Analysis of Various Aspects of Base Station for WiMAX

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Abstract— the original 802.16 standard was based on single carrier physical (PHY) layer and it used time division multiplexed (TDM) MAC layer, whereas the 802.16a standard use OFDM based on physical layer. It also supports Orthogonal Frequency Division Multiple Access (OFDMA) for MAC layer. In 2004, IEEE 802.16-2004 standard was introduced and it mainly targeted the fixed applications. In December 2005, some amendments were made in IEEE 802.16-2004 standard and a new standard IEEE 802.16e-2005 was created which had support for mobility. For practical implementations, WiMAX defines some system and certification profiles.

A system profile defines and includes required and optional features of physical and MAC layers as selected by WiMAX Forum from IEEE 802.16-2004 and IEEE 802.16e-2005 standard. Now days, WiMAX has two system profiles. One is based on IEEE 802.16-2004, OFDM PHY and is called Fixed System profile. The other is based on IEEE 802.16e-2005, scalable OFDMA PHY and it is called mobility system profile. While a certification profile is a specific representation of system profile.

Keywords—PHY, OFDMA, WiMAX, MAC Layer, OFDM PHY

I. INTRODUCTION

Wireless communication is one of the most important achievements in the history of science and communications. These wireless communication networks are the backbone of Cellular networks, Radio and Television channels broadcasting, data transmission and reception through satellites and many others. Due to these wireless communication networks, the communication has become extremely fast and the services remain available to the user almost where ever he goes. The future of wireless technologies appears to be very bright. Worldwide Interoperability for Microwave Access (WiMAX) is the newest communication technology for wireless transmission and it is standardized as IEEE 802.16-2004 and IEEE 802.16-2005 or IEEE 802.16e.

A WiMAX system consists of 2 basic parts:

1. WiMAX tower: Concept wise its same as towers of other cellular networks but its coverage area is much more (around 8000 square kilo meters).
2. WiMAX receiver: It has a small antenna and could be in the form of PCMCIA card or in a small box. Now-a-days, laptops also have this WiMAX receiver built in.

The WiMAX tower stations can be directly connected to Internet backbone with the help of high speed cables like optical fibers. And the tower can also be connected to other towers through Line-of-Sight (LOS) microwaves links and such type of connections are called backhauls [1].

The main characteristics of IEEE 802.16 / WiMAX technology are:

- Carrier frequency is less than 11 GHz. The frequency bands currently used are 2.5 GHz, 3.5 GHz and 5.7 GHz.
- Orthogonal Frequency Division Multiplexing (OFDM) is the technique used for transmission due to its high resource utilization [2].
- Data rate of 10 Mbps at the moment but in near future it will reach up to 70 – 100 Mbps.
- Coverage area spans up to 20 km.

The IEEE 802.16 standard was created in 1999 and it was divided into two sub-groups:

1. 802.16a, center frequency within the interval 2-11 GHz. This technology was intended to be used for WiMAX and it's used for non-line-of-sight (NLOS) communication.
2. 802.16c and its operated in frequency range of 10-66 GHz and used for line-of-sight (LOS) communication.

A certification profile specifies operating frequency, channel bandwidth and duplexing mode. According to WiMAX Forum, there are about 5 fixed and 14 mobile certification profiles as shown in Table 1.1 as published by the WiMAX forum in September 2008. The first two profiles are related to fixed WiMAX and others are related to mobile WiMAX

II. WIMAX TECHNICAL OVERVIEW

WiMAX is a wireless broadband technology which provides a number of flexible solutions for deployment and potential service offerings. The technical overview of WiMAX is as follows:

A. WiMAX Physical Layer

WiMAX is a Bandwidth Wireless Access (BWA) system and data is transmitted at high speed through radio waves using different frequency. The Physical layer establishes (physical) connection between two entities and is responsible for the transmission of bit sequences. It tells us about the type of signals used, type of modulation and demodulation schemes, transmission power and other such physical characteristics.

