed to the encoder in the sequence of natural order with the incremental address of i=0, 1… N-1. This is called C1 coding. Next, with the switch in position 2, the encoder is fed with the interleaved sequence with address j=0, 1… N-1. This is called C2 coding. The encoded bit fed to the interleaver is $A_0B_0 \ldots A_{N-1}B_{N-1}Y_{1,0}Y_{1,1} \ldots Y_{1,M}Y_{2,0}Y_{2,1} \ldots Y_{2,M}$, where M is the number of parity bits.

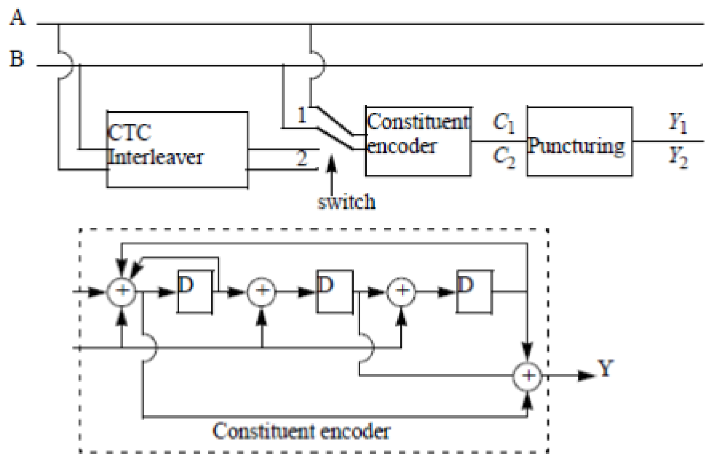


Figure 2.10: Convolutional turbo encoder.

The desired code rate is achieved by selectively deleting the parity bits. The puncturing patterns are identical for both C1 and C2 and are shown in Table 2.4 [5].

2.3.2. Hybrid ARQ (HARQ)

Hybrid ARQ is an ARQ system implemented in the physical layer with FEC that provides improved link performance over a conventional ARQ system at the expense of added complexity. IEEE 802.16e-2005 supports *Type I HARQ* and *Type II HARQ*.

Type I HARQ is also known as *chase combining*, in which the receiver decodes using current and previous HARQ retransmissions. The puncturing pattern of the bits does not change. With each new retransmission, the reliability of the coded bits improves. This process continues until either the decoder is able to correctly decode all bits or the maximum limit for HARQ retransmissions is exceeded.

Table 2.4: Puncturing for Convolutional Turbo Codes.

Code Rate	Y					
	0	1	2	3	4	5
R1/2	1	1				
R2/3	1	0	1	0		
R3/4	1	0	0	1	0	0

Type II HARQ is also known as *incremental redundancy*, in which the redundancy of the bits is changed from one retransmission to the next. This is achieved by changing the puncturing pattern and decreasing the code rate, which improves the Bit Error Rate (BER) of the transmission.

2.3.3. Interleaving

After channel coding, the encoded bits are passed to a two-step interleaving process. The first step ensures that the adjacent coded bits are not mapped onto adjacent subcarriers. This provides frequency diversity and improves the performance of the decoder. The second step ensures that adjacent bits are alternatively mapped to less and more significant bits of the modulation constellation. The interleaving is performed on each FEC block independently.

2.4. Symbol Mapping

The channel encoded binary data are mapped to constellations for a higher data rate. QPSK and 16QAM are mandatory constellations, while some systems may employ 64QAM, at least in downlink, for higher throughput.

Each modulation constellation is scaled by a constant factor such that the average transmitted power is unity. Preamble and mid-amble symbols are further scaled by $2\sqrt{2}$, resulting in an eight-fold power boost, which is necessary for accurate synchronization and channel response estimation.

2.5. Power Control

The power control mechanism allows the BS and the MS to improve the quality of the channel when required for better system performance. The BS uses the UL ranging channel transmissions from various MSs to estimate the initial and periodic adjustments for power control. The BS then utilizes the dedicated *MAC management messages* to direct the MS to make necessary power adjustments. The BS can then adjust the power level and/or the burst profile in order to make them consistent with the channel quality at the receiver. There is no closed loop power control defined on the downlink. This is left up to the vendors to implement it.

Chapter 3. PROBLEM STATEMENT

This chapter explains the rationale behind undertaking the research endeavor.

Our research group at the University of Nebraska-Lincoln's Advanced Telecommunications Laboratory has been actively engaged in designing broadband solutions for railroad networks [8-14]. We have been working with the Federal Railroad Administration and freight railroad industries like Union Pacific and BNSF for our research endeavors. The network infrastructure design procedure involves four essential stages: theoretical analysis, computer simulation based performance analysis, field testing and equipment testing in real world settings. It is imperative to perform a detailed investigation to include all performance scenarios for completeness of this study. This work primarily deals with the equipment testing phase of network design. It is intended to provide comprehensive details of performance specifications of Mobile WiMAX equipment. The specific setup utilized also helps to understand and compare the generic behavior of the two spectrums and decide on the spectrum suitable for a specific deployment scenario. Further, these results can be reliably used for link budget analysis and as a benchmark for equipment quality control and assurance.

The purpose of testing is to evaluate the performance of equipment in real-world scenarios before deployment. Computer simulations are widely used [15-16] as a tool for performance prediction. Although the results from computer simulations are important for initial planning and are fairly easy to obtain due to flexibility of the process, they are seldom accurate. The reason is that computer simulations are based on well-known analytical communication models which assume certain conditions for simplicity that are seldom realized in practice. It is impossible to tweak the already available models in order to specialize them to real test conditions due to the random nature of channel and sheer complexity of the process. Therefore, we need to physically test the equipment to get reliable results. Also, the equipment results help to determine the quality of computer simulation models which is essential to calibrate them for future use. Similarly, the test results can be used as benchmark results for further equipment production and quality control. Finally, it is imperative to test the equipment to verify whether it is actually deployable in real world conditions, since different vendors implement some parameters of the standard in their own specific way.

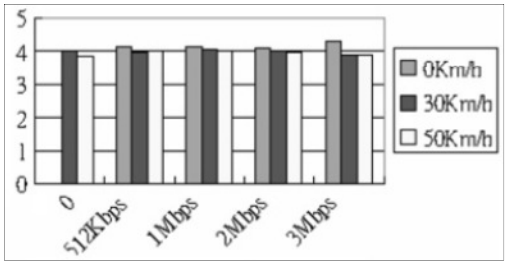
The Federal Communications Commission issues commercial licenses in several spectrums for Mobile WiMAX, among which 2.5 GHz and 3.65 GHz are the most common. However, as explained later in Chapter 4, most academic and industrial research focuses on 2.5 GHz spectrum, primarily because this spectrum goes through the least amount of path loss for the same separation between transmitter and receiver and therefore requires fewer base stations to cover a specific area. Hence, 2.5 GHz spectrum is preferred by large companies with a broad customer base distributed over a larger area. However, the 3.65 GHz spectrum does have some technical and non-technical advantages over the more popular 2.5 GHz spectrum, the most important being the licensing requirement [17-18]. The affordable licensing requirement of the 3.65 GHz spectrum makes it a favorable prospect for deployment as broadband solution by smaller service providers and for local operation monitoring and control by industries. These companies may not require the higher communication range provided by the 2.5 GHz equipment due to their limited service coverage requirements and the commercial advantages of a lower licensing fee of using 3.65 GHz spectrum surpasses the disadvantage of deploying more base stations. Therefore, it is imperative that the performance of 3.65 GHz equipment be taken into consideration before deciding on the details of network design. In [9], some work has been done to quantify the performance of the 3.65 GHz Mobile WiMAX equipment. However, a thorough comparison between the two spectrums under different conditions is lacking. Without such substantial comparison and technical data, it becomes impossible to prefer one spectrum over another. Utilizing the results presented in this report, a concerned party can easily make a decision based on the pros and cons of selecting a particular spectrum. Some research has reported [19-21] on the performance and implementation of 3.5 GHz Mobile WiMAX. However, the band is not available for commercial use in the United States.

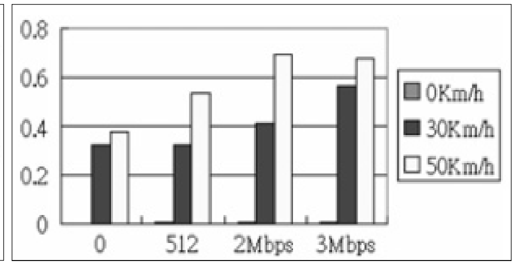
Chapter 4. LITERATURE REVIEW

This chapter surveys the current state of the art of research in area of Mobile WiMAX by discussing the contributions from different researchers and their shortcomings. For detailed analysis of each work, it is recommended that the corresponding literature be referenced. This chapter also introduces the contribution of this work.

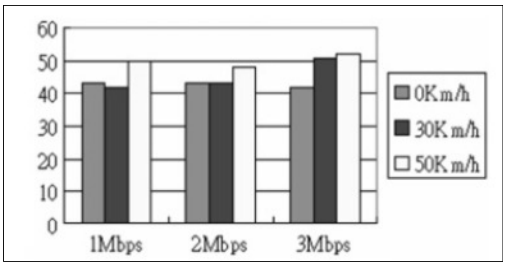
Mobile WiMAX is a popular broadband standard that is being deployed worldwide for different purposes like the last mile alternative for commercial broadband services and industrial operation monitoring and control. Although a lot of research work has been done in area of testing Mobile WiMAX parameters, none of them are totally comprehensive and most of them are not general but serve specific purposes.

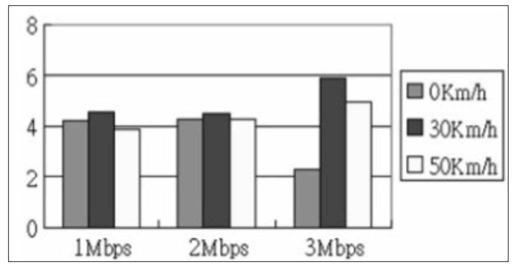
In [22], the authors attempt to improve the quality of video transmission in Mobile WiMAX by making it adaptive. They identified that channel bandwidth variation and disconnection due to handover latency are the critical factors that degrade the quality of wireless video transmission. First they estimated the varying channel bandwidth and detected the handover operation. Then, the streaming server adjusts the video transmission rate based on the estimated bandwidth and inserts an intra frame (I-frame) right after handoff, reducing error propagation. The authors in [23] have proposed an OFDMA channel aware error resilient video coding method using an upward cross-layer design to develop a highly robust method for video transmission, which, unlike in previous methods, does not require modifications of conventional functions of the WiMAX BS. In [24], the performance of deploying Mobile WiMAX for VOIP purposes





(i) **(ii)**





(iii) **(iv)**

Figure 4.1: Selected Results from [24] showing (i) Average MOS (ii) Average Packet Loss (%) (iii) Average One-Way Packet Delay (ms) (iv) Average Jitter (ms) under different conditions of data rate and speed.

has been studied. The authors investigate various performance indicators, e.g., mean opinion score, packet loss, packet delay and jitter of the VoIP service under different conditions of data rate and CPE speed. They observed an excellent performance when the communicating devices were stationary and an acceptable performance when they were moving at the speed of 50 km/hr. A summary of their results is presented in Figure 4.1.

