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A scalar MSDD with multiple antenna reception of Differential Space-Time $\pi/2$-Shifted BPSK Modulation

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Abstract : *In this paper, the issue of blind detection of Alamouti-type differential space-time (ST) $\pi/2$-shifted BPSK modulation in static Rayleigh fading channels is considered. We introduce a novel transformation to the received signal from each receiver antenna such that this binary ST modulation, which has a second-order transmit-diversity, is equivalent to QPSK modulation with second-order receive-diversity. The pre-detection combining of the result of transformation allows us to apply a low complexity detection technique specifically designed for receive-diversity, namely, scalar multiple-symbol differential detection (MSDD). With receiver complexity proportional to the observation window length, our receiver can achieve the performance 1.5dB better than that of conventional differential detection ST and 0.5dB worse than that of a coherent maximum ratio combining receiver (with differential decoding) approximately.*

Key words : *MSDD, Space time modulation*

1. Introduction

The performance of DPSK in traditional wireless communication systems employing one transmit antenna and one or more receive antennas is well documented in the literatures. In recent years, this encoding-detection concept has been extended to cover the scenario where there is more than one transmit antenna. This leads to differential space-time block codes (STBCs), an extension of the STBCs originally proposed in[5]. Differential detection of a differentially encoded phase-shift keying (DPSK) signal is a technique commonly used to recover the transmitted data in a communication system, when channel information (on both the amplitude and phase) is absent at the receiver. Like conventional DPSK, differential STBCs enable us to decode the received signal without channel state information, provided that the channel remains relatively constant during the observation interval [2, 3, 6, 7, 10]. Another similarity between conventional DPSK and differential STBCs is that both suffer a·loss in performance when compared to their respective ideal coherent receiver. For conventional DPSK, multiple-symbol differential detection (MSDD) is one approach often used to overcome the performance loss where decisions are made based on a MSDD flame. Previous research has demonstrated that when there is only one transmit antenna and one receive antenna, the performance of MSDD approaches that of the ideal coherent detector especially when the observation window length is sufficiently large [11, 8]. This observation is true for both the additive white Gaussian noise (AWGN) channel and the Rayleigh fading channel. Furthermore, when the implementation procedure proposed by Mackenthun is employed, the computational complexity of MSDD can be only $N \log N$, provided that the channel is constant over the observation window of the detector[9]. For receive-diversity only systems, Simon and Alouini demonstrated again that the performance of an MSDD-combiner approaches that of a coherent maximum ratio combining (MRC) receiver with differential decoding, when N is sufficiently large [13]. The application of the MSDD concept to detect differentially encoded STBC has been considered by a number of authors [4, 12, 14, 15, 16]. Their results indicate that space-time MSDD (ST-MSDD) can provide substantial performance improvement over the standard space-time (ST) differential detector in [3]. Unfortunately for both the MSDD-combiner and the ST-MSDD, there is no known efficient algorithm for the optimal implementation of these receivers. The complexity of both optimal receivers is exponential in N. In this paper, we will use the term scalar-MSDD to refer to the optimal MSDD for the single channel case [11][9], and the term vector-MSDD to refer to either an MSDD-combiner [13] or

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a ST-MSDD [12].

In light of the exponential complexity of the optimal vector-MSDD, several suboptimal, reduced complexity variants have been proposed for detecting differential STBC. For example, Lampe et al. implemented a code-dependent technique with a complexity that is essentially independent of the observation window length of the detector [4][16]. The concept of decision feedback was employed by Schrober and Lampe in their MSDD for a system employing both transmit and receive-diversity [7]. Similar ideas were also employed by Tarasak and Bhargava in a transmit-diversity only scenario [14], and by Lao and Haimovich in an interference suppression and receive-diversity setting [15]. In addition, Tarasak and Bhargava investigated reducing receiver complexity using a reduced search detection approach [14].

We propose, in this paper, a scalar MSDD receiver with multiple antennas for differential STBC. This receiver employs a $\pi/2$-shifted BPSK constellation, two transmit antennas, and an Alamouti-type code structure [1]. We also employed a novel transformation to the received signal, it is shown that this STBC is equivalent to conventional differential QPSK modulation with second-order receive-diversity. Thus, the various reception diversity techniques can be used. A simple selection-diversity is one possibility. And pre-detection combining introduced by J.H Kim and Paul Ho [17] is another choice to employ scalar-MSDD. Due to the low complexity of the scalar-MSDD, a very large window size N (i.e.64) can be employed to provide the receiver with the performance close to MRC with differential encoding.

