A Serial Time-Division-Multiplexing Chip-Level Space-Time Coded Multi-user MIMO System Based on Three Dimensional Complementary Codes

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Abstract. This paper presents a serial time-division-multiplexing multi-user MIMO system for the chip level space-time coding scheme based on three dimensional complementary codes (3DCCs). In such a 3DCC-based MIMO system, the spread signals corresponding to different element sequences of a 3DCC are transmitted in different time slots in a series way. A "Diversity/Multiplexing Controller" is designed to control the transmit spatial diversity and multiplexing gains according to different channel conditions. Both the theoretical analysis and the computer simulation will prove the capability of the proposed system to eliminate multi-path and multi-user interference compared to the traditional multiuser MIMO solutions.

Keywords: Multi-user MIMO · 3D complementary code · Chip-level space-time coding · CDMA

1 Introduction

As an effort to integrate multiple-input multiple-output (MIMO) and code division multiple access (CDMA) techniques, a kind of chip level space-time coding scheme (CLSTC) is proposed [1], which employs direct sequence spreading to serve users for multiple access and antenna separation simultaneously in MIMO systems with the help of special complementary codes (CCs), or three dimensional complementary codes (3DCCs).

3DCCs are an evolutional version of complementary codes [2] to provide the orthogonality not only among users to achieve code division multiple access, but also among different antennas in a MIMO system to achieve space diversity/multiplexing gains, in order to offer a new paradigm integrating multi-user and multi-antenna techniques to facilitate system optimization.

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In order to offer orthogonality in time-frequency-spatial three fields, the construction of 3DCCs is an extremely challenging issue and a new attempt. In [3] and [4], two construction methods have been proposed to show the feasibility to construct such codes. The design of CDMA systems based on classic complementary codes have been well studied [5,6]. However, few system design or performance analysis of 3DCC-based MIMO system are present till now. The main contribution made in this paper is to present a serial time-division-multiplexing chip-level space-time coded multi-user MIMO system. In such a 3DCC-based MIMO system, the spread signals corresponding to M element sequences of a 3DCCs are transmitted in different time slots in a series way. Additionally, a "Diversity/Multiplexing Controller" is designed to control the transmit spatial diversity and multiplexing gains according to different channel conditions. Based on attractive correlation properties of 3DCCs, this paper analyzes the elimination of multi-user interference (MUI) elimination and diversity gains of such 3DCC-based MIMO system. Finally, the simulated bit error rate performance comparison with traditional multi-user MIMO system will proof the benefits of the proposed 3DCC-based MIMO system on MUI- and multi-path interference (MPI)-resistant performance.

2 Definitions and Code Construction

2.1 Three Dimensional Complementary Codes

Let $\mathcal{G}(K, A, M, N)$ be a family of 3DCCs, which contains K 3DCCs denoted as $\mathbb{G}^{(k)}$, $k \in \{1, 2, \cdots, K\}$, and K is the family size. Each 3DCC contains A sub-2DCCs, $\mathbf{G}^{(k,a)}$, with the same flock size M and code length N, where A is the number of transmit antennas used by the transmitter. Each sub-2DCC $\mathbf{G}^{(k,a)}$ contains M element sequences $\mathbf{g}_m^{(k,a)}$ with the same code length N, $m \in \{1, 2, \cdots, M\}$, and M is the flock size (which determines the number of element codes used by the same user). Therefore, $\mathbb{G}^{(k)}$ can be viewed as a three-dimensional code array, and we have $\mathbb{G}^{(k)}(:, :, a) = \mathbf{G}^{(k,a)}$, $\mathbf{G}^{(k,a)}(m, :) = \mathbf{g}_m^{(k,a)}$, and $\mathbf{g}_m^{(k,a)}(n) = g_{m,n}^{(k,a)}$, where $k \in \{1, 2, \cdots, K\}$, $a \in \{1, 2, \cdots, A\}$, $m \in \{1, 2, \cdots, M\}$, $n \in \{1, 2, \cdots, N\}$ and $g_{m,n}^{(k,a)} \in \{1, -1\}$.

