

ADAPTIVE DIFFERENTIAL SPACE-TIME-SPREADING-ASSISTED TURBO-DETECTED SPHERE PACKING MODULATION

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Abstract - In this contribution a novel adaptive differential space-time spreading assisted turbo detected sphere packing modulation scheme is proposed for improving the achievable throughput of code division multiple access (CDMA) systems. The scheme is capable of accommodating the channel signal-to-noise ratio (SNR) variation of wireless systems by adapting the system parameters. Explicitly, an adaptive transmission scheme constituted by a novel reconfigurable four transmit antenna aided arrangement using a variable spreading factor based differential space-time spreading scheme, as well as variable code rate recursive systematic convolutional codes is introduced. Our results demonstrate that significant effective throughput improvement can be achieved while maintaining a target bit-error-ratio of 10^{-4} . Explicitly, when assuming an ideal Nyquist filter having a zero excess bandwidth, the system's effective throughput varies from 0.25 bits/sec/Hz to 16 bits/sec/Hz.

1. INTRODUCTION

In recent years, the concept of intelligent multi-mode multimedia transceivers has emerged in the context of wireless systems [1]. The fundamental limitation of wireless systems is constituted by the time- and frequency-domain channel fading, that is exemplified in terms of the signal-to-noise ratio (SNR) fluctuations experienced by wireless modems [1, 2]. Furthermore, the continued increase in demand for all types of wireless services, including voice, data and multimedia, increases the need for higher data rates. Therefore, no fixed mode transceiver may be expected to provide an attractive performance at reasonable complexity and interleaver delay. Hence, advanced adaptive multiple-input multiple-output (MIMO) techniques, coded modulation, as well as adaptive modulation and coding arrangements have to be invoked, which are capable of near-instantaneous High Speed Downlink Packet Access (HSDPA) style reconfiguration.

Adaptive modulation and coding techniques that track the time-varying characteristics of wireless channels can be used to significantly increase the data rate, reliability and spectrum efficiency of wireless communication systems. In recent years various adaptive-coding-modulation assisted arrangements have been proposed [3–5]. Different transmission parameters can be adapted, including the transmission power [6], the system bandwidth [7], the modulation scheme [3, 8], the spreading factor (SF) of DS-CDMA systems [9], etc in addition to the code rate or interleaver length of channel coded systems. The fundamental goal of near-instantaneous adaptation is to ensure that the most efficient mode is used in the face of rapidly-fluctuating time-variant channel conditions based on appropriate activation criteria. As a benefit, near-instantaneous adaptive systems are capable

of achieving a higher effective throughput compared to their non-adaptive counterpart.

The detrimental effects of channel fading may be significantly reduced by employing multiple-input-multiple-output (MIMO) schemes including space-time block codes (STBC) [10, 11], coherently detected space-time spreading (STS) [12] and differentially detected space-time spreading (DSTS) [13]. As a further advance, the concept of combining orthogonal transmit diversity designs with the principle of sphere packing (SP) modulation was introduced by Su *et al.* in [14], where it was demonstrated that the proposed SP aided STBC system was capable of outperforming the conventional orthogonal design based STBC schemes of [10]. Furthermore, in [15] the employment of the turbo principle was considered for iterative soft demapping in the context of multilevel modulation schemes combined with channel decoding, where a soft symbol-to-bit demapper was used between the multilevel demodulator and the binary channel decoder. The iterative soft demapping principle of [15] was extended to SP-aided STBC schemes in [16], where the SP demapper was modified for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information.

In this contribution, we propose a novel adaptive DSTS-SP aided technique for supporting a wide range of bit rates, where the transmission of data from the four antennas is adapted by activating two different transmission schemes according to the near-instantaneous channel SNR conditions. Moreover, the transmission bit rate is adjusted with the aid of using a variable spreading factor (VSF). More explicitly, given a fixed bandwidth and a fixed chip rate, the system enables a user to benefit from a higher bit rate while using a lower SF, when the instantaneous SNR is sufficiently high. Furthermore, an iteratively-detected variable-rate recursive systematic convolutional (RSC) code is employed for further enhancing the system's attainable BER performance, where the code rate may be increased for the sake of increasing the achievable system throughput, as the channel quality improves. As a further benefit, the proposed system exploits the implementational advantages of low-complexity differential encoding/decoding, although this is achieved at the cost of the typical SNR degradation of differential encoding. Therefore, the achievable integrity and bit rate enhancements of the system are determined by the following factors:

- The specific transmission configuration used for transmitting data from the four antennas.
- The spreading factor used.
- The RSC encoder's code rate.