2. Differential Space-Time $\pi/2$-Shifted BPSK

2.1 Differential Space-Time $\pi/2$-shifted BPSK signal

A Differential Space-Time $\pi/2$-shifted BPSK wireless communication system in a slow, flat Rayleigh fading channel is considered in this paper. The space-time block code employed falls into the class of the popular two-branch transmission -diversity scheme introduced by Alamouti [16]. With Alamouti type STBC, the transmitted code matrix in the k-th coded interval becomes is given by

$$C[k]=\begin{bmatrix} c_1[k] & c_2[k] \\ -c_2^*[k] & c_1^*[k] \end{bmatrix} \tag{1}$$

$c_1[k]$ and $c_2[k]$ are respectively the complex symbols transmitted by the first and second antennas, in the first subinterval of the k-th coded interval, then the transmitted symbols in the second subinterval by the same two antennas are respectively $-c_2^*[k]$ and $c_1^*[k]$. The various coded symbols are taken from the constellation $S=\{+1,-1,+j,-j\}$. In order to reduce envelope fluctuation in the transmitted signals, the subsets $S_1=\{+1,-1,\}$ and $S=\{+j,-j\}$ of S are used alternately in successive sub-intervals at each transmit antenna. Assuming that $c_1[k]$ is chosen from S_1, it follows that $c_2[k]$ must be chosen from S_2. With this rule of $\pi/2$-shifted BPSK signal transition, the transmitted code matrix in the k-th coded interval becomes

$$C[k]=\begin{bmatrix} c_1[k] & c_2[k] \\ c_2[k] & c_1[k] \end{bmatrix} \tag{2}$$

where $C[k]$ is a member of the set

$V=\{V_1, V_2, V_3, V_4\}$, with

$$V_1=\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}, V_2=\begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}, V_3=\begin{bmatrix} -1 & -j \\ -j & -1 \end{bmatrix}, V_4=\begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix} \tag{3}$$

Since we will be using MSDD in our receiver, $C[k]$s are differentially encoded according to the rule

$$C[k]=D[k]C[k-1] \tag{4}$$

where $D[k]$ is from the set $U=\{U_1, U_2, U_3, U_4\}$, with

$$U_1=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, U_2=\begin{bmatrix} 0 & -j \\ -j & 0 \end{bmatrix}, U_3=\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}, U_4=\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix} \tag{5}$$

It can be easily verified that the U_ns are unitary matrices, and that for any V_m in set V and any U_n in the set U, the product $U_n V_m$ is a member of the set V. These properties ensure that the differential encoding rule in (3) is consistent with our ST $\pi/2$-shifted BPSK signaling format and that ST differential detection, conventional [3] or multiple-symbol [12], can be used to recover the transmitted data from the received signal.

2.2 MSDD Decision Metric

For the purpose of demonstration, we consider the complexity of vector-MSDD decision metric when we demodulate signal from one of the multiple antenna. The transmitted symbols at each transmit antenna will be pulse-shaped by a square root raised cosine (SQRC) pulse, and then transmitted over a wireless link to the receiver. Each link introduces fading to the associated transmitted signal, and the receiver's front end introduces AWGN. The composite received signal from each receive antennas are matched filtered and sampled, twice per encoded interval, to provide the receiver with sufficient statistics to detect the transmitted data. Assuming the channel gains in the two links, f_1 and f_2, are constant within the observation window of the data detector, the two received samples in the k-th interval can be modeled as

$$R[k] = [\, r_1[k], r_2[k]\,]^T = C[k]F + N[k] \tag{6}$$

where

$$F = [f_1, f_2] \tag{7}$$

is the vector of complex channel gains. The channel fading gains are assumed to be independent and identically distributed (i.i.d.) zero-mean complex Gaussian random variables, with unit variance. And

$$N[k] = [\, n_1[k], n_2[k]\,]^T \tag{8}$$

is a noise vector containing the two complex Gaussian noise terms $n_1[k]$ and $n_2[k]$. The sequence of noise samples, $\{..., n_1[k], n_2[k], n_1[k+1], n_2[k+1], ...\}$, is a complex, zero-mean white Gaussian process, with a variance of N_0. It should be pointed out that the fading gains and the noise samples are statistically independent.

