A Simplified Efficient Algorithm for Blind Detection of Orthogonal Space-Time Block Codes

Van Su Pham, Linh Mai, Jae-young Lee and Giwan Yoon, *Member, KIMICS*

Abstract—This work presents a simplified efficient blind detection algorithm for orthogonal space-time codes (OSTBC). First, the proposed decoder exploits a proper decomposition approach of the upper triangular matrix R, which resulted from Cholesky-factorization of the composition channel matrix, to form an easy-to-solve blind detection equation. Secondly, in order to avoid suffering from the high computational load, the proposed decoder applies a sub-optimal QR-based decoder. Computer simulation results verify that the proposed decoder allows to significantly reduce computational complexity while still satisfying the bit-error-rate (BER) performance.

Index Terms—Blind detection, efficient blind detection, QR decomposition, Orthogonal space-time coding, wireless communications

I. INTRODUCTION

ORTHOGONAL space time codes [1]-[3] were introduced in the late 1990s as a transmit-diversity to combat signal fading in wireless communication channels. It has been shown that OSTBCs not only provide full diversity but also allow simple maximum-likelihood (ML) decoding algorithm. These advantages of OSTBC are obtained under the assumption that CSI is perfectly known to the receiver. Practically, CSI can be obtained at the receiver via training signals. In order to achieve sufficiently accurate CSI, however, 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, different blind and semi-blind detection methods that utilize a small amount of pilot symbols have been developed [4]-[8]. [4]-[5] presented the blind and semi-blind detections, so-called cyclic ML detections, which were implemented by iteratively minimizing the ML metric with respect to the channel matrix and data symbols. A strong point of the cyclic ML is its computational simplicity. Unfortunately, the global convergence of the cyclic ML cannot be guaranteed, particularly when it is poor initialized as in the case of blind detection. In [6], other blind and semi-blind decoders for OSTBCs based on semi-definite relaxation (SDR) and sphere decoder (SD) were devised. These decoders were shown to remarkably outperform the cyclic ML with respect to BER performance. Both SDR and SD decoders, however, are applicable only to the case of binary phase-shift keying (BPSK) and quadrature phase shift keying (QPSK) symbols. Moreover, their complexity is quite high compared to that of the cyclic ML, particularly in low and medium signal-to-noise (SNR) regions. In [8], by applying exactly the same method in [6], we show that blind detection of OSTBCs with M-ary phase-shift keying (M-PSK) symbols is equivalent to a quadratic form. In addition, a combination of an SD with a QR-decomposition-based (QRD-based) decoder was used to cope with the quadratic form. The complexity was significantly reduced by lowering the size of SD using to jointly detect a number of transmitted symbols. Then, the QRD-based decoder is employed to detect the remaining ones on a symbol-by-symbol fashion. Thus, in order to increase BER performance, the size of first SD jointly detection is increased. Unfortunately, it has been known that the complexity of SD is still high especially when the system is large and/or the high-level modulation scheme are used.

In this work, in order to reduce the computational load, we apply QRD-based detection for system [8]. Simulation results demonstrate that the complexity of the proposed decoder is significantly reduced while its performance is still reasonable.

The rest of this paper is organized as follows. In section II, the system model is described. The detail of the proposed detection is presented in section III. Computation simulation results for verifying the proposed detection are illustrated in section IV. Finally, we present the conclusion of our work in section V.

II. SYSTEM MODEL

Consider a multiple antenna system with n_T transmit and n_R receive antennas, referred to as

Manuscript received October 10, 2007; revised June 18, 2008. This work was supported by the Korea Science and Engineering Foundation (KOSEF) under ERC program through the Intelligent Radio Engineering Center (IREC) at ICU, Republic of Korea.

The authors are with the School of Engineering, Information and Communications University (ICU), Daejeon 305-732, Korea (e-mail: vansu_pham @icu.ac.kr, mailinh@icu.ac.kr, jae0229@icu.ac.kr, gwyoon@icu.ac.kr)

(n_T, n_R) system. Let $C(s_p)$ be the p^{th} STBC codeword that resulted by mapping information symbol vector $\mathbf{s}_p = \begin{bmatrix} s_{p,1} & s_{p,2} & \cdots & s_{p,K} \end{bmatrix}^T$, whose entries are drawn from some complex M-PSK constellation $\Omega\ (M = 4,8,...)$, into a code matrix with code length L. Then, an orthogonal space-time code block can be expressed as:

$$\mathbf{C}(s_p) = \sum_{k=1}^{K} \left(\mathbf{A}_k \Re\{s_{p,k}\} + j\mathbf{B}_k \Im\{s_{p,k}\} \right) \quad (1)$$

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 satisfying the following conditions [9]:

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

The OSTBC given in (1) has the following property, so called orthogonal property:

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

where $\|.\|_2$ denotes the 2-norm.

