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MIMO System Using Space-Time Block Code with Digital Modulation Techniques

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Abstract: **Multiple-Input Multiple Output (MIMO) links coupled with space-time codes may combat fading and hence may significantly enhance the channel capacity. MIMO systems with multiple antenna elements at both Transmitter and Receiver ends are an efficient solution for future wireless communications systems. They provide higher data rates and longer transmission range by exploiting the spatial domain under the constraints of limited bandwidth and transmit power. The multiple antennas allow MIMO systems to perform precoding (multi-layer beam forming), diversity coding (space-time coding), and spatial multiplexing. This paper presents a detailed study of diversity coding for MIMO systems. Different space-time block coding (STBC) schemes including Alamouti's STBC for 2 transmit antennas as well as orthogonal STBC for 3 and 4 transmit antennas are explored. Finally, these STBC techniques are implemented in MATLAB and analyzed for performance according to their bit-error rates using BPSK, QPSK, 16-QAM, and 64-QAM modulation schemes.**

Keywords: **Space-Time Block Coding (STBC), Orthogonal Space-Time Block Codes (OSTBCs) and Non-orthogonal Space-Time Block Codes (NOSTBCs), Multiple-Input Multiple Output (MIMO) systems, Channel State Information (CSI), Maximal Ratio Combining (MRC), Maximum Likelihood (ML).**

I. INTRODUCTION

The next generation wireless systems are required to have high voice quality as compared to current cellular mobile radio standards and provide high bit rate (up to 2 Mbits/s). There is always a need for methods to send more bits per Hz. A particular solution is the use of multiple antennas at both transmitter (TX) and receiver (RX). In MIMO, the transmit antennas at one end and the receive antennas at the other end are connected and combined in such a way that, the bit error rate (BER) for each user is improved. Advantages of MIMO system include [2], [3]:

A) Precoding-A generalization of beam forming to support multi-layer transmission in multi-antenna wireless communications. When the receiver has multiple antennas, single-layer beam forming cannot simultaneously maximize the signal level at all of the receive antennas. In order to maximize the throughput in multiple receive antenna systems, multi-layer beam forming is required.

B) Diversity coding-A signal can be coded through the transmit antennas, creating redundancy, which reduces the outage probability.

C) Spatial multiplexing-A transmission technique in MIMO wireless communication to transmit independent and separately encoded data signals, so-called *streams*, from each of the multiple transmit antennas.

MIMO system consumes no extra power due to its multiple antenna elements. The total power through all antenna elements is less than or equal to that of a single antenna system, i.e.

$$\sum_{k=1}^{N} p_k \leq p$$

Where N is the total number of antenna elements, p_k is the power allocated through the k_{th} antenna element, and P is the power if the system had a single antenna element [4].
As a consequence of their advantages, MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency or to achieve a diversity gain diversity gain that improves the link reliability. Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi) [5], [6], 4G [7], [8], [9], WiMAX and HSPA+.

II. SYSTEM MODEL

MIMO systems are composed of three main elements, namely the transmitter (TX), the channel (H), and the receiver (RX). In this paper, Nt is denoted as the number of antenna elements at the transmitter, and Nr is denoted as the number of elements at the receiver.

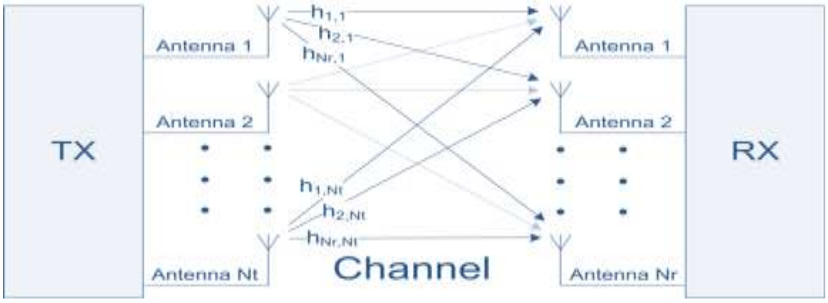

Fig1: Multiple-Input Multiple-Output system block diagram

The Multiple-Inputs are located at the output of the TX (the input to the channel), and similarly, the Multiple-Outputs are located at the input of the RX (the output of the channel).

The channel with Nr outputs and N_t inputs is denoted as a Nr $\times N_t$ matrix:

$$\boldsymbol{H} = \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{pmatrix}$$

Where each entry hi;j denotes the attenuation and phase shift (transfer function) between the j[th] transmitter and the i[th] receiver.

