Low Complexity Ordered Successive Cancellation Algorithm for Multi-user STBC Systems

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ABSTRACT

This paper proposes two detection algorithms for Multi-user Space Time Block Code systems. The first one is linear detection Gaussian Elimination algorithm, and then it combined with Ordered Successive Cancellation to get better performance. The comparisons between receiver and other popular receivers, including linear receivers are provided. It will be shown that the performance of Gaussian Elimination receiver is similar but more simplicity than linear detection algorithms and performance of Gaussian Elimination Ordered Successive Cancellation superior as compared to other linear detection method.

Key Words : Multiuser Systems, Multiple Antenna Systems, Space-Time Block Code, Gaussian Elimination, Ordered Successive Cancelation

Ⅰ. Introduction

Next generation of wireless mobile communication needs reliable transmission of high rate data under potentially difficult environment. Multiple Input Multiple Output system (MIMO) is a technology which uses multiple transmit and/or multiple receive antennas in order to increase channel capacity in wireless systems.

Coding is one of key elements to successful implementation of a MIMO system. Space-time block coding is a simple but ingenious transmit diversity technique in MIMO technology. Space Time Block Code (STBC) [1] involves block encoding an incoming stream of data and simultaneously transmitting the symbols over transmit antennas. STBC can achieve full diversity gain, high rate and spectra efficiency with simple linear receiver.

In order to improve performance, capacity without taking more bandwidth, we consider a group of STBC systems called Multi-user STBC system, which is shown in Fig.1. Such systems have M co-channel users; each user has K antennas and the receiver has N receive antennas. The users can transmit simultaneously and independently space-time block coded data streams over the co-channels to the receiver.

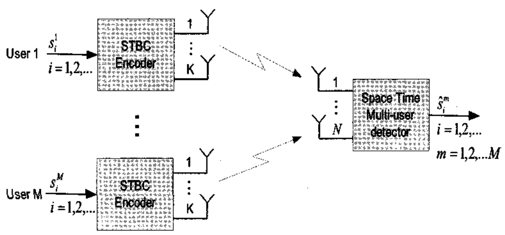

Fig. 1. Mutiuser systems with M users using space time block codes

For a STBC system, Maximum Likelihood detector is an optimum detector, in term of performance. But its complexity increases exponentially with the number of transmit antennas and the symbol alphabet size. Two generalized detection algorithms, Gaussian Elimination (GE)

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and Gaussian Elimination Ordered Successive Cancellation (GEOSUC) can achieve low-complexity by using the algebraic properties of the STBC systems.

The paper is organized as follows. In section II we review a Multi-user STBC System Model that provide in [2] for G2/G3/G4 STBC systems (refer [3] for more details). Two special properties of multi-user STBC equivalent channel matrices will be describe in section III. Section IV proposes two low complexity detection algorithms for multi-user STBC systems. Simulation results are shown in section V. Finally, section VI presents conclusions and final comments.

In the paper, vectors are represented with lower-case boldface letters and matrices upper-case boldface letters; $(\bullet)^*, (\bullet)^T, (\bullet)^H, (\bullet)^{-1}$ denotes complex conjugate, transpose matrix, conjugate transpose matrix and inverse matrix respectively. I_k denotes an identity matrix size k.

II. Multi-user STBC system Model

To build a multi-user STBC system model for the system shown in Fig.1, let us first consider a single MIMO system created by the m^{th} user $(m=1,2,...,M)$ and the receiver.

