Diversity Techniques to combat fading in WiMAX

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Abstract: - The IEEE 802.16 standard is often referred to as WiMAX today. It represents a distillation of the most advanced technology and an industry consensus permitting equipment interoperability. It holds the promise of delivering high speed internet access to business and residential customers and to remote locations where traditional broadband services are unavailable. In the present work, the PHY specified for the Wireless MAN-OFDM case is studied and implemented. Various modulation techniques involved are explored and each of the performances enhancing techniques is evaluated with regard to its functionality in the system. The simulation results show that the Space-Frequency Coded system coupled with Reed-Solomon codes and Convolutional codes efficiently exploits diversity techniques.

Key-Words: - WiMAX, BWA, OFDM, MIMO, STBC, Convolutional Codes, Reed-Solomon codes

1 Introduction

WiMAX, short for `Worldwide Interoperability for Microwave Access', is an effective `last kilometer' solution for delivering broadband directly to homes and offices by the WISPs. The WiMAX technology is based on the IEEE 802.16 standard which in turn defines the Wireless MAN air interface specification for wireless metropolitan area networks [1]. This work deals with the PHY layer specified for the Wireless MAN-OFDM case is studied and implemented. Various diversity techniques that constitute the PHY to provide a robust system are studied and implemented. Before all of it, firstly, a detailed overview of various broadband access technologies is given in the present work. Then the wireless channel mechanisms are studied and then an overview of the WiMAX PHY's system model is given. Various modulation techniques involved are studied and then each of the performance enhancing techniques are studied one by one with regard to their functionality in the system and the value they add to the system. Finally, simulation results are provided to corroborate the theories deduced.

2 WiMAX's diversity techniques

To mitigate the effects of *fading* and *intersymbol interference* when WiMAX is used in the 2-11 GHz range for *non line of sight* (NLOS) operation, various techniques have been introduced into the Physical layer (PHY) of the WiMAX system. The following sections give an overview of some of those techniques.

The three main forms of diversity used by the WiMAX PHY are *Time Diversity*, *Frequency Diversity* and *Spatial Diversity* [2].

2.1 Time Diversity

Time Diversity is achieved by repeatedly transmitting the same signal in different time slots, where the separation between the successive time slots equals or exceeds the coherence time of the channel. If the channel is time varying, each copy will experience different channel conditions and this results in the reception of multiple, independently faded copies of the transmitted signal at the receiver, thereby providing for diversity. The WiMAX system takes advantage of time diversity by incorporating an outer Reed-Solomon block code concatenated with an inner convolutional code into its physical layer. Turbo coding has been left as an optional feature, which can improve the coverage and/or capacity of the system, at the price of increased decoding latency and complexity. In the present work, only an outer Reed-Solomon code concatenated with an inner convolutional code is used. Further details of the Reed-Solomon code and the convolutional code used are included in part 3.

2.2 Frequency Diversity

Spread Spectrum Modulation and Orthogonal Frequency Division Multiplexing (OFDM) are considered as frequency diversity techniques. OFDM exploits frequency diversity by providing simultaneous modulation signals with error control coding across a large bandwidth, so that if a particular frequency undergoes a fade, the composite signal will still be demodulated [2]. Apart from providing a PHY with a single-carrier modulated air interface (WirelessMAN-SCa), the IEEE 802.16a/d standard also defines two other PHYs which use the OFDM scheme [3].

1. Wireless MAN-OFDM is a 256-carrier OFDM scheme where multiple access of different subscriber stations is time-division multiple access (TDMA) based.
2. Wireless MAN-OFDMA is a 2048-carrier OFDM scheme where multiple access of different subscriber stations is provided using a combination of TDMA and OFDMA.

The two OFDM-based systems are more suitable for non-LOS operation because the equalization process is simpler for multicarrier signals. Of the two, the 256-carrier version has been specified by all the system profiles currently defined by the WiMAX Forum, which is a consortium of all the organizations promoting WiMAX. For this reason, the 256-carrier OFDM scheme is considered in this work along with the single carrier scheme. Part 4 further explains this topic.

2.3 Spatial Diversity
Spatial Diversity, also called *Antenna Diversity*, is achieved by having multiple antennas at the transmitter or the receiver or both at the transmitter and the receiver (*Multiple Input Multiple Output* (MIMO) communications). Separation on the order of a few wavelengths is required between two antennas in order to obtain independently faded signals [4] which provide for diversity. In a system with m transmit antennas and n receive antennas, the maximal diversity gain is mn when the fading coefficients between individual antenna pairs are assumed to be independent, identically distributed (i.i.d) Rayleigh faded [5].