In 802.16 standard five physical interfaces are defined.

Where:

- Wireless MAN-SC and Wireless MAN-SC a use Single Carrier (SC) modulation
- Wireless OFDM use Orthogonal Frequency Division Multiplexing (OFDM) with 256 point Fast Fourier Transform (FFT).
- Wireless MAN – OFDMA use Orthogonal Frequency Division Multiple Access (OFDMA) with 2048 point Fast Fourier Transform (FFT).
- Wireless HUMAN is High-speed Unlicensed Metropolitan Area Network

Two major duplexing modes, Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD), are used in 802.16 systems. WiMAX physical layer considers OFDM as its transmission technique for obtaining higher data rates. In Media Access Control (MAC) address, different options are used such as Automatic Repeat Request (ARQ), Address Allocation Server (AAS), Mobility, and Mesh.

B. Basics of OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation scheme because it divides a higher bit rate data stream into multiple parallel lower bit rate streams and modulate each of these streams on separate carriers which are also known as subcarriers [4]. Multicarrier modulation schemes extinguish or minimize intersymbol interference (ISI) in the channel and as a result increasing symbol time. Higher data rate systems have small symbol durations, but due to splitting of higher rate data stream into multiple parallel streams higher symbol durations are achieved.

In OFDM, the subcarriers are selected in such a way that they are all orthogonal to each other over symbol duration. This reduces the need of non-overlapping subcarrier channels for extinguishing ISI. The spacing between subcarriers is important and the subcarrier bandwidth is given as

$$BSC = B / L \qquad (2.1)$$

Where: B represents nominal bandwidth.

L represents number of subcarriers

And it ensures that all the subcarriers are orthogonal to each other over symbol period.

In OFDM, for extinguishing ISI, guard intervals are introduced between symbols. By using larger guard intervals than expected delay spread, ISI can altogether be extinguished. However, the addition of guard intervals decreases bandwidth efficiency and wastes a lot of power. This power wastage depends upon the ratio of symbol duration and guard time. The larger the symbol period, the smaller the bandwidth efficiency and larger the power loss.

C. Parameters of OFDM

The fixed and mobile WiMAX are a little bit different to each other in case of physical layer implementations of OFDM. Fixed WiMAX based on IEEE 802.16-2004 uses OFDM of 256 bits Fast Fourier Transform (FFT) length on the physical layer, while the Mobile WiMAX based on IEEE 802.16e-2005 uses Scalable OFDMA of 128-2048 bit FFT on the physical layer. Table 2.2 shows OFDM parameters for Fixed and Mobile WiMAX.

For Fixed WiMAX OFDM-PHY, the FFT size remains fixed at 256 bits where 192 bits are used for containing data, 8 bits are used as Pilot Subcarriers for channel estimation and synchronization and the remaining 56 bits are used as guard band subcarriers [4]. The FFT size is fix so higher subcarrier spacing is achieved by using larger bandwidths and smaller symbol time. To overcome the delay spread, guard time is used by lowering the symbol time. For Mobile WiMAX OFDMA-PHY, the FFT size can be changed from 128 to 2048 bits. By increasing the bandwidth, the FFT also increases in such a way that subcarrier spacing remains 10.94 kHz due to which OFDM symbol duration remains fixed and the scaling has very little effect on the higher layers. This subcarrier spacing of 10.94 kHz is taken because it provides a good equilibrium between delay spread and Doppler spread requirements when used in mixed (fixed and mobile) environments.

D. Slot and Frame Structure

The physical layer of WiMAX is also responsible for allocation of slots and framing. A slot is a minimum time-frequency resource which can be allocated to a given link by WiMAX system. Now depending on the sub-channelization scheme, every slot has one sub-channel over one, two or three OFDM symbols [5]. The adjacent slot assigned to some specific user is called that user’s data region.