For convenience, let us define:

$$\begin{cases} \mathbf{X}_n = \mathbf{A}_k \\ \mathbf{X}_{n+1} = j\mathbf{B}_k \\ s_n = \Re\{s_{p,k}\} \\ s_{n+1} = \Im\{s_{p,k}\} \end{cases} \quad (k = 1,...,K) \quad (4)$$

Then, the code matrix in (1) can be re-written as:

$$\mathbf{C}(\mathbf{s}) = \mathbf{C}(\mathbf{s}_p) = \sum_{n=1}^{K'} \mathbf{X}_n s_n \quad (5)$$

In (5), $K' = 2K$, the system has been converted into new transmitted vector $\mathbf{s}$ with real entries.

We assume that the transmitter send a data frame consisting of Q consecutive code blocks $\mathbf{G}(\mathbf{s}_{1:Q})$. In addition, the channel is assumed to be quasi-static over the frame length and independently changed from one to another. Then the received signal frame is given by:

$$\mathbf{Y} = \mathbf{HG}(\mathbf{s}_{1:Q}) + \mathbf{W} \quad (6)$$

where $\mathbf{s}_{1:Q} = \begin{bmatrix} \mathbf{s}_1^T & \mathbf{s}_2^T & \cdots & \mathbf{s}_Q^T \end{bmatrix}^T$ is the $QK' \times 1$ vector containing all Q real transmitted signal vectors within a frame, $\mathbf{G}(\mathbf{s}_{1:Q}) = \begin{bmatrix} \mathbf{C}(\mathbf{s}_1) & \mathbf{C}(\mathbf{s}_2) & \cdots & \mathbf{C}(\mathbf{s}_Q) \end{bmatrix}$ is the $n_T \times LQ$ transmitted signal frame; $\mathbf{C}(\mathbf{s}_n)$ is the n^{th} transmitted code matrix; $\mathbf{H}$ is an $n_R \times n_T$ channel matrix; $\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 & \cdots & \mathbf{Y}_Q \end{bmatrix}$ is the $n_R \times LQ$ received signal frame; $\mathbf{W} = \begin{bmatrix} \mathbf{W}_1 & \mathbf{W}_2 & \cdots & \mathbf{W}_Q \end{bmatrix}$ is the $n_R \times LQ$ matrix containing noise sample at the receive antennas. Herein, the noise is assumed to be spatially and temporally white and complex Gaussian distributed with variance σ^2.

By treating $\mathbf{H}$ as an unknown deterministic quantity at the receiver, the blind maximum-likelihood detection for the system in (6) can be expressed as [6]:

$$\{\hat{\mathbf{H}}, \hat{\mathbf{s}}_{1:Q}\} = \arg \min_{\substack{\mathbf{H} \in C^{n_R \times n_T} \\ \mathbf{s}_{1:Q} \in \boldsymbol{\Omega}}} \left\| \mathbf{Y} - \mathbf{HG}(\mathbf{s}_{1:Q}) \right\|_F^2 \quad (7)$$

Following exactly the same method in [6], we are able to reduce the blind detection problem in (7) to:

$$\left[\hat{\mathbf{s}}_{1:Q}\right] = \arg \max_{\mathbf{s}_{1:Q} \in \boldsymbol{\Omega}} \mathbf{s}_{1:Q}^T \mathbf{M}_Y \mathbf{s}_{1:Q} \quad (8)$$

Where

$$\mathbf{M}_Y = \begin{bmatrix} \mathbf{M}_{Y,11} & \mathbf{M}_{Y,12} & \cdots & \mathbf{M}_{Y,1Q} \\ \mathbf{M}_{Y,21} & \mathbf{M}_{Y,22} & \cdots & \mathbf{M}_{Y,2Q} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{M}_{Y,Q1} & \mathbf{M}_{Y,Q2} & \cdots & \mathbf{M}_{Y,QQ} \end{bmatrix} \quad (9)$$

$\mathbf{M}_{Y,mn} \in \square^{K' \times K'}$ is the matrix with the $(k,l)^{th}$ entry defined by:

$$\left[\mathbf{M}_{Y,mn}\right]_{kl} = \Re\{Tr\{\mathbf{Y}_m \mathbf{X}_k^H \mathbf{X}_l \mathbf{Y}_n^H\}\} \ (1 \leq m,n \leq Q)$$

It is clear that the blind ML detection in (8) is a maximization problem of a quadratic form of matrix $\mathbf{M}_Y$.

