Improved Blind Cyclic Algorithm for Detection of Orthogonal Space-Time Block Codes

Minh-Tuan Le, Van-Su Pham, Linh Mai and Giwan Yoon

Abstract— In this paper, we consider the detection of orthogonal space-time block codes (OSTBCs) without channel state information (CSI) at the receiver. Based on the conventional blind cyclic decoder, we propose an enhanced blind cyclic decoder which has higher system performance than the conventional one. Furthermore, the proposed decoder offers low complexity since it does not require the computation of singular value decomposition.

Index Terms—Multiple-input multiple-output, space-time coding, blind detection, diversity, wireless communication.

I. INTRODUCTION

Orthogonal space-time block codes (OSTBCs) [1]-[3] are an attractive means of realizing transmit diversity due to their full diversity as well as their simple maximum-likelihood (ML) decoding algorithm when CSI is perfectly known to the receiver. Practically, CSI can be obtained at the receiver via training signals. However, in order to achieve sufficiently accurate CSI, a long training period may be required. Consequently, a noticeable reduction in data rate can be observed, especially in fast and relatively fast fading channels.

To avoid a significant decrease in the data rate, blind and semi-blind detection methods that utilize a small amount of pilot symbols have been developed [4]-[5]. In [4]-[5], blind and semi-blind detections were implemented by iteratively minimizing the ML metric with respect to the channel matrix and data symbols, resulting in the so-called cyclic ML. A strong point of the cyclic ML is its computational simplicity. Nevertheless, the global convergence of the cyclic ML cannot be guaranteed, particularly when it is poorly initialized as in the case of blind detection. Therefore, when the cyclic ML is employed for the blind detection of OSTBCs, it will result in very poor bit error rate (BER) performance.

In this paper, based on the special property of the dispersion matrices of OSTBCs, we propose a new way to initialize the blind cyclic ML. The proposed method leads to an enhanced cyclic ML which not only has higher BER performance but also offers low detection complexity. Simulation results are provided to verify the performance of the enhanced cyclic ML.

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II. SYSTEM MODEL

Consider a multiple antenna system with n_T transmit and n_R receive antennas, referred to as (n_T, n_R) system. Let $\mathbf{C}(\mathbf{s})$ be the OSTBC function that maps information symbol vector $\mathbf{s} = [s_1, s_2, \ldots, s_K]^T$, whose entries are drawn from some complex M-PSK constellation Ω ($M = 4, 8, \ldots$), into a code matrix with code length L . Then, an orthogonal space-time code block can be expressed as:

$$\mathbf{C}(\mathbf{s}) = \sum_{k=1}^{K} \mathbf{A}_k \Re\{s_k\} + j\mathbf{B}_k \Im\{s_k\} \tag{1}$$

where $\Re\{.\}$ and $\Im\{.\}$ respectively denote the real and imaginary parts, $j = \sqrt{-1}$, $\mathbf{A}_k$ and $\mathbf{B}_k$ are $n_T \times L$ real-valued dispersion matrices.

For OSTBCs, the dispersion matrices have the following properties [6]

$$\begin{aligned} &\mathbf{A}_k\mathbf{A}_k^H = \mathbf{I}_{n_T} \quad \mathbf{B}_k\mathbf{B}_k^H = \mathbf{I}_{n_T} \\ &\mathbf{A}_k\mathbf{A}_n^H = -\mathbf{A}_n\mathbf{A}_k^H \; (k \neq n) \\ &\mathbf{B}_k\mathbf{B}_n^H = -\mathbf{B}_n\mathbf{B}_k^H \; (k \neq n) \\ &\mathbf{A}_k\mathbf{B}_n^H = \mathbf{B}_n\mathbf{A}_k^H \end{aligned} \tag{2}$$

for $k = 1, \ldots K$ *and* $n = 1, \ldots K$

Therefore, the OSTBC given by (1) satisfies:

$$\mathbf{C}(\mathbf{s})\mathbf{C}(\mathbf{s})^H = \|\mathbf{s}\|_2^2 \mathbf{I}_{n_T} \tag{3}$$

where $\|\bullet\|_2$ denotes the 2-norm; $\mathbf{I}_{n_T}$ is a $n_T \times n_T$ identity matrix.

When $\mathbf{C}(\mathbf{s})$ is transmitted through different antennas within L symbol periods, the received signal matrix is given by:

$$\mathbf{Y} = \mathbf{H}\mathbf{C}(\mathbf{s}) + \mathbf{W} \tag{4}$$

where $\mathbf{H}$ is the $n_R \times n_T$ channel matrix, $\mathbf{W}$ is a $n_R \times L$ noise matrix.