The N dimensional received vector $\boldsymbol{r}_m = [r_1, r_2, ..., r_N]^T$ at each time interval can be modeled as:

$$\boldsymbol{r}_m = \boldsymbol{H}_m \boldsymbol{s}_m + \boldsymbol{n}_m \tag{1}$$

where $\boldsymbol{s}_m = [s_1, s_2, ..., s_K]^T$, $\boldsymbol{n}_m = [n_1, n_2, ..., n_N]^T$ and $\boldsymbol{H}_m$ are the transmitted signal vector, the additive white Gaussian noise (AWGN) vector, the co-channel matrix, respectively. Assuming $\boldsymbol{H}_m$ is constant during some blocks of codeword, it can be written as:

$$\boldsymbol{H}_m = \begin{bmatrix} h_{1,1}^m & h_{1,2}^m & \cdots & h_{1,K}^m \\ h_{2,1}^m & h_{2,2}^m & \cdots & h_{2,K}^m \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,1}^m & h_{N,2}^m & \cdots & h_{N,K}^m \end{bmatrix} \tag{2}$$

An STBC transmitted codeword is a $P \times K$ orthogonal matrix with elements $\pm s_1, \pm s_2, ..., \pm s_K$ and their conjugates $\pm s_1^*, \pm s_2^*, ..., \pm s_K^*$. Here P is the number of slots that used to transmit a codeword, and in each slot, K symbols are transmitted through K transmit antennas simultaneously. An example of a complex orthogonal design (also called Alamouti STBC) is given by [3]:

$$G_2 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{3}$$

This is the smallest complex orthogonal design STBC. Because the rate of STBC codes is defined $R = K/P$ so with G_2 we have $R = 1$.

Let consider the a STBC system which has two transmit antennas ($K=2$). Assume that AWGN vector at the receiver is independent and the MIMO channels among all transmitter-receiver antenna pairs are flat Rayleigh fading and it is constant during a STBC codeword transmission period but varies from one period to another. With the input symbols is G_2 the received signal at the i^{th} receive antenna can be written as [2]:

$$[r_i(1) \;\; r_i(2)] = [h_{i,1}(1) \;\; h_{i,2}(2)]\, \boldsymbol{G}_2^T + [n_i(1) \;\; n_i(2)] \tag{4}$$

where $h_{i,j}$ is the channel gain between the i^{th} receive antenna and the j^{th} transmit antenna; $r_i(t)$ and $n_i(t)$ $(t=1,2)$ are receive signal and noise during time slot t. After some simple transformation we can rewrite (4) into a different form as follows:

$$\boldsymbol{r}_{G2} = \boldsymbol{H}_{G2}\boldsymbol{s} + \boldsymbol{n}_{G2} \tag{5}$$

where $\boldsymbol{r}_{G2} = [r_i(1) \;\; -r_i(2)^*]^T$, $\boldsymbol{n}_{G2} = [n_i(1) \;\; -n_i(2)]^T$, $\boldsymbol{s} = [s_1 \;\; s_2]^T$ (input symbols vector before coding) and

$$\boldsymbol{H}_{G2} = \begin{bmatrix} h_1 & h_2 \\ -h_2^* & h_1^* \end{bmatrix} \tag{6}$$

Equation (5) is STBC system model of two transmit antennas system; r_{G2}, H_{G2}, n_{G2} are STBC equivalent received vector, STBC equivalent channel matrix, STBC equivalent noise vector, respectively. Xun Fan et al. proposed STBC equivalent channel matrices for three and four transmit antennas [2] are shown in (7).

Now we consider the multi-user system that has M users, each user with K transmit antennas and the receiver has N antennas like Fig.1. Denote the STBC equivalent channel matrix between the m^{th} user and the i^{th} receive antenna is $H_{GK}^{i,m}$ (where $GK = G2/G3/G4$). Denotes STBC equivalent channel matrix between the m^{th} user and receiver is $\overline{H_m}$. So $\overline{H_m}$ can be expressed as.

$$\overline{H_m} = \begin{bmatrix} H_{GK}^{1,m} \\ H_{GK}^{2,m} \\ \vdots \\ H_{GK}^{N,m} \end{bmatrix} \quad (8)$$

With a multi-user STBC system that has M users, the equivalent channel matrix is created by combine of all equivalent channel matrices of single users.

$$\overline{H} = [\overline{H_1}\ \overline{H_2} \cdots \overline{H_M}] \quad (9)$$

