SUBSPACE-BASED BLIND CHANNEL ESTIMATION FOR STBC-OFDM

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ABSTRACT

This paper proposes a subspace-based blind channel estimation method for space-time coded OFDM system. Using only the redundancy induced by OFDM modulation and space-time block coding (STBC), channel state information (CSI) can be blindly estimated, up to two scalar ambiguities for Alamouti STBC or one for 4T4A3K STBC, even when a single receiving antenna is equipped. Compared with other blind channel estimation method for STBC-OFDM, this method needs neither pre-coding nor over-sampling, and thus has higher system data rate and lower complexity. Simulation results demonstrate the effectiveness of this method.

Keywords: space-time coding blind channel estimation OFDM subspace

1. INTRODUCTION

In MIMO-OFDM system with space time block coding (STBC), Channel estimation is vital to symbol detection. There are many papers dealing with channel estimation algorithms for OFDM-based systems. [2] proposes a (semi-) blind channel estimation algorithm for STBC-OFDM system with precoding. CSI can be estimated up to one or two scalar ambiguities according to the precoding matrices selected. Because the algorithm needs redundant precoding, the overall system data rate is reduced. [4] and [5] use cyclic prefix (CP) and virtual carrier (VC) respectively, to blind identify MIMO-OFDM channels. The receiving antennae are often more than the transmitting antennae. [6] proposes blind channel estimation method for oversampled MIMO space-time coded system, with the assumptions that the transmitted signals can be represented by the generalized space time coding (GSTC). It hasn't proved the identifiability of the algorithm.

This paper deals with blind channel estimation for STBC-OFDM system with transmit diversity and single receive antenna. Utilizing the redundancy inherent in STBC and OFDM, CSI can be estimated blindly up to 1 or 2 ambiguities according to the system configuration. The rest of the paper is arranged as follows: section 2 gives the system model; section 3 presents the channel identification algorithm, putting a great emphasis on the proof of identifiability of the algorithm; simulation results are given in section 4 followed by the conclusion in section 5.

This work was supported by NSFC (60496310, 60272046), NSFJS(BK2005061) and the Grant of PhD Programmes of Chinese MOE (20020286014).

2. SYSTEM MODEL

Suppose the system is equipped with A transmit antennae and only one receive antenna. Before transmission, user data are serial to parallel transformed to form length N data blocks. We denote the i-th block as S_i. Then K adjacent blocks are space-time block coded [1] to transmit in T block intervals. For simplicity, we call the above system a TTAAKK STBC. The often-used OSTBC with two and four transmit antennae have the following coding matrices:

$$\begin{array}{c} \rightarrow time \\ space \downarrow \begin{pmatrix} S_{2i} & -S_{2i+1}^* \\ S_{2i+1} & S_{2i}^* \end{pmatrix} \end{array}, \quad \begin{pmatrix} S_{3i} & -S_{3i+1}^* & S_{3i+2}^* & 0 \\ S_{3i+1} & S_{3i}^* & 0 & S_{3i+2}^* \\ S_{3i+2} & 0 & -S_{3i}^* & -S_{3i+1}^* \\ 0 & S_{3i+2} & S_{3i+1} & -S_{3i} \end{pmatrix}.$$

After STBC, OFDM modulation are performed on each of the transmit antennae. In order to eliminate inter block interference (IBI), a cyclic prefix (CP) with length P, which is at least equal to L, the upper bound of channel orders, is appended in each block. Here we assume P=L, while P>L, which corresponds to channel order overestimation, is straightforward. So the CP-included OFDM block has length Q=N+P. Then the A branches of signals are parallel to serial transformed and transmitted respectively. We denote the A branches of transmitting signals as $u_1(n), \ldots, u_A(n)$.