In [25], the authors test the possible application of Mobile WiMAX in broadcasting by measuring the uplink and downlink throughput performance. They set up equipment in the field and measured different channel performance indicators such as throughput,

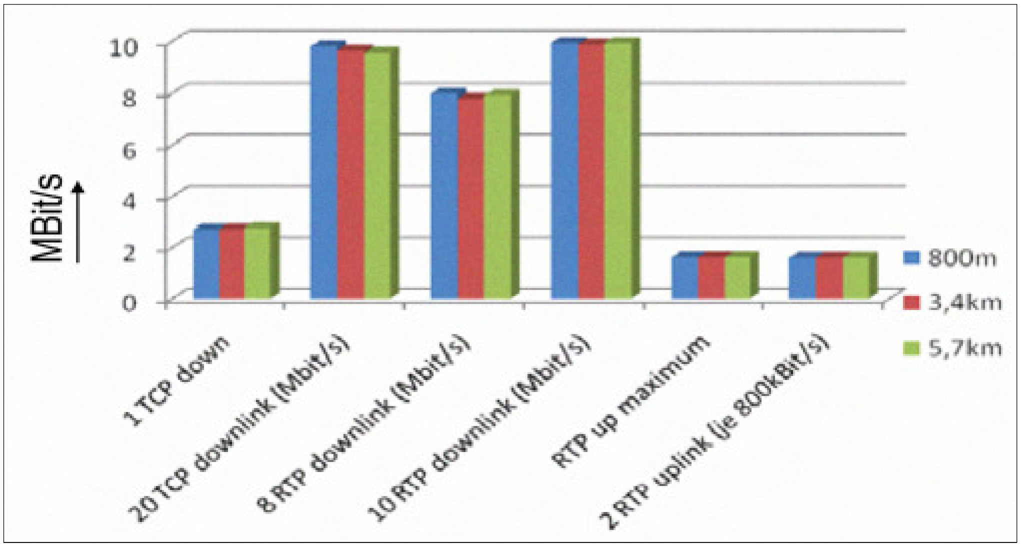
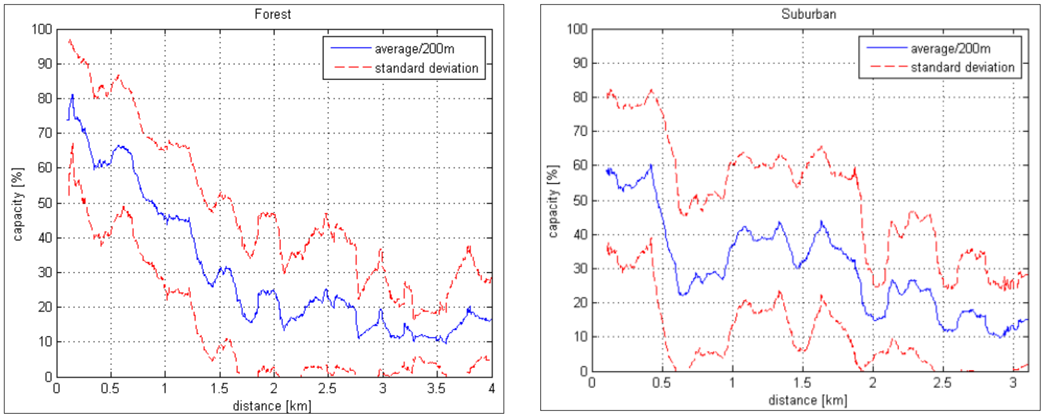


Figure 4.2: TCP and RTP data rates at three different distances from the transmission tower[25].

RSSI, CINR, delay and jitter at different distances from the BS. The maximum achievable spectral efficiency related to the TCP layer was found to be 2.85 Bit/s/Hz in downlink and 2.09 Bit/s/Hz in uplink. They concluded that the uplink rates achieved were promising, and the transmission of broadcasting materials in an appropriate quality was possible. In spite of the work being thorough and producing promising results, the authors have not used the latest devices to perform these tests. Furthermore, they have not accounted for different varieties of channel conditions that a practical system regularly encounters.

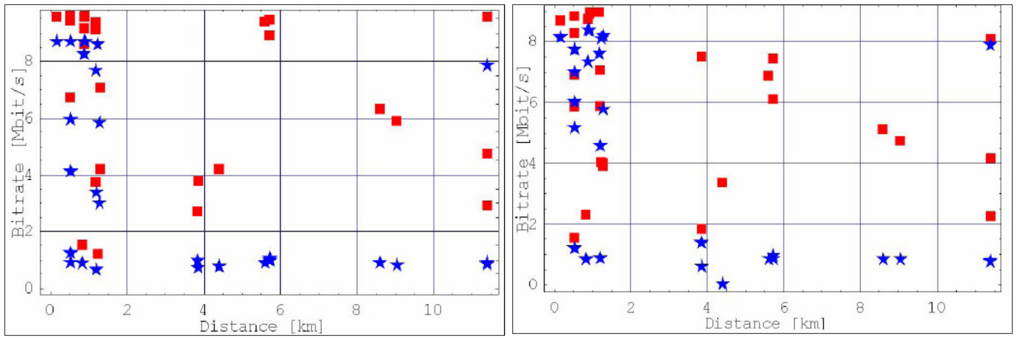
In [26], the authors investigated commercial Mobile WiMAX, with slight modification, as a cost-effective solution for wireless tactical broadband networks within the Finnish Defence Forces. Software defined radio-based prototype systems using commercial WiMAX technology but adapted to NATO's UHF band of 225-400 MHz were used for testing three tactical scenarios relevant to the defense forces. The tests were



(i) **(ii)**

Figure 4.3: Average downlink data capacity achieved in (i) Forest and (ii) Suburban environments [26].

carried out in three different environments—forest, suburban and near line-of-sight--to produce different levels of multipaths and interference for diverse channel conditions. Different system parameters like data rate using FTP application, RSSI, velocity and modulation schemes were observed. A sample of the results showing the throughputs achieved at different channels conditions is shown in Figure 4.3. They conclude that the system provided downlink capacity of 4-6 Mbps up to the range of 20 km under near line-of-sight conditions. Similarly, for forest and suburban environments, an average downlink capacity of 1 Mbps for ranges below 4 km and 3 km respectively were achieved. The work done by the authors is interesting and the results provide insights on the capabilities of Mobile WiMAX. However, the tests are tailor-made for defense purposes with many modifications to the commercial solutions. This makes the results irrelevant for our purpose of designing a Mobile WiMAX infrastructure based on commercial solutions.



(i) **(ii)**

Figure 4.4: UL (blue) and DL (red) performance for (i) UDP and (ii) TCP connections [27].

In [27], the authors focus on physical real-life field testing of WiMAX equipment. After setting up the base station at a particular location, different channel performance parameters like downlink and uplink throughput and received signal strength were measured at 15 different locations representing both urban and suburban areas and at different distances from the BS. A summary of the observed results is shown in Figure 4.4. However their study is limited to Fixed WiMAX and throughput measurement and the results cannot be generalized.

In [28], the authors investigate Fixed WiMAX as a possible broadband solution and report some field test results in a suburban environment. But their results have limited scope and cannot be extrapolated to measure performance in other physical environments. Nonetheless, the vast amount of research work done in Mobile WiMAX certainly strengthens its credibility as a prime contender for the de-facto 4G standard. However, as mentioned in Chapter 3, not much of the research work done can be used in differentiating between the performance of the 2.5 GHz and the 3.65 GHz bands under different operating environments.

This work is intended to provide comprehensive details of performance specifications of Mobile WiMAX equipment. The specific setup utilized also helps to understand and compare the generic behavior of the two spectrums and decide on the spectrum suitable for a specific deployment scenario. Further, these results can be reliably used for link budget analysis and as a benchmark for equipment quality control and assurance.

Chapter 5. METHODOLOGY

In this chapter, the equipment, the laboratory test configuration and the test bed, along with the scenarios used for testing, are described in detail.

5.1. Equipment Used

5.1.1. Mobile WiMAX Devices

For the purpose of getting performance measurements for 2.5 GHz and 3.65 GHz equipment, we used real commercially available devices.

For the 2.5 GHz system, Ruggedcom's RuggedMax WiN7000[29] and RuggedMax WiN5100[30] vehicular subscriber units were used as the base station (BS) and subscriber station (SS), respectively. The devices are shown in Figures 5.1 and 5.2 respectively. They are IEEE 802.16e-2005 and WiMAX Forum Wave2 Profile-

Figure 5.1: RuggedMax WiN7000 Base Station

Figure 5.2: RuggedMaX WiN5100 Subscriber Station

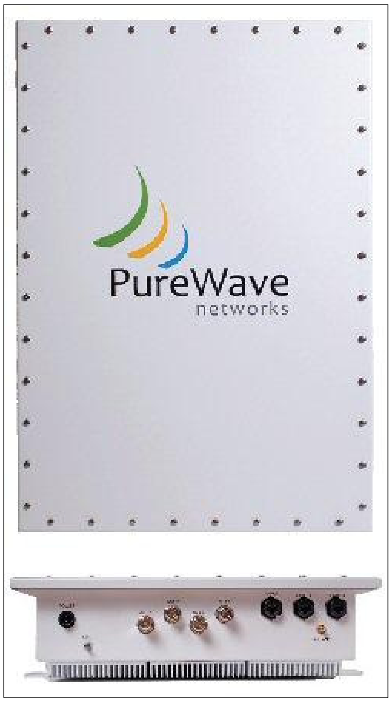


Figure 5.4: Gemtek ODU-series CPE

Figure 5.3: PureWave Quantum 1000 Base Station

compliant devices. The BS is an outdoor installation device while the SS is designed for vehicular operations. Both have two antennas for transmitting and receiving in a 2x2 MIMO configuration. They have provisions for adaptive modulation and coding, automatic power control, HARQ and QoS.