III. MAXIMUM-LIKELIHOOD DETECTION OF OSTBCS

Assuming that the channel state information (CSI) is perfectly known to the receiver, the maximum-likelihood (ML) detection of $\mathbf{s}$ is given by:

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}\in\Omega} \|\mathbf{Y} - \mathbf{H}\mathbf{C}(\mathbf{s})\|_F^2 \tag{5}$$

where $\|\bullet\|_F$ denotes the Frobenius norm.

After some manipulations employing (2), Equation (5) becomes:

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}\in\Omega} \sum_{k=1}^{K} |s_k - \tilde{s}_k|^2 \tag{6}$$

where $\tilde{s}_k = \dfrac{\Re\{Tr(\mathbf{Y}^H \mathbf{H}\mathbf{A}_k)\} - j\Im\{Tr(\mathbf{Y}^H \mathbf{H}\mathbf{B}_k)\}}{\|\mathbf{H}\|_F^2}$ is the decision statistic for transmitted symbol s_k, $Tr(\ )$ denotes the trace operator.

Equation (6) demonstrates that the ML metric decouples into a sum of K terms, where each term depends on exactly one complex symbol. Consequently, the detection of s_k is decoupled from the detection of s_n for $k \neq n$ and is given by:

$$\hat{s}_k = \arg\min_{s_k\in\Omega} (s_k - \tilde{s}_k)^2 \tag{7}$$

Clearly, the orthogonality of OSTBCs allows them to be simply detected.

IV. THE CYCLIC ML FOR THE BLIND DETECTION OF OSTBCS

OSTBCs can be simply detected when CSI is available at the receiver. Practically, CSI can be obtained at the receiver via training signals. However, in order to achieve sufficiently accurate CSI, a long training period may be required. Consequently, a noticeable reduction in data rate can be observed, especially in fast and relatively fast fading channels. In [4], Stoica et al. suggested a blind approach to the detection of OSTBCs, which does not require any training block.

Assuming that the channel is quasi-static, i.e., it remains constant over a frame of Q consecutive code blocks and changes from one frame to another. The received signal corresponding to the pth transmitted code block, $p = 1, 2, \ldots, Q$, is given by:

$$\mathbf{Y}_p = \mathbf{H}\mathbf{C}(\mathbf{s}_p) + \mathbf{W}_p \tag{8}$$

It is further assumed that the noise is spatially and temporally white and complex Gaussian distributed with noise variance σ^2, i.e., $E[\mathbf{W}_p \mathbf{W}_p^H] = \sigma^2 \mathbf{I}_{n_R}$ for $p = 1, 2, \ldots, Q$. Where $E[.]$ denotes the expectation operator; $\mathbf{A}^H$ denotes the Hermitian transpose of $\mathbf{A}$. Then the blind ML detector is given by [4]:

$$\min_{\mathbf{H};\mathbf{s}_p\in\Omega} \sum_{p=1}^{Q} \|\mathbf{Y}_p - \mathbf{H}\mathbf{C}(\mathbf{s}_p)\|_F^2 \tag{9}$$

where $\mathbf{s}_p = [s_{1,p}, s_{2,p}, \ldots, s_{K,p}]^T$ denotes the transmitted signal vector corresponding to the pth block.

It is obvious that the minimization of the ML criterion in (9) cannot determine unique solutions to both $\mathbf{s}_p$ and $\mathbf{H}$ because if $\hat{\mathbf{s}}_p$ and $\hat{\mathbf{H}}$ minimize the ML criterion, so do $\gamma\hat{\mathbf{s}}_p$ and $\hat{\mathbf{H}}/\gamma$ for any nonzero γ. In other words, the blind ML detector in (9) suffers from symbol ambiguity. In order to eliminate the symbol ambiguity, it is assumed in [4] that one of the transmitted symbols is known to the receiver. Without loss of generality, the known symbol is selected to be $s_{pilot} = s_{1,1}$.