For simplicity of analysis, we take the following hypotheses:

(A1) user signals are real, such as ASK signals and other signals transformed to real form, so the conjugation symbol in STBC matrix is dispensable;

(A2) user signals are i.i.d.;

(A3) noise is uncorrelated with user signal and is white;

(A4) the A sub-channels are uncorrelated;

Based on these assumptions, the received signal is:

$$r(n) = \sum_{a=1}^{A} \sum_{i=0}^{L} h_i^a u_a(n-i) + \eta(n), \tag{1}$$

where $\boldsymbol{h}_a \triangleq \begin{pmatrix} h_0^a & h_1^a & \cdots & h_L^a \end{pmatrix}^T$ denotes the channel impulse response (CIS) from the *a-th* transmit antenna to the receive antenna, with h_i^a as its *i*-th tap; $\eta(n)$ is the additive noise at receiver end.

If we consider R successive groups of STBC signals, then the received signals due to these transmitting blocks are:

$$\bar{\boldsymbol{r}} \triangleq \begin{pmatrix} \boldsymbol{r}_{Ti+T-1} \\ \boldsymbol{r}_{Ti+T-2} \\ \vdots \\ \boldsymbol{r}_{T(i-R+1)}(1:N) \end{pmatrix} = \sum_{a=1}^{A} \begin{pmatrix} h_0^a & h_1^a & \cdots & h_L^a & & \\ & \ddots & \ddots & \cdots & \ddots & \\ & & h_0^a & h_1^a & \cdots & h_L^a \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_{Ti+T-1}^a \\ \boldsymbol{u}_{Ti+T-2}^a \\ \vdots \\ \boldsymbol{u}_{T(i-R+1)}^a \end{pmatrix} + \bar{\boldsymbol{\eta}}$$

$$\triangleq \sum_{a=1}^{A} \mathcal{H}_a \mathcal{U}_a + \bar{\boldsymbol{\eta}} , \tag{2}$$

where $\boldsymbol{r}_i = \begin{bmatrix} r(iQ+Q-1) & \cdots & r(iQ) \end{bmatrix}^T$ is a Q dimensional received vector; $\mathcal{H}_a = \begin{pmatrix} h_0^a & h_1^a & \cdots & h_L^a & & \\ & \ddots & \ddots & \cdots & \ddots & \\ & & h_0^a & h_1^a & \cdots & h_L^a \end{pmatrix}$ the $(TRQ-L)\times TRQ$ Toeplitz matrix formed by $\boldsymbol{h}_a$; $\mathcal{U}_a$ the $TRQ\times 1$ enhanced transmitting signal vector from the *a-th* transmit antenna, with subblocks defined as $\boldsymbol{u}_i^a = \begin{bmatrix} u_a(iQ+Q-1) & \cdots & u_a(iQ) \end{bmatrix}^T$; $\bar{\boldsymbol{\eta}}$ is the noise vector which has the same dimension as $\bar{\boldsymbol{r}}$; $\boldsymbol{r}(1:k)$ denotes a vector formed by the first k elements of $\boldsymbol{r}$.

Considering the operation of STBC and OFDM, the transmitting signal $\mathcal{U}_a$ has the following form:

$$\mathcal{U}_a = (I_{TR}\otimes W)(I_R \otimes \tilde{E}_a)\mathcal{S} \triangleq \mathbf{W}_{TR} E_a \mathcal{S} \tag{3}$$

where $W = flipud(\begin{pmatrix} F_{cp}^H \\ F^H \end{pmatrix})$ is a $Q\times N$ IFFT transform matrix with CP, with *flipud* introduced from MATLAB and $(\cdot)^H$ denoting Hermitian transpose; $\mathbf{W}_{TR} \triangleq I_{TR}\otimes W$, where I_N and $\otimes$ means unit matrix with dimension N and kronecker product respectively; $E_a \triangleq I_R \otimes \tilde{E}_a$.

$\mathcal{S} = \begin{pmatrix} S_{Ki+K-1} \\ S_{Ki+K-2} \\ \vdots \\ S_{K(i-R+1)} \end{pmatrix}$ and its subblock $S_i = \begin{bmatrix} s(iN) \\ s(iN+1) \\ \vdots \\ s(iN+N-1) \end{bmatrix}$ are $KRN\times 1$ and $N\times 1$ signal vectors, respectively.