For 3.65 GHz equipment testing, PureWave Network's PureWave Quantum 1000[31] outdoor device was used as base station. It uses a four element antenna array, two for transmitting and all four for receiving. Similarly, we used Gemtek's ODU-series CPE [32] as the subscriber station. It had only two antennas for transmitting as well as receiving. Hence they were connected using a 4x2 MIMO configuration. Both devices were IEEE 802.15e-2005 standard and WiMAX Forum Wave-2 Profile compliant. They have capabilities of adaptive modulation and coding, ARQ, automatic power control and QoS, among others. The BS and SS are shown in Figures 5.3 and 5.4, respectively.

5.1.2. Channel Emulator

ACE 400WB [33], a wireless channel emulator from Azimuth Systems, was used to create wireless channels between the two end devices. The channel emulator is shown in Figure 5.5.

A channel emulator is a sophisticated software controlled unit able to emulate precise user-defined physical channels. Testing equipment by using a channel emulator rather than testing it over the air provides several advantages. The biggest advantage provided by the channel emulator is complete control of channel conditions and parameters over which the devices are to be tested. An *over-the-air* wireless channel is easily and severely

Figure 5. 5: Azimuth System's ACE 400WB Channel Emulator

affected by various parameters, e.g., rain, temperature, and moving people and vehicles, most of which is out of our control. This makes it impossible to recreate any test conditions for any form of comparison. Since we have no control over what parameter is changing and by how much, we cannot single out the effect of each individual parameter on overall network performance. Also, the parameter values rarely remain static, and creating a stable test environment becomes difficult. A channel emulator, on the other hand, allows us to create virtual yet accurate physical channels where we can control the variables and change the parameters one at a time to isolate and study their individual effects on device performance.

A channel emulator is able to create any realistic physical channel with great accuracy. However this work only includes ITU standard channel models —Butler, Pedestrian A and B and Vehicular A and B. The power delay profile of the different channel models is shown in Figure 5.6.

The Butler model is the simplest of the channel models. It is a static non-fading channel model that uses the identity matrix for the channel coefficients. It does not have any multipath components or scattering. The Butler model was emulated at the subscriber velocity of 0 km/hr.

The Pedestrian A model emulates a pedestrian (slowly moving receiver) with minimal impact due to multipath and fading. It is modeled by one direct path and three indirect signal paths, with a maximum path delay of 410 ns. The power in the reflected signal paths is much lower relative to that in the main signal path. The Pedestrian B model also emulates a slowly moving user, but accounts for higher degradation due to multipath and

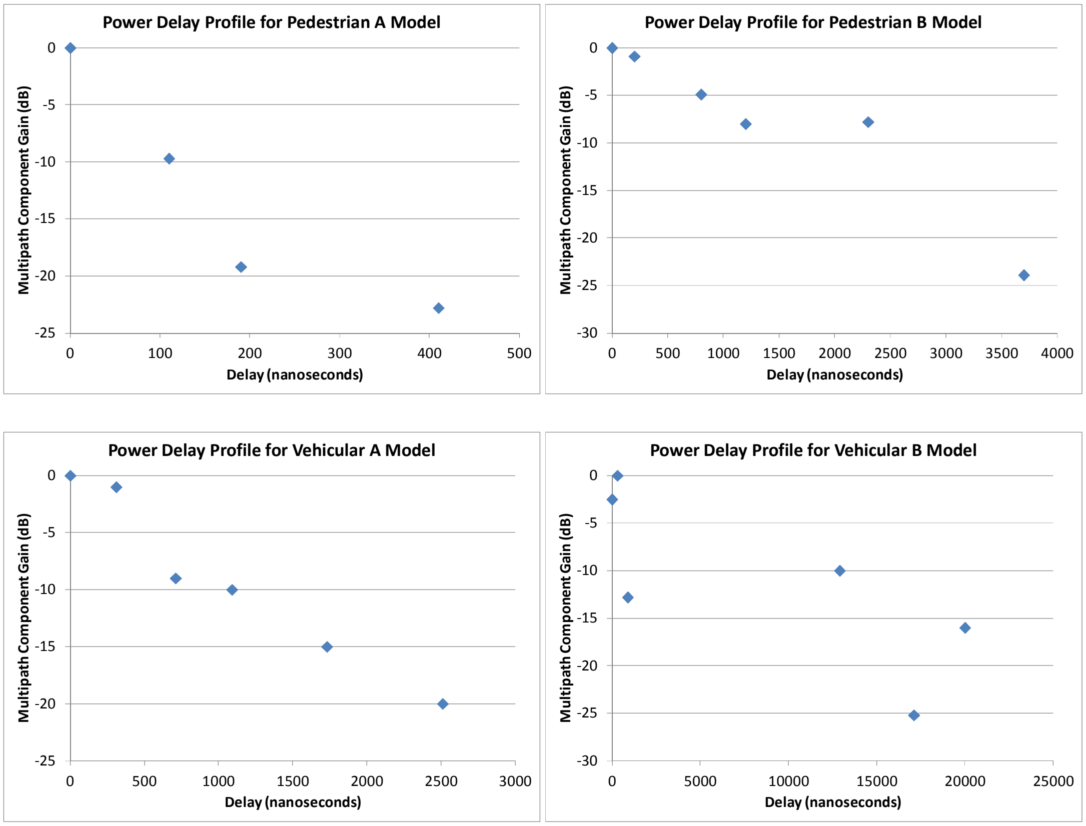


Figure 5.6: Power delay profile showing gain and delay spread of multipath components for different channel models.

fading. Both Pedestrian models have been emulated at velocities of 0 km/h, 2.5 km/h and 5 km/h to investigate the effects of Doppler shift.

The Vehicular A model emulates channel conditions to account for the impairment in performance caused by fast-moving subscribers. In this model, the maximum delay spread is 2,510 ns. The Vehicular B model also models channel conditions for vehicular networks, but accounts for much more severe impacts of multipath fading than Vehicular A does. The maximum delay spread is 20,000 ns and the strongest reflected path is actually 2.5 dB stronger than the direct path. Both vehicular models have been emulated at velocities of 0, 30, 60 and 90 km/hr.

Using the channel emulator settings, the MIMO antennas were configured to have no correlation.

5.2. Network Topology

Figure 5.7 shows a network diagram of the equipment setup for testing. The setup was similar for both the 2.5 GHz and 3.65 GHz testing, except for the tuning of the channel.

For the 2.5 GHz testing, the two antennas of the BS were connected to one of the ports (port A) of the channel emulator. The two antennas of the SS were connected to the other port (port B). The channel emulator created the channel between the two devices as specified by the controlling software, thereby creating a 2x2 MIMO configuration. Each device was connected to a laptop at the respective ends via RJ-45 Ethernet cables. The

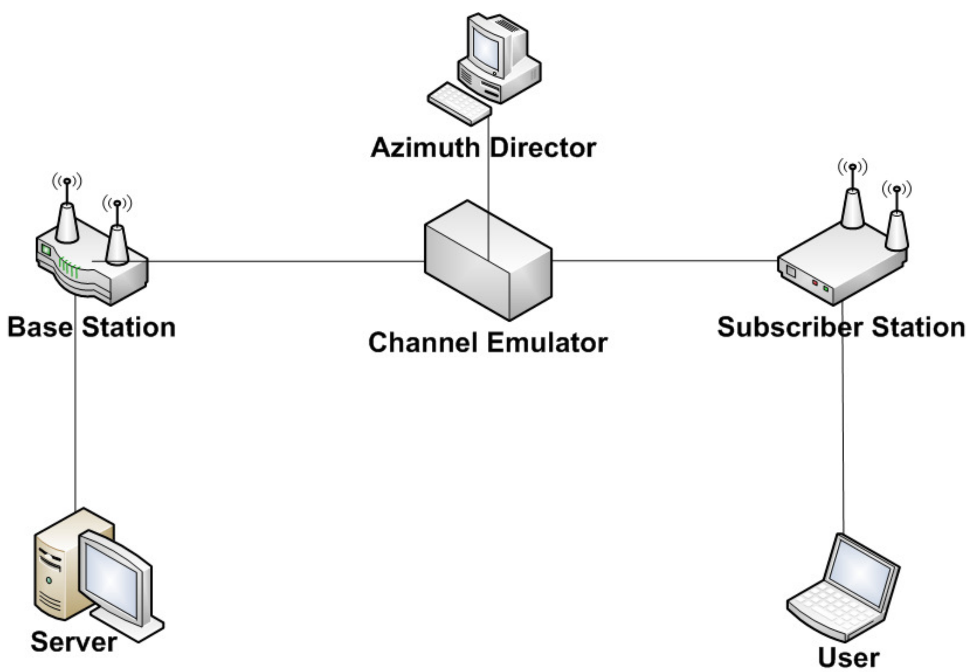


Figure 5.7: Network topology for equipment testing.

purpose of the laptops was to transmit and receive the UDP data traffic as well as manage the devices. Each laptop ran a traffic generator/receiver software for handling data, telnet sessions to extract relevant data from the devices and web interface to control the devices.

The setup for testing the 3.65 GHz equipment was similar except for some minor differences. The 3.65 GHz BS had four antennas, all of which were connected to port A of the channel emulator, thereby forming a 4x2 MIMO configuration. The laptop at the BS end was also connected to the BS via a serial (RS232) interface for managing the device. And finally, only the laptop at the BS side ran telnet sessions, and it was able to report both uplink and downlink results.

The device and link parameters used throughout the testing are summarized in Table 5.1.

Table 5.5: Channel/Device parameters for performance measurement

Channel/Link Parameter	Values	
	2.5 GHz Test	3.65 GHz Test
Central Frequency	2.5 GHz	3.65 GHz
Bandwidth	10 MHz	
Frame Duration	5 ms	
Downlink/Uplink Ratio	35/12	
Uplink Channel Descriptor (UCD) Interval	1000 ms	
Downlink Channel Descriptor (DCD) Interval	1000 ms	
CBR traffic rate (DL)	25 Mbps	
CBR Packet Size	1400 bytes	
BS Transmit Power	23 dBm	
SS Transmit Power	27 dBm (max)	24 dBm (max)
Channel Path Loss	85-135 dB	80-135 dB
ARQ	OFF	
HARQ	OFF	
Power Control	ON	
Adaptive Modulation and Coding	ON	
Antenna Configuration	2x2 MIMO-A	4x2 MIMO-A

Chapter 6. RESULTS AND ANALYSIS

In this chapter, the comprehensive results obtained from the laboratory and field tests are presented.

6.1. Laboratory Test Results

In this sub-section, the results of the tests performed using the channel emulator and the equipments mentioned in Chapter 4 are shown.