This paper is organised as follows. In Section 2, a brief system overview is presented. In Section 3, the adaptive techniques employed are detailed, where adapting the transmission scheme is described in Section 3.1, Section 3.2 justifies the purpose of adapting the SF used while the iteratively detected variable code rate DSTS-SP system is

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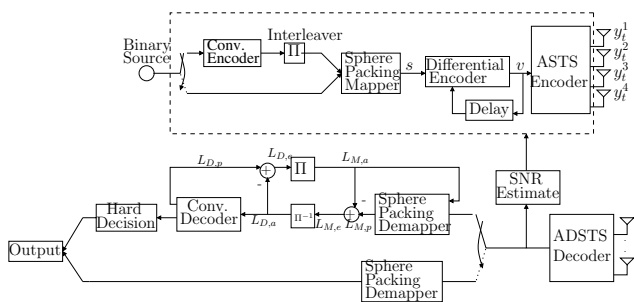


Figure 1: The proposed adaptive differential space-time spreading assisted iteratively detected SP aided system model.

discussed in Section 3.3. In Section 4, we demonstrate how the proposed system performs and finally we conclude in Section 5.

2. SYSTEM OVERVIEW

The adaptive DSTS system considered in this paper employs four transmit antennas and a single receive antenna. A high-level block diagram of the proposed system is shown in Figure 1, where four-dimensional SP modulation and real-valued orthogonal spreading were employed. A suitable transmission mode is selected according to the near-instantaneous channel conditions, which is quantified by the signal-to-noise ratio (SNR) in our case. A low complexity technique of determining the channel conditions to be expected at the receiver in the context of time division duplexing (TDD) is that of exploiting the correlation between the fading envelope of the uplink (UL) and the downlink (DL), since the UL and the DL slots are transmitted at the same frequency and hence are likely to fade coincidentally, unless frequency-selective fading is encountered. Therefore, when transmitting a frame, transmitter A estimates the SNR of receiver B at the other end of the link based on the SNR estimate of receiver A and selects the most appropriate transmission mode accordingly. This paper assumes the availability of a reliable modem-mode signalling link between the transmitter and the receiver, such as the control channel of the HSDPA system.

As shown in Figure 1, the transmitted source bits have two different paths to follow. In the upper path shown in the figure, the transmitted source bits are convolutionally encoded and then interleaved by a random bit interleaver. A variable rate RSC code is employed, where the code rate is varied between $R = \frac{1}{6}$ and $R = \frac{1}{2}$, depending on the near-instantaneous channel conditions. Moreover, when the channel SNR is sufficiently high for the target system performance to be met without channel coding, the transmitted source bits are not channel coded at all. After deciding on whether to invoke channel coding or not, the SP mapper maps B_{sp} number of bits $\mathbf{b} = b_0, \dots, b_{B_{sp}-1} \in \{0, 1\}$ to a SP symbol $\mathbf{s}^l \in S, l = 0, 1, \dots, L-1$, so that we have $\mathbf{s}^l = \text{map}_{sp}(\mathbf{b})$, where $B_{sp} = \log_2 L$ and L represents the number of modulated symbols in the SP signalling alphabet, as described in [16]. Subsequently, each of the four components of a SP symbol is then transmitted using DSTS via four transmit antennas in two or four consecutive time slots, depending on the channel conditions, as detailed in Section 3.1. Furthermore, a VSF is employed by each user, so that the system's effective bit rate can be enhanced along with any improvement in the channel conditions. Therefore, creating signalling modes that enable reliable communication even in poor channel conditions renders the system robust. By contrast, under good channel conditions the spectrally efficient modes are activated, in order to increase the effective throughput.

