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Simple unequal error protection mechanism for multimedia traffic using the Alamouti structure with hierarchical modulation and signal space diversity

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Abstract: Conventional hierarchical modulation (HM) only provides two levels of unequal error protection (UEP) for multimedia traffic transmission. An HM-based scheme is proposed that provides multiple levels of UEP by exploiting the structure of the Alamouti scheme. A typical Alamouti scheme operates based on the assumptions that the modulation scheme used for the transmission at each antenna is the same and that the power in each antenna is equal. In the proposed system, these two operating assumptions are relaxed, in that the modulation schemes as well as the transmission powers for the two antennas are varied in order to propose a multiple level UEP mechanism for multimedia traffic. The concept is applied to a recently proposed system which uses the Alamouti space–time block code (STBC) structure with HM and signal space diversity (SSD), and it is shown via theoretical and simulation results how the simple UEP mechanism can accommodate the simultaneous transmission of multiple classes of multimedia traffic.

1 Introduction

The concept of using unequal error protection (UEP) for the reliable transmission of multimedia data has become important both from a research [1] and commercial [2] perspective. One of the most prominent mechanisms for the implementation of this concept is hierarchical modulation (HM). The fundamental idea with this mechanism is to separate the transmitted data into several multiplexed bit streams of unequal priority from high to low. These streams are then assigned to different bit positions in HM, which allows higher error protection for the high priority (HP) stream at the expense of the lower one. The manner in which this is done will ensure that in the worst-case scenario the HP data stream is recovered when the channel degrades, but allows for both the high and low priority (LP) data to be recovered when the channel improves. The flexibility of the mechanism allows a communication system that is more resilient to the variations that naturally occur in the wireless channel. Previous to HM, this resilience would be achieved using source or channel coding, and the advantage that HM has over such schemes is that it can achieve the same result without sacrificing or requiring additional bandwidth.

HM-based systems have been studied extensively and the research work can be broadly summarised into three categories: performance improvement of HM, application of HM to digital broadcasting and the use of HM for UEP in multimedia traffic transmission. The proposed systems in [3–6] are examples of the first category where HM performance has been enhanced with schemes such as signal space diversity (SSD) and Alamouti space–time block code (STBC). In terms of the second category, the earliest application of HM was for digital broadcasting systems [7, 8]. More specifically, [7] presents a study of hierarchical quadrature amplitude modulation (HQAM) for this application. The commercially available digital video broadcasting (DVB-T) standard [2] uses HQAM for layered video transmission, with the aim of increasing overall system capacity and coverage. A performance study of HM for this standard has been presented in [9]. With the proliferation of digital communication systems, the transmission of multimedia traffic, with its varying quality of service (QoS) requirements, became a prominent research problem. HM has been widely used to provide solutions to this problem, especially when adaptive systems cannot be used [1]. References [10, 11], and more recently [12], present HM-based systems for the transmission of multimedia traffic by enabling the simultaneous delivery of multiple classes of data with UEP requirements. In this context, HM has also been jointly considered with error-correction coding for proposing efficient and flexible UEP mechanisms for multimedia traffic transmission in [13, 14]. The flexibility is achieved because the level of UEP can be finely controlled by modifying the distances between the constellation points, and this can be done without requiring additional bandwidth as compared to channel coding [13].

Traditionally, the number of UEP levels required for multimedia traffic has been limited. For example, in the DVB-T standard [2], the video data encoded by the MPEG-2 only requires UEP for two layers and in such a scenario hierarchical 16 or 64 QAM is sufficient. However, as progressive image or scalable video encoders are incorporated more and more into DVB systems, these HM systems may not meet the system requirements as multiple levels of error protection are needed for such data. Most of the HM-based systems proposed thus far have only considered two levels of UEP, and the published schemes that allow more levels are rare. The very recent work in [1], which is an exception to this, presents a multilevel UEP system for the transmission of progressive image or video data. The system in [1] combines channel coding with HM (for each UEP level) and uses a multiplexer to achieve multiple UEP levels. The system proposed in this paper has the same objective, namely to enable multiple levels of UEP for the transmission of multimedia data; however, it achieves this using a novel yet simple manner by exploiting the Alamouti structure.

Recently, [4] proposed a new transmit diversity scheme using the Alamouti STBC structure with HM combined with SSD, and the system performance showed significant gains achieved by the system over systems without the Alamouti structure. However, since it is essentially an enhanced HM scheme, it has the limitation highlighted above, in that it only allows two levels of UEP. A careful study of the system led to an opportunity to overcome this limitation. The Alamouti structure, with two transmit antennas and once receive antenna, in [4] and in the original proposal of the technique in [15] has two underlying operating assumptions. The first implicit assumption is that the modulation scheme on both transmit antennas is the same and the second is that the transmit power in both the antennas are equal. In this paper these constraints of the basic structure are relaxed to propose a novel yet simple mechanism that has the same motivations as the work in [1], which is to provide multiple levels of UEP for the transmission of multiple classes of multimedia or progressive data streams. More specifically, the proposed scheme uses two different modulation schemes and a power sharing factor between the two transmit antennas of the Alamouti structure to enable the simultaneous transmission of four classes of multimedia data streams requiring different levels of error protection. In this paper, the proposed system uses 16 hierarchical QAM as the modulation technique, which allows four levels of UEP. However, this can be easily extended to more levels using higher orders of HQAM.

The remainder of this paper is organised as follows: Section 2 describes the system model and discusses three components of the proposed scheme, namely HM, SSD and the Alamouti structure. The theoretical model for the bit error rate (BER) performance analysis of the proposed system is discussed in Section 3. The theoretical model has been validated through extensive simulations and these are presented in Section 4. The final conclusions are then discussed in Section 5.