Space Time Coding techniques such as *Space Time Block Codes* (STBC) and *Space Time Trellis Codes* (STTC) aim at achieving high diversity gains. Furthermore, Space Time Trellis codes achieve coding gain also, but the decoding complexity of STTC is much higher compared to that of the STBC. While space-time coding techniques improve the reliability of reception, there are other MIMO techniques that increase the rate of communication for a fixed reliability level by increasing the *degrees of freedom* available for communication [6][7]. One such technique is the *Bell Labs Space Time Architecture* BLAST system which achieves multiplexing gain by transmitting independent symbol streams from multiple transmit antennas. When the paths between individual transmit receive antenna pairs fade independently, multiple spatial parallel channels are created and by transmitting independent information streams through these spatial channels, the data rate can be increased. This effect is also called *spatial multiplexing* [8]. Thus, while the goal of the BLAST system is to achieve multiplexing gain by transmitting M symbols/channel, where M is the number of transmit antennas, the Space Time Coding techniques try to achieve maximum diversity gain and transmit 1 reliable symbol/channel use. The spectral efficiency of the Space time coding schemes can be improved by using modulation techniques that have higher modulation order, but this leads to a degraded error performance as higher constellations have their signals close to each other. Thus there exists a fundamental tradeoff between diversity and multiplexing gains in a point-to-point wireless fading channel that sets a limit on the overall performance of a MIMO system.

The WiMAX PHY designates Space-time block codes as an optional feature that can be implemented in the downlink to provide increased diversity [3]. A 2 x 1 or 2 x 2 Alamouti STBC [9] scheme may be implemented which provides both time diversity and space diversity. The present work implements both the schemes to highlight the advantage of using receive diversity as well, since receive diversity needs no additional transmit power. Alamouti STBC schemes and their implementation in the present work are further explained in part4.

3 Forward Error Correction
There are three basic types of forward error correction codes: *block codes*, *convolutional codes* and *turbo codes* [10].

3.1 Reed-Solomon Codes
Block codes include Reed-Solomon(R-S) codes are capable of correcting errors which appear in bursts and are commonly used in concatenated coding systems. Reed-Solomon code is specified as a (n,k) code, where n is the number of symbols in the codeword that the R-S encoder outputs and k is the number of message symbols input to the encoder. Reed-Solomon codes become more efficient as the code block size increases (keeping the code rate constant), and this property of the Reed-Solomon codes can be used efficiently when long block lengths are desired [10]. Reed-Solomon codes are based on the arithmetic of finite fields, called Galois Fields. Galois Fields are denoted by $GF(p^m)$, here p is

a prime number and m = number of bits per symbol. For Reed-Solomon codes, p = 2. So, if m = 3, the Galois Field used is $GF(2^3)$. Different R-S encoder-decoder systems can have different primitive polynomials to generate the Galois Fields and these primitive polynomials are called *Field Generator Polynomials*. The *Code Generator Polynomial* $g(x)$ of a t-error correcting Reed-Solomon code is given by [11]

$$g(x) = (x - \alpha^{j})(x - \alpha^{j+1})(x - \alpha^{j+2})\ldots\ldots(x - \alpha^{j+2t-1}) \qquad (1)$$

The WiMAX PHY uses a systematic R-S (n = 255*;* k = 239) code where the Galois Field elements are from $GF(28)$, i.e, $m=8$ in this case. The primitive polynomial used in the WiMAX PHY is given by

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

A Reed-Solomon encoder with the above given parameters is used in the present work.

3.2 Convolutional Codes

Convolutional codes differ from block codes in that instead of grouping the information sequences into distinct blocks and then encoding, here a continuous sequence of information bits is mapped into a continuous sequence of encoder output bits. For this reason, convolutional codes are widely implemented in real-time applications. A convolutional code can be thought of as a code with *memory* in the sense that the output of a convolutional encoder depends not only upon the present input, but also on the previous inputs. The input is passed through a *finite state shift register* which has already stored a finite number of past inputs and the output of the encoder is a linear combination of the present input and the contents of the shift register.

The WiMAX PHY uses a rate 1/2, constraint length K = 7 convolutional code whose generator vectors are given by

$$g_0 = [1111001] \text{ for output 1} \qquad (3)$$

$$g_1 = [1011011] \text{ for output 2} \qquad (4)$$

as shown in figure 1 [12].