In this treatise, we considered transmissions over a correlated narrowband Rayleigh fading channel, associated with a normalised Doppler frequency of $f_D = f_d T_s = 0.01$, where f_d is the Doppler frequency and T_s is the symbol duration. The complex Additive White Gaussian

Noise (AWGN) of $n = n_I + jn_Q$ contaminates the received signal, where n_I and n_Q are two independent zero-mean Gaussian random variables having a variance of $\sigma_n^2 = \sigma_{n_I}^2 = \sigma_{n_Q}^2 = N_0/2$ per dimension, with $N_0/2$ representing the noise power spectral density expressed in W/Hz .

At the receiver side of Figure 1, the DSTS decoder decodes the received signal according to the received modem-mode side information. More explicitly, the receiver has to decide whether the data was channel coded and what code rate was used for encoding. If no channel coding was employed, then the received signal will be directly demodulated by the SP demapper of Figure 1. By contrast, if channel coding was employed, then the decoder has to decide which code-rate was employed. As shown in Figure 1, the received complex-valued symbols are demapped to their Log-Likelihood Ratio (LLR) representation for each of the B_{sp} channel-coded bits per sphere packing symbol. The *a priori* LLR values of the demodulator are subtracted from the *a posteriori* LLR values for the sake of generating the extrinsic LLR values $L_{M,e}$, and then the LLRs $L_{M,e}$ are deinterleaved by a soft-bit deinterleaver, again as seen in Figure 1. Next, the soft bits $L_{D,a}$ are passed to the convolutional decoder in order to compute the *a posteriori* LLR values $L_{D,p}$ provided by the Max-Log MAP algorithm for all the channel-coded bits. During the last iteration, only the LLR values $L_{D,i,p}$ of the original uncoded systematic information bits are required, which are passed to the hard decision decoder of Figure 1 in order to determine the transmitted source bits. As seen in Figure 1, the extrinsic information $L_{D,e}$ is generated by subtracting the *a priori* information from the *a posteriori* information according to $(L_{D,p} - L_{D,a})$, which is then fed back to the DSTS-SP demapper as the *a priori* information $L_{M,a}$ after appropriately reordering them using the interleaver of Figure 1. The DSTS-SP demapper of Figure 1 exploits the *a priori* information for the sake of providing improved *a posteriori* LLR values, which are then passed to the channel decoder and then back to the demodulator for further iterations.

3. ADAPTATION SCHEME

The main objective of introducing the proposed system is to maximise the achievable system throughput, while maintaining a specified target BER performance. More specifically, in this treatise we aim for maintaining a target BER of 10^{-4} , while transmitting data at the highest possible effective throughput according to the SNR experienced by the transmitted data frame. The proposed system attempts to maximise the achievable throughput by varying the configuration of the four transmit antennas as in [2]. Additionally, the spreading factor as well as the code-rate of the RSC code employed are also varied. We note furthermore that in [2] coherently detected, non-differential transmissions were used and no channel coding was employed while using conventional modulation.

3.1. Adaptive DSTS Aided SP modulation

In the four transmit antenna aided DSTS encoder, the data is serial-to-parallel converted to four substreams. The new bit duration of each parallel substream, which is referred to as the symbol duration, becomes $T_s = 4T_b$ as illustrated in [5, 12]. The DSTS transmitter conveys a SP symbol in four time slots. Therefore, the DSTS-SP signalling rate becomes $1/4$ and the effective throughput in terms of the symbol rate is related to the number of bits-per-symbol (BPS) as BPS/4.

However, this fixed-mode, four transmit antenna aided DSTS-SP system is unable to maximise the throughput as a function of the channel quality. For example, at a high SNR value, the system provides a lower BER than the target BER value, which imposes a low effective throughput. Thus, an intelligent high-efficiency DSTS system must be capable of monitoring the near-instantaneous channel quality and of adapting the DSTS scheme's mode of operation.

When the channel SNR encountered is low and hence the resultant BER is higher than the target BER, a low-throughput DSTS transmitter mode is activated, which exhibits a high diversity gain, as will be demonstrated shortly. By contrast, when the channel quality is high, and hence the resultant BER is lower than the target BER, then a high-throughput DSTS-assisted transmitter mode having a lower transmit diversity gain is activated.