Let us define:

$$\mathbf{h} = \mathrm{vec}(\mathbf{H})$$
$$\mathbf{s}' = \left[\Re\{\mathbf{s}_1\}^T \cdots \Re\{\mathbf{s}_Q\}^T\ \Im\{\mathbf{s}_1\}^T \cdots \Im\{\mathbf{s}_Q\}^T\right]^T$$
$$\mathbf{F}_p^{(a)} = \left[\mathrm{vec}(\mathbf{Y}_p\mathbf{A}_1^H) \cdots \mathrm{vec}(\mathbf{Y}_p\mathbf{A}_K^H)\right]$$
$$\mathbf{F}_p^{(b)} = \left[-j\mathrm{vec}(\mathbf{Y}_p\mathbf{B}_1^H) \cdots j\mathrm{vec}(\mathbf{Y}_p\mathbf{B}_K^H)\right]$$
$$\mathbf{F} = \left[\mathbf{F}_1^{(a)} \cdots \mathbf{F}_Q^{(a)}\ \mathbf{F}_1^{(b)} \cdots \mathbf{F}_Q^{(b)}\right]$$

We can rewrite the argument in (9) as:

$$\min_{\mathbf{H};\mathbf{s}_p\in\Omega} \sum_{p=1}^{Q} \|\mathbf{Y}_p - \mathbf{H}\mathbf{C}(\mathbf{s}_p)\|_F^2 = \min_{\mathbf{h};\mathbf{s}'\in\Omega} \|\mathbf{F} - \mathbf{h}\mathbf{s}'^T\|_F^2 \tag{10}$$

The minimization problem in (10) implies that $\left\|\mathbf{F}-\mathbf{hs}'^T\right\|_F^2$ must be minimized jointly with respect to $\mathbf{h}$ and $\mathbf{s}'$. Neglecting the constraint that $\mathbf{s}'$ belongs to a finite alphabet, the minimum is achieved when $\mathbf{h}$ and $\mathbf{s}'$ are respectively equal to the left and right singular vectors of $\mathbf{F}$. Mathematically, we have:

$$\tilde{\mathbf{h}}\tilde{\mathbf{s}}'^T=\lambda_1\mathbf{u}_1\mathbf{v}_1^T,\quad \tilde{s}_{1,1}=s_{pilot} \tag{11}$$

where λ_1 is the largest singular value of $\mathbf{F}$, $\mathbf{u}_1$ and $\mathbf{v}_1$ are the associated right and left singular vectors. Based on (11), the initial estimate of $\mathbf{h}$, and thus $\mathbf{H}$, can be achieved.

The blind cyclic ML is summarized as follows:

A. Blind cyclic ML Detector

▪ *Initialization Step*

Compute an initial estimate of $\mathbf{H}$, i.e., $\hat{\mathbf{H}}$, based on (11)

▪ *Iterative Step*

1)Use the latest estimate of $\mathbf{H}$ in Equation (7) to detect each transmitted symbols. After this step, we obtain $\hat{\mathbf{s}}_p,\ p=1,2,\ldots,Q$

2)Using the special property of OSTBCs in (3), the channel is re-estimated as

$$\hat{\mathbf{H}}=\frac{\sum_{p=1}^{Q}\mathbf{Y}_p\mathbf{C}^H(\hat{\mathbf{s}}_p)}{\sum_{p=1}^{Q}\left\|\hat{\mathbf{s}}_p\right\|_2^2}$$

3)Iterate until convergence or until a given number of steps have been carried out.

V. PROPOSED ENHANCED CYCLIC ML DETECTOR

The conventional blind cyclic ML requires the singular value decomposition (SVD) to compute the initial estimate of $\mathbf{H}$. This results in high detection complexity. Furthermore, when the first two largest singular values of $\mathbf{F}$ are relatively close to one another, the decoder is in the border of nonidentifiability, leading to inaccurate estimate of $\mathbf{H}$, and thus a high bit error rate.

To overcome the aforementioned problems of the conventional blind cyclic ML, we proposed a new method for obtaining the initial estimate of $\mathbf{H}$ as follows.

Assuming that the first symbol in the first transmitted code block, $s_{1,1}$, is the pilot one. The corresponding received signal block is given by:

$$\mathbf{Y}_1=\mathbf{HC}(\mathbf{s}_1)+\mathbf{W}_1 \tag{12}$$

Using (1), we can write:

$$\mathbf{Y}_1=\mathbf{H}\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]+\mathbf{H}\sum_{k=2}^{K}\mathbf{A}_k\Re\{s_{k,1}\}+j\mathbf{B}_1\Im\{s_{k,1}\}+\mathbf{W}_1 \tag{13}$$

Since $\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]$ is known to the receiver, multiplying both side of (13) with $\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H$ we get:

$$\begin{aligned}&\mathbf{Y}_1\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H=\\&\mathbf{H}\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H\\&+\mathbf{H}\sum_{k=2}^{K}\mathbf{A}_k\Re\{s_{k,1}\}+j\mathbf{B}_1\Im\{s_{k,1}\}\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H\\&+\mathbf{W}_1\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H\end{aligned} \tag{14}$$