Generally, A determines the number of transmit antennas of a MIMO system and the family size K determines the user capacity of such a system. $\mathbb{G}^{(k)}$ is assigned to user k as its signature code and space-time code. The flock size M determines the number of independent sub-channels required to implement a 3DCCs-base MIMO-CDMA system, and the independent sub-channels can be separated by different sub-carriers or time slots.

2.2 Complementary Correlation and Perfect 3DCCs

Aperiodic correlation, also called partial correlation, will be considered in this paper, because the aperiodic correlation property of spreading codes is more general in system performance evaluation than the periodic correlation property, due to the fact that a periodic correlation function can always be decomposed into two partial correction functions. Therefore, if we have ideal partial correction functions for a code, we can always ensure ideal periodic correlation functions for the same code as shown later.

For any two sequences of length N, $\mathbf{a} = \{a_1, a_2, \cdots, a_N\}$ and $\mathbf{b} = \{b_1, b_2, \cdots, b_N\}$, the aperiodic correlation function $\psi(\mathbf{a}, \mathbf{b}; \tau)$ with positive relative delay τ is defined as

$$\psi\big(\mathbf{a}, \mathbf{b}; \tau\big) = \sum_{n=0}^{N-1-\tau} a_n b_{n+\tau}, \qquad 0 \le \tau \le N-1. \tag{1}$$

The correlation properties of 3DCCs are characterized by the complementary aperiodic correlation function, which is calculated as the sum of the aperiodic correlation functions of all element codes with the same delay τ, or

$$\begin{aligned} \rho\big(\mathbf{G}^{(k_1,a_1)}, \mathbf{G}^{(k_2,a_2)}; \tau\big) &= \sum_{m=0}^{M-1} \psi\big(\mathbf{g}_m^{(k_1,a_1)}, \mathbf{g}_m^{(k_2,a_2)}; \tau\big) \\ &= \sum_{m=0}^{M-1} \sum_{n=0}^{N-1-\tau} g_{m,n}^{(k_1,a_1)} g_{m,n+\tau}^{(k_2,a_2)}, \qquad 0 \le \tau \le N-1, \end{aligned} \tag{2}$$

where $k_1, k_2 \in \{1, 2, \cdots, K\}$ and $a_1, a_2 \in \{1, 2, \cdots, A\}$.

A family of 3DCCs should provide the orthogonality among the signals from both different users and different antennas in order to achieve spatial diversity and/or spatial multiplexing along with orthogonal multiple access in multipath asynchronous communications. Therefore a perfect family of 3DCCs should satisfy the following three constrains:

1. Ideal auto-correlation property to eliminate MPI, i.e.

$$\text{ACF} = \rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(k,a)}; \delta) = \begin{cases} MN, & \delta = 0 \\ 0, & \delta \neq 0 \end{cases} \tag{3}$$

2. Ideal cross-correlation property for the sub-2DCCs belonging to the same 3DCCs to get orthogonality among the signals from different antennas of the same user. We name it as Cross-Correlation Function among Antennas (CCF-A), i.e.

$$\text{CCF-A} = \rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(k,b)}; \delta) = 0, \quad a \neq b \tag{4}$$

3. Ideal cross-correlation property for the sub-2DCCs belonging to different 3DCCs to get orthogonality among the signals from different users. We name it as Cross-Correlation Function among Users (CCF-U), i.e.

$$\text{CCF-U} = \rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(g,b)}; \delta) = 0, \quad k \neq g \tag{5}$$

The construct of a perfect family of 3DCCs can be found in, and in this paper a system architecture of a MIMO-CDMA system based on such perfect 3DCCs will be discussed.