Fig.1 shows frames of OFDM and OFDMA while operated in TDD. The frame is divided into two sub frames, one frame is used for downlink and other frame is used for uplink and both the frames are separated by guard interval. For supporting different traffic profiles, the downlink-to-uplink-sub-frame ratio might change from 3:1 to 1:1. In case of frequency division duplexing, frame structure will remain same and the only difference will be that both downlink and uplink frames will be sent simultaneously over multiple carriers.

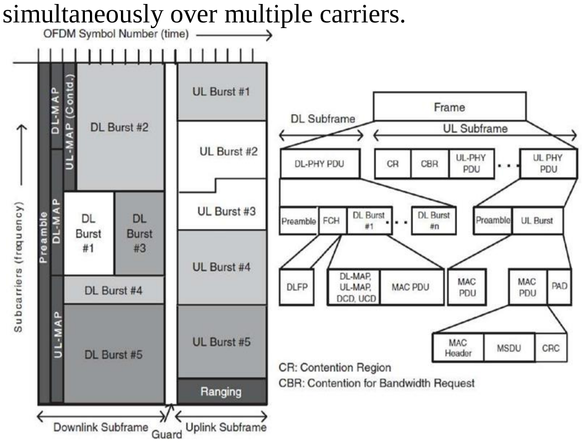

Fig.1: A sample TDD frame structure for mobile WiMAX [5]

E. Physical layer Data rates

In WiMAX, the physical layer data rates changes according to the operating parameters like channel bandwidth, modulation and coding schemes, number of sub channels, OFDM guard time and over sampling rate. Table 2.4 gives us a list of physical layer data rates at different channel bandwidths and modulation and coding schemes [5]. The TDD case is assumed here with a 3:1 downlink-to-uplink bandwidth ratio. It is also assumed that frame size is 5 ms. OFDM guard interval is 12.5 percent and subcarrier permutation scheme is PUSC. And only one OFDM symbol is used for downlink frame overhead while all other data symbols are available for user traffic.

According to IEEE 802.16e-2005 standard, the WiMAX Forum's Network Working Group (NWG) provides and creates network requirements, architecture and protocols for WiMAX. The WiMAX NWG has created a reference model which is used for deploying WiMAX architecture framework and this model also provides interoperability among different WiMAX devices and operators. The reference model is an IP based service model and its single architecture supports fixed, nomadic and mobile deployments of WiMAX. An IP based WiMAX network architecture is shown in Figure 2

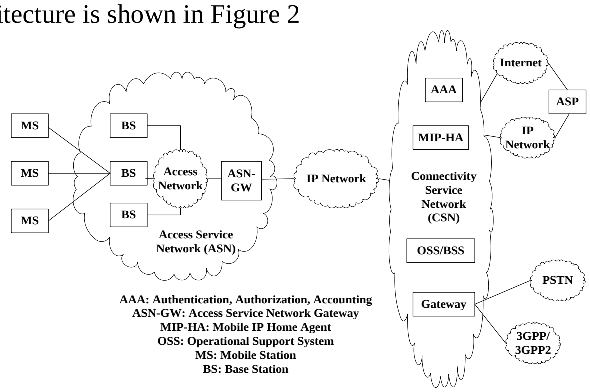

Fig.2: WiMAX network architecture [5]

III. MULTIPLE ANTENNA SYSTEMS IN WIMAX BASE STATION

Modern multiple antenna systems can be implemented in order to get the benefit of multiple path systems when compared to the old designed single antenna systems. In this case, when talk about multiple antenna systems with WiMAX; we will automatically enter in the throughput and better error performance achievement in multiple path scenarios.
Generally, there are three different techniques of implementing multiple antenna systems and we will mainly focus two of them:

A. Diversity Schemes

There are two main types of diversity, one is transmitting diversity and the other is receiving diversity. Diversity is usually between two antennas and each antenna has one channel. One antenna is at the base station and the other is at the service station. The base stations keeps record of the transmission and receive signal information with each channel. However, there can be many antennas at the base station and the service station. Here we will elaborate three different methods under the diversity schemes.