Finally, we obtain the multi-user STBC system model as (10) where s_m, $\overline{r}_i$, $\overline{n}_i$ are the transmitted signal vector (precoding) of the m^{th} user, STBC equivalent received vector at i^{th} receive antenna and STBC equivalent noise vector at i^{th} receive antenna, respectively. Equation (10) can be rewritten in a short form as follows.

$$\overline{r} = \overline{H}s + \overline{n} \quad (11)$$

where $\overline{r}$, $\overline{H}$, s and $\overline{n}$ are multi-user STBC equivalent received vector, multi-user STBC equivalent channel, multi-user STBC transmit symbols vector (precoding), multi-user STBC equivalent noise, respectively.

$$H_{G3} = \begin{bmatrix} h_1 & h_2 & h_3 & 0 \\ h_2 & -h_1 & 0 & -h_3 \\ h_3 & 0 & -h_1 & h_2 \\ 0 & h_3 & -h_2 & -h_1 \\ h_1^* & h_2^* & h_3^* & 0 \\ h_2^* & -h_1^* & 0 & -h_3^* \\ h_3^* & 0 & -h_1^* & h_2^* \\ 0 & h_3^* & -h_2^* & -h_1^* \end{bmatrix} \text{ for } K=3 \text{ and } H_{G4} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2 & -h_1 & h_4 & -h_3 \\ h_3 & -h_4 & -h_1 & h_2 \\ h_4 & h_3 & -h_2 & -h_1 \\ h_1^* & h_2^* & h_3^* & h_4^* \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3^* & -h_4^* & -h_1^* & h_2^* \\ h_4^* & h_3^* & -h_2^* & -h_1^* \end{bmatrix} \text{ for } K=4 \quad (7)$$

$$\underbrace{\begin{bmatrix} \overline{\mathbf{r}}_1 \\ \overline{\mathbf{r}}_2 \\ \vdots \\ \overline{\mathbf{r}}_N \end{bmatrix}}_{PN\times1} = \underbrace{\begin{bmatrix} \mathbf{H}_{GK}^{1,1} & \mathbf{H}_{GK}^{1,2} & \cdots & \mathbf{H}_{GK}^{1,M} \\ \mathbf{H}_{GK}^{2,1} & \mathbf{H}_{GK}^{2,2} & \cdots & \mathbf{H}_{GK}^{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_{GK}^{N,1} & \mathbf{H}_{GK}^{N,2} & \cdots & \mathbf{H}_{GK}^{N,M} \end{bmatrix}}_{PN\times KM} \underbrace{\begin{bmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \\ \vdots \\ \mathbf{s}_M \end{bmatrix}}_{KM\times1} + \underbrace{\begin{bmatrix} \overline{\mathbf{n}}_1 \\ \overline{\mathbf{n}}_2 \\ \vdots \\ \overline{\mathbf{n}}_N \end{bmatrix}}_{PN\times1} \quad (10)$$

$$\overline{\mathbf{H}}_m^H \overline{\mathbf{H}}_m = \left(\left| h_{1,1}^m \right|^2 + \left| h_{1,2}^m \right|^2 + \cdots + \left| h_{i,j}^m \right|^2 + \cdots + \left| h_{N,K}^m \right|^2 \right) \mathbf{I}_K \quad (12)$$

Ⅲ. Properties of multi-user STBC equivalent channel matrices

This section presents two special characteristic of the single user STBC equivalent channel matrix .

Firstly, because $\overline{H}_m$ is an orthogonal matrix we have (12). Denotes

$$\alpha_m = (|h_{1,1}^m|^2 + |h_{1,2}^m|^2 + \cdots + |h_{i,j}^m|^2 + \cdots |h_{N,K}^m|^2)$$

where $h_{i,j}^m$ is the channel gain between the i^{th} receive antenna and the j^{th} transmit antenna of user m^{th}. We can express $\overline{H}_m^H \overline{H}_m$ as:

$$\overline{H}_m^H \overline{H}_m = \alpha_m I_K \tag{13}$$

Here α_m is real number and $\alpha_m > 0$. Denotes and $X_{i,j} = \overline{H}_i^H \overline{H}_j$ and $X = \overline{H}^H \overline{H}$ so X is a $MK \times MK$ matrix which is composed bye a set of $K \times K$ matrices. All elements in diagonal of X have form like (12). X can be written as.

