Linear Dispersion code from Non-Abelian Group

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ABSTRACT

One of the criteria for designing good LD-STBC is maximizing the mutual information between the transmit and receive signals. In this paper, we propose a construction method of $2^k \times 2^k$ LD-STBC by selecting the dispersion matrices among the representations of the non-abelian group $G_{m,r}$ of order 2^{k+2}.

Key Words : LD-STBC, non-abelian group, group representation, information-losseless

Ⅰ. Introduction

Space-time coding is the scheme that provides both diversity gain and coding gain by 0transmitting signals over Rayleigh fading channels using multiple antennas[11]. In [7], Alamouti introduced a simple code to provide full diversity for two transmit antennas. The scheme has been generalized by Tarokh, *et al.* [8] using the theory of orthogonal designs. But these codes generally show poor performance at high rates or with many antennas.

To maximize the multiple-antenna channel capacity, LD-STBCs(Linear-Dispersion Space-Time Block Codes) are proposed as a high-rate coding scheme for any number of transmit and receive antennas by Hassibi, *et al.*[1][2]. The transmitted codeword of LD codes is a matrix in which all transmitted symbols are dispersed by the dispersion matrices(or weight matrices). The LD codes can be used for any number of transmit and receive antennas and are very simple to encode. Furthermore the LD codes can be decoded in a variety of ways including simple linear-algebraic techniques such as successive nulling and canceling and sphere decoding. And the codes satisfy an information-theoretic optimality criterion[1]. In other word, the codes are designed to maximize the mutual information between the transmit and receive signals. In [1] and [2], designing capacity-maximizing LD STBC were resorted to computer search. In [10], a code design scheme using Dihedral group representation is proposed. In [3], such codes are constructed using division algebra. In this paper, we propose a construction by restricting the dispersion matrices to those which form a non-abelian class of groups under matrix multiplication [6]. Our scheme includes the codes proposed by [10] as a special case when the number of transmit antenna is 2.

The paper is organized as follows. In Section Ⅱ, the system model are described and LD codes are reviewed. The group representations are discussed in Section Ⅲ. In Section Ⅳ, we propose a code design and the computer simulation result and conclusion are drawn in Section Ⅴ.

Ⅱ. System Model with Linear Dispersion Code

In this Section, we briefly review the MIMO

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논문번호 : KICS2007-06-258, 접수일자 : 2007년 6월 10일, 최종논문접수일자 : 2008년 1월 14일

system considered in this paper along with a description of the channel. Then we review the linear dispersion code description of linear space time codes[1].

2.1 Signal Model

Consider a MIMO System with M transmit antennas and N receive antennas in a flat fading channel. Let $s \in \mathbb{C}^M$ denote the vector of complex transmitted signals and $x \in \mathbb{C}^N$ denote the vector of complex received signals during any given channel use (i.e, frame length). The transmitted and received signals are related by

$$x = \sqrt{\frac{\rho}{M}} Hs + v \qquad (1)$$

where ρ is the signal to noise ratio at each receive antenna, $H \in \mathbb{C}^{N \times M}$ is the channel matrix and $v \in \mathbb{C}^N$ is the additive noise. Entries in the channel matrix H and additive noise v are assumed to be independent and identically distributed Gaussian random variables with zero mean and unit variance.

2.2 Linear Dispersion Codes

Assume that $s_1, \cdots, s_Q$ are complex symbols with unit average energy over T symbol intervals, typically chosen from r-PSK or r-QAM constellation. Linear Dispersion signal matrix $\boldsymbol{S}$ is defined as [1]

$$\boldsymbol{S} = \sum_{q=1}^{Q} \alpha_q \boldsymbol{A}_q + j\beta_q \boldsymbol{B}_q \qquad (2)$$

where $s_q = \alpha_q + j\beta_q$, $q = 1, \cdots, Q$ and the $M \times T$ complex matrices $\boldsymbol{A}_q$ and $\boldsymbol{B}_q$ are called the dispersion matrices or weight matrices. The rate R of this code is $R = \frac{Q \log_2 r}{T}$.