6.1.1. Effect of Multipath

As explained in Chapter 5, multipath and scattering are one of the most critical phenomena of wireless communication that negatively impact the performance of the system. Since multipath and scattering are ubiquitous, it is very important to quantitatively define their effects on wireless links. In case of strong line of sight

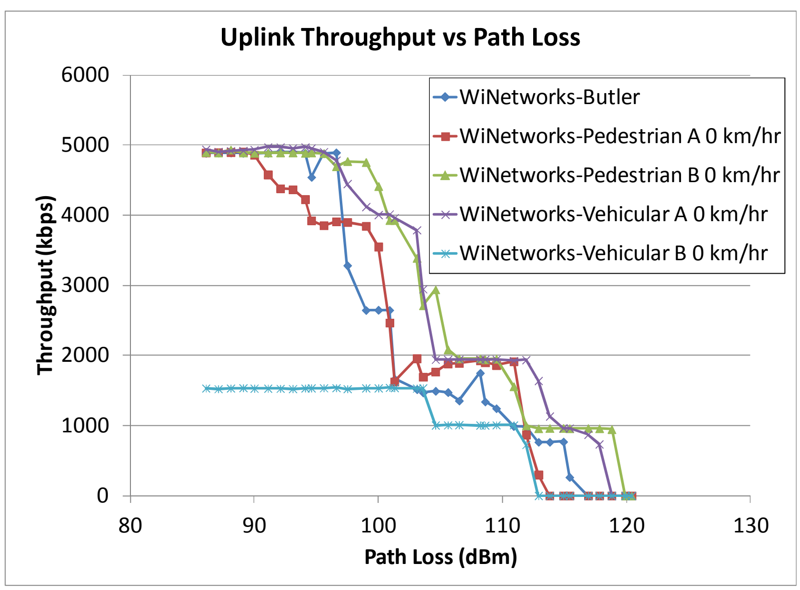


Figure 6.1: End-to-end uplink throughput of 2.5 GHz system at different multipath levels

communications between the BS and the SS and limited scatters around the link, the

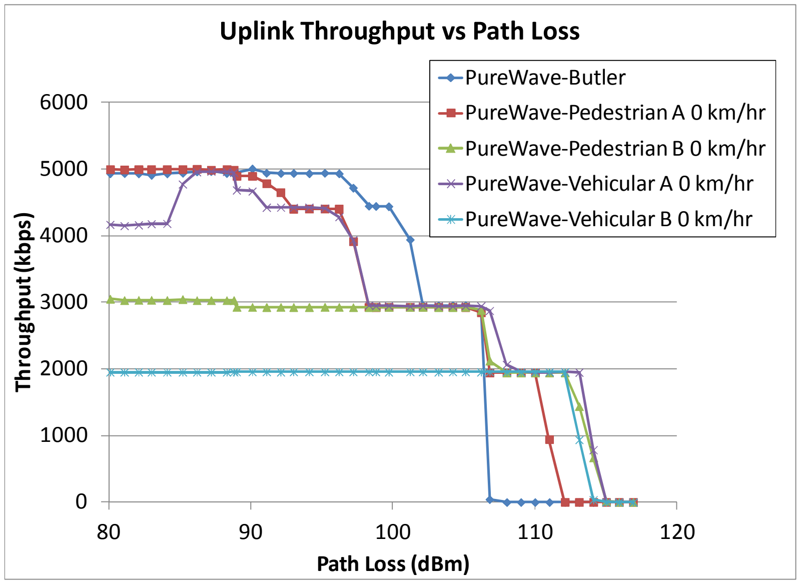


Figure 6.2: End-to-end uplink throughput of 3.65 GHz system at different multipath levels.

effect of multipath and scattering is limited and can be modeled with a Butler model without much loss of accuracy. On the other hand, in a suburban environment, with different scattering objects between the BS and the SS (like trees, buildings, cars, etc.), the multipath components are stronger and severely impact the quality of communication. This is modeled by the Vehicular B model. Since the communication infrastructure is likely to be deployed in either of these two extreme channel models (or anywhere in between), it becomes imperative that a thorough analysis of the link under different multipath and scattering environments is studied.

Figures 6.1-6.4 show the effects of multipath on end-to-end uplink and downlink throughputs at different path loss conditions. To remove the impact of velocity, all channels models are emulated at 0 km/hr.

Figures 6.1 and 6.2 show that with worsening channel conditions with higher multipath and scattering, the effective uplink throughput also decreases. In both 2.5 GHz

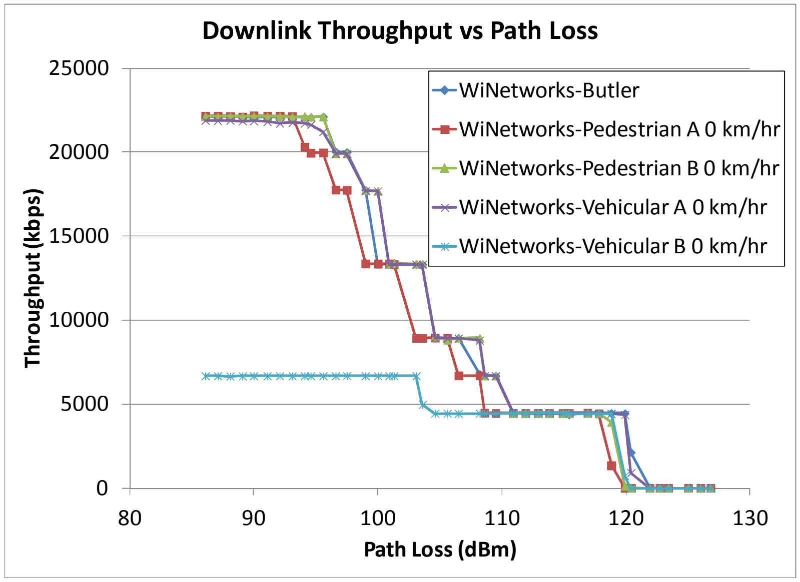


Figure 6.3: End-to-end downlink throughput of 2.5 GHz system at different multipath levels.

and 3.65 GHz systems, the maximum uplink throughput using the Butler model is around 5 Mbps. While using the Vehicular B model with high multipath and scattering, this value drops to around 1.5 Mbps and 2 Mbps respectively for the 2.5 GHz and 3.65 GHz systems.

Similarly, Figures 6.3 and 6.4 show a similar effect on end-to-end downlink. Using the Butler model, the maximum downlink rates achieved were around 22 Mbps and 21 Mbps for 2.5 GHz and 3.65 GHz, respectively. Similarly, using Vehicular B model, the rate drops to 6.5 Mbps and 4 Mbps, respectively.

Therefore, due to the extreme form of multipath as modeled by the Vehicular B model, the downlink throughput decreased by almost 80% and the uplink throughput decreased by almost 70%, which is very significant. This means that if it took two seconds to upload a 10 MB log file from a subscriber to the base station in ideal channel

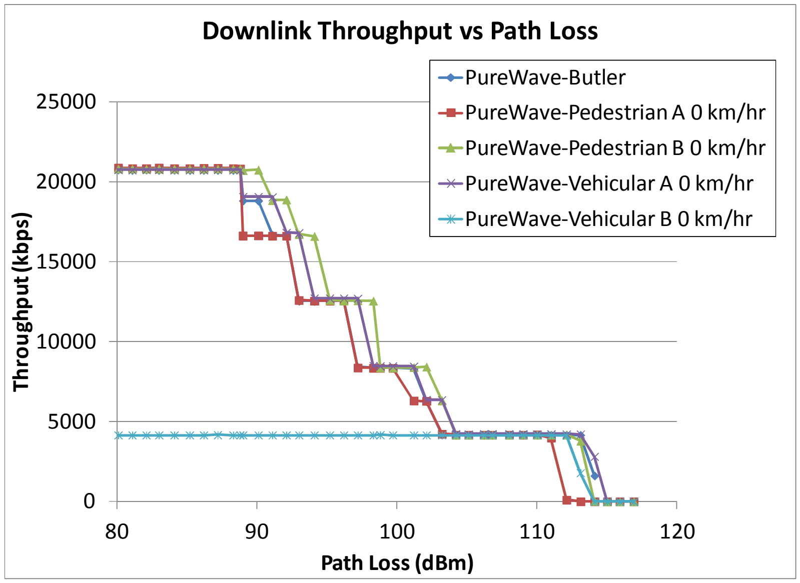


Figure 6.4: End-to-end downlink throughput of 3.65 GHz system at different multipath levels

conditions, it would require on average over five seconds to upload the same file under channel conditions closely modeled by the Vehicular B channel. This delay is very significant, especially if the information is real time or critical. With such high delay, the quality of a real-time signal like voice degrades significantly and becomes incomprehensible. Similarly, the time critical event log (e.g., reporting accidents or device breakdown, may become irrelevant after such long delay.

We can see that the impact of increases in multipath and scattering on both 2.5 GHz and 3.65 GHz systems is similar. Although the 2.5 GHz system has a slightly higher throughput in both uplink and downlink directions while using the Vehicular B model, it is unfair to jump to the conclusion about the superiority of the 2.5 GHz system for reasons discussed in the following sections. Therefore, it is unfair to brand any system as more vulnerable to multipath and scattering. In other words, the results clearly indicate that the losses suffered by selecting the 3.65 GHz spectrum over the 2.5 GHz spectrum due to multipath and scattering is not significantly higher and hence should not

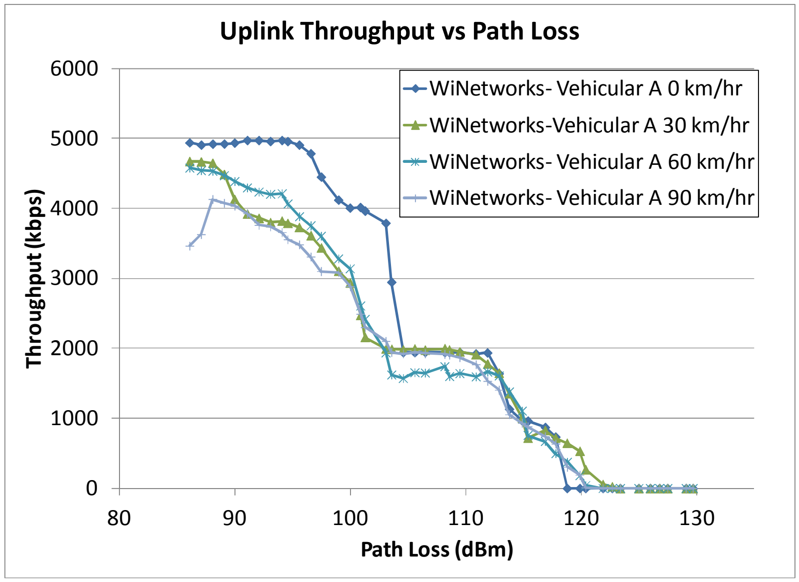


Figure 6.5: End-to-end uplink throughput of 2.5 GHz at different velocities for Vehicular A model.

discourage the designer from choosing the 3.65 GHz spectrum for network implementation.