2 System model

The structure of the proposed system is shown in Fig. 1.

The proposed system currently is a multiple-input and single-output (MISO) system, however, it can be extended to a multiple-input multiple-output (MIMO). In Fig. 1, the modulation blocks consist of two processes, namely HM and SSD. Each modulator i, $i = 1, 2$, has its unique HM constellation parameter that determines the level of UEP

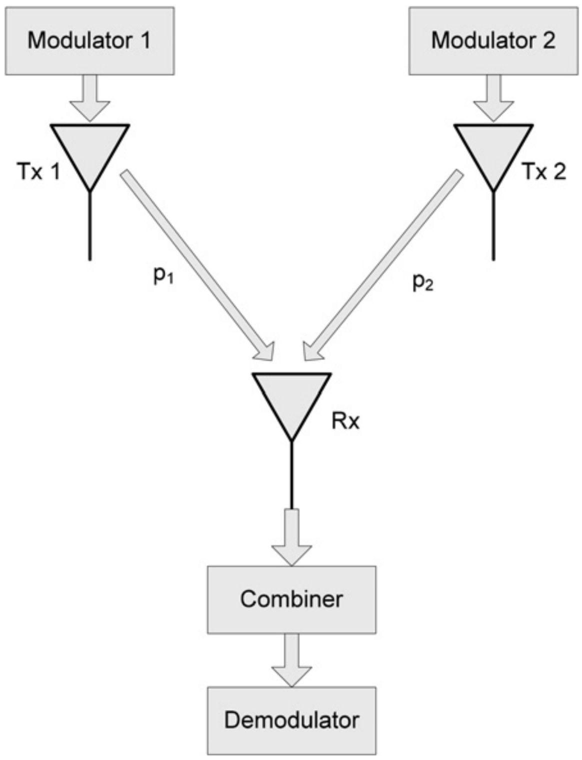

Fig. 1 *Proposed system model*

provided for the HP and LP bits being modulated. Sets of the HM symbols from modulator i are then rotated and interleaved in the SSD process. The output symbols from SSD are then transmitted over the wireless channel using the Alamouti scheme. There are also two power proportionality factors p_1 and p_2, where p_1 is for antenna 1 and p_2 is for antenna 2. These two factors determine how the transmit power is proportioned between two antennas in the Alamouti scheme. Varying the relative difference between p_1 and p_2 varies the level of UEP for the two HM streams transmitted via the respective antenna. In the Combiner block at the receiver, the signals from the two transmit antennas are combined based on the detection of the Alamouti scheme. The combined signals are then passed to the Demodulator block, which includes the de-interleaved process and maximum likelihood (ML) detection. The details of the UEP HM, SSD and the Alamouti processes are discussed in the following subsections.

2.1 Hierarchical modulation

Each modulation block shown in Fig. 1 assumes two separate input bit streams which are of unequal importance. The HM modulator assigns two bits from the HP stream to the most significant bit (MSB) position in the in-phase and quadrature component of each symbol. The remaining bit positions in the in-phase are assigned half of the LP bits, whereas the other half of the LP bits are assigned to the quadrature component of each symbol. The HM symbols are labelled according to a grey-encoded mapping procedure [16], which provides the UEP for the two input bit streams. The level of relative UEP between the two streams is controlled by varying the distances between the constellation points. This is implemented by varying the ratio $\alpha = a/b$, where a and b are the distances between the

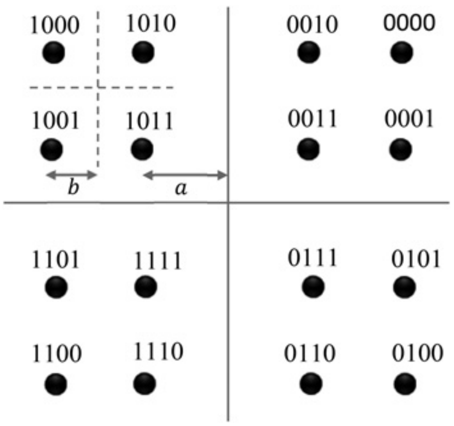

Fig. 2 *4/16-QAM hierarchical constellations*

constellation points and the respective decision boundaries as shown in Fig. 2. The ratio α is commonly referred to as the hierarchical or constellation parameter. In the proposed system model shown in Fig. 1, each modulator has its unique α value (α_1 for modulator 1 and α_2 for modulator 2) and each antenna has its own power factor (p_1 for antenna 1 and p_2 for antenna 2). The α for a modulator determines the relative UEP between the HP and LP streams that is modulated by the modulator, while the relative p values for the two antennas determine the relative UEP between the two sets of HM streams transmitted by the two antennas. As an example, assuming antenna 1 is used to transmit HP and LP streams HP1 and LP1 and antenna 2 is used to transmit high and low streams HP2 and LP2, increasing α_1 and α_2 in each modulator will increase the level of protection for HP1 at the expense of LP1 and HP2 at the expense of LP2, respectively, whereas increasing p_1, and relatively decreasing p_2, will increase the level of protection for HP1 and LP1 at the expense of HP2 and LP2. The novelty in this is that the power factors for each antenna lead to UEP in a manner similar to the hierarchical parameter, but between the two sets of HM streams on the two antennas. Thus, by varying α_1, α_2, p_1 and p_2, the proposed system allows for the UEP of four different bit streams of multimedia traffic. As an example, assuming there are four input data streams ds_1, ds_2, ds_3 and ds_4 with ds_1 requiring the highest level of protection and ds_4 the lowest, the data streams are allocated to the HM-based UEP system as follows: If $\alpha_2 > \alpha_1$ and $p_2 > p_1$, then ds_1 is transported through the HP bit stream of antenna 2, ds_2 is transported through the HP bit stream of antenna 1, ds_3 is transported through the LP bit stream of antenna 2 and ds_4 is transported through the LP bit stream of antenna 1.