In this paper, we are considering a subclass of LD codes in which $\boldsymbol{A}_q = \boldsymbol{B}_q$, for $q = 1, \cdots, Q$. Such LD-STBCs have been considered in [2] and [10] also.

Over successive T channel uses, (1) can be written in matrix equation form as

$$\boldsymbol{X} = \sqrt{\frac{\rho}{M}} H\boldsymbol{S} + \boldsymbol{V} \qquad (3)$$

$$= \sqrt{\frac{\rho}{M}} H \sum_{q=1}^{Q} s_q \boldsymbol{A}_q + \boldsymbol{V} \qquad (4)$$

where $\boldsymbol{S}$ is an $M \times T$ space time codeword, $\boldsymbol{V}$ is an $N \times T$ complex additive Gaussian noise matrix and $\boldsymbol{X} \in \mathbb{C}^{N \times T}$ is the received signal matrix.

We can write (4) in an equivalent vector notation.

$$vec(\boldsymbol{X}) = \sqrt{\frac{\rho}{M}} \boldsymbol{H} \Phi [s_1\ s_2 \cdots\ s_Q]^T + vec(\boldsymbol{V}) \qquad (5)$$

where $vec(\boldsymbol{X})$ is the $NT \times 1$ matrix obtained by stacking all columns of $\boldsymbol{X}$, $\boldsymbol{H} = diag(H, H, \cdots H)$ is an $NT \times MT$ block diagonal matrix, and $\Phi = [vec(\boldsymbol{A}_1)\ vec(\boldsymbol{A}_2) \cdots vec(\boldsymbol{A}_Q)]$ is an $MT \times Q$ matrix.

2.3 Design Criterion

Hassibi and Hochwald [1] suggested that the guideline for designing good STBC should be rather maximizing the mutual information between the transmit and receive signals than the well-known rank-determinant criteria which stem from the pairwise error probability point of view [8][12].

In [10], the maximum mutual information between the transmitted signal vector $[s_1, s_1, \cdots, s_Q]^T$ and the received vector $vec(\boldsymbol{X})$ is given by

$$C_{LDC}(\rho, M, N) = \frac{1}{T} E_{\boldsymbol{H}} \log_2 \left(\det \left(I_{NT} + \frac{\rho}{M} \boldsymbol{H} \Phi \Phi^{\dagger} \boldsymbol{H}^{\dagger} \right) \right) \qquad (6)$$

It is also shown in [10] that

$$C_{LDC}(\rho, M, N) \leq C(\rho, M, N),$$

where $C(\rho, M, N) = E_{\boldsymbol{H}} \log_2 \left(\det \left(I_N + \frac{\rho}{M} \boldsymbol{H} \boldsymbol{H}^{\dagger} \right) \right)$ is the capacity of the channel depicted in Fig.1.

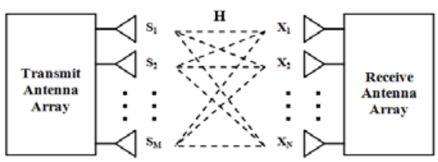

Fig. 1 A flat fading channel with multiple antennas

Definition([10]): If $C_{LDC}(\rho,M,N)=C(\rho,M,N)$ then the space-time block code is said to be information-lossless.

When $Q \geq MT$, if $\Phi\Phi^{\dagger}=\mathrm{I}_{\mathrm{MT}}$ then $C_{LDC}(\rho,M,N)=C(\rho,M,N)$ holds. Moreover, when $Q=MT$ this condition is equivalent to $tr(\boldsymbol{A}_i\boldsymbol{A}_j^{\dagger})=\delta_{ij}$, where $\delta_{ij}=1$ if $i=j$ and 0 otherwise [10].