B. *Space Time Coding (STC)*

Space Time Coding is the popular scheme of transmits diversity. In this technique, we send the information through two different antennas which are called transmitters. Thus, we are using two mediums space and time to transmit the information so this technique is called space time coding and this technique is similar to the Alamouti scheme according to the 802.16 standard.

Our main focus of using this scheme is to enhance the error rate performance of the systems which send the information through coded medium. We will take two antennas at the base station as shown in the Figure 3.1. When we want to send the data bits of 1000, we have to use the modulator to send the data bits. The modulator converts these data bits into symbols called s_1 and s_2. After this, these symbols enter an encoder known as space time encoder, which then sends s_1 followed by - s_2* to antenna 1 and s_2 followed by s_1* to antenna 2. In the figure, the (*) is the complex conjugate of the symbols. When these symbols are transmitted from the base station, then it will be transmitted two different symbols towards the receiver antenna.

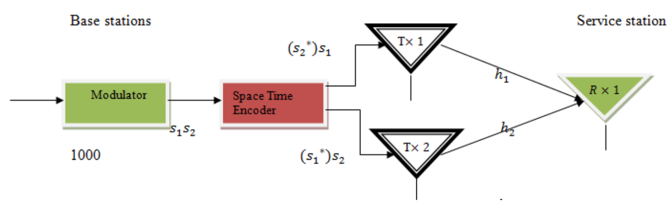

Fig.3: Space Time coding scheme [6]

The 2 × 4 Space Time Coding (Alamouti) is known as rate 1 code because data is neither decreased nor increased. As shown in above scenario, there are complex channel gains h_1 and h_2 from antenna 1 and 2 to the receive antenna and we assumed that over two symbol time, the channel is constant; that is, $h_1(t=0) = h_1(t=T) = h_1$.
The received signal r (t) is written as

$$r(0) = h_1 s_1 + h_2 s_2 + n(0),$$

$$r(T) = -h_1 s_2^* + h_2 s1^* + n^*(T)$$

Where n (T) is a White Gaussian noise sample. We assume that channel is known at the receiver, so we can use the following diversity combining scheme

$$y1 = h1^* r(0) + h_2 r^*(T)$$

$$y2 = h_2^* r(0) - h_1 r^*(T)$$

This can be expressed as

$$y_1 = h_1^* (h_1 s_1 + h_2 s_2 + n(0)) + h_2 (-h_1^* s_2 + h_2^* s_1 + n^*(T))$$

$$y_1 = (|h_1|^2 + |h_2|^2) s_1 + h_1^* n(0) + h_2 n^*(T)$$

Similarly,

$$y_2 = (|h_1|^2 + |h_2|^2) s_2 + h_2^* n(0) - h_1 n^*(T)$$

Thus, the two received samples r (0) and r* (T) combines linearly with the help of this simple decoder. This also eliminates all the interference so the resulting signal-to-noise ratio can be computed as

$$\gamma_{\Sigma} = \frac{(|h_1|^2 + |h_2|^2)^2 \, \varepsilon_x}{|h_1|^2 \, \sigma^2 + |h_2|^2 \, \sigma^2 \, 2}$$

$$\gamma_{\Sigma} = \frac{(|h_1|^2 + |h_2|^2)^2 \, \varepsilon_x}{\sigma^2 \, 2}$$

$$\gamma_{\Sigma} = \frac{\sum_{i=1}^{2} |h_i|^2 \, \varepsilon_x}{\sigma^2 \, 2}$$

Thus for space and time coding, the total transmit energy per data symbol will be ε_x and each is send twice $\varepsilon x/2$. The linear decoder used here is the simplest decoder with zero mean noise.

C. Antenna Switching (AS)

Antenna switching can be applicable to both downlink and uplink transmission systems. This is the simplest scheme to obtain diversity gains of the systems. In this scheme, we choose the one antenna with the best channel gain rather than using the multiple antennas to get the combination of signals.