Decoding of convolutional codes is performed using the *Viterbi algorithm* [13] which uses the *maximum likelihood* decoding principle.

This convolutional encoder is used in the present work. Both Reed-Solomon codes and Convolutional codes provide a *coding gain* which is a measure of the amount of additional SNR that would be required to provide the same BER performance for an uncoded message signal in the same channel conditions.

4. STBC and OFDM in WiMAX systems

4.1 Space Time Block Codes

In Space Time Block Codes (STBC), the data stream to be transmitted is encoded in *blocks* which are distributed among spaced antennas and across time.

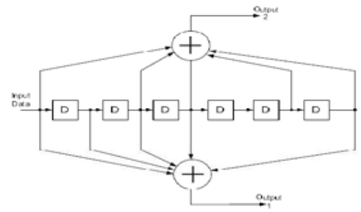

Fig 1: Convolutional encoder used in the WiMAX PHY

This distribution of transmitted symbols over multiple transmits antennas and different time slots can be represented in the form of a matrix as shown below.

$$\begin{array}{cc} timeslots \downarrow & \begin{bmatrix} s_{1,1} & s_{1,2} & \cdots & s_{1,n_t} \\ s_{2,1} & s_{2,2} & \cdots & s_{2,n_t} \\ \vdots & \vdots & \vdots & \vdots \\ s_{T,1} & s_{T,2} & \cdots & s_{T,n_t} \end{bmatrix} \\ & \underset{antennas}{\rightarrow} \end{array}$$

n_t is the number of transmit antennas and T is the number of time slots. Each row represents a time slot and each column represents one antenna's transmissions over time. While it is necessary to have multiple transmit antennas, it is not necessary to have multiple receive antennas, although to do so improves performance. Alamouti invented a simple transmit diversity technique with two transmit antennas [9] popularly known as the Alamouti STBC which provides full $n_t n_r$ diversity with little or no rate penalty. This technique uses the maximum likelihood decoding at the receiver and is used in the present work to provide for antenna diversity.

Suppose we have two transmit and two receive antennas. Two different symbols s_1 and s_2 are transmitted from antenna 1 and antenna 2 respectively during the first time slot. During the second time slot, antenna 1 transmits $-s^*_2$ (negative conjugate of s_2) and antenna 2 transmits s^*_1. The transmitted symbol matrix can be represented as

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \qquad (5)$$

If $h_{t,r}$ is considered to be the complex channel response between transmit antenna t and receive antenna r, then the discrete-time received signals at antenna 1 during the two symbol intervals are

$$r_1^1 = h_{1,1}\frac{s_1}{\sqrt{2}} + h_{2,1}\frac{s_2}{\sqrt{2}} + n_1^1 \tag{6}$$

$$r_2^1 = h_{1,1}\frac{s_1^*}{\sqrt{2}} + h_{2,1}\frac{s_1^*}{\sqrt{2}} + n_2^1 \tag{7}$$

And the corresponding signals at receive antenna 2 are

$$r_1^2 = h_{1,2}\frac{s_1}{\sqrt{2}} + h_{2,2}\frac{s_2}{\sqrt{2}} + n_1^2 \tag{8}$$

$$r_2^1 = -h_{1,2}\frac{s_1^*}{\sqrt{2}} + h_{2,2}\frac{s_1^*}{\sqrt{2}} + n_2^2 \tag{9}$$

Where n^q_p is the noise sample at receive antenna q during the time slot p. The noise samples are independent and identically distributed complex Gaussian zero-mean random variables with power $N_0/2$. The vector received signal is formed by stacking the scalar received signals as shown below.

$$r = \begin{bmatrix} r_1^1 \\ (r_2^1)* \\ r_1^2 \\ (r_2^2)* \end{bmatrix} \tag{10}$$

It can be noticed that every other matched filter output is complex conjugated before creating the signal vector r. Then the received signal vector can be shown as [14]

$$r = \boldsymbol{H}s + n \tag{11}$$

where

$$\boldsymbol{H} = \begin{bmatrix} h_{1,1} & h_{2,1} \\ h_{2,1}^* & -h_{1,1}^* \\ h_{1,2} & h_{2,2} \\ h_{2,2}^* & -h_{1,2}^* \end{bmatrix} \tag{12}$$

$$s = \frac{1}{\sqrt{2}}\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \tag{13}$$

and

$$n = \begin{bmatrix} n_1^1 \\ (n_2^1)* \\ n_1^2 \\ (n_2^2)* \end{bmatrix} \tag{14}$$