The $TN\times KN$ elementary matrices $\tilde{E}_a$ are determined by STBC selected. For Alamouti STBC they take forms

$$\tilde{E}_1 = \begin{pmatrix} -I & \\ & I \end{pmatrix}; \qquad \tilde{E}_2 = \begin{pmatrix} & I \\ I & \end{pmatrix},$$

while for 4T4A3K OSTBC, $\tilde{E}_1$ to $\tilde{E}_4$ have forms:

$$\begin{pmatrix} 0 & 0 & 0 \\ I & & \\ & -I & \\ & & I \end{pmatrix}, \begin{pmatrix} I & & \\ 0 & 0 & 0 \\ & & I \\ & I & \end{pmatrix}, \begin{pmatrix} & -I & \\ & & -I \\ 0 & 0 & 0 \\ I & & \end{pmatrix}, \begin{pmatrix} & & -I \\ & I & \\ I & & \\ 0 & 0 & 0 \end{pmatrix}.$$

From equation (2) and (3), we can get:

$$\bar{\boldsymbol{r}} = \sum_{a=1}^{A} \mathcal{H}_a \mathbf{W}_{TR} E_a \mathcal{S} + \bar{\boldsymbol{\eta}} \triangleq \mathbf{H}\mathcal{S} + \bar{\boldsymbol{\eta}} , \tag{4}$$

where $\mathbf{H} \triangleq \sum_{a=1}^{A} \mathcal{H}_a \mathbf{W}_{TR} E_a$ is the equivalent channel matrix. Equation (4) gives the model for an ATx-1Rx STBC-OFDM system. Based on this, a blind channel estimation method will be developed in the next section.

3. CHANNEL ESTIMATION ALGORITHM

3.1. Subspace based blind channel identification

From equation (4), channel identifiable condition requires **H**, a $(TRQ-L)\times KRN$ matrix, be full column rank. A necessary condition for this is $(TRQ-L)\geq KRN$, i.e., $R \geq L/(TQ-KN)$, which can be satisfied by any positive integer R. From [3], we know that $\mathcal{H}_a \mathbf{W}_{TR} E_a$ is full column rank iff channel A does not have any zeros on OFDM sub-carriers. Based on this result, we furthermore have the following lemma:

lemma 1: When the A sub-channels are uncorrelated, the matrix **H** defined in (4) is full column rank with probability 1.

If the conditions in **lemma 1** hold, the noise subspace has dimension $d = TRQ-KRN-L$, and can be denoted as $V_{noi} = \begin{pmatrix} v_1 & v_2 & \cdots & v_d \end{pmatrix}$. Due to the orthogonality between noise subspace and signal subspace, we can get:

$$v_i^H \mathbf{H} = v_i^H \sum_{a=1}^{A} \mathcal{H}_a \mathbf{W}_{TR} E_a = 0 , \quad i = 1,\ldots,d . \tag{5}$$

Considering the interchangeability of Toeplitz matrix, we get:

$$v_i^H \mathcal{H}_a = \boldsymbol{h}_a^T V_i , \tag{6}$$

where V_i is a $(L+1)\times TRQ$ Toeplitz matrix with first row $[v_i^H \; zeros(1,L)]$ and first column $[v_i(1) \; zeros(1,L)]^H$. So we have from equation (5) and (6):

$$v_i^H \mathbf{H} = [\boldsymbol{h}_1^T \;\; \cdots \;\; \boldsymbol{h}_A^T](I_A \otimes V_i) \begin{bmatrix} \mathbf{W}_{TR}E_1 \\ \vdots \\ \mathbf{W}_{TR}E_A \end{bmatrix} \triangleq \boldsymbol{h}^T (I_A \otimes V_i) \begin{bmatrix} \mathbf{W}_{TR}E_1 \\ \vdots \\ \mathbf{W}_{TR}E_A \end{bmatrix} , \tag{7}$$

where $\boldsymbol{h}^T = [\boldsymbol{h}_1^T \;\; \cdots \;\; \boldsymbol{h}_A^T]$ is a composite channel vector of the A sub-channels.

