Channel-Matched Space-Time Code Selection and Adaptive Modulation for Rayleigh Fading Channels

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***Abstract*— Space-Time Block Codes represent an exciting development in the field of wireless communication. It is a promising technique to increase the data rates with minimal decoding complexity. In this paper, we present an adaptive transmission system for Rayleigh fading Multiple Input Multiple Output channels. Code selection and adaptive modulation are combined together by two feedback scenarios. Channel State Information is sent back from the receiver to the transmitter controlling three feedback decision bits. By applying these adaptive techniques, the system adjusted its performance with the channel conditions. As a result, signal transmission with an improved coding gain and diversity near to the maximum diversity order is achieved. The proposed system has shown enhanced bit error rate performance and better outage data throughput, when compared with non adaptive systems.**

Keywords--Space-Time Block Codes; Multiple Input Multiple Output; Channel State Information; feedback; Adaptive Modulation.

I. Introduction

Third-generation wireless communication systems are required to provide data bit rates of up to 2 Mbits/s. Recently released fourth-generation standards will push these rates even higher, possibly over 100 Mbits/s [1]. To support such high rates, multiple antennas can be employed to increase channel capacity.

As a result of Space Time Coding (STC) [4], the transmitted signal resists the multipath fading effects that increases the Bit Error Rate (BER) by depending on both time and space diversity. It was shown in [4] that an orthogonal full-rate design, offering full diversity for any arbitrary complex symbol constellation, is limited to the case of two transmit antennas. Data-rate or decoding simplicity must be sacrificed if the number of transmit antennas is increased.

Most Space Time Block Codes (STBCs) are designed under the assumption that the transmitter has no knowledge about the channel. On the other hand, it has been shown in [3] that an outage performance with perfect Channel State Information (CSI) available at the transmitter and at the receiver is better compared to the case when only the receiver has perfect knowledge of the channel.

When applying adaptive modulation, great enhancements in the system performance are achieved. Constantly changing the modulation scheme with the varying channel conditions and thus, yielding higher data throughput when compared with the non adaptive systems [7]. According to [4], an orthogonal complex 4x4 code matrix is not full rate on the other hand, the Extended Alamouti 4x4 near orthogonal code matrix is full rate

Thus sacrificing the code orthogonality, code selection technique is used to overcome this problem. The proposed system combines adaptive modulation and code selection techniques depending on the CSI available at both the transmitter and receiver, this combined system outstands the non-adaptive systems in both bit error rate (BER) results and outage data throughput.

The paper is organized as follows. Section II reviews the simple 2x1 Alamouti scheme [4] and the Extended Alamouti scheme with code selection technique [3]. Section III presents the proposed system combining adaptive modulation with code selection techniques. The system simulation and results will be presented in Section IV. Finally, Section V contains the paper conclusion.

II. Alamouti and Extended Alamouti Schemes

A. Alamouti Scheme

In 1998, the preliminary form of STBC was introduced by Alamouti [4]. It linearly and orthogonally encodes a data stream and transmits it simultaneously across the channel. The encoder takes a block of two modulated symbols S_1 and S_2 in each encoding operation and maps them to two transmit antennas according to a code matrix given in (1). After transmission, the data stream is successfully extracted at the receiver due to the orthogonal encoding.

$$S = \begin{bmatrix} S_1 & S_2 \\ S_2^* & -S_1^* \end{bmatrix} \quad (1)$$

At the receiver, the signals are expressed as:

$$R_1 = h_1 S_1 + h_2 S_2 + n_1 \quad (2)$$
$$R_2 = h_1 S_2^* - h_2 S_1^* + n_2 \quad (3)$$

Or, written in the vector form, as mentioned in [5]

$$r = Sh+n \quad (4)$$

where ***n*** represents Gaussian noise.

B. 4x1 Extended Alamouti Scheme and code selection

The Extended Alamouti Space Time Block Coding (EA-STBC) uses four transmit antennas and one receiver antenna [3]; as a result, four symbols are transmitted each time slot. The code matrix is generated as a result of “alamoutisation” of the basic Alamouti code mentioned in (1) [2]. In other words, two Alamouti codes are used to build up the EA-STBC for four transmit antennas. The resulting code extends over four time slots and is described in [3][5] by the following signal matrix,

$$S_1 = \begin{pmatrix} S_1 & S_2 & S_3 & S_4 \\ S_2^* & -S_1^* & S_4^* & -S_3^* \\ S_3^* & S_4^* & -S_1^* & -S_2^* \\ S_4 & -S_3 & -S_2 & S_1 \end{pmatrix} . \quad (5)$$