In this paper, we are utilizing group representations to construct the weight matrices satisfying $\Phi\Phi^{\dagger}=\mathrm{I}_{MT}$.

Ⅲ. Representations of Non-Abelian Group, $G_{m,r}$

Designing LD codes is in fact the design of weight matrices. Here we propose a design scheme to construct weight matrices using non- abelian group $G_{m,r}$.

The group $G_{m,r}$ is defined as follows :

$$G_{m,r}=\langle \sigma,\tau \mid \sigma^m=1,\ \tau^n=\sigma^t,\ \tau\sigma\tau^{-1}=\sigma^r \rangle,$$

where n is the order of r modulo m and $t=m/\gcd(r-1,m)$. The group $G_{m,r}$ has order mn.

When m is odd and $\gcd(n,t)=1$, $G_{m,r}$ becomes a fixed-point free group, i.e., the group whose representations do not have eigenvalue 1. The rank criterion tells us that if the unitary representations of a group are used as STBC codewords, then the group must be fixed-point -free for the full diversity gain. The fixed-point -free group $G_{m,r}$ is well studied in [6]. In this paper, we utilize the group $G_{m,r}$ for the design of weight matrices, and we are considering the case when $m=2^k$ only. In this case, the group is no more fixed-point-free.

Let ρ be an irreducible representation of the normal subgroup $H=\langle\sigma\rangle$ and the irreducible representation $G_{m,r}$ on H be denoted by $\triangle$. Then the representations of σ and τ are derived in [6] as

$$\triangle(\sigma)=\begin{bmatrix}\rho(\sigma) & 0 & \cdots & 0\\ 0 & \rho(\sigma)^r & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & \rho(\sigma)^{r^{n-1}}\end{bmatrix} \qquad (7)$$

and

$$\triangle(\tau)=\begin{bmatrix}0 & 1 & 0 & \cdots & 0\\ 0 & 0 & 1 & \cdots & 0\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & 0 & \cdots & 1\\ \rho(\sigma)^t & 0 & 0 & \cdots & 0\end{bmatrix} \qquad (8)$$

Note that ρ is an irreducible representation of the cyclic subgroup H, and $\rho(\sigma)=w$ where w is a primitive m-th root of unity.

Ⅳ. Code Design

As mentioned in section Ⅱ, when $Q \geq MT$, $C_{STBC}(\rho,M,N)=C(\rho,M,N)$ if $\Phi\Phi^{\dagger}=\mathrm{I}_{MT}$. But the smaller Q is more beneficial in terms of coding gain. Thus, we set $Q=MT$. Since the representation of group $G_{m,r}$ is an $n\times n$ matrix (see (7) and (8)), we have $M=T=n$ and we need $Q=n^2$ weight matrices.

Lemma 1:

Let $G_{m,r}=\langle \sigma,\tau \mid \sigma^m=1,\ \tau^n=\sigma^t,\ \tau\sigma\tau^{-1}=\sigma^r \rangle$. If we set $m=2^k$ and $r=8\alpha+3$, where $k(\geq 3)$ and α are arbitrary integers, then the order n of r modulo m is 2^{k-2}.

Proof) It is easy to see that

$$\begin{aligned} r^{2^{k-2}}-1 = &(r^{2^{k-3}}+1)(r^{2^{k-4}}+1)\cdots \\ &(r^{2^1}+1)(r^{2^0}+1)(r^{2^0}-1) \end{aligned} \qquad (9)$$