To recover the data contained in the $R[k]$s, the receiver can employ the ST-differential detector in [3]. The metric adopted by this simple detector can be expressed in the form $M = |R^{\dagger}[k]\tilde{D}[k]\tilde{C}[k] + R[k-1]\tilde{C}[k-1]|^2$, where $\tilde{D}[k] \in U$ represents a hypothesis for the data symbol $D[k]$, $\tilde{C}[k-1] \in V$, represents a hypothesis for transmitted symbol $C[k-1]$, and $|\ |$denotes the magnitude of a complex vector. Since M is actually independent of $\tilde{C}[k-1]$, the hypothesis on $D[k]$ that maximizes the metric M is chosen as the most likely transmitted data symbol. Although simple, this detector was shown to exhibit a 3-dB loss in power efficiency when compared to the ideal-coherent receiver. To narrow this performance gap, a vector-MSDD can be used instead [11]. This detector organizes the $R[k]$s into overlapping blocks of size N, with the last vector in the previous block being the first vector in the current block. For the block starting at time zero, the decoding metric can be expressed in the form $J = \left| \sum_{k=0}^{N-1} R^{\dagger}[k] (\prod_{i=1}^{k} \tilde{D}[i]) \tilde{C}[0] \right|^2$. Like the metric M, this vector-MSDD metric is independent of $\tilde{C}[0]$. Consequently, the detector selects the hypothesis $(\tilde{D}[1], \tilde{D}[2], ..., \tilde{D}[N-1])$ that maximizes J, as the most likely transmitted pattern in this interval. It is clear from the expression of J that there are altogether 4^{N-1} hypotheses to consider. So far, there does not exist any algorithm that performs this search in an efficient and yet optimal fashion.

3. Coherently-Combined Scalar ST-MSDD Receiver

As shown in the Fig. 1, the system we considered in this paper includes a ST modulation and L receiver antennas followed by signal transformation blocks and a Scalar-MSDD with pre-detection combiner. The approach we adopt to mitigate the complexity issue in the vector-MSDD, is to first transform the received signal vector in (6) into one that we would encounter in a receive-diversity only system. Thus each signal from the multiple antennas are transformed into independent 2nd order receiver diversity signals. Although the optimal vector-MSDD in this latter case still has an exponential complexity [13], we now have the option of using coherent combining [17] in conjunction with a scalar-MSDD. The following subsection provides details about the transformation required to turn our second-order transmit-diversity system and L-th order receiver diversity, into an equivalent 2L-th order receive-diversity system.

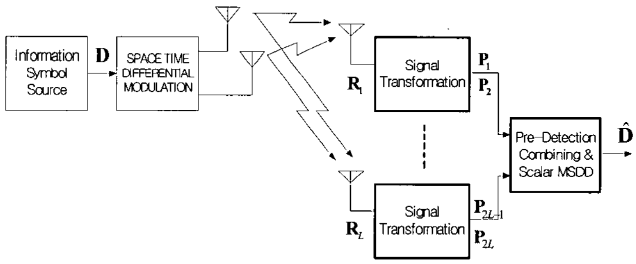

Fig. 1 Block diagram of transmitter, channel model and Receiver performing signal transformation and Scalar MSDD

3.1 Transformation from Transmit-Diversity to Receive-Diversity

Each antenna followed by signal transformation in order to convert transmission diversity signal into receiver diversity. In this section, only the transformation of the signal from the 1st antenna is introduced but extension to L antenna system is straight forward. To assist in the development of transformation, we first expand (6) to obtain

$$\begin{aligned} r_1[k] &= f_1 c_1[k] + f_2 c_2[k] + n_1[k] \\ r_2[k] &= f_1 c_2[k] + f_2 c_1[k] + n_2[k] \end{aligned} \tag{9}$$

This equation clearly illustrates the structure of the received signal samples. Moreover, we can deduce from the equation that the average SNR in the received sample $r_1[k]$ is

$$r = \frac{\frac{1}{2}E\left[|f_1c_1[k] + f_2c_2[k]|^2\right]}{\frac{1}{2}E\left[|n_1[k]|^2\right]} = \frac{2}{N_0} \tag{10}$$

where $E[\,\cdot\,]$ is the expectation operator. The same SNR also appears in the received sample $r_1[k]$.

Next, we introduce the new variables by simply add and subtract $r_1[k]$ and $r_2[k]$

$$\begin{aligned} p_1[k] &= r_1[k] + r_2[k] = g_1 b[k] w_1[k], \\ p_2[k] &= r_1^*[k] + r_2^*[k] = g_2 b[k] w_2[k] \end{aligned} \tag{11}$$

where

$$\begin{aligned} g_1 &= f_1 + f_2 \\ g_2 &= f_1^* - f_2^* \end{aligned} \tag{12}$$

are two new fading gains,

$$b[k] = c_1[k] + c_2[k] \tag{13}$$

is an equivalent transmitted symbol, and equivalent data symbol $u[k]$ is related according to