Jointly consider all the base vectors in noise subspace and let $\mathbf{V} = \sum_{i=1}^{d} V_i$ and $B = (I_A \otimes \mathbf{V}) \begin{bmatrix} \mathbf{W}_{TR}E_1 \\ \vdots \\ \mathbf{W}_{TR}E_A \end{bmatrix}$, we finally get:

$$\boldsymbol{h}^T B = 0 . \tag{8}$$

So the CSI can be blindly estimated as a linear combination of the base vectors of the left null space (of B), the dimension of which is determined by the rank of B. From the analysis of the next subsection, we know that when Alamouti STBC is used, B looses rank by 2; while when 4T4A3K OSTBC is used, it looses rank by 1. These numbers correspond to the dimension of the null space of B, and also to estimation ambiguities, which is common to all blind channel estimation algorithm and can be eliminated by a few training sequences.

3.2. Proof of the identifiability

Suppose the true composite channel is $\boldsymbol{h}$ and the estimated one is $\boldsymbol{g}^T = (\boldsymbol{g}_1^T \ \cdots \ \boldsymbol{g}_A^T)$. From the fact that they share the same signal subspace, we know that there exists a full rank matrix $J \in C^{KRN \times KRN}$ which satisfies:

$$\sum_{a=1}^{A} \mathcal{H}_a \mathbf{W}_{TR} E_a J = \sum_{a=1}^{A} \mathcal{G}_a \mathbf{W}_{TR} E_a \qquad (9)$$

where $\mathcal{G}_a$ is Toeplitz matrix generated by $\boldsymbol{g}_a$ similar to $\mathcal{H}_a$.

If we partition $\mathcal{H}_a$ as $\mathcal{H}_a = \left(\mathcal{H}_{a1} \ \mathcal{H}_{a2} \ \cdots \ \mathcal{H}_{a,R}\right)$, with each subblock $\mathcal{H}_{a,i} = \left(H_{a,(i-1)T+1} \ \cdots \ H_{a,iT}\right)$ a $(TRQ-L) \times TQ$ matrix; J as $J = \begin{pmatrix} J_{11} & \cdots & J_{1,R} \\ \vdots & \ddots & \vdots \\ J_{R,1} & \cdots & J_{R,R} \end{pmatrix}$, with each subblock a $KN \times KN$ matrix; and $\mathcal{G}_a$ in the same way as $\mathcal{H}_a$, then equation (9) turns into:

$$\sum_{a=1}^{A} [\mathcal{H}_{a1} \ \cdots \ \mathcal{H}_{a,R}](I_R \otimes \mathbf{W}_T \tilde{E}_a) J = \sum_{a=1}^{A} [\mathcal{G}_{a1} \ \cdots \ \mathcal{G}_{a,R}](I_R \otimes \mathbf{W}_T \tilde{E}_a). \qquad (10)$$

lemma 2: When partitioned as above, the submatrix of $\mathcal{H}_a$ ($\mathcal{G}_a$) are independent, i.e., there does not exist a nonzero vector $\boldsymbol{\theta} = \left(\theta_1 \ \cdots \ \theta_R\right)^T$ s.t. $\theta_1 \mathcal{H}_{a1} + \theta_2 \mathcal{H}_{a2} + \cdots + \theta_R \mathcal{H}_{a,R} = 0$, nor a $TRQ \times TQ$ non-zero matrix $\Gamma = \left(\lambda_1^T \ \cdots \ \lambda_R^T\right)^T$ with each block a $TQ \times TQ$ matrix, s.t. $\mathcal{H}_{a1}\lambda_1 + \mathcal{H}_{a2}\lambda_2 + \cdots + \mathcal{H}_{a,R}\lambda_R = 0$.