3 A Serial Time-Division-Multiplexing Multi-user MIMO System Based on 3DCCs

3.1 System Models

In 3DCCs based multi-user system, each user will be allocated a particular 3DCCs from a code set as both its signature code and space-time code. A user should spread its data with M element sequences of 3DCCs, respectively. Transmitted over wireless channels, M streams of spread signals are required to be separated at a receiver, because there is no correlation constraint on the correlation properties between different element sequences. Therefore, M streams of spread signals are normally transmitted in M independent subchannels. Considering the compatibility of the existing, this paper proposed a serial time-division-multiplexing (TDM) multi-user MIMO system based on 3DCCs mentioned above, as shown in Figs. 1 and 2.

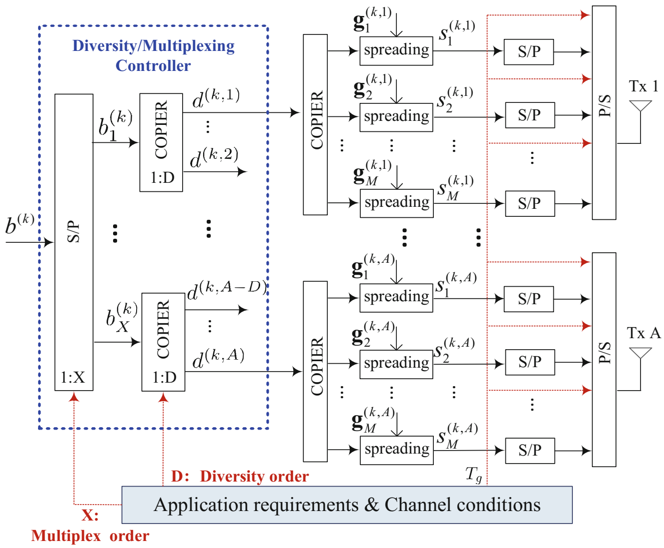

Fig. 1. The structure of the transmitter of user k.

Let us consider an $A \times X$ MIMO system with K users, where the corresponding transmitter (taking user k as an example) and receiver (e.g., user g) are shown in Figs. 1 and 2. Let $b^{(k)}$ represent the polarized binary source data from user k, and it is mapped to A streams of signals, $\{d^{(k,a)}\}_{a=1}^{A}$, by "Diversity/Multiplexing Controller" module. Owing to the orthogonality of the signals among different antennas ensured by 3DCCs, both space diversity and multiplexing are supported by the 3DCC-based multiuser MIMO system, which is controlled by the "Diversity/Multiplexing Controller" module according to

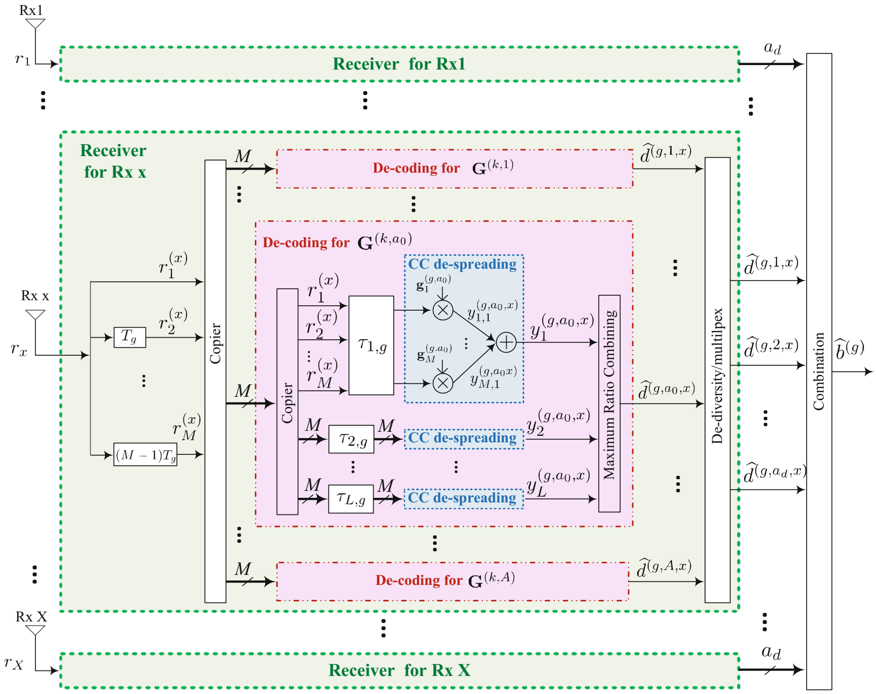

Fig. 2. The structure of the receiver of user g.