6.1.2. Effect of velocity

Mobile WiMAX, as discussed in earlier chapters and as the name suggests, was proposed to address the issues of subscriber mobility. Mobile nodes require the network to have certain well-designed MAC layer features like efficient handover. They also require the physical layer design to address issues such as changing path loss and channel response and Doppler Shift.

Figures 6.5 to 6.8 illustrate the impact of subscriber velocity on end-to-end uplink and downlink throughputs at different path loss conditions. To remove the effect of multipath, same channel model (Vehicular A) has been emulated at different velocities. The results show the performance of the system at velocities of 0 km/hr, 30 km/hr, 60 km/hr and 90

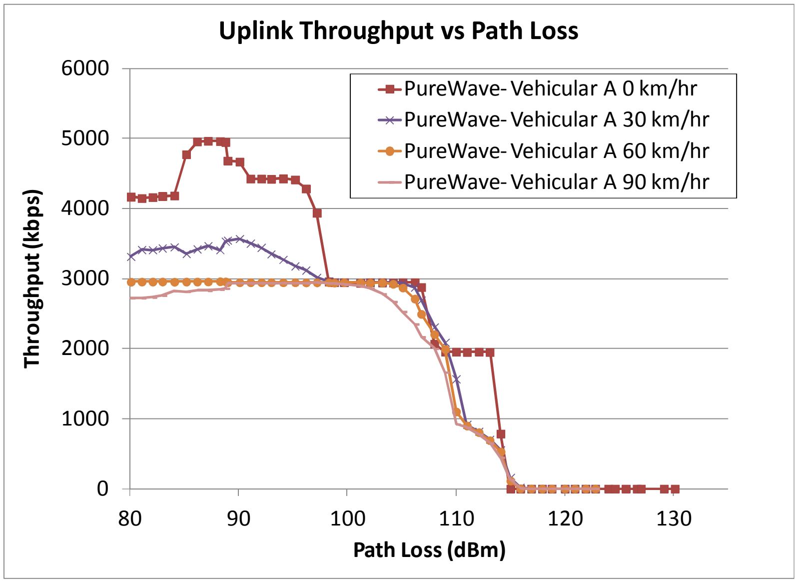


Figure 6.6: End-to-end uplink throughput of 3.65 GHz at different velocities for Vehicular A.

km/hr. A wide range of relative subscriber velocity has to be considered due to the diverse nature of the deploying environment, which ranges from slowly moving subscribers to railcars at full speed. The effects of velocity not presented in the results can be interpolated.

This test is designed to evaluate the quantitative effect of Doppler Shift only, as other parameters remain static. Due to the relative velocity between the BS and the SS, the frequency of the received signal is different from the transmitted signal, which may result in loss of synchronization. For high speed transportation mediums, the Doppler Shift is higher, resulting in higher loss of synchronization and more packet loss.

Figures 6.5 and 6.6 show that increasing velocity has an negative impact in net end-to-end uplink throughput for both 2.5 GHz and 3.65 GHz systems. This is because increase in relative subscriber velocity with respect to the base station leads to increased Doppler shift, which results in loss of synchronization at the receiving station causing packet

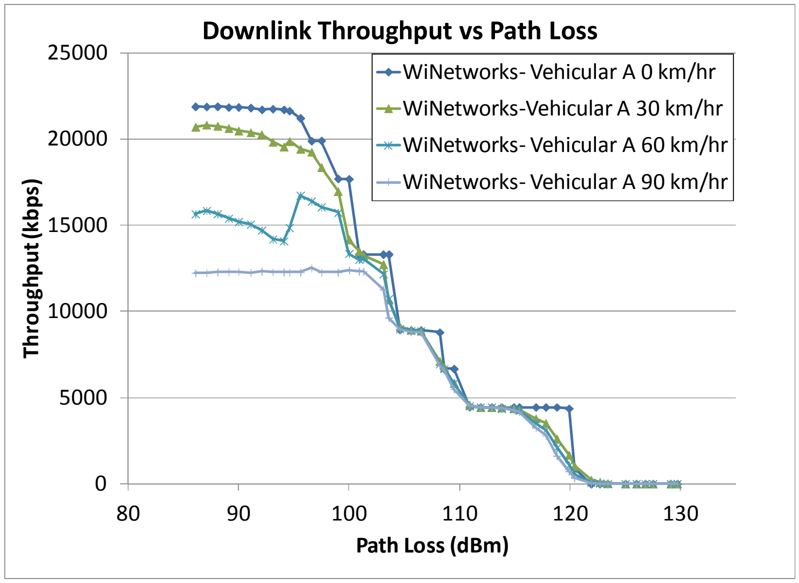


Figure 6.7: End-to-end downlink throughput of 2.5 GHz at different velocities for Vehicular A model.

losses and lower throughput. The maximum achievable uplink throughput for both systems is around 5 Mbps at 0 km/hr. It drops to around 4 Mbps and 3Mbps for 2.5 GHz and 3.65 GHz systems, respectively, at 90 km/hr.

A similar impact of increasing velocity is seen on end-to-end downlink throughput for both systems. From the maximum for 22 Mbps and 21 Mbps for 2.5 GHz and 3.65 GHz systems at 0 km/hr, the downlink throughput drops to 12.5 Mbps and 10 Mbps, respectively, for the same path loss conditions.

It is obvious that increasing velocity has a negative effect on the maximum rate at which data can be delivered in both systems. Similar to Section 6.1.1, 2.5 GHz system seems to have a slightly better performance when channel conditions gradually worsen.

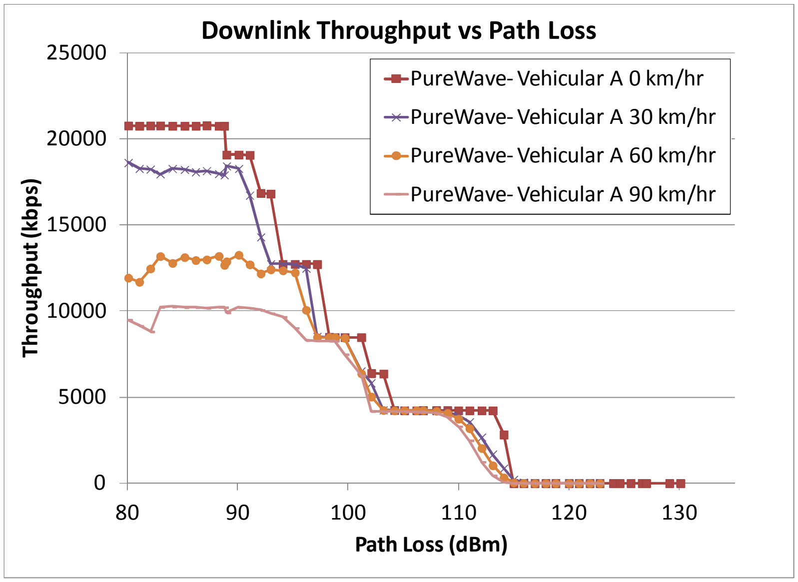


Figure 6.8: End-to-end downlink throughput of 2.5 GHz at different velocities for Vehicular A model.

Furthermore, we can also observe that the drop in throughput when the model is switched from Vehicular A to Vehicular B at a velocity of 0 km/hr is much higher than the drop when the velocity is increased from 0 km/hr to 90 km/hr using the same model. This clearly implies that the impact of multipath is much severe than the impact of increasing velocity for both 2.5 GHz and 3.65 GHz systems.

To put this conclusion in perspective quantitatively, the loss in downlink throughput due to changing in velocity from0 km/hr to 90 km/hr is around 50%, compared to around 30% for the uplink throughput. In other words, as described in section 6.1.1, uploading a 10 MB log file at 0 km/hr would require an average time of 2 seconds, whereas it would require about 3.5 seconds doing the same at 90 km/hr. Though this delay is still significant, it is not as bad as the case with an increase in multipath.

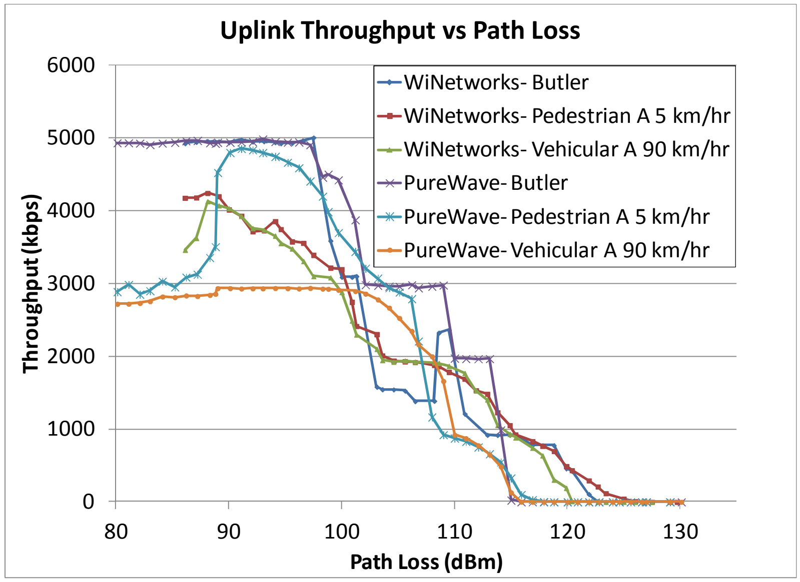


Figure 6.9: End-to-end uplink throughput.

Finally, it is also noticed that the impact of increasing velocity or Doppler Shift on network performance is similar for both systems. Therefore, a designer need not be worried about the impact on performance at high subscriber speed while selecting the 3.65 GHz system for network design, as the increase in losses due to use of the higher frequency spectrum is not very significant.