2.2 Signal space diversity

Without consuming any additional bandwidth, transmit power or space, SSD is a technique that takes advantage of the intrinsic diversity of multi-dimensional constellations to improve BER performance. The implementation of the SSD mechanism for the UEP Alamouti transmit diversity technique shown in Fig. 1 is as follows. Let x_i^{I} and x_i^{Q} represent the in-phase and quadrature components of the HQAM symbol x_i. Four consecutive HQAM symbols (two from each modulator) $x_i = x_i^{\mathrm{I}} + jx_i^{\mathrm{Q}}$ where $i \in \{1, 2, 3, 4\}$, are rotated using the rotation matrix in (1) [3].

Table 1 Encoding and transmit sequence for the Alamouti scheme

	Time slot 1	Time slot 2	Time slot 3	Time slot 4
antenna 1	s_1	$-s_2^*$	s_3	$-s_4^*$
antenna 2	s_2	s_1^*	s_4	s_3^*

$$R^{\theta_k} = \begin{bmatrix} \cos\theta_k & \sin\theta_k \\ -\sin\theta_k & \cos\theta_k \end{bmatrix} \quad (1)$$

The corresponding in-phase and quadrature components $\tilde{x}_i^{\mathrm{I}}$ and $\tilde{x}_i^{\mathrm{Q}}$ of the rotated HQAM symbol $\tilde{x}_i$ are given by $[\tilde{x}_i^{\mathrm{I}} \quad \tilde{x}_i^{\mathrm{Q}}] = [x_i^{\mathrm{I}} \quad x_i^{\mathrm{Q}}]R^{\theta_k}$, $k \in \{1, 2\}$.

In [3] the rotation angle θ_k is dependent on the HQAM hierarchy parameter α and was calculated based on the design criteria for the HQAM modulation. In the design criteria approach, the geometry of the HQAM constellations is analysed and a θ_k is chosen which maximises the minimum Euclidian distance between the constellation points. The θ_k is determined by calculating the inverse of (2).

$$\tan\theta_k = \frac{\alpha_k}{\alpha_k + 3} \quad (2)$$

Returning to the description of the SSD process, the rotated symbol streams are then grouped into pairs and passed through a component interleaver where the in-phase and the quadrature components in each pair are interleaved to produce new symbol pairs as shown in (3). As a result, the in-phase and the quadrature components of each $\tilde{x}_i$ experiences independent fading.

$$s_i = \tilde{x}_i^{\mathrm{I}} + j\tilde{x}_{i+2}^{\mathrm{Q}} \quad i \in \{1, 2\} \quad (3a)$$

$$s_i = \tilde{x}_i^{\mathrm{I}} + j\tilde{x}_{i-2}^{\mathrm{Q}} \quad i \in \{3, 4\} \quad (3b)$$

2.3 UEP Alamouti scheme

The proposed UEP Alamouti scheme operates as follows: The two symbol pairs (s_1, s_2) and (s_3, s_4) are simultaneously transmitted in time slot 1 and slot 3, respectively, whereas $(-s_2^*, s_1^*)$ and $(-s_4^*, s_3^*)$ are simultaneously transmitted in time slot 2 and slot 4 ('*' denotes the complex conjugate). This encoding and transmission sequence is shown in Table 1.

The symbols are transmitted over fading channel h_i, $i \in \{1, 2, 3, 4\}$ and is perturbed by additive white Gaussian noise (AWGN) n_i, $i \in \{1, 2, 3, 4\}$. It is assumed that h_i remains constant during every pair of time slots and takes independent values from one pair of time slots to another.

The received signals in each time slot are given by

$$r_1 = p_1 h_1 s_1 + p_2 h_2 s_2 + n_1 \quad (4a)$$

$$r_2 = -p_1 h_1 s_2^* + p_2 h_2 s_1^* + n_2 \quad (4b)$$

$$r_3 = p_1 h_3 s_3 + p_2 h_4 s_4 + n_3 \quad (4c)$$

$$r_4 = -p_1 h_3 s_4^* + p_2 h_4 s_3^* + n_4 \quad (4d)$$

where p_i, $i \in \{1, 2\}$ is the power factor for each antenna given by

$$p_1 = (1 - q) \quad (5a)$$

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$$p_2 = (1 + q) \tag{5b}$$

where q represents the ratio of power shared between the two antennas in the Alamouti STBC structure. The other variables in (4) are as follows: s_i, $i \in \{1, 2, 3, 4\}$ are the interleaved symbols defined in (3); n_i, $i \in \{1, 2, 3, 4\}$ are independent and identically distributed (i.i.d) entries according to the complex Gaussian distribution $\mathcal{CN}(0, 1)$ and h_i, $i \in \{1, 2, 3, 4\}$ where $h_i = \rho_i e^{j\theta_i}$ denotes the channel fading from the transmit antennas in each respective time slot. The amplitude ρ_i is modelled as the Rayleigh distributed random variable according to

$$f(\rho_i) = \frac{\rho_i}{\sigma^2}\exp\left(-\frac{\rho_i}{\sigma^2}\right) \tag{6}$$

where $E[(\rho)^2] = \rho^2$ is the average fading power.