When the transmitted symbols are drawn from M-

PSK constellation, the inner product $\mathbf{s}_{1:Q}^T \mathbf{s}_{1:Q}$ is a constant. Thus, we can alternatively re-write (8) as:

$$\left[\hat{\mathbf{s}}_{1:Q}\right] = \arg\max_{\mathbf{s}_{1:Q}\in\mathbf{\Omega}} \mathbf{s}_{1:Q}^T \left[\rho\mathbf{I} - \mathbf{M}_Y\right] \mathbf{s}_{1:Q} \quad (10)$$

Where $\rho < \infty$ is some real constant chosen so that $\rho\mathbf{I} - \mathbf{M}_Y$ is positive definite. By applying Cholesky factorization of $\rho\mathbf{I} - \mathbf{M}_Y$ to give $\rho\mathbf{I} - \mathbf{M}_Y = \mathbf{R}^T\mathbf{R}$, $\mathbf{R} \in \mathbb{R}^{QK'\times QK'}$ is an upper triangular matrix. The problem (10) becomes:

$$\left[\hat{\mathbf{s}}_{1:Q}\right] = \arg\max_{\mathbf{s}_{1:Q}\in\mathbf{\Omega}} \left\|\mathbf{R}\mathbf{s}_{1:Q}\right\|_2^2 \quad (11)$$

From (11) we can solve by using zero-forcing decision feedback (ZF-DE) or sphere decoder (SD).

III. PROPOSED DECODER

When none of the transmitted symbols in $\mathbf{G}\left(\mathbf{s}_{1:Q}\right)$ are known to the receiver, the blind detection problem in (11) inevitably suffers from symbol ambiguity [6]. Consequently, the receiver is handling (11) under the assumption that at least one pilot symbol (symbol known to both the transmitter and receiver) is required.

Without loss of generality, we assume that there are P pilot symbols, $1 \le P \le K$, in the first code block $\mathbf{C}\left(\mathbf{s}_1\right)$ of $\mathbf{G}\left(\mathbf{s}_{1:Q}\right)$. Moreover, at the receiver, the signal vector $\mathbf{s}_{1:Q}$ is organized such that its last $P' = 2P$ entries contain the real and imaginary parts of P pilot symbols, while remaining entries contain the real and imaginary parts of data symbols. Let us denote $\mathbf{s}_p$ and $\mathbf{s}_d$ be the $P'\times 1$ and $(QK'-P')\times 1$ vectors respectively comprising the last P' entries and the first $(QK'-P')$ entries of $\mathbf{s}_{1:Q}$, i.e., $\mathbf{s}_{1:Q} = \left[\mathbf{s}_d^T \quad \mathbf{s}_p^T\right]^T$. In addition, let matrix $\mathbf{R}$ be partitioned as:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_d & \mathbf{Z} \\ 0 & \mathbf{R}_p \end{bmatrix} \quad (12)$$

Where $\mathbf{Z}$ is a $(QK'-P')\times P'$ matrix, and $\mathbf{R}_d$ and $\mathbf{R}_p$, are, respectively, $(QK'-P')\times(QK'-P')$ and $P'\times P'$ upper triangular matrices. Then (11) can be re-expressed as:

$$\left[\hat{\mathbf{s}}_d\right] = \underset{\mathbf{s}_d\in\mathbf{\Omega}}{\mathrm{argmin}} \left\|\mathbf{R}_d\mathbf{s}_d + \mathbf{Z}\mathbf{s}_p\right\|_2^2 + \left\|\mathbf{R}_p\mathbf{s}_p\right\|_2^2 \quad (13)$$

By defining $\mathbf{x} = -\mathbf{Z}\mathbf{s}_p$, and noting that $\left\|\mathbf{R}_p\mathbf{s}_p\right\|_2^2$ is not a function of $\mathbf{s}_d$, we can write:

$$\left[\hat{\mathbf{s}}_d\right] = \underset{\mathbf{s}_d\in\mathbf{\Omega}}{\mathrm{argmin}} \left\|\mathbf{x} - \mathbf{R}_d\mathbf{s}_d\right\|_2^2 \quad (14)$$

From (14), we can see that it represents the blind and semi-blind detection problems of OSTBCs. In the case the number of pilot symbol $P = 1$, (14) becomes the blind detection problem. It is worth mentioning that for small number of pilot symbols, (14) is simpler than the one presented in [6] since it avoids computing a matrix inversion.