6.1.3. Throughput Comparison

Throughput or data rate is the most important quantitative performance measurement index of a communication link, which directly determines the number of subscribers the BS is able to serve with acceptable quality. It is also the major parameter that determines the link budget analysis. The net throughput deliverable over a link is affected by the effects of multipath and scattering, and relative subscriber velocity and path loss to various degrees. In order to implement a network infrastructure, it is advisable to inspect the performance of the link in terms of net throughput delivered under different channel

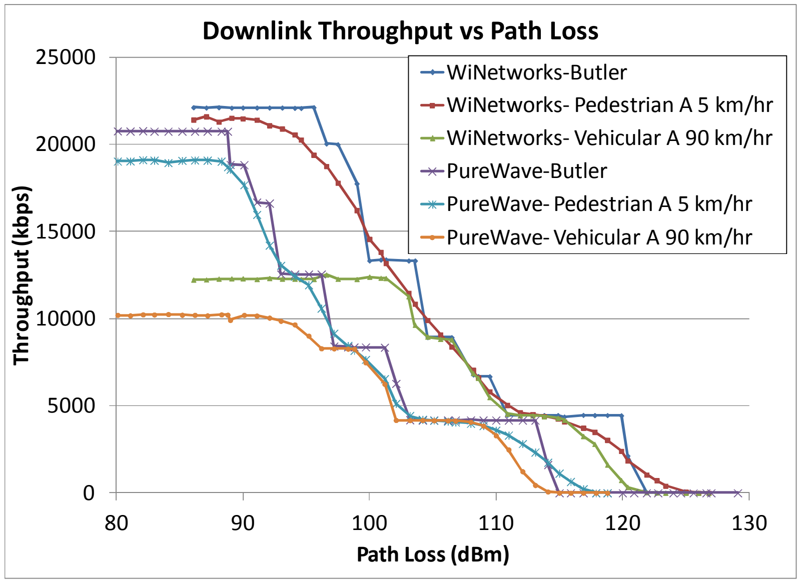


Figure 6.10: End-to-end downlink throughput.

conditions.

The maximum achievable uplink and downlink throughput for the 2.5 GHz and 3.65 GHz system at the minimum path loss conditions are 22 Mbps and 5 Mbps, and 21 Mbps and 5 Mbps, respectively. These transmission rates are very good and a major improvement over previous communication standards like 3G, which required delivering data at the minimum rate of 200 kbps.

Figures 6.9 and 6.10 show the comparison between uplink and downlink throughputs for the 2.5 GHz and 3.65 GHz systems, respectively. As expected, the throughputs decrease with an increase in path loss. We can observe that the downlink throughput curves are monotonic, while the uplink curves are not. This behavior is caused by uplink power control. The BS directs the SS to transmit at a higher power so as to maintain a constant uplink RSSI to compensate for the increase in path loss. This sudden increase in transmit power improves the uplink CINR, resulting in a surge in uplink throughput. Also, we can observe that the 2.5 GHz system can communicate up to a path loss of 125 dBm, while in the case of 3.65 GHz, the link dies at a path loss of 115 dBm. This behavior of 3.65 GHz is consistent with the observations in Sections 6.1.1 and 6.1.2; however, we should refrain from making any conclusion about the seemingly superior performance of the 2.5 GHz system.

Figures 6.11 and 6.12 respectively show uplink and downlink CINR with respect to path loss. We can see that the downlink CINR values in Figure 6.12 of the 2.5 GHz system are significantly better compared to those of the 3.65 GHz system at the same channel conditions and the same BS transmit power of 23 dBm. CINR clearly accounts for much of the apparent superior performance shown by the 2.5 GHz system in terms of higher throughput and maximum path loss before communication stops. The higher CINR of the 2.5 GHz system can be attributed to the vendor-specific implementations of hardware and firmware.

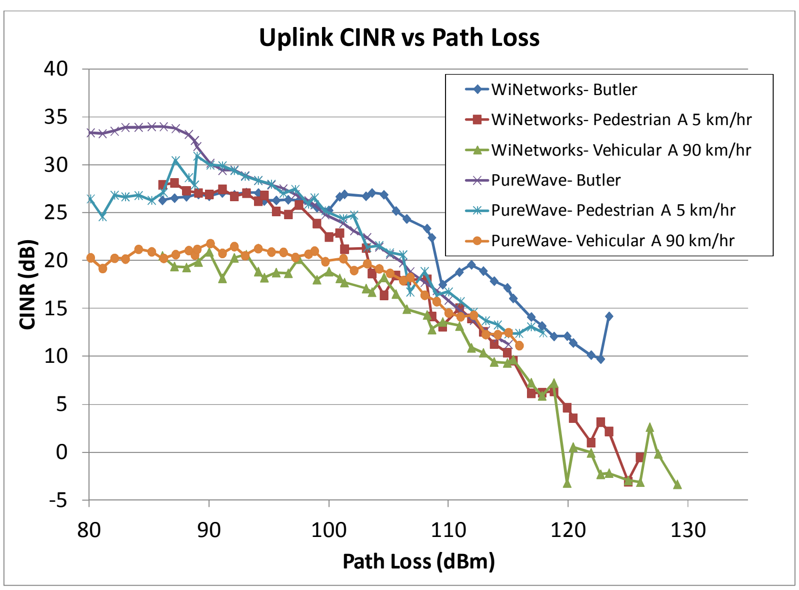


Figure 6.11: Effect of path loss on uplink CINR

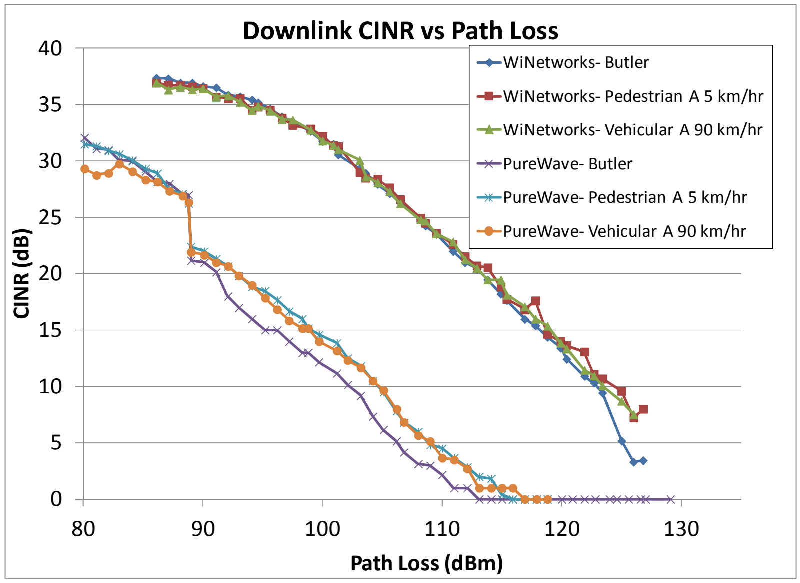


Figure 6.12: Effect of path loss on downlink CINR.

Figures 6.13 and 6.14 respectively show the uplink and downlink end-to-end throughputs with respect to the CINR values in the corresponding direction. In Figure 6.14, it seems like for the same downlink CINR, the downlink throughput for the 3.65 GHz system is higher. However, this is entirely due to path loss. For example, for the Vehicular A 90 km/hr channel model, at an average downlink CINR of 25 dB, the downlink throughput for 3.65 GHz system is about 10 Mbps, while it is only about 7 Mbps for the 2.5 GHz system. However, from Figure 6.12, it is seen that this CINR value of 25 dB corresponds to a path loss of 110 dBm for the 2.5 GHz system, while the same CINR value corresponds to 90 dBm for the 3.65 GHz system. Therefore, the apparent higher throughput seen in Figure 6.14 is actually due to this difference of 20 dB lower path loss or, in other words, better channel conditions rather than performance superiority of the 3.65 GHz system.

Also, as shown in Figure 6.13, the uplink throughput vis-a-vis the uplink CINR curves is highly fluctuating, which is expected. As path loss increases, the general trend for

CINR is to decrease. However, due to uplink power control, there are certain instances when CINR also increases in spite of the path loss being lower as shown in Figure 6.11. If we draw a horizontal line representing a fixed CINR through any of the channel model curves in Figure 6.11, it would intersect the curve at multiple points or path loss values. This makes the CINR value the same for different path losses or, in other words, CINR repeats. An exactly similar case can be made for uplink throughput as clearly demonstrated in Figure 6.9. This pattern of uplink CINR and uplink throughput to repeat at different path loss values tends to make unusual CINR-throughput pairs and give rise to high fluctuations.

Furthermore, Figures 6.9 to 6.14 clearly illustrate the necessity of including throughput, path loss and CINR as important performance evaluation descriptors. Basing the conclusion by excluding either of them leads to misinformation.

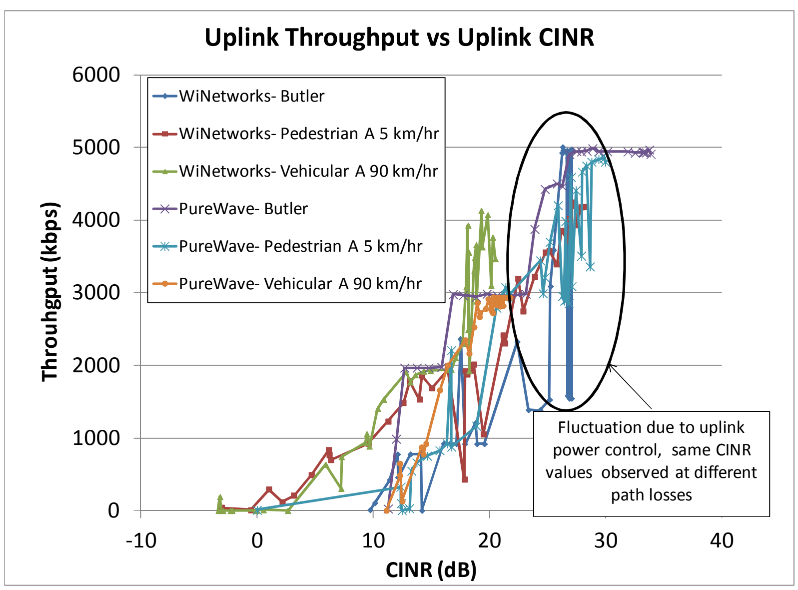


Figure 6.13: Effect of uplink CINR on uplink throughput.

6.1.4. Coverage Comparison

Coverage of a serving BS represents the region around it, which it can reliably serve. Ideally, it is a perfect circle with the BS at the center and a definite coverage radius. However, in practice such ideal coverage is impossible due to obstacles causing scattering and diffraction and asymmetric radiation from the transmitting antenna. The coverage area of the BS is also a critical factor in link budget analysis. It directly determines the number of and the separation between BSs that must be set up to work together to serve a larger service area or customer base.