$$\mathbf{X} = \mathbf{H}^H \mathbf{H} = \begin{bmatrix} \alpha_1 \mathbf{I}_K & \mathbf{X}_{1,2} & \cdots & \mathbf{X}_{1,M} \\ \mathbf{X}_{2,1} & \alpha_2 \mathbf{I}_K & \cdots & \mathbf{X}_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{X}_{M,1} & \mathbf{X}_{M,2} & \cdots & \alpha_M \mathbf{I}_K \end{bmatrix} \tag{14}$$

Secondly, the value of α_m proportion to SNR in term of detected block symbols which means the bigger α_m the higher SNR. In the next section, we will implement two algorithms by using the characteristics of the equivalent channel.

Ⅳ. Detection algorithms

4.1 Common ZF and MMSE Detection Algorithms

This subsection reviews two well known Linear Detection algorithms are Zero-Forcing (ZF) and minimum mean square error (MMSE). In ZF and MMSE detectors, symbols can be detected by multiplying the received signal vector with matrices given by.

$$\tilde{\mathbf{H}}_{ZF} = (\overline{\mathbf{H}}^H \overline{\mathbf{H}})^{-1} \overline{\mathbf{H}}^H = (\mathbf{X})^{-1} \overline{\mathbf{H}}^H$$
$$\tilde{\mathbf{H}}_{MMSE} = (\overline{\mathbf{H}}^H \overline{\mathbf{H}} + \sigma^2 \mathbf{I}_{MK})^{-1} \overline{\mathbf{H}}^H = (\mathbf{X} + \sigma^2 \mathbf{I}_{MK})^{-1} \overline{\mathbf{H}}^H \tag{15}$$

where σ^2 is noise variance. Calculation inverse matrix of a $MK \times MK$ matrix will cost $O((MK)^3)$ operations [4]. The big O notation denotes the time complexity of a problem. It is the number of steps that it takes to solve a problem as a function of the size of the input (usually measured in bits). In this case $O((MK)^3)$ means we need $(MK)^3$ steps to calculate the inverse matrix of matrix X. If we divide X into block of smaller matrices we can reduce the computational complexity significantly. Next subsection will present Gaussian Elimination (GE) [4] that can use to reduce the computational at receiver.

4.2 Gaussian Elimination algorithm

By denoting $Y_m = \overline{H}_m^H \overline{r}$ and $Y = \overline{H}^H \overline{r}$, we have:

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \\ \vdots \\ \mathbf{Y}_M \end{bmatrix} \tag{16}$$

Using ZF, the detected symbols can be detected by this equation

$$\hat{\mathbf{s}} = (\overline{\mathbf{H}}^H \overline{\mathbf{H}})^{-1} \overline{\mathbf{H}}^H \overline{\mathbf{r}}$$

or

$$\hat{\mathbf{s}} = \mathbf{X}^{-1} \overline{\mathbf{H}}^H \overline{\mathbf{r}}.$$

So we can transform it to following equation.

$$\mathbf{X}\hat{\mathbf{s}} = \mathbf{Y} \tag{17}$$

Solving the equation we will find out the detected symbols $\hat{s}$. To solve this equation we use GE. GE performs elementary row operations to put the augmented matrix $[\mathbf{X}|\mathbf{Y}]$ into upper triangular form as below:

$$\begin{bmatrix} \mathbf{X}_{1,1} & \mathbf{X}_{1,2} & \cdots & \mathbf{X}_{1,M} & \mathbf{Y}_1 \\ 0 & \mathbf{X}'_{2,2} & \cdots & \mathbf{X}'_{2,M} & \mathbf{Y}'_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \mathbf{X}'_{M,M} & \mathbf{Y}'_M \end{bmatrix} \quad (18)$$