3.1.1. Single Layer Four-Antenna DSTS-SP System

The high-diversity four transmit antenna aided DSTS-SP mode of operation acts as follows. At time instant $t = 0$, the arbitrary reference symbols v_0^1, v_0^2, v_0^3 and v_0^4 are transmitted from the four antennas. At time instants $t \geq 1$, a block of B_{sp} bits arrives at the SP mapper of Figure 1, where the B_{sp} bits are mapped to a real-valued four dimensional SP symbols selected from the set $S = \{s^l = [a_{l,1}, a_{l,2}, a_{l,3}, a_{l,4}] \in \mathbb{R}^4 : 0 \leq l \leq L - 1\}$, where L is the number of legitimate SP constellation points having a total energy of $E \triangleq \sum_{l=0}^{L-1} (|a_{l,1}|^2 + |a_{l,2}|^2 + |a_{l,3}|^2 + |a_{l,4}|^2)$.

Assume that $v_t^k, k = 1, 2, 3, 4$, represents the symbols transmitted from the four antennas. Then, differential encoding is carried out as follows:

$$\mathbf{V}_t = \begin{pmatrix} v_t^1 \\ v_t^2 \\ v_t^3 \\ v_t^4 \end{pmatrix} = a_t^1 \cdot \begin{pmatrix} v_{t-1}^1 \\ v_{t-1}^2 \\ v_{t-1}^3 \\ v_{t-1}^4 \end{pmatrix} + a_t^2 \cdot \begin{pmatrix} v_{t-1}^2 \\ -v_{t-1}^1 \\ v_{t-1}^4 \\ -v_{t-1}^3 \end{pmatrix} + a_t^3 \cdot \begin{pmatrix} v_{t-1}^3 \\ -v_{t-1}^4 \\ -v_{t-1}^1 \\ v_{t-1}^2 \end{pmatrix} + a_t^4 \cdot \begin{pmatrix} v_{t-1}^4 \\ v_{t-1}^3 \\ -v_{t-1}^2 \\ -v_{t-1}^1 \end{pmatrix}. \quad (1)$$

The differentially encoded symbols are then spread according to [5, 12] with the aid of the spreading codes $\underline{c}_1, \underline{c}_2, \underline{c}_3$, and \underline{c}_4 , which are generated from the same user-specific spreading code \underline{c} by ensuring that they are orthogonal using the simple code-concatenation rule of Walsh-Hadamard codes, yielding longer codes and hence a proportionately reduced per antenna throughput.

The differentially encoded data is then divided into four quarter-rate substreams and the four consecutive differentially encoded symbols are then spread to the four transmit antennas using the mapping of:

$$y_t^1 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^1 - \underline{c}_2 \cdot v_t^2 - \underline{c}_3 \cdot v_t^3 - \underline{c}_4 \cdot v_t^4) \quad (2)$$

$$y_t^2 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^2 + \underline{c}_2 \cdot v_t^1 + \underline{c}_3 \cdot v_t^4 - \underline{c}_4 \cdot v_t^3) \quad (3)$$

$$y_t^3 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^3 - \underline{c}_2 \cdot v_t^4 + \underline{c}_3 \cdot v_t^1 + \underline{c}_4 \cdot v_t^2) \quad (4)$$

$$y_t^4 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^4 + \underline{c}_2 \cdot v_t^3 - \underline{c}_3 \cdot v_t^2 + \underline{c}_4 \cdot v_t^1). \quad (5)$$

The received signal at the output of the single receiver antenna can be represented as:

$$r_t = h_1 \cdot y_t^1 + h_2 \cdot y_t^2 + h_3 \cdot y_t^3 + h_4 \cdot y_t^4 + n_t, \quad (6)$$

where h_1, h_2, h_3 , and h_4 denote the narrow-band complex-valued channel impulse responses (CIR) corresponding to the four transmit antennas, while n_t represents the AWGN having a variance of σ_n^2 .

The received signal r_t is then correlated with $\underline{c}_1, \underline{c}_2, \underline{c}_3$, and \underline{c}_4 according to the following operation: $d_t^k = \underline{c}_k^\dagger \cdot r_t$, with $k = 1, 2, 3, 4$ and \dagger representing the Hermitian of the vector.