Now, sphere decoding can be applied to (14) to obtain the blind or semi-blind ML solution $\hat{\mathbf{s}}_d$. Although SD provides exact solution, its complexity is still rather high, particularly when the problem size is large. In our previous work, [8], we downsize the SD by jointly SD only J last components of $\mathbf{s}_d$, while the remaining will be decoded by using QRD-based decoder. In order to improve BER performance, the value J increases. That means that the complexity increases. In this work, we consider the trade off complexity-performance by applying QRD-based decoder to (14). The simplified proposed decoder can be summarized as follows:

Input: $\mathbf{x}$, $\mathbf{R}_d$ Output: $\hat{\mathbf{s}}_d = \left[\hat{s}_1 \quad \cdots \quad \hat{s}_{QK'-P'}\right]$

Step 1: Form $\mathbf{x} = -\mathbf{Z}\mathbf{s}_p$

Step 2: Apply ZF-DFE QRD-based decoder algorithm to (14)

IV. SIMULATION RESUTLS

In this section, we investigate the performance and complexity of the proposed decoder by applying it to a $(4,1)$ system with the complex-valued code rate ¾ OSTBC [10]. The transmitted symbols are generated by the 8-PSK modulator. In these simulations, we only consider the blind detection, i.e., $P = 1$. The frame length is set to $Q = 8$. The channel is assumed to be quasi-static within the frame length, and independently changed from one frame to another. The channel gains are randomly created according to an i.i.d zero-mean complex Gaussian distribution with variance 0.5 per dimension. The constant ρ is set equal to $\rho = 1.001\lambda_{\max}$, where $\lambda_{\max}$ is the largest eigen-value of $\mathbf{M}_Y$.

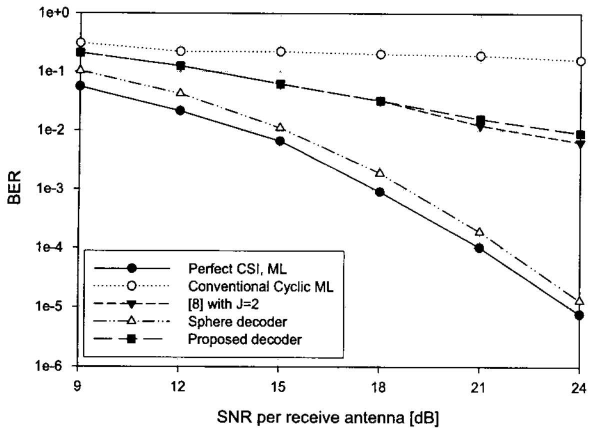


Fig. 1 Comparison of BER performance versus SNR of the (4,1) system with the complex-valued code rate ¾ OSTBC employing 8-PSK modulation.

Fig.1 illustrates the BER performance versus SNR of the considered system when the proposed detection and its counterparts are employed. As can be seen from the figure that the proposed detection significantly outperforms the conventional cyclic ML one, while shows comparable performance with [8] for the simplest case$(J=2)$.

In order to compare the complexity of the proposed decoder with those of its counterparts, we implement the decoder in float-point C. The complexity of each decoder is obtained by counting the number of additions, subtractions, multiplications, divisions and square roots. It is worth mentioning that these comparisons are relatively quantity since these implementations are depended on the tricks. The average complexity comparison is shown in Fig.2.

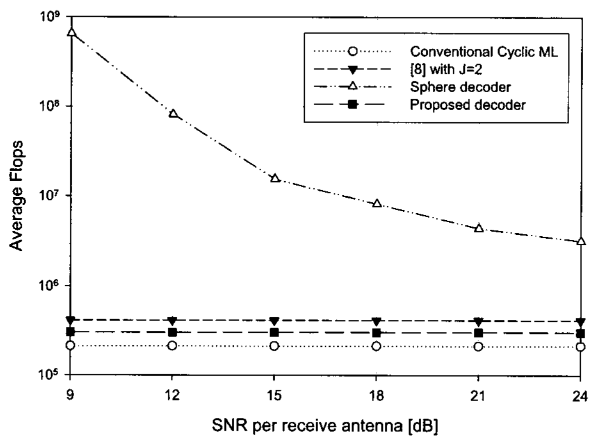


Fig. 2 Average complexity as function of SNR when the proposed detection and its counterparts are used. (4,1) system with complex-valued code rate ¾ OSTBC employing 8-PSK modulation is considered.

From Fig.2 we see that complexity of the proposed detection although is higher than that of the conventional cyclic ML, it is lower than that of [8] for the simplest case $(J=2)$. In other worth, the proposed detection can provide comparable BER performance while requires lower computational load in comparison with the simplest case of [8].