channel conditions and performance requirements, i.e., (1) if the diversity mode is employed to improve the error probability, $\{d^{(k,a)}\}_{a=1}^{A}$ are A copies from the source signal $b^{(k)}$; (2) if the multiplexing mode is employed to enhance data rate, they are generated by serial to parallel operation (or S/P) from $b^{(k)}$; (3) if $A > 2$, a hybrid diversity and multiplexing mode can also be employed to achieve both diversity gain and multiplex capability.

Then, A streams of signals $\{d^{(k,a)}\}_{a=1}^{A}$ of user k are spread by M element sequences of ath of the 3DCC $\mathbb{G}^{(k)}$. Take ath antenna and mth element sequence as an example. The mathematical expressions are given as follows:

$$s_m^{(k,a)}(t) = \sqrt{p_t}\sum_{i=0}^{B-1} d^{(k,a)}(i)G_m^{(k,a)}(t-iT) \tag{6}$$

where B is the length of a data block and p_t is the transmit power. $T = NT_c$ and T_c is a chip duration $G_m^{(k,a)}(t)$ is the spreading chip waveform of the mth element sequence of the ath sub-2DCC of $\mathbb{G}^{(k)}$, or

$$G_m^{(k,a)}(t) = \sum_{n=1}^{N} g_{m,n}^{(k,a)} q(t - nT_c + T_c) \tag{7}$$

where $q(t)$ is the impulse response of chip waveform-shaping filter, which is a rectangular shape in this paper for simplicity.

In the proposed The TDM 3DCCs-based MIMO system, M streams of spread signals corresponding to M element sequences are transmitted in different time slots in a series way and they are separated by a guard with length T_g, or

$$S^{(k,a)}(t) = \sum_{m=1}^{M} s_m^{(k,a)}(t - m\Delta + \Delta) \tag{8}$$

where $\Delta = T_c N + T_g$.

In this paper, asynchronous multiuser communication is considered and the channel is assumed to suffer frequency selective Rayleigh fading. At the xth receiver antenna of user g, carrier-demodulated signal can be written as

$$r^{(x)}(t) = \sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} S^{(k,a)}(t - \tau_{l,k} - \theta_k) + n(t) \tag{9}$$

where $h_{k,l}^{(a,x)}$ is lth path channel coefficient of from ath transmit antenna of user k to xth receive antenna of user g and $\tau_{l,k}$ is the corresponding channel delay. θ_k is the delay among users due to asynchronous communication and $n(t)$ is Gaussian noise with power spectrum density N_0.

Assuming $|\tau_{l,k} - \tau_{z,g} + \theta_k - \theta_g| \le T_g$, where $l, z \in \{1, 2, \cdots, L\}$, $k, g \in \{1, 2, \cdots, K\}$. After time-division de-multiplexing, we get

$$r_m^{(x)}(t) = \sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} s_m^{(k,a)}(t - \tau_{l,k} - \theta_k) + n(t) \tag{10}$$

Then the M signal streams $\{r_m^{(x)}\}_{m=1}^{M}$ are de-coded by the 3DCCs $\mathbb{G}^{(g)}$, as the following three steps.