To derive the decoder equations of the DSTS receiver, the received despread signals $d_t^k, k = 1, 2, 3, 4$, are rearranged in vectorial form as follows:

$$R_t^1 = (d_t^1, d_t^2, d_t^3, d_t^4) \quad (7)$$

$$R_t^2 = (-d_t^2, d_t^1, d_t^4, -d_t^3) \quad (8)$$

$$R_t^3 = (-d_t^3, -d_t^4, d_t^1, d_t^2) \quad (9)$$

$$R_t^4 = (-d_t^4, d_t^3, -d_t^2, d_t^1) \quad (10)$$

$$R_{t+1} = (d_{t+1}^1, d_{t+1}^2, d_{t+1}^3, d_{t+1}^4). \quad (11)$$

To decode the transmitted symbols $a_t^k, k = 1, 2, 3, 4$, the decoder uses Equations (7)-(11) and computes:

$$Re\{R_{t+1} \cdot R_t^\dagger\} = \sum_{i=1}^4 |h_i|^2 \cdot \sqrt{\sum_{j=1}^4 |v_t^j|^2 \cdot a_{t+1}^k + N_k}, \quad (12)$$

where $Re\{\cdot\}$ denotes the real part of a complex number and N denotes the noise term. The receiver estimates a_t^k based on Equation (12) by employing a Maximum Likelihood (ML) decoder.

3.1.2. Twin Layer Four-Antenna DSTS-SP System

Again, in its most robust but lowest-throughput mode, the above scheme transmits one SP symbol in $4T_b$ duration and hence the effective transmission rate becomes $1/4T_b$. By contrast, when the channel quality improves, the transmitter divides the four antennas into two groups of two transmit antennas for the sake of increasing the effective throughput by creating two independent second-order DSTS-aided subchannels. In this case, at time instants $t \geq 1$, a block of $2B_{sp}$ bits arrives at the SP mapper of Figure 1, where each of the B_{sp} bits is mapped to a four-dimensional SP symbol selected from the set $S = \{s^l = [a_{l,1}, a_{l,2}, a_{l,3}, a_{l,4}] \in \mathbb{R}^4 : 0 \leq l \leq L - 1\}$. The four components of the four-dimensional SP symbol are combined according to $C_l = \sqrt{\frac{2L}{E}}(x_{l,1}, x_{l,2}), l = 0, 1, \dots, L - 1$, where we have $\{x_{l,1}, x_{l,2}\} = \{a_{l,1} + ja_{l,2}, a_{l,3} + ja_{l,4}\}$.

In this mode, the differential encoding is carried out as follows:

$$v_t^1 = (x_1 \cdot v_{t-1}^1 + x_2 \cdot v_{t-1}^{2*}) \quad (13)$$

$$v_t^2 = (x_1 \cdot v_{t-1}^2 - x_2 \cdot v_{t-1}^{1*}) \quad (14)$$

$$v_t^3 = (x_3 \cdot v_{t-1}^3 + x_4 \cdot v_{t-1}^{4*}) \quad (15)$$

$$v_t^4 = (x_3 \cdot v_{t-1}^4 - x_4 \cdot v_{t-1}^{3*}). \quad (16)$$

The differentially encoded symbols are then spread with the aid of the spreading codes $\underline{c}_1, \underline{c}_2, \underline{c}_3$ and \underline{c}_4 to the transmit antennas. In this case, each user is assigned two spreading codes $\underline{c}, \underline{c}'$. The spreading codes used in this second-order diversity scenario are generated as follows:

$$\underline{c}_1^T = [\underline{c} \quad \underline{c}], \quad \underline{c}_2^T = [\underline{c} \quad -\underline{c}] \quad (17)$$

$$\underline{c}_3^T = [\underline{c}' \quad \underline{c}'], \quad \underline{c}_4^T = [\underline{c}' \quad -\underline{c}']. \quad (18)$$