The MIMO signal model is described as

$$\vec{r} = H\vec{s} + \vec{n}$$

Where $\vec{r}$ is the received vector of size Nr × 1, H is the channel matrix of size Nr ×Nt,$\vec{s}$ is the transmitted vector of size Nt×1, and $\vec{n}$ is the noise vector of size Nr ×1.

III. SPACE-TIME BLOCK CODING

Space-time coding introduces redundancy in space, though the addition of multiple antennas, and redundancy in time, through channel coding. Two prevailing space-time coding techniques are Space Time Block Codes (STBC) and Space Time Trellis Codes (STTC). STBC provide diversity gain, with very low decoding complexity.

This can be achieved by transmitting several replicas of the same information through each antenna. By doing this, the probability of losing the information decreases exponentially. The different replicas sent for exploiting diversity are generated by a space-time encoder which encodes a single stream through space using all the transmit antennas and through time by sending each symbol at different times. This form of coding is called Space-Time Coding (STC).

The most dominant form of STCs are space-time block codes (STBC) because of their decoding simplicity. Now we will discuss about different types of STBC techniques.

A. Alamouti's STBC

Alamouti's STBC uses two transmit antennas regardless of the number of receive antennas. The Alamouti scheme encoding operation is given by

$$G_2 = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

At a time t, the symbol s_1 and symbol $_{s2}$ are transmitted from antenna 1and antenna 2 respectively. Assuming that each symbol has duration T, then at time t + T, the symbols$-s_2^*$ and s_1^* , where (.)*denotes the complex conjugate, are transmitted from antenna 1 and antenna 2 respectively. Alamouti STBC reduces the effect of fading at mobile stations while only requiring extra antenna elements at the base station, where it is more economical than having multiple antennas at the receivers. However, if having more antennas at the receivers is not a problem, this scheme can be used with 2 transmit antennas and Nr receives antennas while accomplishing a 2Nr full diversity.

B.Orthogonal Space-Time Block Codes

Orthogonality means that the STBC is designed such that the vectors representing any pair of columns taken from the coding matrix is orthogonal. They allow low complexity maximum likelihood decoding and guarantee full diversity. An orthogonal STBC is characterized by a code matrix $\mathbf{G}_{p\times n}$ where *p* denotes time delay or block length and *n* represents the number of transmit antennas. The entries of **G** are linear combinations of *k* data symbols or their conjugate that belong to an arbitrary signal constellation.

(i) Orthogonal Space-Time Block Codes for Nt = 3:

(a)Nt = 3 with Rate ½:

$$\mathcal{G}_3 = \begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{pmatrix}$$

This code transmits 4 symbols every 8 time intervals, and therefore has rate 1/2.

(b)Nt=3 with Rate ¾

A higher rate code with Nt=3 is given by

$$\mathcal{H}_3 = \begin{pmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{-s_1-s_1^*+s_2-s_2^*}{2} \\ \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} & \frac{s_2+s_2^*+s_1-s_1^*}{2} \end{pmatrix}$$

It is seen from H_3 that 3 symbols are transmitted every 4 time intervals, and therefore has rate 3/4.

(ii) Orthogonal Space-Time Block Codes for Nt= 4

(a) Nt = 4 with Rate ½

The code block for 4 transmit antennas with rate ½ is given by:

$$\mathcal{G}_4 = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{pmatrix}$$

This is similar to G_3, where 4 symbols are transmitted in 8 time intervals with rate ½.

(b) Nt = 4 with Rate ¾

$$\mathcal{H}_4 = \begin{pmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} & -\frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{-s_1-s_1^*+s_2-s_2^*}{2} & \frac{-s_2-s_2^*+s_1-s_1^*}{2} \\ \frac{s_3^*}{\sqrt{2}} & -\frac{s_3^*}{\sqrt{2}} & \frac{s_2+s_2^*+s_1-s_1^*}{2} & -\frac{s_1+s_1^*+s_2-s_2^*}{2} \end{pmatrix}$$

C. Decoding Of Space Time Block Code

One particularly attractive feature of orthogonal STBCs is that maximum likelihood decoding can be achieved at the receiver with only linear processing. In order to consider a decoding method, a model of the wireless communications system is needed.

At time t, the signal r_t^j received at antenna j is:

$$r_t^j = \sum_{i=1}^{n_T} \alpha_{ij} s_t^i + n_t^j$$

where α_{ij} is the path gain from transmit antenna i to receive antenna j, s_t^i is the signal transmitted by transmit antenna i and n_t^j is a sample of additive white Gaussian noise (AWGN).