The received signals within four successive time slots, assuming one receiver antenna, are given in [3] as,

$$r_1 = S_1 h_1 + S_2 h_2 + S_3 h_3 + S_4 h_4 + n_1 \quad (6)$$
$$r_2 = S_2^* h_1 - S_1^* h_2 + S_4^* h_3 - S_3^* h_4 + n_2 \quad (7)$$
$$r_3 = S_3^* h_1 + S_4^* h_2 - S_1^* h_3 - S_2^* h_4 + n_3 \quad (8)$$
$$r_4 = S_4 h_1 - S_3 h_2 - S_2 h_3 + S_1 h_4 + n_4. \quad (9)$$

With complex conjugation of (7) and (8), we obtain,

$$y_2 = r_2^* \quad , \quad n_2 = n_2^* \quad (10)$$
$$y_3 = r_3^* \quad , \quad n_3 = n_3^* \quad (11)$$

Resulting in (12), the matrix equation representing the transmission scheme,

$$y = H_{v1} s + n \quad (12)$$

where H_{v1} is the virtual effective channel matrix and is equal to,

$$\boldsymbol{H}_{v1} = \begin{pmatrix} h_1 & h_2 & h_3 & h_4 \\ -h_2^* & h_1^* & -h_4^* & h_3^* \\ -h_3^* & -h_4^* & h_1^* & h_2^* \\ h_4 & -h_3 & -h_2 & h_1 \end{pmatrix} \quad (13)$$

It is shown in [3] that H_{v1} is nearly orthogonal. As mentioned in [4] that fully orthogonal codes achieve full diversity gain. So, to overcome the problem of near orthogonal codes, the code selection technique is proposed in [3].

The signal transmission is described by the vector form discussed in (4) where **r** is the (4x1) vector of the received signals. **S** is the space time block code that could be either S_1 as defined in (5) or S_2 defined in (14) depending on a feedback bit b_3, and finally, **n** is the (4x1) noise vector [5]. In [3][5], the EA-STBCs are generated from each others by changing the signs, which is obvious in the generated code named S_2 in (14).

$$S_2 = \begin{pmatrix} -S_1 & S_2 & S_3 & S_4 \\ -S_2^* & -S_1^* & S_4^* & -S_3^* \\ -S_3^* & S_4^* & -S_1^* & -S_2^* \\ -S_4 & -S_3 & -S_2 & S_1 \end{pmatrix} \quad (14)$$

Similarly, H_{V2} is generated if S_2 is used,

$$\boldsymbol{H}_{v2} = \begin{pmatrix} -h_1 & h_2 & h_3 & h_4 \\ -h_2^* & -h_1^* & -h_4^* & -h_3^* \\ -h_3^* & -h_4^* & -h_1^* & h_2^* \\ h_4 & -h_3 & -h_2 & -h_1 \end{pmatrix} \quad (15)$$

As in [5], we obtain

$$G = H_{vi}^H H_{vi} = H_{vi} H_{vi}^H$$

$$= h^2 \begin{pmatrix} 1 & 0 & 0 & \mathbf{X_i} \\ 0 & 1 & -\mathbf{X_i} & 0 \\ 0 & -\mathbf{X_i} & 1 & 0 \\ \mathbf{X_i} & 0 & 0 & 1 \end{pmatrix} \quad (16)$$

where i =1 or 2 and $h^2 = h_1^2 + h_2^2 + h_3^2 + h_4^2$ (17)

$$X_1 = \frac{2\,\mathrm{Re}\left(h_1 h_4^* - h_2 h_3^*\right)}{h^2}, \quad \text{when } S_1 \text{ is sent} \quad (18)$$

And

$$X_2 = \frac{2\,\mathrm{Re}\left(-h_1 h_4^* - h_2 h_3^*\right)}{h^2}, \quad \text{when } S_2 \text{ is sent} \quad (19)$$

It is known from [6] that **G** should be an identity matrix to achieve full diversity and an optimum system performance. But, on the other hand, if G is not an identity matrix as in (16), channel dependent parameter named X_i appears leading to interference between the four channel parameters. Thus, X_i should be as small as possible to reach near orthogonality of STBC used.

Thus, code selection is applied between the two transmission codes S_1 and S_2. By computing the values of X_1 and X_2 from (18) and (19), respectively, the system returns feedback bit $\boldsymbol{b_3}$ to the transmitter to select the code block corresponding to the minimum value of X.