IV. CONCLUSIONS

In this paper, a simplified efficient algorithm based on QR decomposition for blind detection of OSTBCs employing M-PSK symbols has been proposed. By exploiting new QRD-based signal model and the proposed detection, the system is able to obtain reasonable BER performance while requiring relatively low computational load. Therefore, the proposed detection is a promisingly applicable approach for blind detection of OSTBCs.

ACKNOWLEDGMENT

This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST)
(No. R11-2005-029-06003-0)

REFERENCES

[1] S.M. Alamouti, *"A simple transmit diversity technique for wireless communications"*, IEEE J. Sel. Areas Comm., Vol.16, No.8, Oct.1998, pp.1541-1458.

[2] V. Tarokh, H. Jafarkhani and A.R. Calderbank, *"Space-time block codes from orthogonal designs"*, IEEE Trans. Inform. Theory, Vol.45, No.7, Jul.1999, pp.1456-1467.

[3] P. Stoica and G. Ganesan, *"Space-time block codes: A maximum SNR approach"*, IEEE Trans. Inform. Theory, Vol.47, No.5, May.2001, pp.1650-1656.

[4] P. Stoica and G. Ganesan, *"Space-time block codes: Trained, blind and semi-blind detection"*, Digital Signal Processing, Vol.13, 2003, pp.93-105.

[5] E.G. Larsson, P. Stoica and J. Li, *"Orthogonal space-time block codes: Maximum-likelihood detection for unknown channels and unstructured interferences"*, IEEE Trans. Signal Proc., Vol.51, No.2, Feb.2003, pp.362-372.

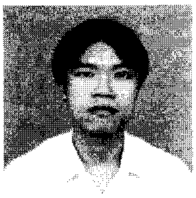
[6] W.K. Ma, B.N. Vo, T.N. Davidson and P.C. Ching, *"Blind ML detection of orthogonal space-time block codes: Efficient high performance implementations"*, IEEE Trans. Signal Proc., Vol.54, No.2, Feb.2006, pp.738-751.

[7] T. Cui and C. Tellambura, *"Joint channel estimation and data detection for OFDM systems via Sphere decoding"*, IEEE Proc. Globecom'04, Vol.4, Dec.2004, pp.3656-3660.

[8] Minh-Tuan Le, Van-Su Pham, Linh Mai and Giwan Yoon, *"Efficient Algorithm for Blind Detection of Orthogonal Space-Time Block Codes"*, IEEE Sign. Proc. Lett., Vol.14, No.5, May.2007, pp.301-304.

[9] E.G. Larsson and P. Stoica, *Space-time block coding for wireless communications*, Cambridge University Press, 2003.

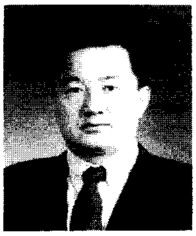
[10] B. Vucetic and J. Yuan, *Space-Time Coding*, Wiley, 2003.



Van Su Pham
Member KIMICS. Received B.S. degree in Electronic Engineering, Hanoi University, Vietnam, in 1999. Received M.S. degree in Electrical Engineering, Information and Communications University (ICU), Taejon, Korea in 2003. Since Feb. 2004, he has been a Ph.D. student in Communication Electronics Lab, Information and Communications University (ICU), Daejeon, Korea. The research areas of interest include intelligent algorithms, space-time coding and MIMO systems.

Linh Mai
Member KIMICS. Received B.S. degree in Natural Science, Hanoi University, Vietnam, in 1996. M.S. degree in ITIMS, Hanoi, Vietnam, in 1998. From 1998 to summer 2001, he was a teacher of Posts and Telecommunications Institute of Technology (PTIT), Vietnam. Since 2001 to present, he has been a Ph.D. student in Communication Electronics Lab, Information & Communications University (ICU), Daejeon, Korea. The research areas of interest are RF devices, designs & applications.

Jae-young Lee
Member KIMICS. Received B.S. degree in Information technology, Soon Chun Hyang University (SCH) in 2006. Since 2006, she has been an M.S. student in Communication Electronics Lab, Information and Communications University (ICU), Daejeon, Korea. The research areas of interest are RF devices, designs & applications.



Giwan Yoon
Member KIMICS. Received B.S. degree in Seoul National University (SNU), in 1983 and M.S. degree in KAIST, in 1985, both Seoul, Korea. Received Ph.D. degree in The University of Texas at Austin, in 1994, Texas, USA. From 1985 to 1990, he was with LG Group, Seoul, Korea. From 1994 to 1997, he was with digital equipment corporation, MA, USA. Currently, he is a professor of school of engineering, Information and Communications University (ICU), Daejeon, Korea. His major research areas of interest include multifunctional intelligent devices & their technologies for RF and wireless applications.