Step 1. CC de-spreading for a_0th antenna of user g for l_0 path, $a_0 = \{1, 2, \cdots, A\}$ and $l_0 = \{1, 2, \cdots, L\}$.

$$\begin{aligned} y_{l_0}^{(g,a_0,x)} &= \sum_{m=1}^{M} \int_0^{NT_c} r_m^{(x)}\left(t + \tau_{l_0,g}\right) G_m^{(g,a_0)}(t)dt \\ &= \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} d^{(k,a)} \int_0^{NT_c} G_m^{(k,a)}(t - \tau_{l,k} - \theta_k + \tau_{l_0,g}) G_m^{(g,a_0)}(t)dt + \omega \\ &= \frac{1}{MN} \sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} d^{(k,a)} \underbrace{\sum_{m=1}^{M}\sum_{n=1}^{N-\delta} g_{m,n}^{(k,a)} g_{m,n+\delta}^{(g,a_0)}}_{\rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(g,a_0)}; \delta)} + \omega \end{aligned} \tag{11}$$

where $\delta = (\tau_{l,k} + \theta_k - \tau_{l_0,g})/T_c$, $\omega = \sum_{m=1}^{M} \int_0^{NT_c} n(t) G_m^{(g,a_0)}(t)dt$ is sampled additive white noise. According to the ideal CCF-U of 3DCCs in (5), we get

$$y_{l_0}^{(g,a_0,x)} = \sqrt{p_t} h_{g,l_0}^{(a_0,x)} d^{(g,a_0)} + \omega \tag{12}$$

Step 2. Combine L detected data of a_0 sub-2DCCs of user g by maximum ratio combining (MRC), or

$$\widehat{d}^{(g,a_0,x)} = \sum_{l=1}^{L} \left(h_{g,l}^{(a_0,x)}\right)^* y_l^{(g,a_0,x)} = \sqrt{p_t}\sum_{l=1}^{L} |h_{g,l}^{(a_0,x)}|^2 d^{(g,a_0)} + \sum_{l=1}^{L} \left(h_{g,l}^{(a_0,x)}\right)^* \omega$$

Step 3. De-diversity/multiplex the detected A according to the diversity/multiplexing modes employed by the transmitter of user g. (1) to recover the multiplexed streams through parallel to serial operation (or P/S); (2) to combine the streams for space diversity gain.

Step 4. Combine the detected data from X receive antennas of user g, or

$$\widehat{b}^{(g)} = \sqrt{p_t}\sum_{x=1}^{X}\sum_{a=a_1}^{a_d}\sum_{l=1}^{L} |h_{g,l}^{(a,x)}|^2 b^{(g)} + \sum_{x=1}^{X}\sum_{a=a_1}^{a_d}\sum_{l=1}^{L} \left(h_{g,l}^{(a,x)}\right)^* \omega \tag{13}$$

3.2 Analysis on MUI, MPI and Diversity Gains

In (11), the detected signal $y_{l_0}^{(g,a_0)}$ for l_0th path a_0 transmit antenna of user g contains useful signal U, multipath interference I_{MP}, multiuser interference I_U, interference among antennas I_A and noise ω, or

$$\begin{aligned} y_{l_0}^{(g,a_0)} &= \frac{1}{MN}\sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} d^{(k,a)} \rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(g,a_0)}; \delta) + \omega \\ &= U + I_{MP} + I_A + I_U + \omega \end{aligned} \tag{14}$$

According to the ideal correlation properties of 3DCCs in (3) (5), we get

$$\begin{cases} U &= \frac{1}{MN}\sqrt{p_t} h_{g,l_0}^{(a_0,x)} d^{(g,a_0)} \rho(\mathbf{G}^{(g,a_0)}, \mathbf{G}^{(g,a_0)}; 0) = \sqrt{p_t} h_{g,l_0}^{(a_0,x)} d^{(g,a_0)} \\ I_{MP} &= \frac{1}{MN}\sum_{l=1, l\neq l_0}^{L} \sqrt{p_t} h_{g,l}^{(a_0,x)} d^{(g,a_0)} \rho(\mathbf{G}^{(g,a_0)}, \mathbf{G}^{(g,a_0)}; \frac{\tau_{l,g}-\tau_{l_0,g}}{T_c}) = 0 \\ I_A &= \frac{1}{MN}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{g,l}^{(a,x)} d^{(g,a)} \rho(\mathbf{G}^{(g,a)}, \mathbf{G}^{(g,a_0)}; \frac{\tau_{l,g}-\tau_{l_0,g}}{T_c}) = 0 \\ I_U &= \frac{1}{MN}\sum_{k=1,k\neq g}^{K}\sum_{a=1}^{A}\sum_{l=1}^{L} \sqrt{p_t} h_{k,l}^{(a,x)} d^{(k,a)} \rho(\mathbf{G}^{(k,a)}, \mathbf{G}^{(g,a_0)}; \frac{\tau_{l,k}-\theta_k-\tau_{l_0,g}}{T_c}) = 0 \end{cases}$$