The columns of H are seen to be orthogonal and this is the key aspect of Alamouti STBC's effectiveness. At the receiver, a decision statistic vector d is formed by matched filtering the received signal vector with respect to the channel.

$$d = H^H r \tag{15}$$

$$d = H^H(Hs + n) \tag{16}$$

$$d = \begin{bmatrix} E_h & 0 \\ 0 & E_h \end{bmatrix} s + H^H n \tag{17}$$

$$d = E_h s + v \tag{18}$$

where

$$E_h = |h_{1,1}|^2 + |h_{1,2}|^2 + |h_{2,1}|^2 + |h_{2,2}|^2 \tag{19}$$

and

$$v \sim N_c(0, \frac{E_h N_0}{2} I) \tag{20}$$

Since $H^H H$ is diagonal, there is no intersymbol interference, i.e., the decision statistics of each of the symbols do not depend upon the other symbol as shown in equations 21 and 22.

$$d_1 = [d]_1 = \frac{E_h}{\sqrt{2}} s_1 + v_1 \tag{21}$$

$$d_2 = [d]_2 = \frac{E_h}{\sqrt{2}} s_2 + v_2 \tag{22}$$

where $v1$ and $v2$ are Gaussian with mean 0 and variance $\sigma^2_d = E_h N_0/2$, $N_0/2$ being the variance of the noise samples. The final maximum likelihood estimates are given by

$$\hat{s}_1 = \arg \min_{s \in S} |d_1 - s|^2 \tag{23}$$

$$\hat{s}_2 = \arg \min_{s \in S} |d_2 - s|^2 \tag{24}$$

Since this scheme transmits two symbols in two time slots, the rate of code is 1, i.e., there is no sacrifice in bandwidth to achieve full transmit antenna diversity. However, there is a 3dB SNR loss since the transmit power is distributed across the two antennas. This scheme is useful when high throughput is required at low SNR. Alamouti scheme works only for the two transmit antenna case when complex symbols are used. There are no full rate space-time block code matrices for more than two transmit antennas when complex symbols are used.

Tarokh *et al* provided examples of lower rate code matrices that provide full diversity when complex symbols are used [15]. There are full rate space time block codes only for 2, 4 and 8 transmit antennas when the symbols are real.

In the STBC scheme, the receiver assumes that each received signal is composed of a linear superposition of current symbols corrupted by noise. But in channel conditions where there is high delay spread, such assumption is not entirely valid since there exists a channel-induced ISI component and the performance of STBC might be sensitive to such environments. Since there is no memory between consecutive blocks and since the block length is very short, a very little coding gain can be expected. Since the scheme has a very simple decoder structure, it can be concatenated to a powerful outer error correction code [16]. In the present work, the STBC scheme is concatenated with an outer convolutional code which does soft decision decoding using the Viterbi algorithm. The Viterbi algorithm used requires soft inputs to be input into it which necessitates the need for calculating the bitwise log likelihood ratios (LLR) of the received symbols. The calculation of bitwise LLRs of the received symbols in an STBC system is explained in the following section.

4.1.1 Bitwise LLR calculations for an STBC system

The modulation used in the present work is BPSK. So the bitwise LLRs of the received symbols when BPSK symbols are transmitted are calculated.

With BPSK modulation, each of the two transmitted symbols in the block can be either 1 or -1, where it is assumed that either symbol has unit energy. Let *s* be one of the symbols transmitted and let *d* be its decision statistic. The log-likelihood ratio can be calculated from *d* using the equation [17]

$$\lambda_1(d) = ln\left[\frac{p(d|s=1,H)}{p(d|s=-1,H)}\right] \tag{25}$$

If $\lambda(d)>0$, then $s = 1$, else $s = -1$. Thus the bit transmitted can be found according to which symbol is transmitted for a bit 0 or bit 1.

With QPSK modulation, each of the two transmitted symbols in the block can be one from 1,-1, j,-j, where it is assumed that all the symbols have unit energy. Let *s* be one of the symbols transmitted and *d* be its decision statistic. Then log-likelihood ratio of the k^{th} bit λ_k is given by [17]

$$\lambda_{k=}ln\left[\frac{\sum_{s\in S_k^1} p(s|d)}{\sum_{s\in S_k^0} p(s|d)}\right] \tag{26}$$

where $p(s|d)$ is the conditional pdf of s given d. Applying the Bayes'rule, equation 26 can be written as

$$\lambda_{k=}ln\left[\frac{\sum_{s\in S_k^1} p(d|s)}{\sum_{s\in S_k^0} p(d|s)}\right] \tag{27}$$

when symbols are equally likely. Therefore LLR for the first bit is

$$\lambda_1(d) = ln\left[\frac{p(d|s=-1)+p(d|s=-j)}{p(d|s=1)+p(d|s=j)}\right] \tag{28}$$