The maximum-likelihood detection rule is to form the decision variables.

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$$R_i = \sum_{t=1}^{n_T} \sum_{j=1}^{n_R} r_t^j \alpha_{\epsilon_t(i)j} \delta_t(i)$$

Where $\delta_k(i)$ is the sign of s_i in the k^{th} row of the coding matrix $\epsilon_k(p) = q$ denotes that s_p is (up to a sign difference), the (k, q) element of the coding matrix, for $i = 1, 2 ... n_T$ and then decide on constellation symbol s_i that satisfies

$$s_i = \arg\min_{s \in \mathcal{A}} \left(|R_i - s|^2 + \left(-1 + \sum_{k,l} |\alpha_{kl}|^2 \right) |s|^2 \right),$$

With $\mathcal{A}$ the constellation alphabet. Despite its appearance, this is a simple, linear decoding scheme that provides maximal diversity.

IV.SIMULATIONS

The Rayleigh channel model is used while doing these matlab simulations. Considering the case of Nr =1 up to Nr=4 we stimulate G_2, G_3, G_4 ,H_3 and H_4.Here BPSK,QPSK,4-QAM,16-QAM and 64-QAM are modulated ,while reaching 40dB SNR the simulation is stopped. Blocks of 10^4 symbols are stimulated per sample until 100 bit errors are obtained.

V.RESULTS AND ANALYSIS

Here we study the performance of each block code discussed earlier for the different cases of constant Nr, Nt , rate, and diversity order. Since the results obtained for BPSK and QPSK are nearly identical keeping the other variables unchanged, thus here we have shown the result of QPSK only.

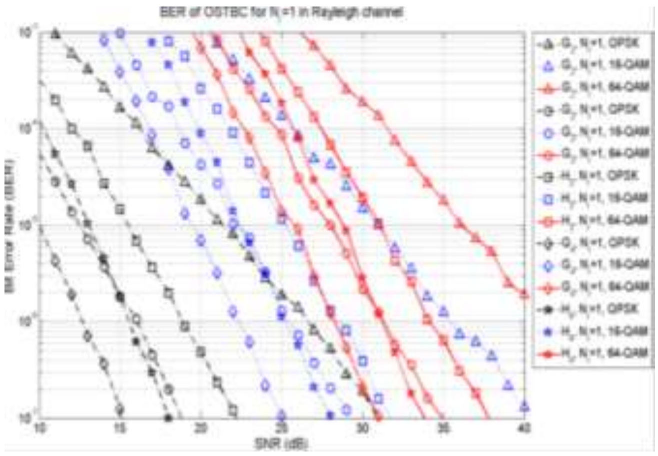

Fig2: Bit error rate versus SNR of OSTBC for Nr = 1.

In fig2 we have fixed the value of N_r to 1.From this figure we can see that as more bits/symbol are transmitted, the performance for each different block codes degrades .It is observed that at high SNR for any particular modulation the best performance is obtained for G_4 followed by H_4, G_3 ,H_3 and G_2.However at low SNR G_3 shows better performance than H_4.The same thing happens for the cases of N_r =2,N_r=3 and N_r=4 as well.

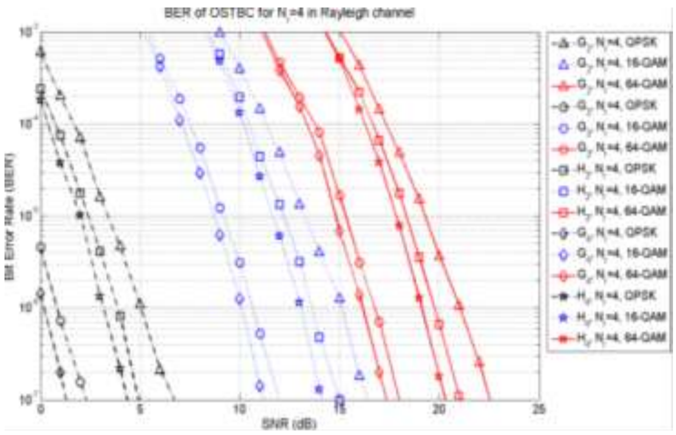

Fig3: BER versus SNR of OSTBC for Nr = 4.