$$b[k] = b[k-1]u[k] \tag{14}$$

where $u[k]$ is from the set $\{1, j, -1, -1\}$. And

$$\begin{aligned} w_1[k] &= n_1[k] + n_2[k] \\ w_2[k] &= n_1^*[k] - n_2^*[k] \end{aligned} \tag{15}$$

are two new noise terms. It can be shown that the new fading gains g_1 and g_2 are independent Gaussian random variables, with a variance of 2. Similarly, it can also be shown that the new noise samples $w_1[k]$ and $w_2[k]$are independent and have variance $2N_0$. These results mean that the SNR in the samples $p_1[k]$ and $p_2[k]$ is also r, in other word, the original SNR is preserved. Of foremost interest, note the new symbol $b[k]$ is shared by $p_1[k]$ and $p_2[k]$. Consequently, (11)corresponds to the received signal encountered in a second-order receive-diversity system. Furthermore, $b[k]$ belongs to the QPSK signal set $X = \{x_1, x_2, x_3, x_4\}$, where

$$x_1 = 1 + j,\ x_2 = 1 - j,\ x_3 = -1 - j,\ x_4 = -1 + j \tag{16}$$

In comparing (3) with (16), we can quickly see that x_i is simply the row (or column) sum of V_i. In addition, if $V_n = U_m V_k$, then it can be shown that $x_n = y_m x_k$, where y_m is the row (or column) sum of the unitary matrix U_m in (5). Thus there is a simple relationship between the differential ST encoding in (3) and the implicit differential encoding in the equivalent second-order receive-diversity QPSK system. The advantage of transforming the original STBC into an equivalent second-order receive-diversity QPSK system will be demonstrated in the next section.

3.2 Coherent Combining for ST Scalar-MSDD reception

In this section, we apply our transformed signal to suboptimal MSDD for MPSK with diversity reception proposed by Jae H. Kim and Paul Ho in [18]. For convenience, main ideas are repeated in this section.
The receiver derives a single stream of detection statistics, denoted by $\{z[k]\}$, from $\{p_i[k]\}_{i=1}^{2L}$ according to

$$z[k] = \sum_{i=1}^{2L} q_i p_i[k] \tag{17}$$

where $\{q_i\}_{i=1}^{2L}$ are approximately chosen values. Following, scalar MSDD is performed on only the detection statistics $\{z[k]\}$. Note that (17) is a linear "pre-detection combiner" with $\{q_i\}$ being the weighting coefficients. Since only one MSDD is involved in the detection of the information contained in $\{z[k]\}$, and the channel is assumed to be static, the metric

$$\rho = \left| z^*[0] + \sum_{k=0}^{N-1} z^*[k] \left(\prod_{l=1}^{k} \tilde{u}[l] \right) \right| \tag{18}$$

is optimal and the Mackenthun algorithm [9] can be used to search for the data pattern that maximizes it. Once again, the complexity of this algorithm is only $O(N\log N)$.

The simplest way to generate the single stream of detection statistics $\{z[k]\}$from multiple streams of received samples is through selection combining (SC) of the strongest branch. But SC does not provide sufficient improvement from conventional differential detection. The weakness of SC can be overcome through the adoption of coherent combining(CC), at the expense of a modest increase in implementation complexity .In this section, we present a direct approach for CC that matches well with the signal processing structure in MSDD.

The complex gain g_i in equation (12) can be expressed in terms of its magnitude $|g_i|$ and its phase ϕ_i, according to $g_i = |g_i| e^{j\phi_i}$. Since Rayleigh fading is assumed, $|g_i|$ is a

Rayleigh random variable and ϕ_i is uniformly distributed in the interval $[0, 2\pi]$. The product of $p_m[k]$ and $p_i^*[k]$ can be expressed in terms of $|g_i|$, $|g_m|$, ϕ_i and ϕ_m as

$$\begin{aligned}\mu_{m,i}[k] &= p_m[k]p_i^*[k] \\ &= |g_i||g_m|e^{j(\phi_m-\phi_i)} + |g_m|e^{j\phi_m}b[k]n_i^*[k] \\ &\quad + |g_i|e^{-j\phi_i}b^*[k]n_m[k] + n_m[k]n_i^*[k]\end{aligned} \tag{19}$$

This product represents differential detection across the i-th and the m-th branches at time index k. In the context of the CC proposed in this section, the first term in (19) is the signal component, and the remaining three terms are noise. In theory, we can obtain the relative phase distortion between the m-th and the i-th branches according to

$$\psi_{m,i} \triangleq \phi_m - \phi_i = \mathrm{R}\left\{E\left[\mu_{m,i}[k]\right]\right\} \tag{20}$$

where the $\mathrm{R}\{\cdot\}$ operator provides the phase of a complex number and the expectation is taken over the channel noises. Once $\psi_{m,i}$ is obtained, we can co-phase the two branches according to $p_m[k] + e^{j\phi_{m,i}}p_i[k]$.