To understand antenna switching, let us take example of Airpan's Easy product technique as shown in Figure 4. This product gives 90^0 antenna separation and it chooses the antennas which provide the best signal level at any time. This scheme is useful in desktop deployment scenario.

Fig.4: Airpan's Easy ST with 4×90^0 [6]

D. Smart Antenna Systems

Smart antenna systems technique can be obtained by implementing different ways such that null steering and beam-forming. Due to this it is also called adaptive antenna systems because the pattern which channels follow is directly towards the user and away from the source of interference.

E. Classified MIMO Theory Shortcomings

To understand better the performance gain of MIMO in WiMAX systems, we can emphasize the previous expressions related to spatial multiplexing and from that we can draw the following assumptions,

- Fading will be frequency straight. In other words, data entries of H are of various and scalar values so we can ignore the multipath ways.
- The total number of antennas will be separated with each other due to the different and random values of entries.
- Noise will be negligible and interference is being small.

Finally, all the above supposition will be applicable to the MIMO in the WiMAX systems in term of performance and data bits.

IV. SIMULATION AND OUTCOMES

We have tried to analyze the effect of Signal-to-Noise Ratio (SNR) on Bit Error Rate (BER) for Diversity and MIMO techniques using different modulation and demodulation schemes and by increment and decrement of the number of antennas at transmitter and receiver sides. Following parameters are used in our simulations

Table 1: List of Parameter

Parameter	Description
Number of Packets	1000
Multiple SNR values	0 to 20 (in steps of 2)
Binary Phase Shift Keying (BPSK) Quadrature Phase Shift Keying (QPSK) Quadrature Amplitude Modulation (QAM)	Modulation and Demodulation Schemes
Rayleigh Channel with flat fading	Communication Channel

We have simulated the system by using Transmit Diversity (Space Time Coding) and Receiver Diversity (Maximum Ratio Combining) techniques. Based on the mathematical calculations given in chapter 3, we have simulated our system first by using 1 transmit antenna and 1 receive antenna (means no diversity). Then we used 2 transmit antennas and 1 receive antenna for Space Time Coding. And for Maximum Ratio Combining (MRC), we used 1 transmit antenna and 2 receive antennas.

In this simulation, we assume that the Rayleigh channel is already known at the receiver. We generated a stream of random numbers and then fed these numbers into a modulator. The modulated signals are then fed into an encoder. The encoded signals are then transmitted through the Rayleigh channel. At the receiver side, the signals are decoded and demodulated giving the actual data.

A. Transmit and Receive Diversity using BPSK

Figure 5 shows the BER for different values of the SNR for the three transmit and receive diversity schemes using BPSK modulation scheme. All the plots are best fitted by using berfit function.

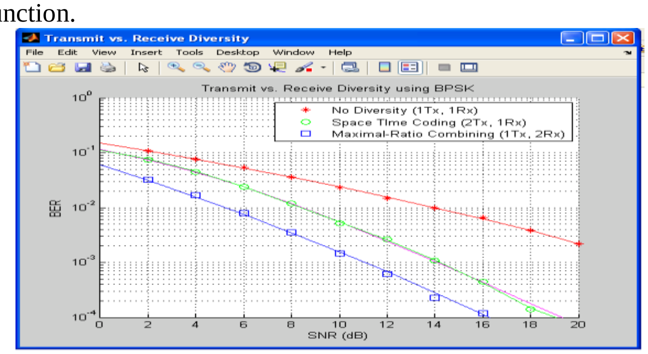

Fig.5: BER / SNR Representation of Transmit and Receive Diversity using BPSK

The simulation shows that by using 2 transmit and 1 receive antenna for Space Time Coding, we get the same diversity order (which is 2x1 = 2) as we get for 1 transmit and 2 receive antennas for Maximum Ratio Combining (which is 1x2 = 2). As clearly visible, Maximum Ratio Combining technique gives better performance in terms of BER as compared to Space Time Coding. The simulation also shows great enhancement in system performance by using diversity techniques as compared to the case of no diversity.