Due to the Toeplitz property of $\mathcal{H}_a$ and $\mathcal{G}_a$, the full column rank of $\mathbf{W}_{TR}$, we can derive from **lemma 2** that J is a block diagonal matrix with identical diagonal blocks, i.e., J has the form

$$J = I_R \otimes \tilde{J}, \quad \tilde{J} = \begin{pmatrix} J_{11} & \cdots & J_{1K} \\ \vdots & \ddots & \vdots \\ J_{K1} & \cdots & J_{KK} \end{pmatrix}_{KN \times KN}. \qquad (11)$$

Because different STBCs incur different matrices E_a, in the following we detail our proof with Alamouti STBC and 4T4A3K OSTBC respectively.

3.2.1. Alamouti STBC

For Alamouti STBC, $T = A = K = 2$. Considering w.l.o.g. the i-th block in equation (10), we get:

$$\sum_{a=1}^{A} \mathcal{H}_{ai} \mathbf{W}_T \tilde{E}_a \tilde{J} = \sum_{a=1}^{A} \mathcal{G}_{ai} \mathbf{W}_T \tilde{E}_a.$$

Using the partition of $\mathcal{H}_{a,i}$ and $\mathcal{G}_{a,i}$, we get from above:

$$\begin{aligned} &(H_{2,2i} - H_{1,2i-1} \quad H_{2,2i-1} + H_{1,2i})(I_2 \otimes W)\tilde{J} \\ &= (G_{2,2i} - G_{1,2i-1} \quad G_{2,2i-1} + G_{1,2i})(I_2 \otimes W) \end{aligned}. \qquad (12)$$

Expand the above equation and use **lemma 2**, we have:

$$(H_{2,2i} \ \ H_{1,2i})(I_2 \otimes W)\tilde{J} = (G_{2,2i} \ \ G_{1,2i})(I_2 \otimes W) \qquad \text{(13-a)}$$

$$(-H_{1,2i-1} \ \ H_{2,2i-1})(I_2 \otimes W)\tilde{J} = (-G_{1,2i-1} \ \ G_{2,2i-1})(I_2 \otimes W). \qquad \text{(13-b)}$$

Partition the following matrices as: $W = \left(w_1 \ \ w_2 \ \cdots \ w_Q\right)^H$, $H_{a,2i} = \left(\tilde{\boldsymbol{h}}_1^a \ \ \tilde{\boldsymbol{h}}_2^a \ \cdots \ \tilde{\boldsymbol{h}}_Q^a\right)$ and $G_{a,2i} = \left(\tilde{\boldsymbol{g}}_1^a \ \ \tilde{\boldsymbol{g}}_2^a \ \cdots \ \tilde{\boldsymbol{g}}_Q^a\right)$, equation (13-a) turns into

$$\sum_{q=1}^{Q} \left(\tilde{\boldsymbol{h}}_q^2 w_q^H \quad \tilde{\boldsymbol{h}}_q^1 w_q^H\right)\tilde{J} = \sum_{q=1}^{Q} \left(\tilde{\boldsymbol{g}}_q^2 w_q^H \quad \tilde{\boldsymbol{g}}_q^1 w_q^H\right). \qquad (14)$$

Using **lemma 2**, we get:

$$\left(\tilde{\boldsymbol{h}}_q^2 w_q^H \quad \tilde{\boldsymbol{h}}_q^1 w_q^H\right)\tilde{J} = \left(\tilde{\boldsymbol{g}}_q^2 w_q^H \quad \tilde{\boldsymbol{g}}_q^1 w_q^H\right), \quad q = 1,\ldots,Q. \qquad (15)$$

Because $\tilde{\boldsymbol{h}}_q^a$ and $\tilde{\boldsymbol{g}}_q^a$ are all $(TRQ-L) \times 1$ vectors, with nonzero parts $\left(h_0^a \ \ h_1^a \ \cdots \ h_L^a\right)^T$ and $\left(g_0^a \ \ g_1^a \ \cdots \ g_L^a\right)^T$ respectively, we have from equation (15) that

$$\left(h_l^2 w_q^H \quad h_l^1 w_q^H\right)\tilde{J} = \left(g_l^2 w_q^H \quad g_l^1 w_q^H\right), \quad \begin{matrix} l = 0,\ldots,L \\ q = 1,\ldots,Q \end{matrix}. \qquad (16)$$