The differentially encoded data is then spread to the transmit antennas and transmitted using the mapping of:

$$y_t^1 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^1 + \underline{c}_2 \cdot v_t^{2*}) \quad (19)$$

$$y_t^2 = \frac{1}{\sqrt{4}} (\underline{c}_1 \cdot v_t^2 - \underline{c}_2 \cdot v_t^{1*}) \quad (20)$$

$$y_t^3 = \frac{1}{\sqrt{4}} (\underline{c}_3 \cdot v_t^3 + \underline{c}_4 \cdot v_t^{4*}) \quad (21)$$

$$y_t^4 = \frac{1}{\sqrt{4}} (\underline{c}_3 \cdot v_t^4 - \underline{c}_4 \cdot v_t^{3*}). \quad (22)$$

The signal at the output of the single receiver antenna can be represented as:

$$r_t = h_1 \cdot y_t^1 + h_2 \cdot y_t^2 + h_3 \cdot y_t^3 + h_4 \cdot y_t^4 + n_t. \quad (23)$$

The received signal r_t is then correlated with c_1, c_2, c_3 and c_4 according to the following operation, $d_t^k = c_k^\dagger \cdot r_t, k = 1, 2, 3, 4$. Differential decoding is carried out by using the received data of two consecutive time slots in a similar fashion to Equation(12) in order to arrive at $\sum_{i=1}^2 |h_i|^2 \cdot \sqrt{\sum_{j=1}^2 |v_{t-1}^j|^2} \cdot a_{t+1}^k + N_k$. Therefore, this scheme transmits two SP symbols in $2T_b$ duration resulting in an effective throughput, which is four times that of the previous system characterised in Section 3.1.1.

3.2. VSF-Based DSTS-SP System

As a further novel aspect of the proposed DSTS-SP system, different bit rates can be accommodated by using VSF. In this section we discuss the employment of VSF codes in adaptive rate DSTS-SP systems, where the chip rate is kept constant and hence so is the bandwidth, while the effective bit rate is varied by varying the spreading factor over the course of transmissions. For example, when stipulating a constant chip rate, the number of bits transmitted using a SF of 32 is half of that when employing SF= 16.

When the channel quality is high, a low SF can be used in order to increase the throughput and conversely, when the channel conditions are hostile, a high SF is employed for maintaining the target BER performance. To elaborate further, Figure 4.33a of [5, p.180] illustrates that using orthogonal VSFs does not affect the BER versus E_s/N_0 performance, where E_s is the spread symbol's energy and N_0 is the noise power spectral density. Hence no performance gain is attained when comparing the adaptive-rate scheme to a fixed-rate one. However, it was demonstrated in Figure 4.33b of [5, p.180] that plotting the BER curves versus the chip SNR (CSNR) defined as $E_s/N_0/SF$ results in SF dependent BER performance. Therefore, it was concluded in [5, p.180] that upon accommodating the channel quality fluctuations, using VSFs, the spread symbol's SNR is varied accordingly for the sake of maintaining a constant CSNR according to the expression $SNR = CSNR \cdot SF$. For example, when the channel quality is high and hence a low SF is used, the transmitter power - which is proportional to the SNR at a given fixed N_0 value - is also reduced. Therefore, the CSNR is always maintained at the specific value associated with the highest SF. In other words, the VSF regime accommodates the channel quality variations by adapting the SF according to the near-instantaneous channel quality without increasing the transmitted power above that associated with the highest SF [5]. When the SF is decreased, the SNR is proportionately decreased.

3.3. Variable Code Rate Turbo Detection Aided DSTS-SP System

As already discussed in Section 3.1, the detected DSTS signals can be represented by Equation (12), where a received SP symbol \tilde{s} is then constructed from the estimates $\hat{a}_1, \hat{a}_2, \hat{a}_3$ and \hat{a}_4 . The received sphere-packed symbol \tilde{s} can be written as

$$\tilde{s} = h \cdot \sqrt{\frac{2L}{E}} \cdot s^1 + N, \quad (24)$$

where we have $h = \sum_{i=1}^4 |h_i|^2 \cdot \sqrt{\sum_{j=1}^4 |v_{t-1}^j|^2}$ or $h = \sum_{i=1}^2 |h_i|^2 \cdot \sqrt{\sum_{j=1}^2 |v_{t-1}^j|^2}$ according to the DSTS scheme employed in conjunction with $s^1 \in S, 0 \leq l \leq L - 1$, and N is a four-dimensional Gaussian random variable having a variance of σ_N^2 , since the SP symbol constellation S is four-dimensional.