B. Transmit and Receive Diversity using QPSK

Figure 6 shows the BER for different values of the SNR for the three transmit and receive diversity techniques using QPSK modulation scheme.

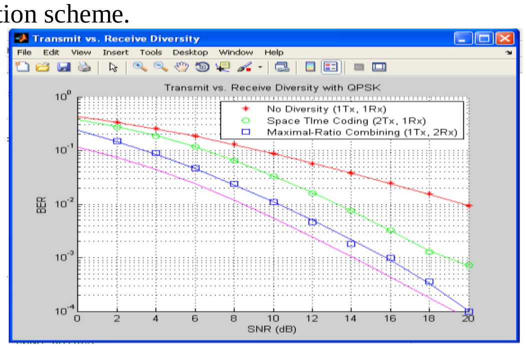

Fig.6: BER / SNR Representation of Transmit and Receive Diversity using QPSK

Using the same parameters but changing the modulation scheme from BPSK to QPSK, we get the above plot. By observing Figure 5 and Figure 6, we can say that by using higher modulation schemes the scales shift upwards as QPSK puts twice as many bits in each symbol. By using BPSK, Maximum Ratio Combining was giving zero BER at SNR = 16 but with QPSK it is shifted to SNR = 20. But still Maximum Ratio Combining provides best performance results.

C. Transmit and Receive Diversity using 4-QAM

Figure 7 shows the BER for different values of the SNR for the three transmit and receive diversity techniques using 4QAM modulation scheme. By using 4QAM, the scale shifts up as compared to BPSK but Maximum Ratio Combining technique is still giving the best performance. This shows that modulation schemes are giving here only scaling factor due to multiple bits in each symbol and doesn't have much effect on the system in terms of BER.

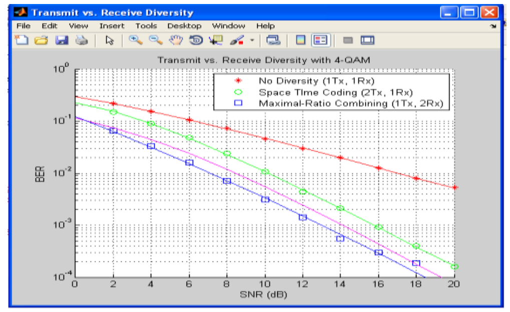

Fig.7: BER / SNR Representation of Transmit and Receive Diversity using 4QAM

D. Comparison of different Diversity techniques

Figure 8 shows comparisons among different diversity schemes where all the systems have diversity order of 4. For this simulation, we have compared Space Time Coding with 4 transmit and 1 receive antenna using QPSK modulation (Diversity order: 4x1=4), Space Time Coding with 2 transmit and 2 receive antennas using BPSK modulation (Diversity order: 2x2=4) and Maximum Ratio Combining with 1 Transmit and 4 Receive antennas using BPSK modulation (Diversity order: 1x4=4). By observing the plots, we can say that by using higher modulation scheme like QPSK if we increase the antennas at transmitter side, the BER decreases and performance of the system increases in Space Time Coding Technique. We also observed that by using BPSK modulation scheme and by using 2 antennas at transmitter and 2 antennas at receiver side, the BER of system decreases as compared to 1 Transmit antenna and 4 Receive antennas using QPSK modulation scheme. We also observed that by using BPSK modulation and by increasing the number of antennas to 4 at receiver side in Maximum Ratio Combining, it provides the best BER performance than all other systems.