Similarly, LLR for the second bit is

$$\lambda_2(d) = ln\left[\frac{p(d|s=-1)+p(d|s=j)}{p(d|s=1)+p(d|s=-j)}\right] \tag{29}$$

4.2 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a bandwidth efficient, multi-carrier transmission technique that is tolerant to channel disturbances such as multipath fading. In OFDM, a high rate serial data stream is split up into a set of low-rate sub-streams, each of which is modulated on a separate subcarrier. By lowering the rate of the stream, the symbol duration is increased so that it is longer compared to the delay spread of the time-dispersive channel. Another way of looking at it is that by lowering the rate of the stream, the bandwidth of the subcarrier is squeezed so that it is small compared with the coherence bandwidth of the channel, thereby making the individual subcarriers experience flat fading, which requires simple equalization techniques. Thus OFDM effectually converts a frequency-selective fading channel into a set of parallel flat fading channels. Lowering the rate of the substreams can be compensated for by selecting a set of *orthogonal* subcarriers whose spectra overlap, but at the same time do not interfere with each other, thereby avoiding inter-channel interference [18]. The orthogonality allows simultaneous transmission on a lot of subcarriers in a tight frequency space without interfering with each other. Let *N* be the number of carriers available in the OFDM system and one PSK or QAM symbol is transmitted per carrier. One OFDM symbol consists of *N* PSK or QAM symbols whose symbol duration is *T*. The continuous-time baseband signal transmitted over the channel over symbol interval [0;*T*] is given by [19]

$$s(t) = \sum_{k=0}^{N-1} s_k e^{j2\pi\frac{k}{T}t} \tag{30}$$

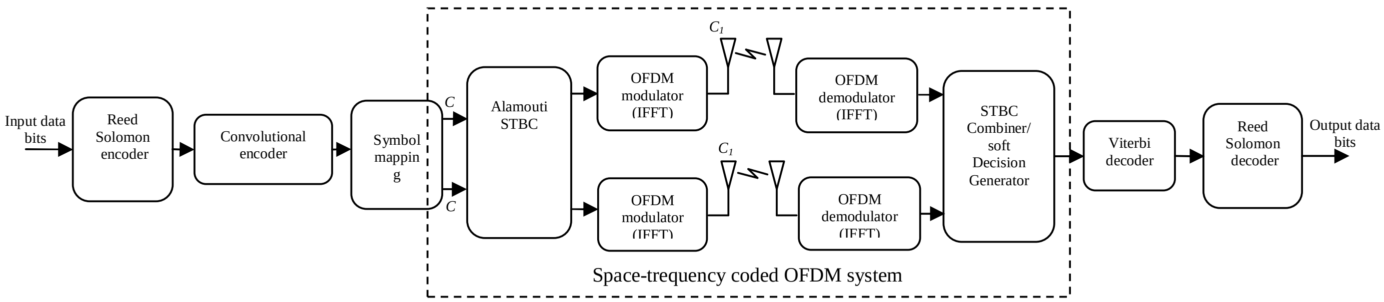

Fig.2: Basic system model

5. System Model

Figure 2 shows the basic system model of the WiMAX PHY that is simulated in this work. The *Bit Error Rate* (BER) performance of the system is simulated and the variation in performance, as different diversity techniques are introduced, is noticed.

6. Simulation Results

The performance of the wireless communication system implemented in terms of its bit error rate (BER) with respect to the signal to noise ratio (SNR). SNR is given by E_b/N_0, where E_b is the energy per bit and $N_0/2$ is the two-sided noise spectral density.

We first start by presenting the performance of the system in AWGN and flat fading channels when none of the diversity techniques are used. Later on, we begin to add each diversity technique and show the improvement in performance.

Figures 3 and 4 show the BER performance of the system when QPSK and BPSK modulations are used respectively with no channel coding and diversity techniques employed. Here, the fading coefficient is varied for every symbol transmitted, i.e., different transmitted symbols see different fading conditions. Next we show how the performance of the system changes in flat fading conditions with the usage of different techniques.