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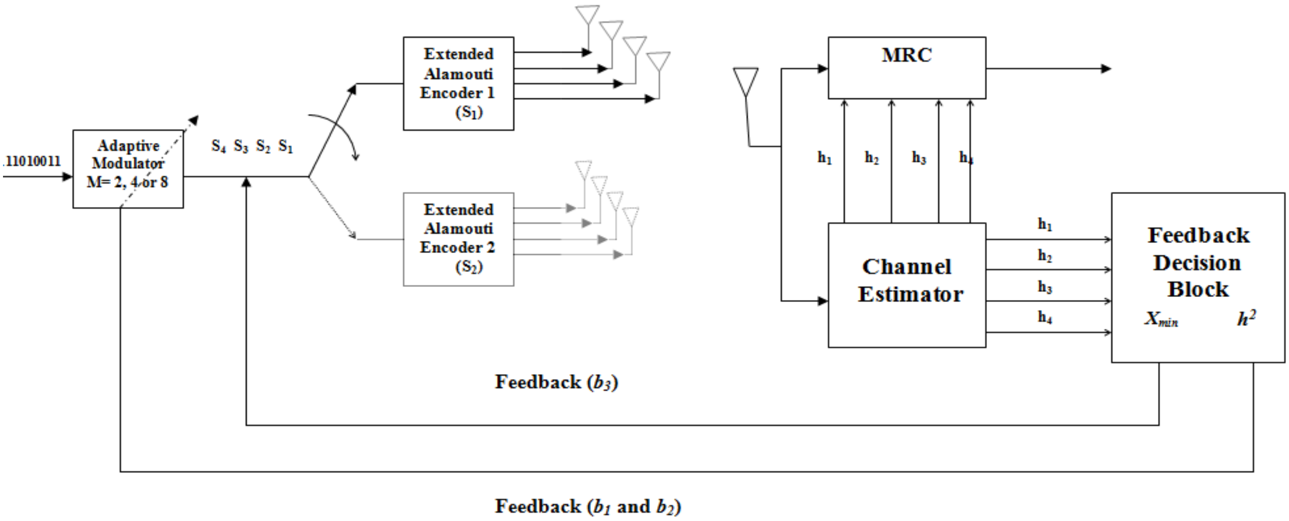

Figure 1. Combined Adaptive Modulation and Code Selection Techniques

III. PROPOSED COMBINED ADAPTIVE MODULATION AND CODE SELECTION TECHNIQUES

The combined adaptive transmission system proposed in this paper requires full knowledge of CSI at both the transmitter and the receiver. Figure 1 presents the block diagram of the proposed combined system. Binary data is fed into an adaptive M-ary modulator set to three modulation states, BPSK, QPSK or 8-ary PSK. Switching between these modulation techniques requires two feedback bits $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$. The data is then encoded with either one of two Extended Alamouti block codes S_1 or S_2. Switching between these block codes requires a feedback bit $\boldsymbol{b_3}$. The encoded data is then transmitted through four time slots, using four different antennas. At the receiver end, the transmitted signals are received using one receiver antenna. Finally, Maximum Ratio Combining (MRC) is used for signal detection at the receiver.

Choosing between S_1 and S_2 at the transmitter is considered a type of system adaptation, or, in other words, matching the code selection process with the value of channel dependent interference parameter X_i given in (18) and (19). Adaptive modulation is also applied which denotes the matching of the modulation technique with the channel conditions. Higher order modulation is assigned to the system at poor channel conditions. In this way we could benefit from the channel response, whereas the channel is considered as gain for the transmitted signal. In this paper, we have investigated three modulation techniques, BPSK, QPSK and 8-PSK, therefore requiring two feedback bits $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$ implemented between the receiver end and the modulator in the transmitter as shown in Figure 1.

For acquiring the CSI, two thresholds are defined to assign a modulation scheme to the system using bits $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$**;** the third feedback bit $\boldsymbol{b_3}$ returns information on the code block that will be used to encode the modulated data.

From (17), $\boldsymbol{h^2}$ is easily computed, and, according to its value, the suitable modulation is chosen. As a result, the adaptive modulation system controls the outage data rate. In the following section, performance of the proposed system which combines adaptive modulation and code selection will be investigated.

IV. SIMULATION AND RESULTS

In our simulations, we have used flat Rayleigh fading channel remaining constant during the transmission of each code block [3]. At the receiver side, we have used MRC receiver. The BER results have been averaged over 10^5 realizations of i.i.d channel matrix. We simulated MIMO systems with two and four transmit antennas and a single receive antenna. BPSK, QPSK [3] and 8-PSK modulation techniques are used in the adaptive modulation process. In the simulations of the adaptive modulation systems, the BER and the modulation order (M) are averaged for each value of Signal to Noise Ratio (SNR). The results are introduced in three parts; part A presents the processes of adaptive modulation and code selection while, the BER results are presented in part B. To visualize the data throughput more clearly and to support the enhanced BER results, Figure of Merit is calculated, which is presented in part C.