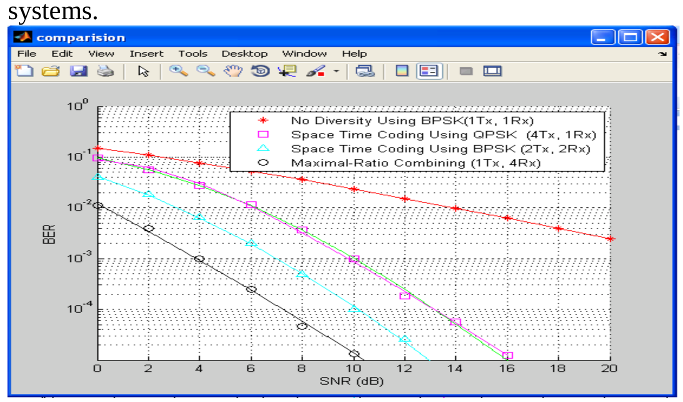

Fig.8: Comparison among different Diversity Techniques

V. Multiple Input Multiple Output (MIMO) techniques

For Spatial Multiplexing or MIMO systems, we have simulated our system using BPSK for Zero Forcing Equalizer and for Minimum Mean Square Error (MMSE) equalizer. Figure 9 shows two MIMO systems. Both systems are using 2 transmitting and 2 receiving antennas and BPSK modulation scheme. But one system is using zero forcing equalizer while the other system is using minimum mean square equalizer. As we can observe, a zero forcing equalizer doesn't seem to be the best choice to equalize the received symbols as it ignores the effects of additive noise components in the system and does not take any benefit of diversity gain. A MMSE equalizer minimizes the additive noise in the channel so it seems to be a better choice for MIMO systems. The plots clearly show us that a MIMO system with MMSE gives better BER performance than a Zero Forcing equalizer system. In this simulation, a MIMO system with MMSE is giving 3 dB improvements as compared to MIMO system with Zero Forcing Equalizer

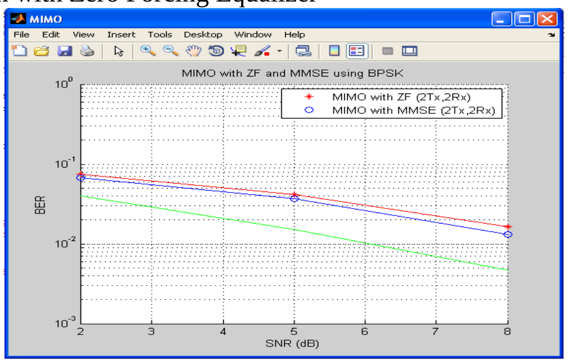

Fig.9: MIMO with ZF and MMSE

By the using higher modulation schemes like QPSK and QAM, the scale will be shifted upwards whereas the shape of the plots will remain same and MIMO with MMSE will keep on performing better.

VI. CONCLUSION

In this work, we have studied and analyzed different types of antenna techniques used in WiMAX systems. We simulated these multiple antenna techniques using MATLAB. First we simulated Diversity techniques both for transmit and receive diversity and then Spatial Multiplexing (MIMO) using Zero Forcing and Minimum Mean Square Error (MMSE) equalizers for analyzing Bit Error Rate (BER) performance. We used BPSK, QPSK and QAM modulation schemes in our simulations. In Diversity techniques, we used different antenna scenarios and different modulation schemes for simulating Space Time Coding and Maximum Ratio Combining. After carefully comparing the plots of these scenarios, we came to the conclusion that Maximum Ratio Combining system gives us best BER performance in Diversity techniques regardless of modulation scheme. On the other hand, a MIMO system with MMSE gives better BER performance than Zero Forcing equalizer system. We can also conclude that the modulation schemes doesn't directly affect the BER performance of system as they just shift the scale upward or downward depending upon which modulation scheme is used while the behavior of the system remains the same. The diversity gain is also very important and it should also be increased while using a higher modulation scheme for better BER performance. So for Diversity techniques, Maximum Ratio Combining gives better BER performance and for Spatial Multiplexing (MIMO) techniques, Minimum Mean Square Error (MMSE) gives better BER performance.