In this case, the number of receiving antenna is fixed to 4.It is observed that the performance order is same as for the case of N_r=1 at low SNR. Here the best performance order is obtained for G_4 followed by G_3 , H_4 , H_3 and G_2. One possible reason for this behavior is that the higher rate of H_4 causes lower channel gain per symbol and therefore higher BER for a particular SNR.

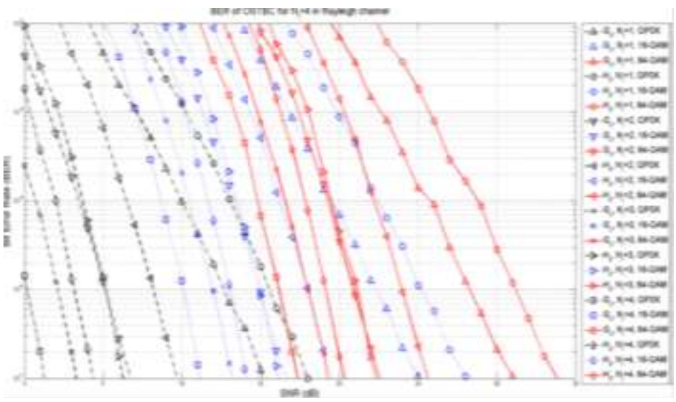

Fig4: Bit error rate versus SNR of OSTBC for Nt = 4.

Figure 4 shows the BER curve keeping N_t= 4 constant and varying the N_r from 1 to 4. It can be observed that for any modulation and block code, the gain of using 3 more antennas is approximately 14dB. However, between Nr = 1 and Nr = 2 the gain is approximately 8dB, between Nr = 2 and Nr = 3 the gain is approximately 4dB, and between Nr = 3 and Nr = 4 the gain is approximately 2dB. This result suggests as Nr increases, the gain gradually decreases. Apart from this the second observation is that, for any Nr and modulation scheme, G3 and G4 have a 3dB gain over H3 and H4 respectively. The performance of G4 with Nr = 2 is similar to that of H4 with Nr =3, while G4 with Nr = 1 is outperformed by H4 with Nr = 2, and G4 with Nr = 3 outperforms H4 with Nr=4.

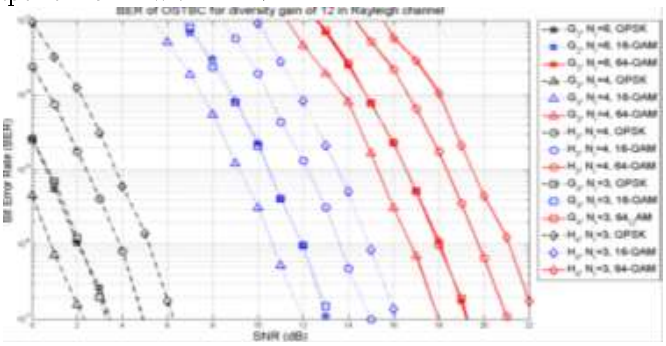

Fig5: BER vs. SNR of OSTBC for spatial diversity 12

A BER curve is shown in figure 5 for the case of equal diversity gain. The stimulation of G_2 with N_r = 6, G_3 and H_3 with N_r = 4 and G_4 and H_4 with N_r = 3 is done. The diversity gain in each case is therefore 12. From this figure we see that having fewer number of transmit antennas and more number of receive antennas results in better performance. G3 and H3 with Nr = 4 have a 2dB performance gain over G4 and G4 with Nr = 3 respectively.

Again, from this figure it is observed that G2 with Nr = 6 has similar performance as to G4 with Nr = 3. This observation suggests that there is an upper limit at which using few Nt transmit antennas and more Nr receive antennas becomes equivalent to using more Nt transmit antennas and fewer Nr receive antennas.

VI. CONCLUSION

In this paper we have discussed MIMO channel modeling techniques with an introduction to Space-Time Coding was provided by presenting Alamouti's scheme. With the encoding and decoding algorithms we have discussed block codes schemes with different code rates. It was observed that higher diversity gain doesn't always imply better performance. This was observed when G3 outperformed H4 at low SNR. Similarly, it was observed that equal diversity gain does not imply equal performance. This was particularly demonstrated when G3 outperformed all others for equal diversity gain. Also, we observed diminishing returns for every scheme as the number of received antennas increased. It was particularly interesting to find that althoughH3 and H4 have higher rate than G3 and G4, the performance of G3 and G4 is greater. Finally, we conclude that it is preferable to use a low constellation order with high code rate than high constellation order with low code rate.

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