Figure 6.15 shows the comparison of uplink and downlink coverage of 2.5 GHz and 3.65 GHz systems under the same channel conditions and BS transmit power. The path loss values from Figures 6.9 and 6.10 have been converted to the distance values by using the popular Friis equation,

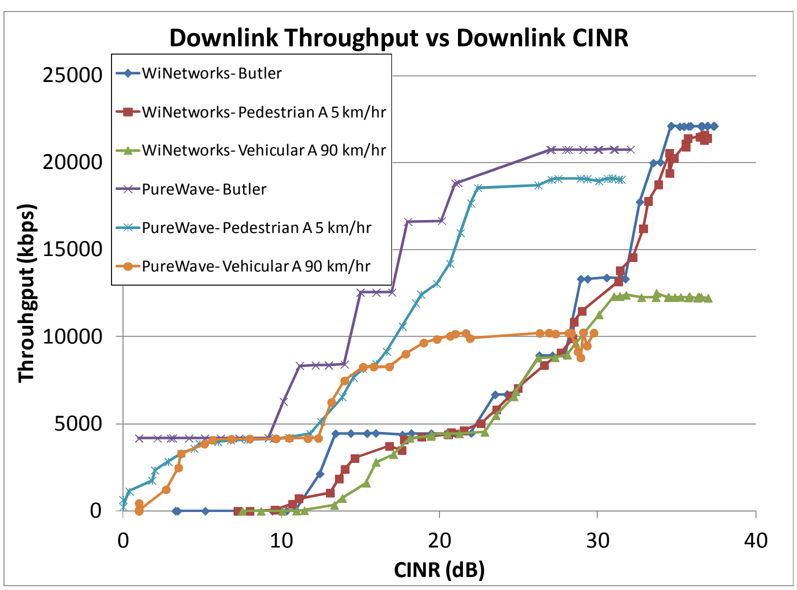


Figure 6.14: Effect of downlink CINR on downlink throughput.

$$Path\ Loss = 10n \log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (6.1)$$

where d is the separation between BS and SS, λ is the wavelength of the carrier wave and n is the path loss exponent.

Since the 3.65 GHz system suffers from higher path loss at the same distance, it is expected to have a lower coverage. We are more interested in exploring how much of the loss in coverage can be attributed to the use of higher frequency and how much of it can be attributed to proprietary vendor implementation of the protocols. Furthermore, it is of prime importance to evaluate if this loss can be compensated for by the financial gains of using a 3.65 GHz license.

It is observed that for a 2.5 GHz system the maximum achievable throughput is around 22 Mbps. Assuming an average bandwidth utilization by each user to be around 0.5 Mbps, the BS can support on average 40 to 45 active users at a time with satisfactory

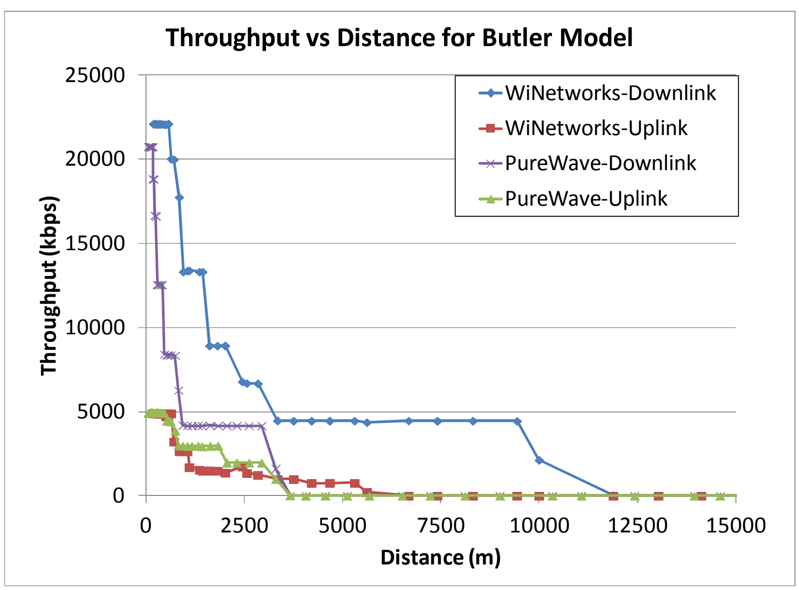


Figure 6.15: Effect of increasing separation between BS and SS on throughput

performance within a coverage radius of about 12 km under best channel conditions (path loss exponent, n=2). The maximum achievable throughput for the 3.65 GHz system is around 21 Mbps. Therefore, it can still serve the same number of users on average but within a much smaller coverage radius of 3.5 km. However, as discussed in earlier sections, we have to take into account the performance losses due to the difference in CINR.

Under the same channel conditions and transmit power, the coverage radius of a source 'd' is related to the transmit frequency 'f' by,

$$d \propto \frac{1}{f} \tag{6.2}$$

This gives the theoretical coverage radius for the 3.65 GHz base station, under the aforementioned channel conditions and transmission power, as 8 km. Due to the CINR difference, this value was observed to be only 3.5 km. Finally, we should note that, due to federal regulations, 3.65 GHz equipment is transmit power-restricted and hence operates at lower maximum power under commercial use, which further reduces their coverage and performance.

6.2. Field Test Results

In this sub-section, the results obtained while testing the same equipment in real world test beds are shown. Though the lab test results are sufficient to draw reliable conclusions, it is advisable to test the network on field for multiple reasons. Firstly, field tests help to validate laboratory tests. And secondly, it is necessary to test the equipment in the real world where it will be eventually deployed.

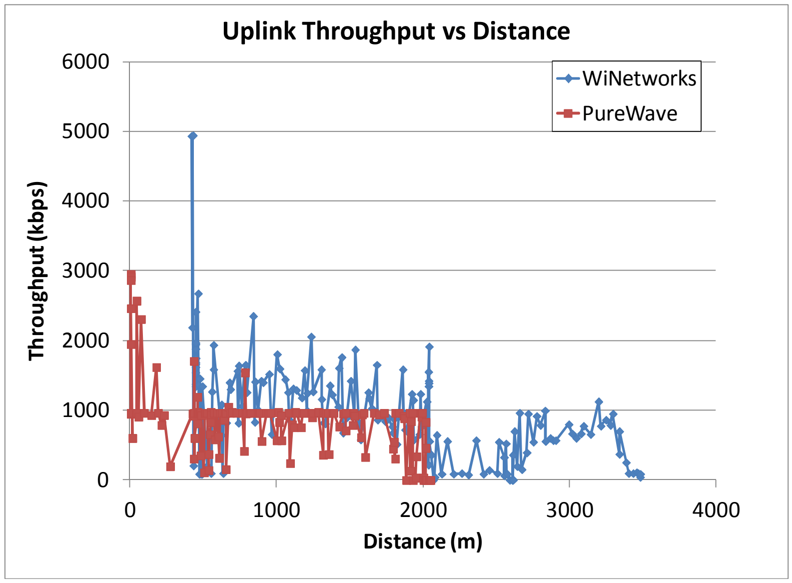


Figure 6.16: Change in uplink throughput with distance.

Figures 6.16 to 6.21 show the field test counterparts of Figures 6.9 to 6.14 shown in section 6.1.2.

Figures 6.16 and 6.17 show the uplink and downlink throughput achieved under the test conditions with respect to separation between BS and SS as measured by a GPS unit. Since the test bed area is a suburban environment with large multipath and scattering in some places and direct line of sight in some, the throughput curves show large fluctuations. Also, as mentioned in Chapter 4, due to randomly changing wireless environment beyond our control, the test conditions cannot be exactly reproduced to make a fair comparison between the two spectrums. Nonetheless, they do conform to the values obtained in the laboratory tests to a large extent. As with results obtained in laboratory tests, the 2.5 GHz system seems to produce a higher throughput.

Figures 6.18 and 6.19 show the uplink and downlink CINR respectively with regard to the separation between BS and SS. These figures are again similar to their lab test

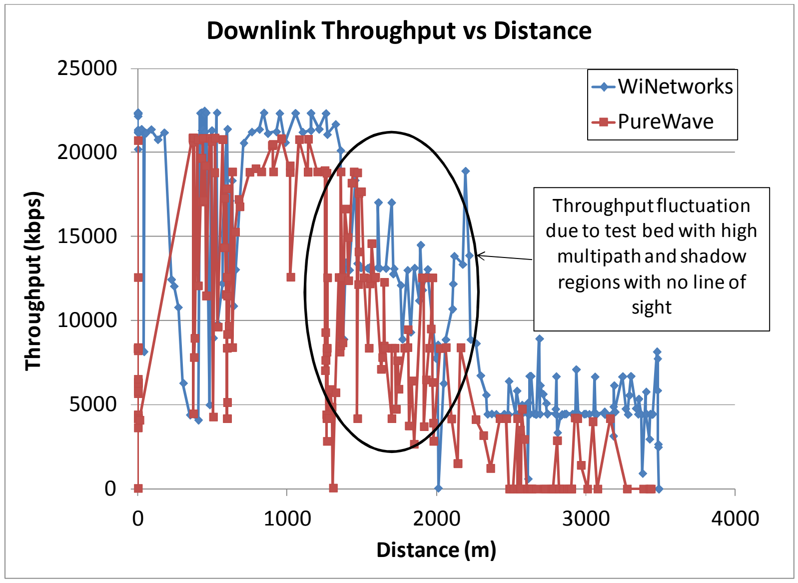


Figure 6.17: Change in downlink throughput with distance.

counterparts. It can be clearly noticed that the 2.5 GHz system has a higher CINR under the same distance and transmit power. Again, as discussed earlier the channel conditions cannot be guaranteed to be identical, but they do not prohibit us from making a conclusion. This higher CINR, as explained earlier, is attributed to the vendor specific device implementation of hardware and firmware and explains the higher throughput for the 2.5 GHz system.

Figures 6.20 and 6.21 respectively show the uplink and downlink end-to-end throughput with regard to the CINR in corresponding link direction. As seen with the laboratory test results, the downlink throughput of the 3.65 GHz equipment is limited within a lower range of CINR values and seems to have a higher throughput than 2.5 GHz for a given downlink CINR. But as explained in an earlier case, this is due to differences in path loss, or more appropriately, a separation between BS and SS in this case.