6.1 Space Time Block Codes

Alamouti Space Time Block Codes using 2 antennas at the transmitter and 1 and/or 2 antennas at the receiver is implemented. For Alamouti STBC, the channel is assumed to be quasi-static, i.e., the fading coefficients between the transmit and receive antennas are held constant during the two time slots the symbols are transmitted. Figures 5 and 6 show the performance of the system varies with the usage of Alamouti STBC in flat fading conditions.

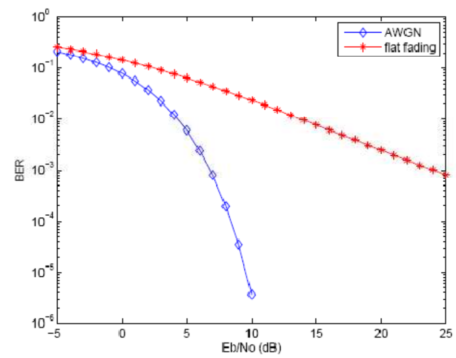

Fig 3: BER performance of the system when QPSK modulation is used and no error reduction techniques are implemented

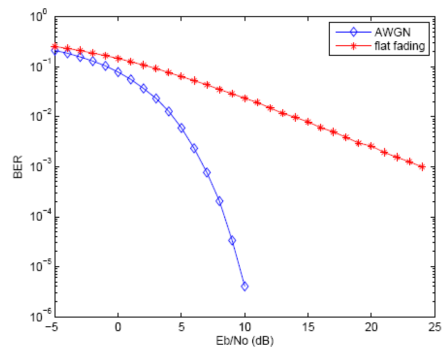

Fig 4: BER performance of the system when BPSK modulation is used and no error reduction techniques are implemented

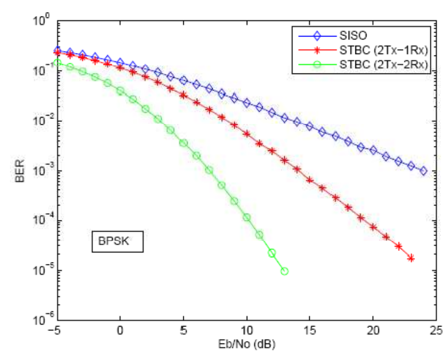

Fig 5: BER performance of the BPSK modulated system when Alamouti STBC is implemented

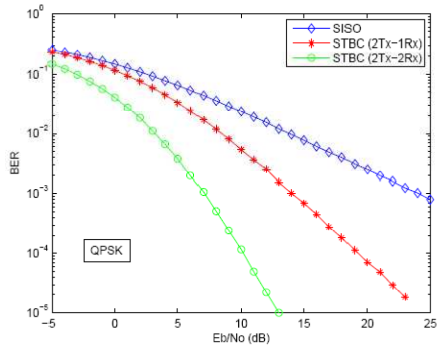

Fig 6: BER performance of the QPSK modulated system when Alamouti STBC is implemented

6.2 Convolutional codes

The variation in the performance of the system with the usage of a channel coding technique such as the convolutional coding is presented next. As discussed in part 3, a rate 1/2, constraint length $K = 7$ convolutional code whose generator vectors are given by

g_0 = [1111001] for output 1 (31)

g_1 = [1011011] for output 1 (32)

is used

Figures 7 and 8 shows the variation in the system's performance when channel coding is implemented via convolutional coding and it can be clearly observed that a coding gain is achieved.

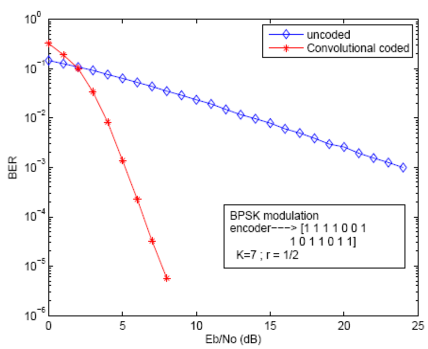

Fig 7: BER performance of the BPSK modulated system when Convolution coding is added

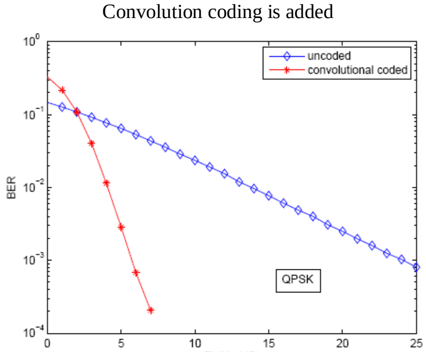

Fig 8: BER performance of the QPSK modulated system when Convolutional coding is added

6.3 Reed-Solomon codes

As described previously, Reed-Solomon code is used in concatenation with inner Convolutional code to provide further coding gain. A systematic R-S (n = 255; k = 239) code where the Galois Field elements are from $GF(2^8)$, i.e, m = 8 is used as the outer Reed-Solomon code in this work.