A. Adaptive modulation and code selection Processes

This section presents the behavior of the proposed combined system for a given sample of ten time frames for the same SNR.

In Figure 2, the normalized channel response is represented against time frame. It is quiet obvious that the channel is varying at each frame. By extensive simulation of the proposed system according to the simulation environment mentioned at the beginning of this section, it was noticed that the values of $\boldsymbol{h^2}$ lies between a certain range of numbers. Two middle values were chosen as the threshold values to control the adaptive modulation process. During the time frames that contain values of the normalized channel beneath threshold 1, BPSK (M=2) is assigned. While QPSK (M=4) is used during the time frames containing values of the normalized channel in between threshold 1 and threshold 2. Finally, 8-PSK (M=8), is assigned otherwise (above threshold 2) as shown below.

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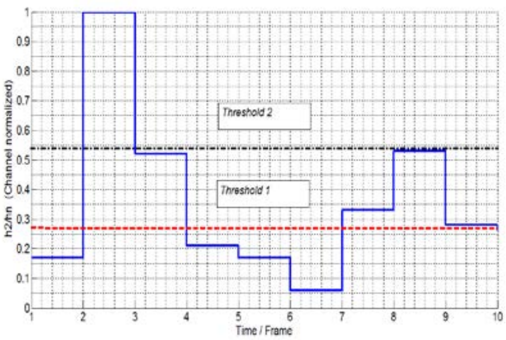

Figure 2. Channel Response Normalized (h^2/h_n) Against Time/Frame

On the other hand, Figure 3 shows the system response (from the adaptive modulation aspect) towards the variation of the normalized channel values- presented in Figure 2 for the exact ten time frames leading to variation in the modulation order used at each frame.

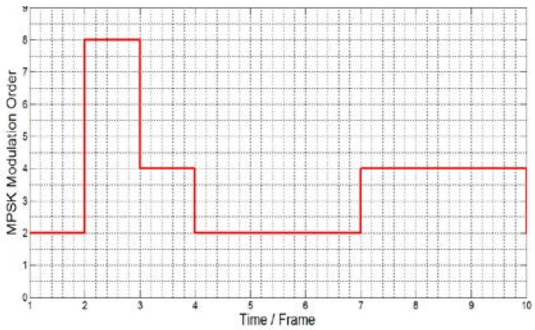

Figure 3. MPSK Modulation Order at each Time/Frame

Figure 4 represents the values of the channel dependent parameter, Xi, against the same time frames presented in Figures 2 and 3. With varying values of X_1 and X_2, code switching between S_1 and S_2 is applied by the system as shown below. For easy visualization of this process, S_1 is represented by 1 and S_2 is represented by 1.5**.**

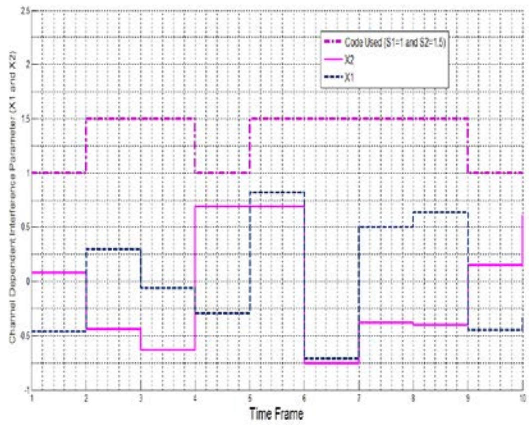

Figure 4. Code Selection Technique

B. BER Results

For the system setup mentioned in the beginning of Section IV, this section shows the resulting performances (BER against SNR) for the proposed combined system against non adaptive systems. Figure 5 shows the resulting BER against SNR for the 2x1 simple Alamouti scheme that uses adaptive modulation against non-adaptive system (no code selection is applied in both systems). Performance improvement is obvious, for the same BER the adaptive system is almost 7dB better than the non-adaptive one.

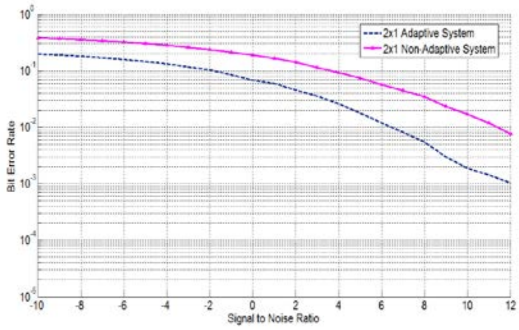

Figure 5. BER for 2x1 Adaptive Alamouti scheme against 2x1 Non-Adaptive Alamouti scheme

Figure 6 shows the BER results for the proposed system (adaptive modulation and code selection techniques) against the non-adaptive system that uses only QPSK modulation. The proposed system gives 7dB SNR improvement than the non adaptive system.