Then roots of the equation will be calculated as follow:

$$\hat{s}_m = \frac{1}{\mathbf{X}'_{m,m}}\left(\mathbf{Y}'_m - \sum_{i=m+1}^{M} \mathbf{X}'_{m,i}\mathbf{s}_i\right) \quad (19)$$

Tab. 1 presents Gaussian Elimination algorithm which is used for solving equation (17). From (1-1) to (1-8) are elementary row operations and from (1-9) to (1-15) are calculating $\hat{s}_m$ successively.

Table. 1 Gaussian elimination algorithm

INPUT: $\mathbf{X}$, $\mathbf{Y}$
OUTPUT: $\hat{\mathbf{s}}$
(1-1) for $k = 1 : M-1$ // transform time
(1-2) for $i = k+1 : M$ // row index
(1-3) $\mathbf{Y}_i = \mathbf{Y}_i - \mathbf{Y}_k \mathbf{X}_{i,k} / \mathbf{X}_{k,k}$
(1-4) for $j = k+1 : M$ // column index
(1-5) $\mathbf{X}_{i,j} = \mathbf{X}_{i,j} - \mathbf{X}_{i,j} \mathbf{X}_{k,j} / \mathbf{X}_{k,k}$
(1-6) end
(1-7) end
(1-8) end
(1-9) $\hat{\mathbf{s}}_M = \mathbf{Y}_M / \mathbf{X}_{M,M}$
(1-10) for $i = M-1 : 1$
(1-11) $\hat{\mathbf{s}}_i = \mathbf{Y}_i / \mathbf{X}_{i,i}$
(1-12) for $j = i+1 : M$
(1-13) $\hat{\mathbf{s}}_i = \mathbf{s}_i - 1/\mathbf{X}_{i,i}(\mathbf{X}_{i,j}\mathbf{s}_j)$
(1-14) end
(1-15) end

The complexity of the Gaussian Elimination algorithm for a $n \times n$ matrix is $O(n(n-1)/2)$ and instead of calculating the inverse matrix of the $MK \times MK$ matrix, we only need calculate the inversion of the $K \times K$ matrices, and then the complexity of our Gaussian Elimination is $O(K^3 M(M-1)/2)$ per codeword interval. In case of MMSE, we use $(X + \sigma^2 I_{MK})$ instead of X

4.3 Gaussian Elimination Ordered Successive Cancellation Algorithm

The Ordered Successive Cancellation (OSUC) such as V-BLAST [5] has gained a lot of popularity because of its simplicity. This algorithm includes four main operations: ordering, nulling, slicing and updating [6],[7].

In Tab. 2 we present an Ordered Successive Cancellation algorithm that uses the special characteristic of multi-user equivalent channel and row operations are performed by Gaussian Elimination. So that we call the algorithm is Gaussian Elimination Ordered Successive Cancellation (GEOSUC) algorithm. Before using Gaussian Elimination, from (2-1) to (2-8) rows of matrix will be sorted into the ascending order of α_m. This process is implemented by bubble sort algorithm, which has complexity $O(M^2)$ in the worst case. And swapping rows process of matrix X in (2-4) and (2-5) will cost M^2 operations. From (2-9) to (2-16) are Gaussian Elimination process and from (2-16) to (2-25) are updating and slicing process. In (2-24), $Q(\bullet)$ is quantization function that slide detected signals to the nearest constellations. The complexity of GEOSUC (not include slicing process) is a sum of complexity of GE algorithm and ordering process. Hence the complexity of GEOSUC algorithm is $O(2M^2 + K^3 M(M-1)/2)$.

V. Simulation Results

In this section, simulation results are provided to demonstrate the performance of our two proposed algorithms. All the simulations use QPSK input symbols. Channel is flat Rayleigh fading and the receiver has 4 antennas. Assume that the channel is known at the receiver perfectly. The

Linear Detection (LD) algorithm using in the simulations is Zero Forcing.