Expanding equation (16), we get:

$$\begin{aligned} w_q^H (h_l^2 J_{11} + h_l^1 J_{21}) &= g_l^2 w_q^H \\ w_q^H (h_l^2 J_{12} + h_l^1 J_{22}) &= g_l^1 w_q^H \end{aligned}, \quad l = 0,\ldots,L;\ q = 1,\ldots,Q. \qquad (17)$$

For fixed l, take all the q=1,…,Q into consideration and notice that W is full column rank, we finally get:

$$(h_l^2 J_{11} + h_l^1 J_{21}) = g_l^2 I; \ \ (h_l^2 J_{12} + h_l^1 J_{22}) = g_l^1 I, \quad l = 0,\ldots,L. \qquad (18)$$

From assumption (A4) and the knowledge of matrix theory, we can further determine that J_{11}, J_{12}, J_{21} and J_{22} are all diagonal matrix. We denote them as:

$$J_{11} = \alpha I, \quad J_{21} = \beta I, \quad J_{12} = \kappa I, \quad J_{22} = \gamma I. \qquad (19)$$

Similarly, we can get from equation (13-b) that

$$(-h_l^1 J_{11} + h_l^2 J_{21}) = -g_l^1 I; \ \ (-h_l^1 J_{12} + h_l^2 J_{22}) = g_l^2 I, \ \ l = 0,1,\ldots,L. \qquad (20)$$

Inserting equation (19) into equation (18) and (20), we get after simplifying that

$$\alpha = \gamma\ , \quad \beta = -\kappa\ . \tag{21}$$

So from equation (19), (21), (13-a) and using the Toeplitz property of channel matrix, we eventually arrive at:

$$\begin{aligned} \boldsymbol{g}^T &\triangleq (\boldsymbol{g}_1^T\ \boldsymbol{g}_2^T) = \left(\beta \boldsymbol{h}_2^T + \alpha \boldsymbol{h}_1^T \quad \alpha \boldsymbol{h}_2^T - \beta \boldsymbol{h}_1^T\right) \\ &= \alpha\left(\boldsymbol{h}_1^T \quad \boldsymbol{h}_2^T\right) + \beta\left(\boldsymbol{h}_2^T \quad -\boldsymbol{h}_1^T\right) \end{aligned} . \tag{22}$$

Because $\left(\boldsymbol{h}_1^T \quad \boldsymbol{h}_2^T\right)$ and $\left(\boldsymbol{h}_2^T \quad -\boldsymbol{h}_1^T\right)$ are independent, the estimated composite channel vector has two scalar ambiguities. So the matrix B looses rank by 2.

3.2.2. 4T4A3K OSTBC

Using the similar method, we can prove the identifiability of a 4T4A3K OSTBC system. Some results are as follows:

$$\tilde{J} = \alpha I_{KN} = \alpha I_{3N}\ , \tag{23}$$

$$\boldsymbol{g}^T \triangleq (\boldsymbol{g}_1^T \quad \boldsymbol{g}_2^T \quad \boldsymbol{g}_3^T \quad \boldsymbol{g}_4^T) = \alpha(\boldsymbol{h}_1^T \quad \boldsymbol{h}_2^T \quad \boldsymbol{h}_3^T \quad \boldsymbol{h}_4^T)\ . \tag{24}$$

So the estimated composite channel vector has only one scalar ambiguity and matrix B looses rank by 1.

4. SIMULATIONS

In this section, simulations are done with time invariant Rayleigh fading channels. The system parameters are set as: number of subcarriers is 32, length of CP is 4, user information sequences are BPSK modulated. We use normalized root mean squared error (NRMSE) as estimation criteria, which is defined as

$$NRMSE = \frac{1}{\|h\|}\sqrt{\frac{1}{D(L+1)}\sum_{i=1}^{D}(\|\hat{h}^{(i)} - h\|^2)}\ , \tag{25}$$

where D is Monte Carlo tries, which is set to 50 in this paper. The ambiguity of the estimation is eliminated before calculating the NRMSE.