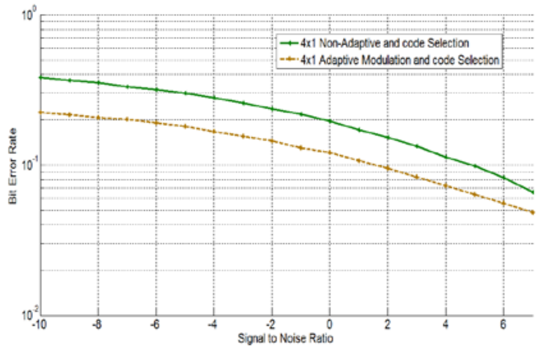

Figure 6. BER for 4x1 Adaptive system against 4x1 non adaptive system.

Figure 7 shows the BER performance improvements for the proposed combined adaptive system that uses three modulation schemes (at the same time) against non adaptive systems using BPSK, QPSK and 8-PSK each at a time, The results shows at least 4 dB of SNR improvement as shown in the figure.

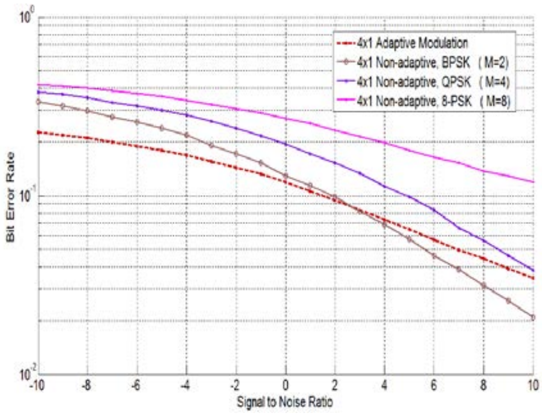

Figure 7. The 4x1 combined system against non adaptive systems using BPSK, QPSK and 8-PSK

At almost 3 dB, the performance of the 4x1 BPSK outstands the proposed combined system which is expected as the BPSK should have the optimum performance (lower BER) for all ranges of SNR on the account of the data throughput. On the other hand, the proposed combined system shows better throughput than the other non-adaptive systems as will be shown in Figure 8.

C. *Figure of Merit*

Figure of merit is an indication of the data throughput of the system. It is drawn against the SNR and it is calculated by the following formula,

$$\text{Figure of Merit} = M^* (1\text{-BER}) \qquad (20)$$

where M is the modulation order.

Figure 8 shows the resulting figure of merit for 4x1 proposed combined adaptive system against non-adaptive BPSK and QPSK. As clearly shown, the adaptive system shows better figure of merit than the other systems therefore better throughput. For the adaptive system, in the calculation of the above formula, M is averaged along the whole adaptive modulation process (as mentioned earlier). Its quiet clear that the figure of merit tends to M in each case where M_{max}=M.

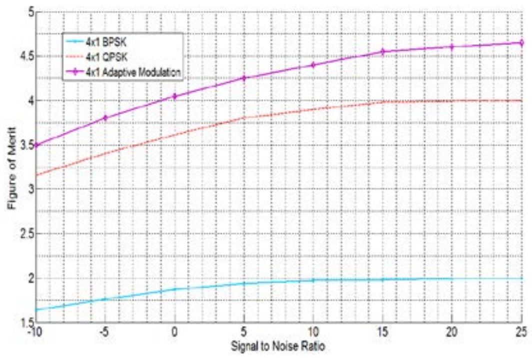

Figure 8. Figure of Merit results for the 4x1 Adaptive System Against 4x1 non Adaptive Systems.

V CONCLUSION

By combining both adaptive modulation and code selection to the 4x1 Extended Alamouti system, performance improvements are visible in all the presented results. With assigning higher order modulation to the system when $\boldsymbol{h}^2$ is above threshold 2, it is considered as a gain for the transmitted signal therefore the signal is more robust to noise. Figure of Merit results indicate better throughput for the adaptive system by calculating the average modulation order (Maverage) through out the process which will be greater than that of the BPSK and QPSK individually. In addition, code selection between the non- orthogonal codes S_1 and S_2 to reach the code with minimum value of X_i, in other words, the near orthogonal code. Changing the receiver and the number of the receiver antennas could be considered later on to achieve near optimum performances.

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