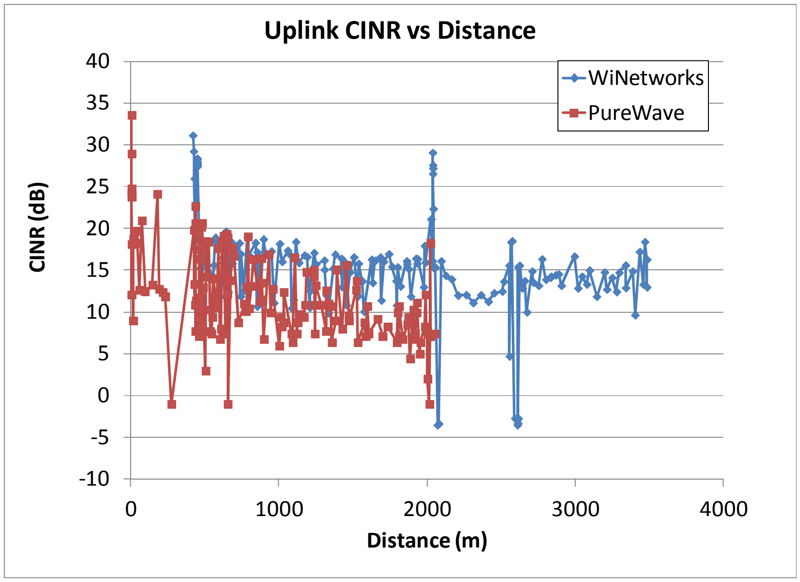


Figure 6.18: Uplink CINR under test bed channel conditions

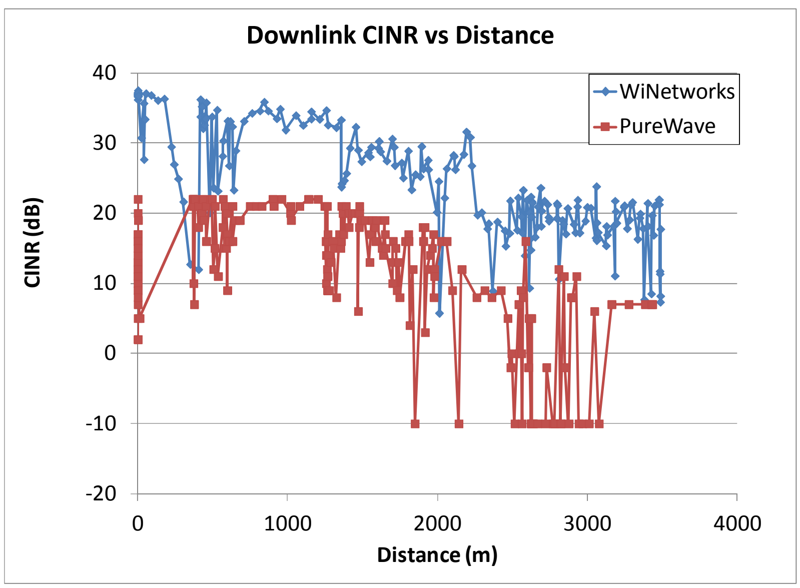


Figure 6.19: Downlink CINR under test bed channel conditions.

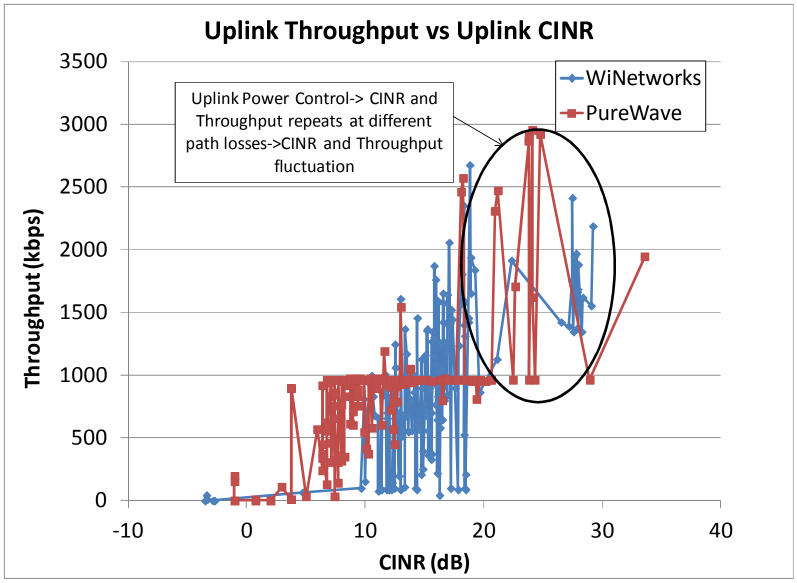


Figure 6.20: Effect of uplink CINR on uplink throughput in the test bed.

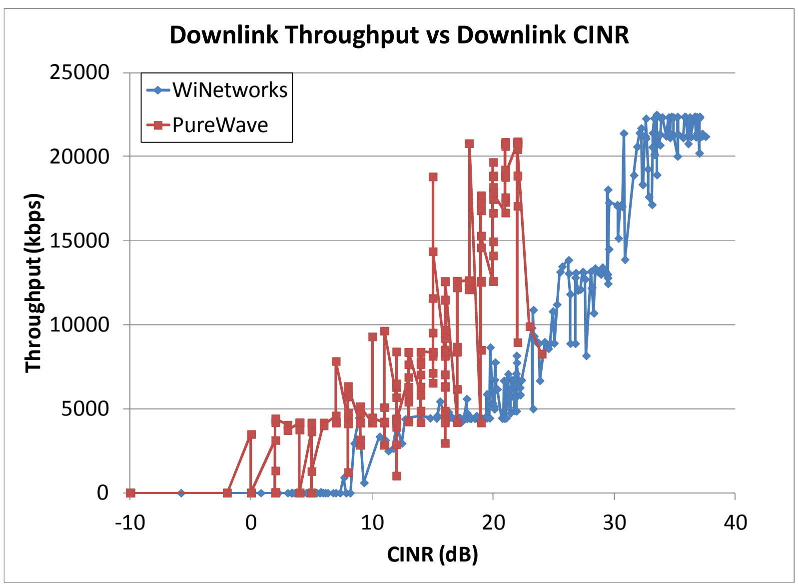


Figure 6.21: Effect of uplink CINR on uplink throughput in the test bed.

Chapter 7. SUMMARY AND CONCLUSION

This chapter summarizes the research undertaken along with reiterating the rationale behind the endeavor, highlights the obtained results, and finally concludes the document.

7.1. Summary

The human desire to communicate has motivated the field of communications. The technology behind communications has gradually evolved from the prehistoric age of semaphores to the modern age of smart phones and broadband internet. With each stage of advancement, communications technology has become smaller, more reliable and cheaper and more widespread. However, the human need to communicate has continuously evolved, demanding more cost-effective and bandwidth- efficient means of information transfer. Different organizations such as the ITU have recognized and addressed these needs, producing four generations of mobile communications over the last fifty years. The latest among them is the fourth generation of wireless cellular standards, more popularly known as 4G, which promises a high data transfer rate capable of delivering high quality multimedia services like video streaming and IP TV. Mobile WiMAX has emerged as one of the prime contenders to satisfy the ITU requirements of 4G network and become the *de facto* standard of the latest generation.

The FCC issues licenses for Mobile WiMAX in various spectrums, of which 2.5 GHz and 3.65 GHz are the most common. The 2.5 GHz spectrum has widespread commercial use, as it undergoes relatively lower propagation losses providing higher range and requiring fewer number of base stations to be installed for the same coverage. Therefore, most academic and industrial research has been centered on this spectrum. However, certain entities like Wireless ISPs with a smaller customer base and companies needing some communications infrastructure for local management and control operations could prefer the use of the 3.65 GHz spectrum, particularly due to its favorable licensing requirements. In this work, we have provided a generic in-depth quantitative performance description of the 3.65 GHz spectrum and compared it with the performance of the 2.5 GHz spectrum. Our results are primarily intended for the purpose of selection of an appropriate spectrum for the user based on requirements. Furthermore, these results can also be used for link budget analysis and equipment benchmarking for quality control.

For obtaining the required performance indicators, off-the-shelf commercial equipment was used as described in Chapter 5. For testing the 2.5 GHz spectrum, Ruggedcom's RuggedMax WiN7000 and RuggedMax WiN5100 vehicular subscriber unit were used as the base station (BS) and subscriber station (SS), respectively. Similarly, for testing the 3.65 GHz spectrum, PureWave Network's PureWave Quantum 1000outdoor device was used as the base station and Gemtek's ODU-series CPE was used as the subscriber station. A software-controlled channel emulator was used to emulate physical channels between the end devices. The parameters of the channel were varied and the desired statistics were observed.

In Chapter 6, results pertaining to the effects of change in velocity and multipath and scattering on uplink and downlink throughput and effects of path loss or distance between BS and SS on uplink and downlink throughput and coverage and CINR for both laboratory and field tests were presented. It is shown that increasing multipath and scattering and increasing relative subscriber velocity adversely affects both 2.5 GHz and 3.65 GHz spectrums. The increase in multipath and scattering was observed to be more severe than that of the increase in velocity. Further, there is no evidence to indicate any significant performance losses due to increases in multipath and scattering or relative subscriber velocity by opting for the 3.65 GHz spectrum over the 2.5 GHz spectrum. It is shown that in ideal channel conditions, the maximum achievable downlink throughput using the 2.5 GHz and the 3.5 GHz systems was around 22 Mbps and 21 Mbps, respectively, under given channel conditions and device configurations. Although the 2.5 GHz spectrum appears to have higher throughput, it is shown that this is entirely due to higher CINR, which is directly related to vendor specific implementation of device hardware and software. Further, it is shown that the coverage radius of the 2.5 GHz and the 3.5 GHz systems was 12 km and 3.5 km (8 km theoretically) respectively under the best channel conditions and 200 m and 120 m in a suburban environment with high multipath and scattering. Assuming an average user bandwidth utilization of 0.5 Mbps, both systems can serve on average of 40 to 45 users satisfactorily within the aforementioned distance from the serving base station. Also, it can be asserted that the quality of a communication link cannot be decided by just looking at the data rate and/or coverage. Other performance indicators such as CINR must be taken into account to avoid misleading conclusions. Furthermore, the field test results conform to the data observed in the lab test results, which lends more credibility to the above analysis.

7.2. Conclusions

Alhough 2.5 GHz Mobile WiMAX has been a favorite area for researchers in wireless communications, not much significant work has been published in the area of 3.65 GHz Mobile WiMAX. However, the 3.65 GHz spectrum is often a more favorable option for implementation in some cases and in absence of any significant data to compare the spectrums, it becomes impossible to select one over the other. In this study, an in-depth quantitative study of the 3.65 GHz Mobile WiMAX was performed and the results were compared with those obtained from the 2.5 GHz spectrum. It is seen that, other than lower coverage radius, the 3.65 GHz system suffered no other significant performance losses when compared with the 2.5 GHz system. The question of opting for 3.65 GHz over 2.5 GHz can be totally based on the financial gains of a lower licensing fee over the need to install a higher number of base stations to serve the same area, without worrying about the performance losses of the 3.65 GHz spectrum. With regard to our test beds and research for the North American railroad companies, the use of the 3.65 GHz system is recommended.

The area of Mobile WiMAX is still evolving towards fulfilling ITU's 4G requirements. This research can be further extended to study the performance comparison by using different antenna configurations (MIMO and beamforming) and different packet types other than UDP. Similarly, different vendor broadband solutions can be tested for similar results, and other performance parameters such as packet losses, jitter, latency and EVM (Error Vector Magnitude) can be measured.

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