Fig. 1 gives channel estimation error (CEE) performances w.r.t. signal to noise ratio (SNR) and data length when Alamouti STBC is selected. The smooth window parameter R is set to 2. Fig. 2 displays CEE performance when 4T4A3K OSTBC is used with R set to 1. From these figures we can see that with 400 or more data points, CSI can be estimated to a relatively flat platform. Besides, we can see that CEE performance of 4T4A3K OSTBC system is relatively better than that of Alamouti STBC system, which is caused by surplus redundancy induced by the former.

5. CONCLUSIONS

In this paper, we propose a channel estimation algorithm for space-time coded OFDM system and prove that the estimated CSI contains only two (for Alamouti STBC) or one (for 4T4A3K OSTBC) scalar ambiguities. The algorithm needs neither precoding nor oversampling, and thus promotes system data rate and lowers complexity. Simulations show that this method has high estimation precision. For a system with multiple receive antennae, the channels from all transmitting antennae to each receiving antenna can be estimated independently. So the algorithm can be easily extended to MIMO case.

6. REFERENCES

[1] S.M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, pp.1451-1458, Oct. 1998.

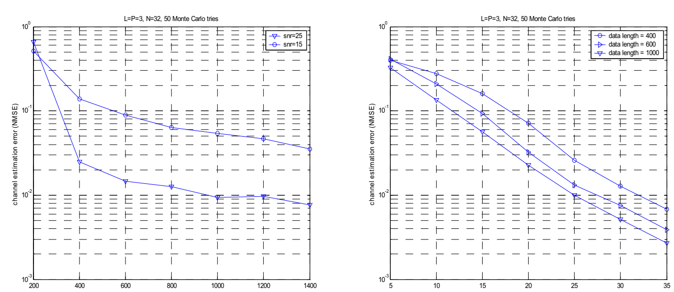
[2] Shengli Zhou, Bertrand Muquet, and Georgios B. Giannakis, "Subspace-based (semi-) blind channel estimation for block precoded space-time OFDM," *IEEE Trans. Signal Processing*, vol.50, pp.1215-1228, May 2002.

[3] Anna Scaglione, and Georgios B. Giannakis, "Redundant filterbank precoders and equalizers Part I and Part II," *IEEE Trans. Signal Processing*, vol.47, pp.1988-2022, Jul. 1999.

[4] W.Bai, C. He, L. Jiang, and H. Zhu, "Blind channel estimation in MIMO-OFDM systems," *Proc. GLOBECOM*, vol.1, pp.317-321, Nov. 2002.

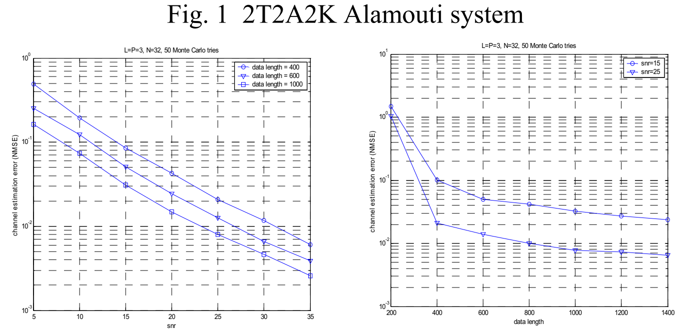
[5] Changyong Shin, and Edward J.Powers, "Blind channel estimation for MIMO-OFDM systems using virtual carriers," *Proc. GLOBECOM*, vol.4, pp.2465-2469, Nov. 2004.

[6] Zhiguo Ding, and Darren B.Ward, "Subspace approach to blind and semi-blind channel estimation for space-time block codes," *IEEE Trans. Wireless Communications*, vol.4, pp.357-362, Mar. 2005.



(a) CEE vs. SNR (b) CEE vs. data length

Fig. 1 2T2A2K Alamouti system



(a) CEE vs. SNR (b) CEE vs. data length

Fig.2 4T4A3K OSTBC system