The received signals at the receiver are then combined according to an adaptation of the Alamouti scheme (given in [15]) using (7).

$$y_1 = \left((h_1)^* r_1 + h_2 (r_2)^*\right)/p_1 \tag{7a}$$

$$y_2 = \left((h_2)^* r_1 - h_1 (r_2)^*\right)/p_2 \tag{7b}$$

$$y_3 = \left((h_3)^* r_3 + h_4 (r_4)^*\right)/p_1 \tag{7c}$$

$$y_4 = \left((h_4)^* r_3 - h_3 (r_4)^*\right)/p_2 \tag{7d}$$

The recombined signals are then de-interleaved and passed through the ML detector using the decision rules in (8), which are presented in [17]

$$\hat{x}_1 = \arg\min_{\tilde{x}_i \in \tilde{S}} \left\{ \mu_2 \left| y_1^{\mathrm{I}} - \mu_1 \tilde{x}_i^{\mathrm{I}} \right|^2 + \mu_1 \left| y_1^{\mathrm{Q}} - \mu_2 \tilde{x}_i^{\mathrm{Q}} \right|^2 \right\} \tag{8a}$$

$$\hat{x}_2 = \arg\min_{\tilde{x}_i \in \tilde{S}} \left\{ \mu_2 \left| y_2^{\mathrm{I}} - \mu_1 \tilde{x}_i^{\mathrm{I}} \right|^2 + \mu_1 \left| y_2^{\mathrm{Q}} - \mu_2 \tilde{x}_i^{\mathrm{Q}} \right|^2 \right\} \tag{8b}$$

$$\hat{x}_3 = \arg\min_{\tilde{x}_i \in \tilde{S}} \left\{ \mu_1 \left| y_3^{\mathrm{I}} - \mu_2 \tilde{x}_i^{\mathrm{I}} \right|^2 + \mu_2 \left| y_3^{\mathrm{Q}} - \mu_1 \tilde{x}_i^{\mathrm{Q}} \right|^2 \right\} \tag{8c}$$

$$\hat{x}_4 = \arg\min_{\tilde{x}_i \in \tilde{S}} \left\{ \mu_1 \left| y_4^{\mathrm{I}} - \mu_2 \tilde{x}_i^{\mathrm{I}} \right|^2 + \mu_2 \left| y_4^{\mathrm{Q}} - \mu_1 \tilde{x}_i^{\mathrm{Q}} \right|^2 \right\} \tag{8d}$$

where $\tilde{x}_i = \tilde{x}_i^{\mathrm{I}} + j\tilde{x}_i^{\mathrm{Q}}$; $\tilde{S}$ represents rotated constellation set; $\hat{x}_i$, $i \in \{1, 2, 3, 4\}$ represent the detected symbol for the respective time slots; $\mu_1 = |p_1 h_1|^2 + |p_2 h_2|^2$ and $\mu_2 = |p_1 h_3|^2 + |p_2 h_4|^2$.

3 Performance analysis

One of the first attempts at the performance analysis of HM is presented by [16] in which the BER is determined by considering the probability that a transmitted symbol exceeds a set decision boundary and thus results in an error. This approach becomes unnecessarily complicated and time-consuming when the symbols are rotated as in SSD. Simpler BER expressions for hierarchical 16-QAM with SSD is derived in [3] using a nearest neighbourhood (NN) approach and are shown to be highly accurate. The expressions in [3] are modified in this section to derive an accurate approximation of the BER for the proposed HM and SSD-based UEP Alamouti scheme.

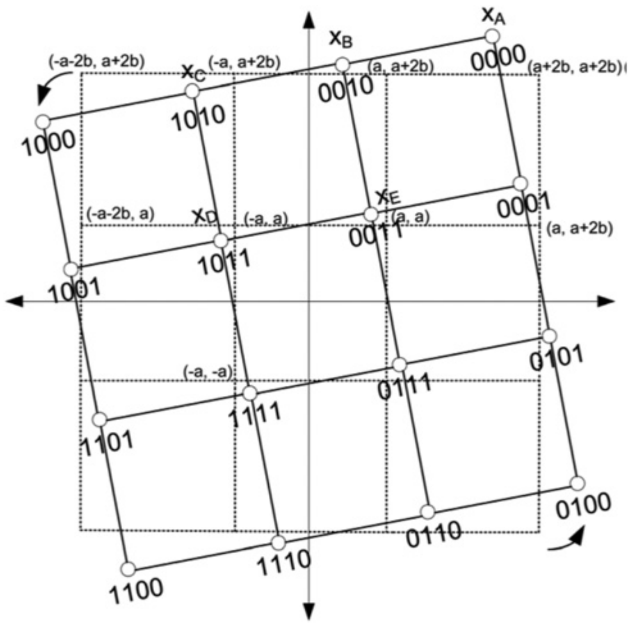

Fig. 3 *Rotated HQAM constellations*

The BER for the HP bits transmitted using each antenna in the UEP Alamouti transmit diversity HM SSD system is given by [4]

$$P_{HP} = \frac{1}{2}P(X_B \to X_C) + \frac{1}{8}P(X_B \to X_D) + \frac{1}{8}P(X_E \to X_C) \tag{9}$$

In (9), $P(X_B \to X_C)$ represents the pairwise error probability (PEP) of perpendicular neighbouring symbols of the constellation set as shown in Fig. 3, and is given by (see (10))

where $\bar{\gamma}$ is the average signal-to-noise ratio (SNR) per hierarchical 16-QAM symbol; p_i, $i \in \{1, 2\}$ is the power factor for each antenna given by (5); θ is the optimum rotation angle; $S_k = 2\sin^2(k\pi/2n)$; $\beta_1 = \left(\alpha_i^2/\left(\alpha_i^2 + 2\alpha_i + 2\right)\right)$, where α_i, $i \in \{1, 2\}$ is the hierarchical parameter for each antenna; and n is the number of summations. n greater than 6 will result in an accurate approximation. $P(X_B \to X_D)$ and $P(X_E \to X_C)$ represent the PEP of diagonal neighbouring symbols as given by (11) and (12). (See equation (11) and (12) on the bottom of the next page) where $\beta_2 = 1/\left(\alpha_i^2 + 2\alpha_i + 2\right)$.