VII. FUTURE SCOPE

In future, our simulated bit error rate performance results can be tested and verified practically. Further research can be helpful to make it more efficient and reliable in performance. It is also possible to find some other diversity constellations or modulation schemes or making of a simulation toolbox (like Communication toolbox) to get more efficient bit error rate performance in WIMAX.

VIII. REFERENCES

[1] How WiMAX Works [Online] Available: http://computer.howstuffworks.com/wimax1.htm [
[2] Loutfi Nuaymi, WiMAX Technology for Broadband Wireless Access, John Wiley and Sons, 2007.
[3] D. Pareek, The Business of WiMAX, Chapter 1, John Wiley, 2006.
[4] OFDM Basics [Online]. Available: http://wireless.agilent.com/wireless/helpfiles/n7615b/ofdm_basics.htm [Accessed: July. 03.2009].
[5] J. G. Andrews, A. Ghosh, R. Muhamed, Fundamentals of WiMAX Understanding Broadband Wireless Networking, Chapter 2, Prentice Hall, 2007.
[6] Multiple Antenna Systems in WiMAX [White Paper Online] Available: www.airspan.com/pdfs/Whitepaper_Multiple_Antenna_Systems.pdf
[7] Maximum Ratio Combining Diversity [Online] Available: http://www.wirelesscommunication.nl/reference/chaptr05/diversit/mrc.htm
[8] [8] G. Foschini and M. Gans. On limits of wireless communications in a fading environment when using multiple antennas. Wireless Personal Communications, 6:311–335, March 1998.
[9] E. Teletar. Capacity of multi-antenna gaussian channels. European Transactions Telecommunications, 6:585–595, November–December 1999.
[10] A. Edelman. Eigenvalues and condition number of random matrices. PhD thesis, MIT, 1989.
[11] A. Tulino and S. Verdu. Random matrix theory and wireless communications. Foundations and Trends in Communications and Information Theory, 1(1):1–186, 2004.
[12] J. G. Proakis. Digital Communications. 3rd ed., McGraw-Hill, 1995.
[13] S. Verdu. Multiuser Detection. Cambridge University Press, 1998.

[14] B. M. Hochwald and S. ten Brink. Achieving near-capacity on a multiple-antenna channel. IEEE Transactions on Communications, 51(3):389–399, March 2003.
[15] G. J. Foschini. Layered space-time architecture for wireless communication in a fading environment when using multiple antennas. Bell Labs Technical Journal, 1(2):41–59, 1996.
[16] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky. Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture. IEE Electronics Letters, 35:14–16, January 1999.
[17] H. Bolcskei, R. W. Heath, and A. J. Paulraj. Blind channel identification and equalization in OFDM based multiantenna systems. IEEE Transactions on Signal Processing, 50(1):96–109, January 2002.
[18] G. L. Stuber, J. R. Barry, S. W. McLaughlin, Y. Li, M. Ingram, and T. G. Pratt. Broadband MIMOOFDM wireless communications. Proceedings of the IEEE, pp. 271–294, February 2004.
[19] M. Chiani, M. Z. Win, and A. Zanella. On the capacity of spatially correlated MIMO Rayleigh-fading channels. IEEE Transactions on Information Theory, 49(10):2363–2371, October 2003.
[20] R. Blum. MIMO capacity with interference. IEEE Journal on Selected Areas in Communications, 21(5):793–801, June 2003.
[21] R. W. Heath and A. J. Paulraj. Switching between multiplexing and diversity based on constellation distance. In Proceedings, Allerton Conference on Communications, Control, and Computing, September 2000.
[22] L. Zheng and D. Tse. Diversity and multiplexing: A fundamental trade-off in multiple antenna channels. IEEE Transactions on Information Theory, 49(5), May 2003.
[23] J. R. Barry, D. G. Messerschmitt, E. A. Lee, Digital Communication, 3rd Edition, Chapter 11, Springer-Verlag New York, LLC, 2003.