This will generate the sample $(|g_i|+|g_m|)e^{j\phi_m}b[k]+n_m[k]+e^{j\phi_{m,i}}n_i[k]$, whose average SNR is larger than the SNR of the individual constituent branches.

and co-phases the signals in the different branches to the reference branch J whose power is among the largest, using

$$z[k] = \sum_{i=1}^{2L} e^{j\phi_{J,i}}p_i[k] \tag{21}$$

This coherently combined signal is then detected by the single-channel MSDD. Note that the block-processing nature of (21) matches perfectly with the block processing nature of the MSDD. Essentially, we are running two differential detectors in this CC-MSDD receiver; one across diversity branches, and the other one across time.

4. Results

This section details the results obtained via simulation of our system. MSDD of length N=16, 32, 64 are considered. The Space-Time Coded signal is received by multiple antennas. In this simulation we considered one and two receive antenna systems operating in static or quasi-static Reileigh fading channels. The results are shown in Fig. 2 and Fig. 3, along with the performance of conventional ST-DD, equivalent to conventional equal gain combining (EGC), and the coherent detection lower bound(i.e. MRC with differential decoding).

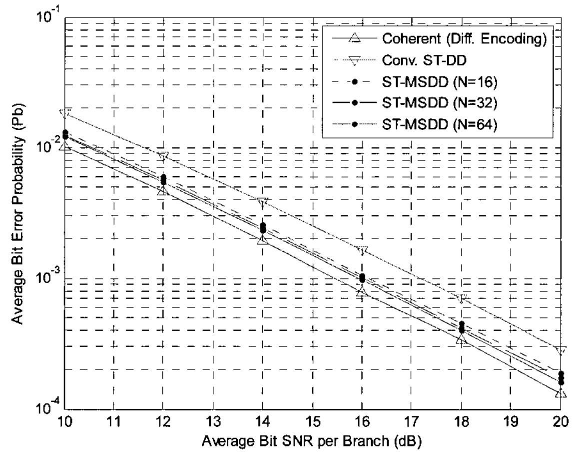

Fig. 2 BER of ST-MSDDs with two transmit antennas and single receive antenna

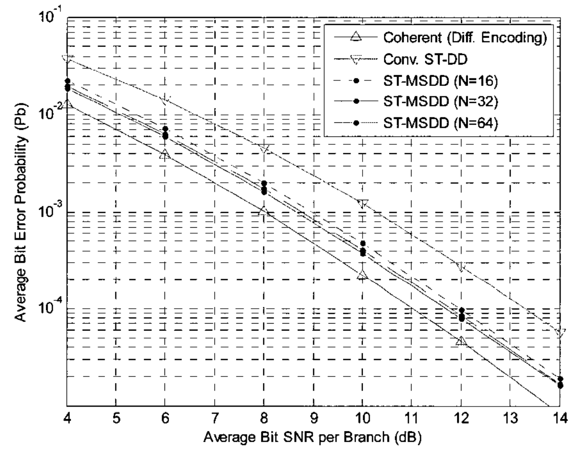

Fig. 3 BER of ST-MSDDs with two transmit antennas and two receive antennas

Fig. 2 and Fig. 3 show the performance comparison when the Differential Space-Time signal is received by one antenna and two antennas respectively. The results indicate that there is a significant improvement in performance from the conventional ST-DD. The MSDD with N=16 already provide about 1.3dB gain over conventional ST-DD for one receive antenna reception. And the gap between MRC receiver and ST-MSDD when N=64 is about 0.6dB. Again, the complexity is linearly increased with the help of proposed combining technique and Mackenthun algorithm.

5. Conclusion

In summary, we present a sub-optimum scalar MSDD receiver for diversity reception of ST-DM with a novel transformation on a specific Alamouti type space-time modulation, and obtain a scalar, receive-diversity-only equivalent. With this transformation, it is simple to apply low complexity, high performance, receive-diversity techniques. Using STBC MSDD to obtain the lower performance bound of coherent detection would require implementing an algorithm with complexity $4^{N-1}$where 4 is the cardinality of the transmission symbol set and N is a large number of transmitted space-time symbols. For the system discussed in this paper, the performance close to the coherent detection lower bound is achieved using a receiver with complexity of essentially $N\log_2 N$, given by the complexity of the scalar-MSDD [9] . Clearly, the scalar equivalent system employed in this paper offers a low complexity method to achieve the performance of approaching coherent detection.

Acknowledgments

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