The BER for the LP bits is given by

$$P_{LP} = P(X_A \to X_B) \tag{13}$$

where $P(X_A \to X_B)$ represents the PEP such that a transmitted symbol is detected as a perpendicular neighbour within the same quadrant (as shown in Fig. 3) and is given by (see equation (14) on the bottom of the next page).

The BERs of the data streams transmitted via antennas 1 and 2 are calculated using (9) and (13), and the subsequent PEP

$$P(X_B \to X_C) = \frac{1}{4n}\left(\frac{2}{2 + p_i\bar{\gamma}\beta_1\cos^2\theta}\right)\left(\frac{2}{2 + p_i\bar{\gamma}\beta_1\sin^2\theta}\right) + \frac{1}{2n}\sum_{k=1}^{n-1}\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_1\cos^2\theta}\right)\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_1\sin^2\theta}\right) \tag{10}$$

expressions, with the index i of α_i and p_i being 1 for antenna 1 and 2 for antenna 2.

Furthermore, it was observed in [4] that a 2×1 Alamouti transmission system can be regarded as a 1×2 MRC receive diversity system with a 3 dB penalty. Similarly, since a 2×1 Alamouti transmitted hierarchical QAM with SSD can be regarded as a 1×2 hierarchical QAM with SSD, the average SNR variable, $\bar{\gamma}$, in (10)–(12) and (14) is divided by 2 to incorporate the 3 dB penalty.

4 Simulations and discussion

The theoretical expressions mentioned in the last section are plotted in this section to show the performance of the proposed HM SSD Alamouti transmit diversity UEP mechanism. In addition, the proposed system was implemented in MATLAB and extensive Monte-Carlo simulations were conducted. The simulations were conducted under the i.i.d. Rayleigh fading channel with AWGN as defined in Section 2. As discussed in the system model of the proposed system, it is assumed that each modulation block in Fig. 1 receives two separate input bit streams carrying data of unequal importance, thus the system provides UEP to four bit streams requiring different levels of protection. In the first subsection, the performance of the proposed system without the SSD component of the system, that is, the UEP Alamouti scheme with only HM is presented, whereas in the second subsection the results of the complete UEP Alamouti scheme with HM and SSD are presented.

4.1 Almouti STBC HM without SSD

In the first half of the system performance study, the system is configured to use the Alamouti STBC HM without SSD. On varying the two parameters α_i and p_i, $i \in \{1, 2\}$, on each transmit antenna leads to four scenarios: (1) $\alpha_1 = \alpha_2$ and $p_1 = p_2$; (2) $\alpha_1 \neq \alpha_2$ and $p_1 = p_2$; (3) $\alpha_1 = \alpha_2$ and $p_1 \neq p_2$ and (4) $\alpha_1 \neq \alpha_2$ and $p_1 \neq p_2$. In scenario 1, the system only provides two levels of UEP for two types of data, while in all the other scenarios, the system provides four levels of UEP for four types of multimedia data. Given that the objective of the system is to provide UEP for four classes of traffic, only scenarios 2–4 are considered in the performance study.

In scenario 2 mentioned previously, the system uses a different α value in the modulation block for each antenna, for example, with $\alpha_1 = 1$ for antenna 1 and $\alpha_2 = 3$ for antenna 2, while keeping the power on each antenna the same, that is, $p_1 = p_2 = 1$. This is equivalent to running two concurrent HM processes with varying hierarchical parameters. The graphs presented in Fig. 4*a* show how such a structure can be used to provide UEP for four classes of multimedia data. The theoretical and simulation curves are shown using the solid lines and markers, respectively. The HP and LP streams on antenna 1 are represented in Fig. 4*a* as HP1 and LP1 and the HP and LP streams on antenna 2 as HP2 and LP2. The theoretical results are based on (9) and (13) with $\theta = 0$. The curves in Fig. 4*a* show the high accuracy of the theoretical expressions used to model the proposed system.

In scenario 3, the system keeps the hierarchical parameter α for both antennas the same; for example, $\alpha_1 = \alpha_2 = 3$, while varying powers allocated to the two antennas with $p_1 = 0.5$ and $p_2 = 1.5$. In this case, although the HM processes on both antennas are equivalent, the varying of the power factor leads to UEP for four classes of traffic. Comparing the set of BER curves for the two antennas in Fig. 4*b*, it can be observed that the relative increasing of the power factor for antenna 2 leads to relatively better BER performance for the data streams transmitted using antenna 2 as compared to those transmitted using antenna 1. Thus this power factor can be used to provide UEP between each set of bit streams on each antenna in a manner similar to HM, which provides UEP for each bit stream within the set. Once again the theoretical and simulation curves are shown using solid lines and markers, respectively, and it can be seen that the simulation results also validate the system theoretical performance.

In the final scenario, the system varies both parameters between the two antennas with $\alpha_1 = 2.0$ and $p_1 = 0.5$ for antenna 1, and $\alpha_2 = 3.0$ and $p_2 = 1.5$ for antenna 2. The BER curves are shown in Fig. 4*c* with solid lines for the theoretical results and the markers for the simulation results. In this scenario the system also provides four levels of UEP for four classes of multimedia traffic.