Figures 9 and 10 show the performance of the system when concatenated Reed-Solomon-Convolutional coding is implemented in the system.

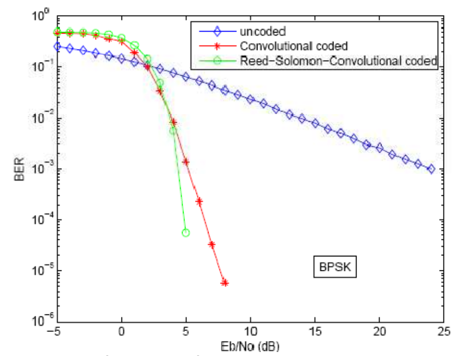

Fig 9: BER performance of the BPSK modulated system when concatenated Reed-Solomon-Convolution coding is added

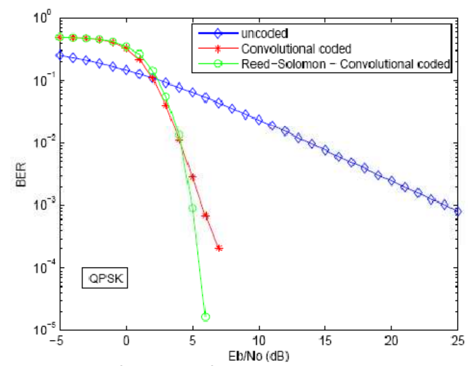

Fig 10: BER performance of the QPSK modulated system when concatenated Reed-Solomon-Convolution coding is added

It can be observed that Reed-Solomon codes provide additional coding gain to what can be achieved by using only convolutional coding. Reed-Solomon codes can themselves provide enormous gain even when not concatenated with a convolutional code, but concatenated with an Alamouti STBC system as can be observed from figures 11 and 12. Thus combining the features of Reed-Solomon codes, Convolutional codes and Alamouti STBC, a robust system that provides high coding gain and diversity gain is developed.

Figure 13 shows the performance of the system for BPSK modulation when time diversity and spatial diversity techniques are employed. The above figures show the performance of the system in only flat fading channels. Frequency selective channels severely degrade the performance of the present system and they are countered by introducing OFDM into the present system.

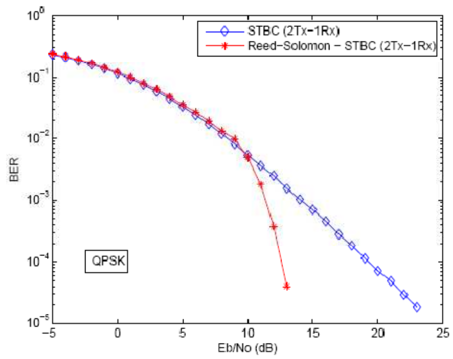

Fig 11: BER performance of the QPSK modulated system when Reed-Solomon coding is used along with STBC 2Tx-1Rx

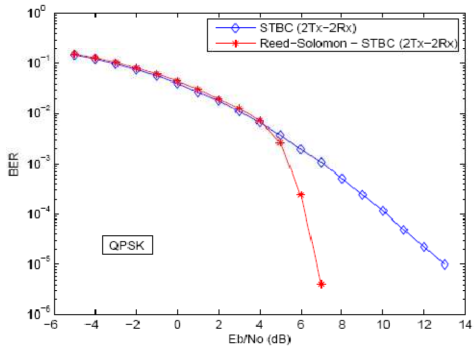

Fig 12: BER performance of the QPSK modulated system when Reed-Solomon coding is used along with STBC 2Tx-2Rx

6.4 OFDM

As mentioned earlier, OFDM is a frequency diversity technique that converts a frequency-selective fading channel into a set of parallel flat fading channels onto which other diversity techniques can be applied. OFDM systems utilizing error-correction coding are often referred as coded OFDM (COFDM) systems. Combining the OFDM transmission technique with the Alamouti STBC technique yields a *space-frequency coded* orthogonal frequency division multiplexing technique [20] whose working model is described below with the help of figure 2.

In figure 1, $C1$ and $C2$ are two different sets of symbols each containing a number of symbols equal to the number of used carriers. Since a 256-carrier OFDM system is used here, $C1$ and $C2$ consist of 256 symbols each which are transmitted on the 256 carriers.