The SP symbol \tilde{s} carries B_{sp} channel-coded bits $\mathbf{b} = b_{0, \dots, B_{sp}-1} \in \{0, 1\}$. As discussed in [16], the max-log approximation of the

SP Modulation	$L = 16$
No. of Tx Antennas	4
No. of Rx Antennas	1
Channel	Correlated Rayleigh Fading with $f_D = 0.01$
Mode 1	Four Tx antennas DSTS-SP system SF=32, RSC code-rate=1/4, $BE = 0.25$
Mode 2	Four Tx antennas DSTS-SP system SF=32, RSC code-rate=1/2, $BE = 0.5$
Mode 3	Two Groups of two Tx antennas DSTS-SP system, SF=16, RSC code-rate=1/6, $BE = 4/3$
Mode 4	Two Groups of two Tx antennas DSTS-SP system, SF=16, RSC code-rate=1/4, $BE = 2$
Mode 5	Two Groups of two Tx antennas DSTS-SP system, SF=16, RSC code-rate=1/2, $BE = 4$
Mode 6	Two Groups of two Tx antennas DSTS-SP system, SF=8, No channel coding, $BE = 16$

Table 1: System parameters

LLR value of bit k for $k = 0, \dots, B_{sp} - 1$ can be written as [15]

$$\begin{aligned} L(b_k/\bar{s}) &= L_a(b_k) \\ &+ \max_{s^1 \in S_1^k} \left[-\frac{1}{2\sigma_N^2} (\bar{s} - \alpha \cdot s^1)^2 + \sum_{j=0, j \neq k}^{B_{sp}-1} b_j L_a(b_j) \right] \\ &- \max_{s^1 \in S_0^k} \left[-\frac{1}{2\sigma_N^2} (\bar{s} - \alpha \cdot s^1)^2 + \sum_{j=0, j \neq k}^{B_{sp}-1} b_j L_a(b_j) \right], \end{aligned} \quad (25)$$

where $\alpha = h \cdot \sqrt{\frac{2L}{E}}$, S_1^k and S_0^k are the subsets of the symbol constellation S , where we have $S_1^k \triangleq \{s^1 \in S : b_k = 1\}$ and likewise, $S_0^k \triangleq \{s^1 \in S : b_k = 0\}$. In other words, S_i^k represents all symbols of the set S , where we have $b_k = i \in \{0, 1\}, k = 0, \dots, B_{sp} - 1$.

For a detailed account of how turbo detection is carried out, please refer to [13]. Naturally, the code rate of the RSC code employed affects both the system's performance as well as the throughput. More specifically, as the RSC code rate increases, the system's effective throughput increases at the expense of degrading the system's performance. Therefore, when the channel SNR is low, and hence the resultant BER is higher than the target BER, a powerful low throughput low-rate RSC code is activated. By contrast, when the channel quality is high and hence the resultant BER is lower than the target BER, a higher throughput scheme corresponding to a higher-rate RSC code is activated.

4. RESULTS AND DISCUSSIONS

We considered a SP modulation scheme associated with $L = 16$ and using four transmit antennas as well as a single receiver antenna in order to demonstrate the performance improvements achieved by the proposed system. All simulation parameters are listed in Table 1, where BE represents the bandwidth efficiency of the system in b/s/Hz. The target BER of the system is 10^{-4} .

Figure 2 plots the BER as well as the spectral efficiency performance of the proposed adaptive turbo detected DSTS-SP system. The BER curve of the adaptive DSTS-SP system, which can be read by referring to the y -axis on the left of the figure, is plotted along with those of the non-adaptive modes. The system employs an interleaver depth ranging between 48,000 bits and 16,000 bits, depending on the code rate of the RSC code employed. Moreover, six turbo detection iterations are employed in conjunction with the system parameters outlined in Table 1. The BER performance reaches the target BER around $SNR = 5$ dB and it does not exceed the target BER for higher SNRs, while switching between the different transmission modes.