The study of the BER curves shown in Figs. 4*a*–*c* leads to the following summary on the effect of the two system parameters on the BER curves, and thus the level of UEP, for the data transmitted by the system. As expected of HM-based systems,

$$P(X_B \to X_D) = \frac{1}{4n}\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2(\alpha_i \cos\theta - \sin\theta)^2}\right)\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2(\alpha_i \sin + \cos\theta)^2}\right) + \frac{1}{2n}\sum_{k=1}^{n-1}\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2(\alpha_i \cos\theta - \sin\theta)^2}\right)\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2(\alpha_i \sin + \cos\theta)^2}\right) \tag{11}$$

$$P(X_E \to X_C) = \frac{1}{4n}\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2(\alpha_i \cos\theta + \sin\theta)^2}\right)\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2(\alpha_i \sin - \cos\theta)^2}\right) + \frac{1}{2n}\sum_{k=1}^{n-1}\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2(\alpha_i \cos\theta + \sin\theta)^2}\right)\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2(\alpha_i \sin - \cos\theta)^2}\right) \tag{12}$$

$$P(X_A \to X_B) = \frac{1}{4n}\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2 \cos^2\theta}\right)\left(\frac{2}{2 + p_i\bar{\gamma}\beta_2 \sin^2\theta}\right) + \sum_{k=1}^{n-1}\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2 \cos^2\theta}\right)\left(\frac{S_k}{S_k + p_i\bar{\gamma}\beta_2 \sin^2\theta}\right) \tag{14}$$

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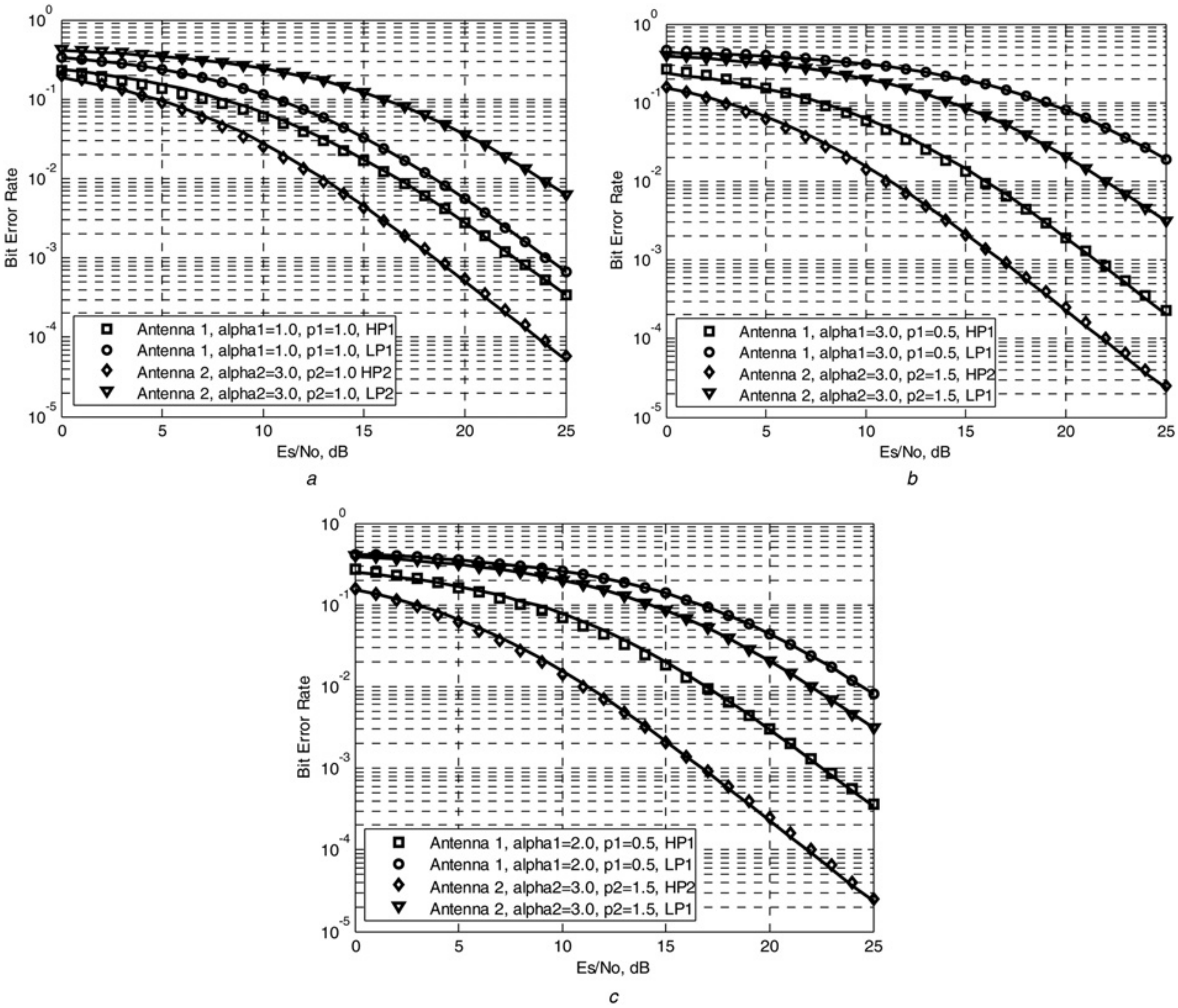

Fig. 4 *BER of the UEP Alamouti STBC HM system in scenarios 2–4*

a Scenario 2
b Scenario 3
c Scenario 4

the relative difference between the hierarchical parameter value (α) for each antenna leads to the relative UEP for the HP and LP streams on each antenna, with a higher level of protection for the HP stream when compared to the LP stream when the α is high and a lower level of protection for the HP stream when it is low. On the other hand, the relative difference between the power factor value (p) for each antenna leads to a relative UEP difference for both sets of data streams transmitted using antennas 1 and 2. Thus, a higher p value for antenna 2 will lead to lower BER curves, and hence results in higher relative UEPs, for both the HP and LP streams on antenna 2 as compared to antenna 1. Thus, these two system parameters in combination therefore enable the novel yet simple system to flexibly provide UEP for four classes of multimedia traffic with varying UEP requirements.