After some manipulation, we get:

$$\begin{aligned}&\mathbf{Y}_1\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H=\left|s_{1,1}\right|^2\mathbf{H}\\&+\mathbf{H}\sum_{k=2}^{K}\mathbf{A}_k\Re\{s_{k,1}\}+j\mathbf{B}_1\Im\{s_{k,1}\}\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H\\&+\mathbf{W}_1\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H\end{aligned} \tag{15}$$

By considering the last two terms in the right-hand side of (15) as the noise terms, the the channel can be initially estimated as follows:

$$\hat{\mathbf{H}}=\frac{1}{\left|s_{1,1}\right|^2}\mathbf{Y}_1\left[\mathbf{A}_1\Re\{s_{1,1}\}+j\mathbf{B}_1\Im\{s_{1,1}\}\right]^H \tag{16}$$

Clearly, the proposed method for calculating the initial estimate of $\mathbf{H}$ is much simpler than the conventional method since no SVD is required.

Now, the enhanced blind cyclic ML detector is summarized as follows.

A. Enhanced blind cyclic ML Detector

▪ *Initialization Step*

Compute an initial estimate of using Equation (16)

▪ *Iterative Step*

1)Use the latest estimate of $\mathbf{H}$ in Equation (7) to detect each transmitted symbols. After this step, we obtain $\hat{\mathbf{s}}_p,\ p=1,2,\ldots,Q$

2)Using the special property of OSTBCs in (3), the channel is re-estimated as

$$\hat{\mathbf{H}} = \frac{\sum_{p=1}^{Q} \mathbf{Y}_p \mathbf{C}^H(\hat{\mathbf{s}}_p)}{\sum_{p=1}^{Q} \|\hat{\mathbf{s}}_p\|_2^2}$$

3)Iterate until convergence or until a given number of steps have been carried out.

VI. SIMULATION RESULTS

In this section, we investigate performance of the proposed decoder by applying it to a (3, 3) system with the complex-valued rate 3/4 OSTBC [3]. Transmitted symbols are generated by the 8-PSK modulator. The frame length is fixed at $Q = 48$. The channel is assumed to remain constant within each frame, and changes randomly from one frame to the next. The channel gains are randomly created according to an i.i.d. zero-mean complex Gaussian distribution with equal variance of 0.5 per real dimension.

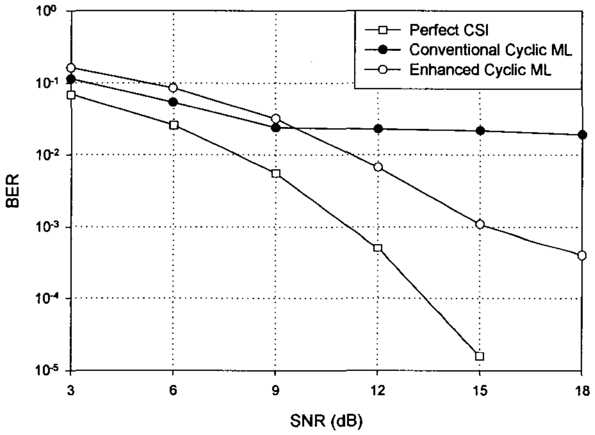

Fig. 1 BER-versus-SNR curves of the (3, 3) system with the complex-valued rate ¾ OSTBC employing 8-PSK modulation; Blind detection.

Fig. 1 shows the BER performances of the system when the proposed decoder, the conventional cyclic ML decoder are employed. One can see from Fig. 1 that in the low SNR region, the proposed method slightly underperforms the conventional cyclic ML. This is possibly due to the affect of the Gaussian noise. However, in the medium and high signal-to-noise ratio (SNR) regions, the initial estimate of $\mathbf{H}$ becomes more accurate. Consequently, the proposed method offers a remarkable improvement in BER performance as compared to the conventional cyclic ML. The results in Fig. 1 also indicate that performance of the enhanced cyclic ML is still quite far from that of perfect CSI case. To reduce the gap, more pilot symbols would be required.

VII. CONCLUSION

In this paper, an enhanced blind cyclic ML decoder is proposed. Based on the special property of the dispersion matrices of OSTBCs, a new method of calculating the initial estimate of the channel matrix is presented. The new method provides more accurate estimate of the channel matrix at medium and high SNRs, thereby resulting in better BER performance. In addition, it is much simpler than the conventional cyclic ML. Consequently, the enhanced cyclic ML can be a potential way for the blind detection of OSTBCs.

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