Since $r^2 \equiv 1(\mathrm{mod}8)$, $r^{2^i} \equiv 1(\mathrm{mod}4)$. Thus $r^{2^i}+1 \equiv 2(\mathrm{mod}4)$ for $i \geq 1$. From (9), we have

$$r^{2^{k-2}}-1=A\cdot 2^{k-3}(r^2-1)=A^{'}\cdot 2^k$$

where both A and $A^{'}$ are odd. Thus, $r^{2^{k-2}} \equiv 1(\mathrm{mod}2^k)$. Now, assume that λ is the smallest positive integer such that $r^{\lambda} \equiv 1\,(\mathrm{mod}\,2^k)$. Then λ should divide 2^{k-2}, i.e., $\lambda=2^i$ and $i \leq k-2$.
But

$$\begin{aligned} r^{2^i}-1 = &(r^{2^{i-1}}+1)(r^{2^{i-2}}+1)\cdots \\ &(r^{2^1}+1)(r^{2^0}+1)(r^{2^0}-1) \\ = &\ B\cdot 2^{i+2} \end{aligned}$$

where B is an odd integer. Thus, $2^k|(B\times 2^{i+2})$, which implies that $k\le i+2$. Therefore $i=k-2$, i.e., 2^{k-2} is the order of r modulo 2^k. □

From lemma 1, when we set $m=2^k$ and r is any integer congruent to 3 modulo 8, the order of $G_{m,r}$ is four times n^2. What we are going to do is to select n^2 elements out of $4n^2$ group elements of $G_{m,r}$ and use their representations as the weight matrices of our LD-STBC as in the following Theorem.

Theorem 2:

Let $G_{m,r}=\langle \sigma,\tau\,|\,\sigma^m=1,\ \tau^n=\sigma^t,\ \tau\sigma\tau^{-1}=\sigma^r\rangle$ with $m=2^k$ and $r\equiv 3 (\mathrm{mod}\ 8)$.

Set

$$\{A_l|l=1,\cdots,2^{2k-4}\}=\left\{\frac{1}{2^{k-2}}\triangle(\tau^i\sigma^j),\ \frac{1}{2^{k-2}}\triangle(\tau^i\sigma^{j+\frac{m}{4}})\ \Big|\ 0\le i\le 2^{k-3}-1,\ 0\le j\le 2^{k-2}-1\right\} \quad (10)$$

Then the matrix

$$\Phi=[vec(A_1)\,vec(A_2)\cdots vec(A_{2^{2k-4}})] \quad (11)$$

satisfies $\Phi\Phi^{\dagger}=\mathrm{I}_{2^{2k-4}}$.

Proof) It is enough to show that every row of Φ is orthogonal to every other row of Φ.

Using (10) and (11), we can make the matrix Φ (Fig. 2). As shown in Fig. 2, each row contains only $2^{k-2}(=n)$ non-zero entries.

We are going to show that the first (c_1) and the last row (c_{n^2}) are orthogonal. It is not difficult to show in a similar fashion that the inner product of any two rows in Φ is also zero.

Two rows c_1 and c_{n^2} can be written as follows.

$$c_1=(w^0\,w^1\cdots w^{\frac{m}{8}-1}\ w^{\frac{m}{4}}\ w^{\frac{m}{4}+1}\cdots w^{\frac{m}{4}+\frac{m}{8}-1}\ 0\cdots 0)$$

$$c_{n^2}=(w^0\,w^{r^{n-1}}\,w^{2r^{n-1}}\cdots w^{(\frac{m}{8}-1)r^{n-1}}\ w^{\frac{m}{4}r^{n-1}}\ w^{(\frac{m}{4}+1)r^{n-1}}\cdots w^{(\frac{m}{4}+\frac{m}{8}-1)r^{n-1}}\ 0\cdots 0)$$

The inner product of c_1 and c_{n^2} is given by

$$c_1c_{n^2}^{\dagger}=\sum_{i=0}^{m/8-1}\left\{\left(w^{1-r^{n-1}}\right)^i+\left(w^{1-r^{n-1}}\right)^{(i+\frac{m}{4})}\right\} \quad (12)$$

Since $w^{1-r^{n-1}}=w^{(r-1)/r}$ and $\gcd(r,m)=1$, the order of $w^{1-r^{n-1}}$ is same as that of w^{r-1}. The order of w^{r-1} is $t=m/\gcd(r-1,m)$, and in the case of