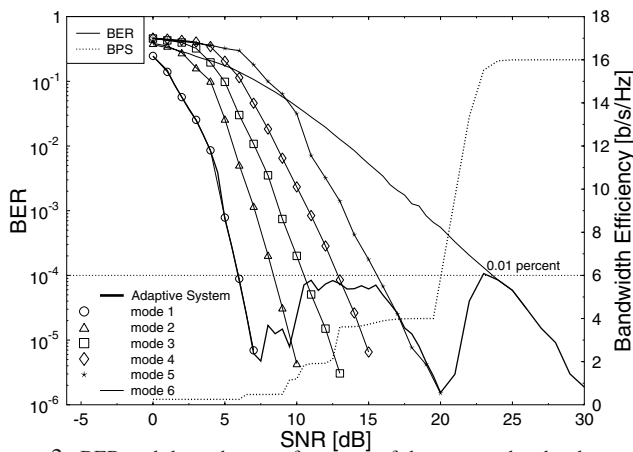


Figure 2: BER and throughput performance of the proposed turbo detected adaptive DSTS-SP system for a target BER of 10^{-4} .

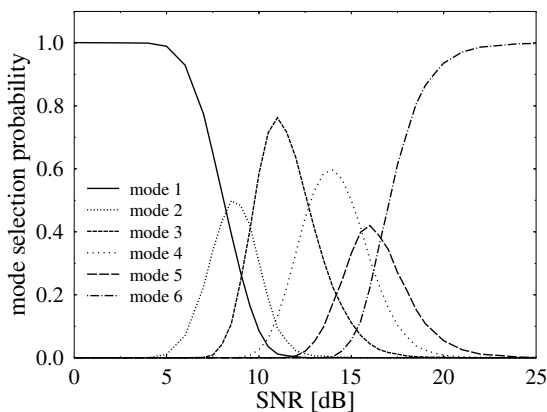


Figure 3: The mode selection probability of the proposed adaptive DSTS-SP system at a target BER of 10^{-4} .

The y -axis at the right of Figure 2 plots the achievable effective bandwidth efficiency of the proposed adaptive turbo detected DSTS-SP system, while employing an interleaver depth ranging from 48,000 bits to 16,000 bits, depending on the transmission mode employed. Six turbo detection iterations and the system parameters outlined in Table 1 were invoked. Depending on the channel quality quantified in terms of the channel SNR, the transmitter activates one of the transmission modes outlined in Table 1. The bandwidth efficiency of the system varies from 0.25 b/s/Hz for the minimum-throughput mode to 16 b/s/Hz for the highest-throughput mode. For example, if we calculate the bandwidth efficiency of mode 1, employing the $L=16$ SP modulation scheme using $SF = 32$ and an RSC code rate of $1/4$ yields $4 \cdot 1/4 \cdot 1/4 = 0.25$ b/s/Hz, since each SP symbol is transmitted in four time slots. Similarly, for the highest-throughput mode using the $L=16$ SP modulation scheme, $SF = 8$ and no channel coding, we arrive at $2 \cdot 4 \cdot 4/2 = 16$ b/s/Hz, since two SP symbols are transmitted in two time slots.

Finally, Figure 3 portrays the mode selection probability of the proposed adaptive turbo detected DSTS-SP system. It is clear from the figure that as the average SNR increases, the higher-throughput systems are employed more often.

5. CONCLUSION

In this paper we proposed a novel adaptive DSTS system that exploits the advantages of differential encoding, iterative demapping, as well as SP modulation, while adapting the system parameters for the sake of achieving the highest possible throughput, as well as maintaining a

given target BER. The proposed adaptive DSTS-SP scheme benefits from a substantial diversity gain, while using four transmit antennas without the need for pilot-assisted channel envelope estimation and coherent detection. The proposed scheme reaches the target BER of 10^{-4} at an SNR of about 5 dB and maintains it for SNRs in excess of this value, while increasing the effective throughput. The system's bandwidth efficiency varies from 0.25 bits/sec/Hz to 16 bits/sec/Hz. Our future research will consider the design of an optimised adaptive DSTS-SP scheme, where adaptation will be based on the estimated BER value of the received frame rather than on the less reliable channel quality metric constituted by the channel SNR.

6. REFERENCES

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