At a given symbol period, the OFDM block transmitted from the first antenna is $C1 = c1[1]\ c1[2]\ c1[3] \ldots c1[K]$ and the OFDM block transmitted from the second antenna is $C2 = c2[1]\ c2[2]\ c2[3] \ldots c2[K]$, where $c_i[p]$ is the symbol from the i th OFDM block transmitted on the p th carrier and K is the number of carriers. During the next symbol period, the block $-C^*_2$ is transmitted from the first antenna and the block C^*_1 is transmitted from the second antenna. Fading is assumed to be quasi-static over the two symbol periods, i.e., the fading coefficients on different frequencies between a transmit/receive antenna pair are held constant during this period. The soft estimates for transmitted signals $c_1[k]$ and $c_2[k]$ at the j^{th} receive antenna can be calculated from [13] and are given by [25]

$$\begin{bmatrix}\tilde{C}_1^j[k]\\ \tilde{C}_2^j[k]\end{bmatrix} = \sqrt{E_s}\begin{bmatrix}|H_{1j}[k]|^2+|H_{2j}[k]|^2 & 0\\ 0 & |H_{1j}[k]|^2+|H_{2j}[k]|^2\end{bmatrix}\times\begin{bmatrix}C_1[k]\\ C_2[k]\end{bmatrix}+\begin{bmatrix}n_{1j}[k]\\ n_{2j}[k]\end{bmatrix} \quad (33)$$

Where $H_{ij}\ [k]$ denotes the normalized channel frequency response for the k th tone, corresponding to the channel between the i^{th} transmit antenna and the j^{th} receive antenna and Es is the transmitted symbol energy. The performance of this space-frequency coded system, when combined with the Reed-Solomon -Convolutional code FEC, is shown in figure 16 for BPSK modulation.

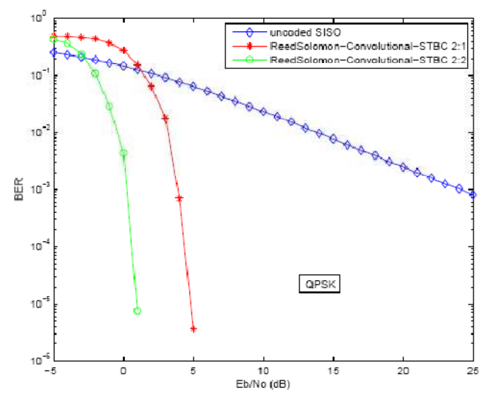

Fig 13: BER performance of the QPSK modulated system when concatenated Reed-Solomon-Convolutional coding is used along with Alamouti STBC

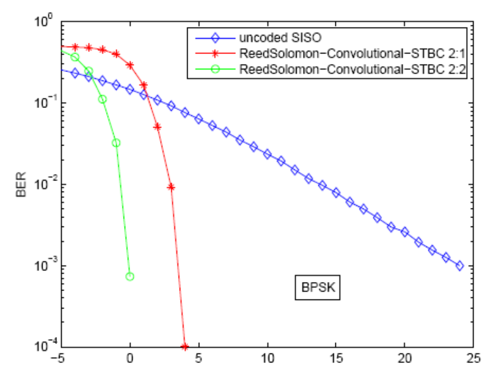

Fig 14: BER performance of the BPSK modulated system when concatenated Reed-Solomon-Convolutional coding is used along with Alamouti STBC

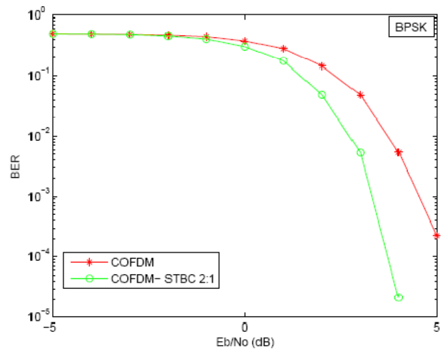

Fig 15: BER performance of the BPSK modulated system when concatenated Reed-Solomon-Convolutional coding is used along with the space-frequency coded system

7 Conclusion

From the results given in the previous sections, it can be concluded that the Space-Frequency Coded system coupled with Reed-Solomon codes and Convolutional codes efficiently exploits diversity techniques. These are, time, space and frequency diversity to overcome fading found in the radio channel and provides high performance at low SNRs for the WiMAX PHY. Also, the present work overview the key aspects of the IEEE 802.16 Physical layer and demonstrates their functionality.

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