Therefore, both the multipath interference and multiuser interference are eliminated in the proposed system. Now we deduce the bit error rate (BER) and diversity gain of the above system with assumption $L = 1$ for simplicity.

$$\widehat{b}^{(g)} = \sqrt{p_t}\sum_{x=1}^{X}\sum_{a=a_1}^{a_d} |h_g^{(a,x)}|^2 b^{(g)} + \sum_{x=1}^{X}\sum_{a=a_1}^{a_d} \left(h_g^{(a,x)}\right)^* \omega \tag{15}$$

where A_d is the number of antennas of user g transmit the same data, i.e. using diversity mode. Assuming $p_t = \frac{E_b}{A_d XMNT_c}$, the instantaneous signal-noise ratio (SNR) before decision is:

$$\gamma_b = \frac{1}{A_d X}\sum_{x=1}^{X}\sum_{a=a_1}^{a_d} |h_g^{(a,x)}|^2 \frac{E_b}{N_0} \tag{16}$$

Assuming the channels between any antennas are suffer independent Rayleigh fading, we get the probability density of γ_b is

$$p(\gamma_b) = \frac{1}{(A_d X - 1)! \gamma_b^{A_d X}} \overline{\gamma}^{A_d X - 1} e^{-\gamma_b / \overline{\gamma}} \tag{17}$$

where $\overline{\gamma} = \frac{E_b}{A_d X N_0}$. Then we get the BER as

$$\begin{aligned} P(\gamma_b) &= \int_0^\infty Q\sqrt{2\gamma_b} p(\gamma_b) d\gamma_b \\ &= \left[\frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}\right)\right]^{A_d X} \sum_{x=0}^{A_d X - 1} \binom{A_d X - 1 + x}{x} \left[\frac{1}{2}\left(1 + \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}\right)\right]^x \end{aligned} \tag{18}$$

If $\overline{\gamma} \gg 1$, we get

$$P_2(\gamma_b) \approx (4\gamma)^{-A_d X} \binom{2A_d X - 1}{A_d X} \tag{19}$$

Finally, we get the diversity gain of the above system as

$$g_d(\gamma) = - \lim_{\gamma \to \infty} \frac{log\left[(4\gamma)^{-A_d X} \binom{2A_d X - 1}{A_d X}\right]}{log(\gamma)} = A_d X \tag{20}$$

4 Simulation Results and Discussion

BERs of five kinds of 2×1 multiuser MIMO systems over either a Rayleigh flat fading channel or a multi-path channel are shown in Figs. 3 and 4, respectively. In the simulations, a family of 3DCCs $\mathcal{G}(8, 2, 8, 8)$ was employed in the proposed S-TDM MIMO system. "STBC+Gold" denotes a MIMO system using space-time block codes (STBCs) [7] as space-time codes and Gold sequences ($N = 63$) as spreading codes. "STS+Walsh" means a MIMO system using space-time-spreading (STS) [8] as space-time and spreading codes and Walsh sequences ($N = 64$) as spreading codes. In the simulations, $T_c = 0.025$ μs and an uncoded BPSK modulation were employed. The multi-path channel is a three-path tapped-delay line model with its normalized path gain coefficients vector as $[-1.92, -5.92, -9.92]$ dB and delay vector as $[0\ 0.025\ 0.075]$ μs.