4.2 Alamouti STBC HM with SSD

The complete UEP Alamouti STBC HM SSD system is discussed in this subsection. In terms of the simulation study of the system, the simulation scenarios are the same as those for the system without the SSD mechanism, which was discussed in Section 4.1. The results for scenarios 2–4 can be seen in Fig. 5, and they show how the simple yet novel transmit diversity can be used to provide UEP for four classes of multimedia traffic. Once again the solid lines are for the theoretical results and the markers are for the simulation results.

The curves in Figs. 5*a–c* show a close match between the simulation and the theoretical formulation of the system at a BER rate above 10^{-3}. However, below this BER rate there is a discernible difference between the theory and simulation, especially for the ‘Antenna 2, HP’ curves. Upon further analysis of the system operation, it was noted that due to the interleaving process of the SSD mechanism, the in-phase and quadrature-phase components of each symbol experience asymmetric fading through the transmission process. In order to compensate for this, an asymmetric fading coefficient (between 0 and 1) was introduced heuristically to reduce the SNR on the quadrate component (relative to the in-phase component) in the expressions used to determine the system BERs. Currently, the value of the coefficient has been determined numerically, but in future work, a more rigorous mathematical analysis of this aspect of the system will be investigated. However, the introduction of this asymmetric fading coefficient leads to a much closer match between the theoretical and simulation curves throughout the BER range. As an example, the results from