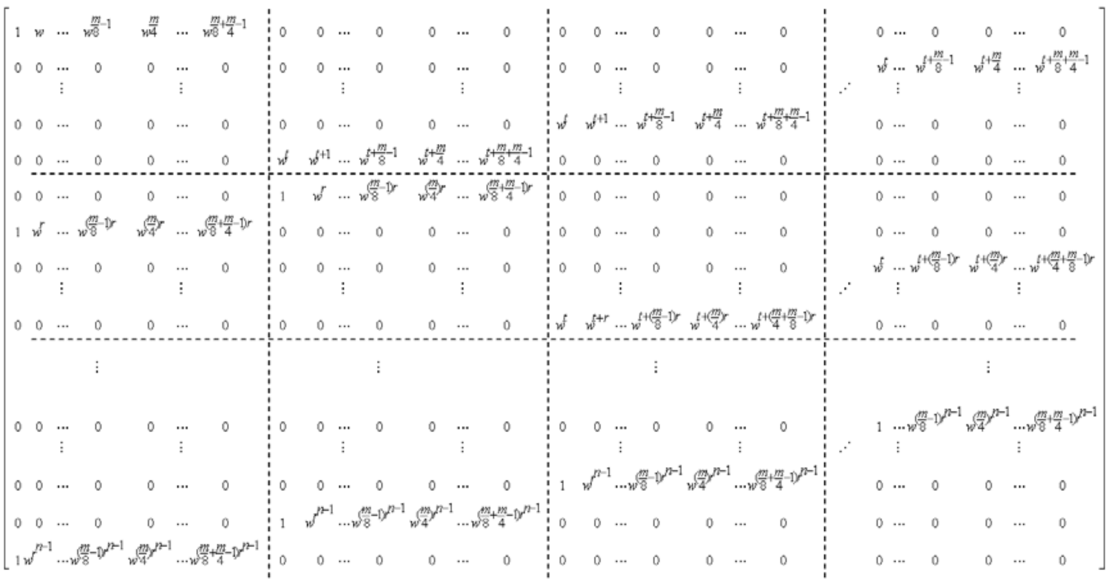

Fig. 2 Matrix Φ

$m=2^k$ and $r\equiv 3(\mathrm{mod}8)$, $t=m/2=2^{k-1}$. Thus $(w^{1-r^{n-1}})^{m/4}=-1$, which makes (12) be zero. □

V. Simulation Results and Conclusions

In this section, we show the performance of LD code proposed in this paper by the simulation on the exemplary LD codes with $M=4$ and rate 4 constructed from $G_{16,3}$.

Example :

$$G_{16,3}=\{H,\ \tau H,\ \tau^2 H,\ \tau^3 H\}$$

where $H=\langle\sigma\rangle$, and $\sigma^{16}=\tau^4=1$. From (7) and (8), the representations $\bigtriangleup(\sigma)$ and $\bigtriangleup(\tau)$ are given as follows.

$$\bigtriangleup(\sigma)=\begin{bmatrix} w & 0 & 0 & 0 \\ 0 & w^3 & 0 & 0 \\ 0 & 0 & w^{3^2} & 0 \\ 0 & 0 & 0 & w^{3^3} \end{bmatrix}\quad \bigtriangleup(\tau)=\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ w^8 & 0 & 0 & 0 \end{bmatrix}$$

where $w=\exp(j2\pi/16)$. The 16 weight matrices from (10) can be represented as

$$\{A_i\,|\,i=1,\cdots,16\}=$$

$$\left\{\sqrt{\frac{1}{4}}\bigtriangleup(\tau^j\sigma^i),\ \sqrt{\frac{1}{4}}\bigtriangleup(\tau^j\sigma^{i+4})\,|\,j=0,1,2,3\ i=0,1\right\}$$