Table. 2 Gaussian elimination Ordered Successive Cancellation Algorithm GEOSUC

```
INPUT: X, Y, α
OUTPUT: s̄
(2-1)  for i = 1 : M-1
(2-2)     for j = 1 : i
(2-3)        if α(j-1) > α(j)
(2-4)           swap α(j-1) and α(j)
(2-5)           swap X(j-1,:) and X(j,:)
(2-6)        end
(2-7)     end
(2-8)  end
(2-9)  for k = 1 : M-1            // transform time
(2-10)    for i = k+1 : M         // row index
(2-11)       Y_i = Y_i - Y_k X_{i,k} / X_{k,k}
(2-12)       for j = k+1 : M      // column index
(2-13)          X_{i,j} = X_{i,j} - X_{i,j} X_{k,j} / X_{k,k}
(2-14)       end
(2-15)    end
(2-16) end
(2-17) ŝ_M = Y_M / X_{M,M}
(2-18) s̄_M = Q(ŝ_M)
(2-19) for i = M-1 : 1
(2-20)    ŝ_i = Y_i / X_{i,i}
(2-21)    for j = i+1 : M
(2-22)       ŝ_i = s_i - 1/X_{i,i}(X_{i,j} s_j)
(2-23)    end
(2-25) end
```

Fig.2 shows the complexity comparison of three detection algorithms, linear detection, GE and GEOSUC with K=2. GE is the most simplicity algorithm and follows by GEOSUC and Linear Detection algorithm. When the number of users increases we can see the complexity of Linear Detection algorithm much more than GE and GEOSUC.

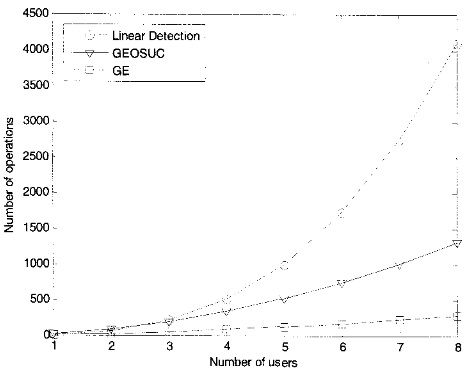

Fig. 2. Complexity comparison of Linear Detection, GE and GEOSUC algorithms

Fig.3 shows the performance of three multi-user STBC systems, which have one, two and three users and two transmit antennas each user. The figure shows that performance of GEOSUC is litter better than GE. LD 2 users and GE 2 users are overlap due to they has same performance. However, GE complexity is much lower than ZF.

In case 1 user, all algorithms have same performance.

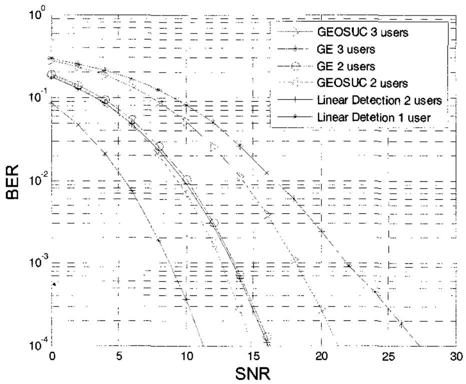

Fig. 3. BER of multi-user STBC systems with 2 transmit antennas users

Ⅵ. Conclusion

We have proposed GE and GEOSUC, two low complexity detection algorithms for Multi-user STBC systems. By dividing the channel into blocks of smaller matrices and exploiting the special characteristics of the STBC equivalent channel, we develop low complexity and better performance algorithms.

The complexity of GE and GEOSUC are better than linear detection ZF and MMSE, which have complexity . The more number of users the lower of complexity we get. The simulation also shows that the performance of GEOSUC outperforms the linear detection.

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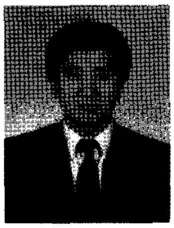

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