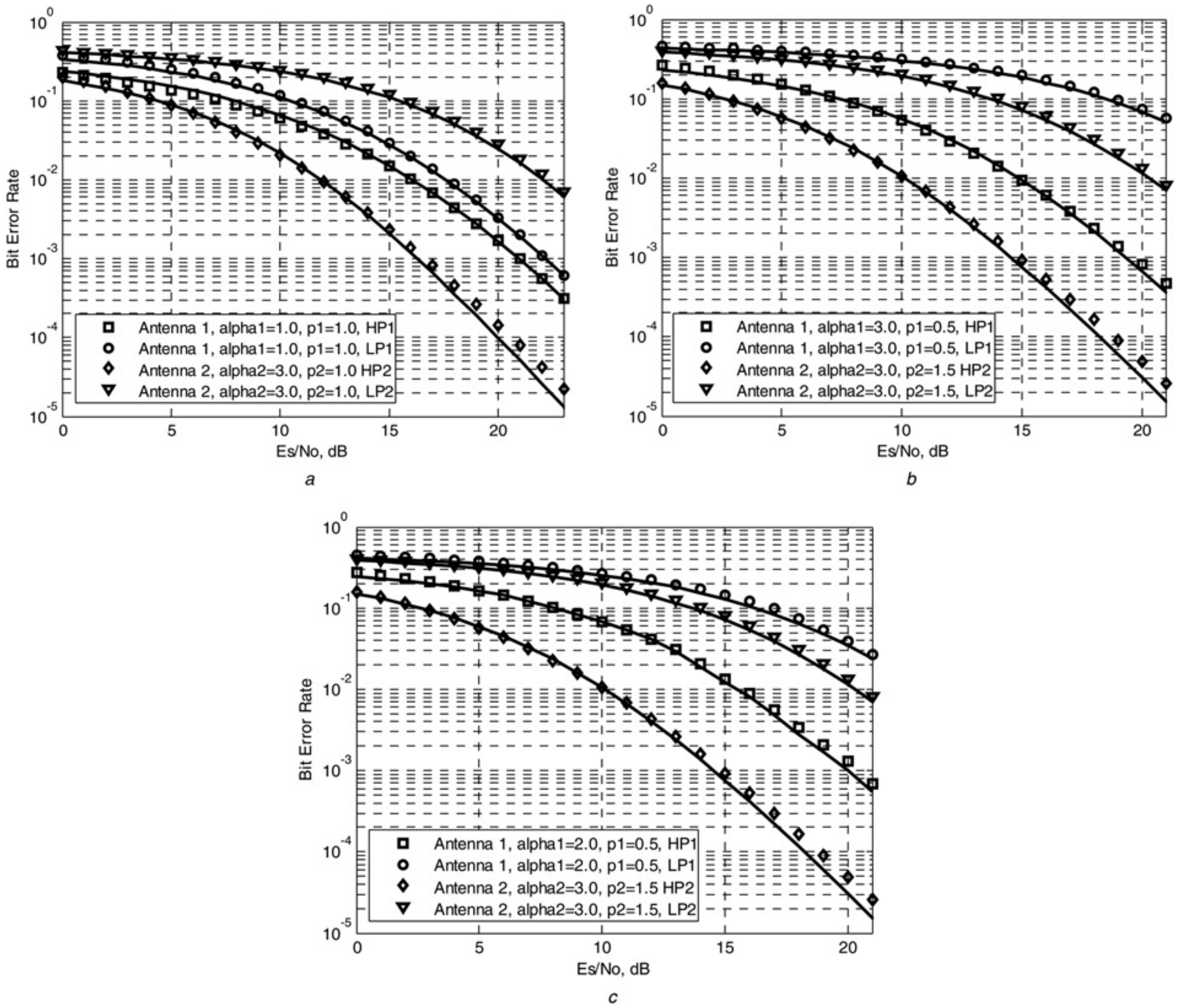

Fig. 5 *BER of the UEP Alamouti STBC HM SSD system in scenarios 2–4*

a Scenario 2
b Scenario 3
c Scenario 4

scenario 3 are shown Fig. 6, and a much closer match can be seen between the theoretical and simulation curves when compared to the equivalent curves in Fig. 5*a*, especially for the HP2 data stream at BER rates below 10^{-3}.

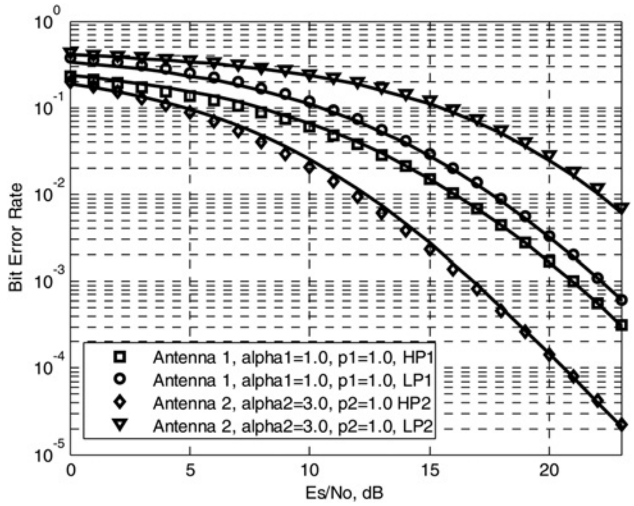

Fig. 6 *BER of the UEP Alamouti STBC HM SSD system in scenario 2 (with asymmetric fading coefficient)*

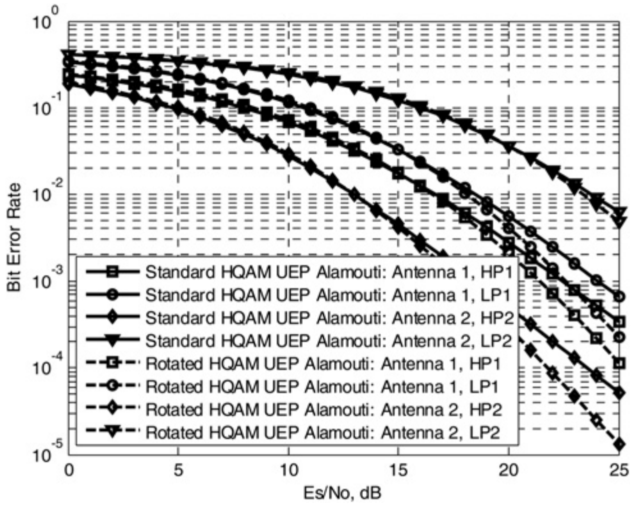

Fig. 7 *Comparison of the UEP Alamouti HM system with and without SSD*

In terms of the overall objectives of the proposed system, the system in this configuration achieves the same outcome as that achieved in the configuration without the SSD mechanism, in that, the varying of HM modulation parameter and the power factor between the two antennas of the UEP Alamouti structure allows the system to support four classes of multimedia data requiring different levels of error protection.

Finally, the motivation for incorporating the SSD mechanism into the UEP Alamouti STBC HM system is shown by presenting the performance improvement of the system with SSD as compared to without SSD. Fig. 7 compares the theoretical performance of the system with and without the SSD mechanism. In the setup for the comparison, the hierarchical parameters are $\alpha_1 = 1$ for antenna 1 and $\alpha_2 = 3$ for antenna 2, while the power factor on each antenna is the same, that is, $p_1 = p_2 = 1$. As the graphs in Fig. 7 show, there is a noticeable improvement in incorporating the SSD mechanism into the transmit diversity system. To get a numerical measure of the improvement, if the BER of the HP bit streams transmitted using antenna 2 (Antenna 2, HP2 in Fig. 7) at a BER of 10^{-4} is considered, the Alamouti STBC HM SSD system demonstrates an approximate gain of 2 dB over the Alamouti STBC HM system without the SSD component. The first aspect of the SSD scheme which results in this improved error performance is constellation rotation. The rotation causes each transmitted symbol to have two distinct components, which reduces the possibility of error in the symbol detection. The second aspect is the component interleaving which results in independent fading for each component. This increases the chance of the detector recovering the original symbol even if one component, in-phase or quadrature-phase, is affected by channel fading.

5 Conclusion

In this study, a simple UEP mechanism for the simultaneous transmission of different classes of multimedia traffic was presented. The mechanism was based on a Alamouti STBC transmission system using HM with and without SSD, in which the level of hierarchy using rotated HM and the power proportioned between the two transmit antennas was varied to produce UEP for different traffic streams. It was demonstrated via accurate theoretical and simulations results that the proposed UEP Alamouti transmit diversity system with HM can be easily configured and used for the transmission of four classes of multimedia traffic. It was shown that the incorporation of the SSD mechanism into the base UEP Alamouti STBC HM scheme further enhances the BER performance of the system. In future work, the system's two adaptable parameters, namely the level of hierarchy using rotated HM and the power proportionality parameter, will be used to design a channel adaptive multimedia traffic transmission system.

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