and A_i's are

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ w^8 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ w^8 & 0 & 0 & 0 \\ 0 & w^8 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 1 \\ w^8 & 0 & 0 & 0 \\ 0 & w^8 & 0 & 0 \\ 0 & 0 & w^8 & 0 \end{bmatrix}$$

$$\begin{bmatrix} w^4 & 0 & 0 & 0 \\ 0 & w^{12} & 0 & 0 \\ 0 & 0 & w^4 & 0 \\ 0 & 0 & 0 & w^{12} \end{bmatrix} \begin{bmatrix} 0 & w^{12} & 0 & 0 \\ 0 & 0 & w^4 & 0 \\ 0 & 0 & 0 & w^{12} \\ w^{12} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & w^4 & 0 \\ 0 & 0 & 0 & w^{12} \\ w^{12} & 0 & 0 & 0 \\ 0 & w^4 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & w^{12} \\ w^{12} & 0 & 0 & 0 \\ 0 & w^4 & 0 & 0 \\ 0 & 0 & w^{12} & 0 \end{bmatrix}$$

$$\begin{bmatrix} w^1 & 0 & 0 & 0 \\ 0 & w^3 & 0 & 0 \\ 0 & 0 & w^9 & 0 \\ 0 & 0 & 0 & w^{11} \end{bmatrix} \begin{bmatrix} 0 & w^3 & 0 & 0 \\ 0 & 0 & w^9 & 0 \\ 0 & 0 & 0 & w^{11} \\ w^9 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & w^9 & 0 \\ 0 & 0 & 0 & w^{11} \\ w^9 & 0 & 0 & 0 \\ 0 & w^{11} & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & w^{11} \\ w^9 & 0 & 0 & 0 \\ 0 & w^{11} & 0 & 0 \\ 0 & 0 & w^1 & 0 \end{bmatrix}$$

$$\begin{bmatrix} w^5 & 0 & 0 & 0 \\ 0 & w^{15} & 0 & 0 \\ 0 & 0 & w^{13} & 0 \\ 0 & 0 & 0 & w^7 \end{bmatrix} \begin{bmatrix} 0 & w^{15} & 0 & 0 \\ 0 & 0 & w^{13} & 0 \\ 0 & 0 & 0 & w^7 \\ w^{13} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & w^{13} & 0 \\ 0 & 0 & 0 & w^7 \\ w^{13} & 0 & 0 & 0 \\ 0 & w^7 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & w^7 \\ w^{13} & 0 & 0 & 0 \\ 0 & w^7 & 0 & 0 \\ 0 & 0 & w^5 & 0 \end{bmatrix}$$

The performance obtained from a simulation with $s_q\in\{\pm 1\}$is shown is Fig 3.

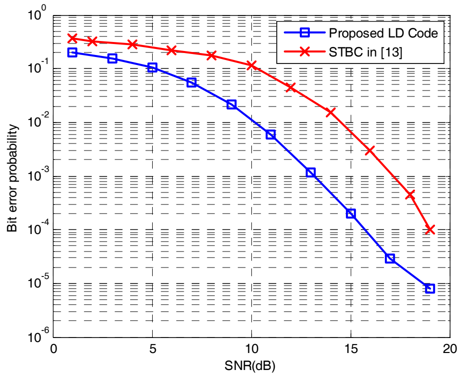

Fig. 3 Bit error rate for $M=4, N=2, 4bit/\mathrm{sec}/Hz$ STBCs proposed LD code and bit error rate for STBCs in [13]

Fig 3. is the performance comparison between our proposed code and the code in [13]. We can find that the proposed codes have 3dB advantages at a BER of 10^{-4}.

In this paper we have proposed the linear dispersion codes using non-abelian group representations. The proposed codes can be applied to the system with any 2^k transmit antennas. To see whether our proposed code meets the rank-determinant criterion and the generalization for the case of $m\neq 2^k$ are remained as further works.

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