As seen from the results in Fig. 3, in the flat fading channel, both 3DCC-based and "STS+Walsh" schemes achieve MUI-free, while the BER performance of "STBC+Gold" scheme deteriorates significantly in multiuser scenario due to the bad cross-correlation property of Gold sequences.

In the multi-path fading channel, only the proposed system achieves MUI-free multiuser communications, while the BER performance of "STBC+Gold" degrades significantly in multiuser scenario due to the bad cross-correlation

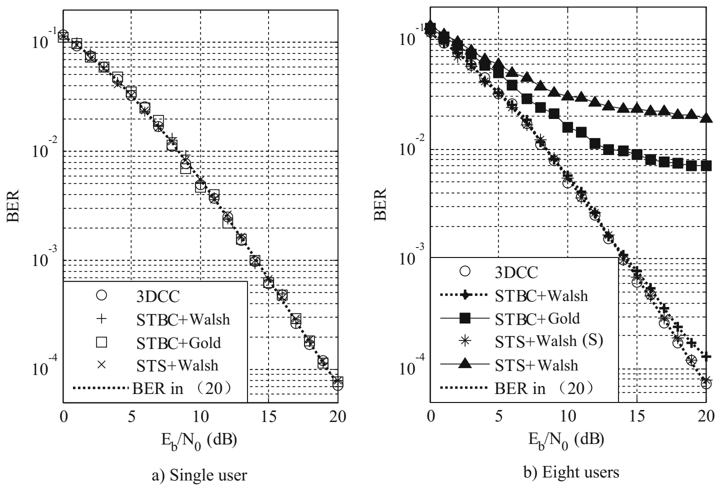

Fig. 3. BER performance of 2 × 1 3DCC-based MIMO systems with different space-time and spreading codes over a flat fading channel.

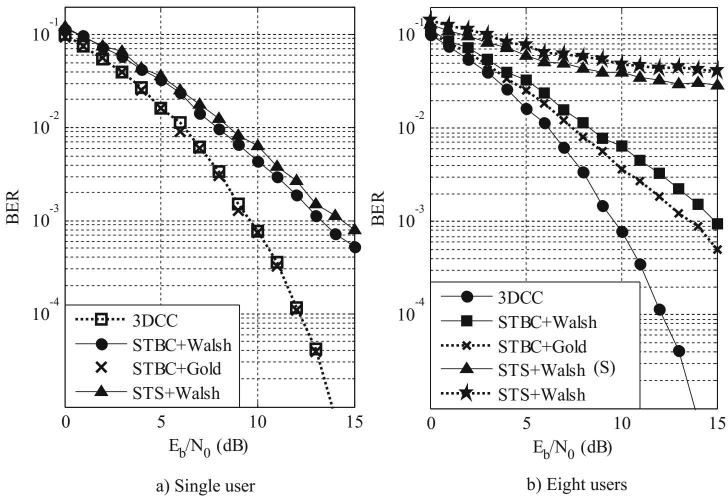

Fig. 4. BER performance of 2 × 1 3DCC-based MIMO systems with different space-time and spreading codes over a multi-path channel.

property of Gold sequences. The BER performance of "STS+Walsh" deteriorates significantly in both single-user and multiuser scenarios due to the bad auto-correlation property of Walsh sequences. Additionally, the proposed system achieves a better BER in the multi-path fading channel than it in a flat fading channel. This result not only proves the capability of such a system to eliminate both MPI and MUI, but also shows its superior capability to achieve multi-path diversity gains.

5 Conclusions

In this paper, we presented a serial time-division-multiplexing chip-level space-time coded multi-user MIMO system based on such 3DCCs. Both the theoretical analysis and the computer simulation prove the capability of the proposed system to eliminate MPI and MUI in multiuser MIMO communications. Additionally, providing both diversity and multiplex is a salient feature of the proposed system, which make it in particular well suited for futuristic wireless communication systems to fit to varying channel conditions and application requirements.

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