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2-DIMENSIONAL BLOCK SPREAD CDMA WITH FREQUENCY-DOMAIN SPACE-TIME CODED TRANSMIT DIVERSITY

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ABSTRACT

In broadband wireless communication systems, the presence of the frequency-selective fading and multi-access interference (MAI) severely degrades the bit error rate (BER) performance and limits the uplink capacity. 2-dimensional (2D) block spread CDMA makes it possible to achieve MAI-free uplink transmission with low-complexity single-user detection and therefore, it is very attractive. Space-time coded transmit diversity (STTD) using minimum mean square error frequency-domain equalization (MMSE-FDE) can be jointly used with 2D block spread CDMA. In this paper, the frequency-domain STTD is presented for the uplink of 2D block spread CDMA. The achievable BER performance is evaluated by computer simulation to show that frequency-domain STTD can offer significantly improved uplink BER performance.

I. INTRODUCTION

In a very frequency-selective fading channel, the use of some advanced equalization techniques is indispensable [1,2]; otherwise the signal transmission performance becomes very poor. Frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can significantly improve the bit error rate (BER) performance [3]. Further performance improvement can be achieved by transmit/receive antenna diversity [4, 5]. STTD using MMSE-FDE, called frequency-domain STTD in this paper, is a promising diversity technique [6,7].

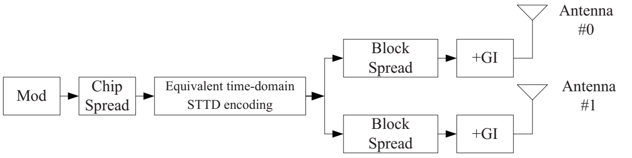
However, for the uplink (from mobile-to-base) transmission, different users' signals are asynchronously received via different fading channels and therefore, multiple access interference (MAI) occurs. The presence of MAI limits the uplink capacity. The use of 2-dimensional (2D) block spreading can be applied to solve the MAI problem [8],[9],[10]. In this paper, to further improve the uplink performance of a 2D block spread CDMA, frequency-domain STTD is introduced.

The remainder of the paper is organized as follows. Section 2 describes the uplink transmission system model of 2D block spread CDMA using frequency-domain STTD. The achievable uplink BER performance is evaluated by computer simulation in Sect. 3. Finally, Sect. 4 offers some concluding remarks.

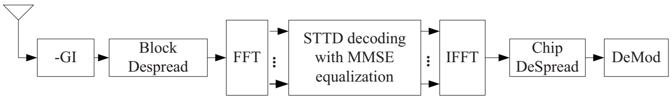
II. 2D BLOCK SPREAD CDMA WITH FREQUENCY-DOMAIN STTD

The transmission systems model of uplink 2D block spread CDMA with frequency-domain two-antenna STTD is shown in Fig.1. 2D block spread CDMA is implemented by two-level spreading: the chip-level spreading and block-level spreading. The chip-level spreading and the block-level spreading have different roles. The former is the same as traditional DS-(or MC-) CDMA. It is used to achieve the frequency diversity gain, while the latter is used to remove the MAI. STTD encoding is carried out between the chip-level spreading and block-level spreading.

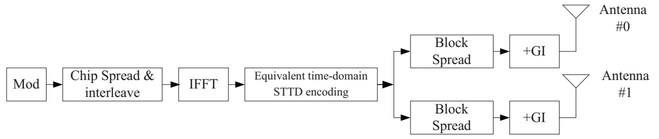
We assume that U users are simultaneously accessing the same base station. The data symbol sequence to be transmitted from the u-th user is denoted by $\{d_u(n); n = 0 \sim 2N_c/SF_f - 1\}$, where SF_f is the chip-level spreading factor and N_c is the FFT/IFFT block size for performing MMSE-FDE. All users transmit the same number of data symbols, which is $2N_c/SF_f$, in one block.



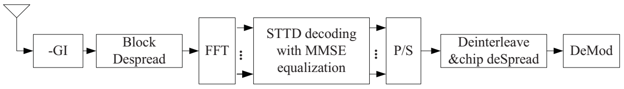
(a) DS-CDMA transmitter for one user



(b) DS-CDMA receiver for one user



(c) MC-CDMATransmitter for one user



(d) MC-CDMA receiver for one user

Figure 1: Transmission system model of uplink 2D block spread CDMA using frequency-domain STTD. Equivalent time-domain STTD encoding is used.

A. Chip-level spreading

The data symbol sequence $\{d_u(n); n = 0 \sim 2N_c/SF_f - 1\}$ to be transmitted is spread by chip-level spreading code $\{c_u^{SF_f}(t); t = 0 \sim SF_f - 1\}$ with the spreading factor SF_f. The resulting DS-CDMA chip sequence $\{s_u(t); t = 0 \sim 2N_c - 1\}$ is given as

$$s_u(t) = d_u\left(\lfloor t/SF_f \rfloor\right) c_u^{SF_f}(t \bmod SF_f), \tag{1}$$

which is then divided into two N_c-chip blocks, even chip block $\{s_{u,e}(t); t = 0 \sim N_c - 1\}$ and odd chip block $\{s_{u,o}(t); t = 0 \sim N_c - 1\}$. $s_{u,e}(t)$ and $s_{u,o}(t)$, t =0~N_c-1, are respectively given as

$$\begin{cases} s_{u,e}(t) = s_u(t) \\ s_{u,o}(t) = s_u(t + N_c) \end{cases}. \tag{2}$$

Note that in the case of MC-CDMA, N_c-point IFFT is applied to each chip-block to generate an MC-CDMA signal of N_c samples. Then, a group of even and odd N_c-chip blocks are STTD encoded.

B. Equivalent time-domain STTD encoding

The frequency-domain representations of even chip block $\{s_{u,e}(t); t = 0 \sim N_c - 1\}$ and the odd chip block $\{s_{u,o}(t); t = 0 \sim N_c - 1\}$ are given by $\{S_{u,e}(k); k = 0 \sim N_c - 1\}$ and $\{S_{u,o}(k); k = 0 \sim N_c - 1\}$, respectively. The frequency-domain STTD encoder encodes each pair of the same frequency components, $S_{u,e}(k)$ and $S_{u,o}(k)$, according to the Alamouti's 2-antenna STTD encoding rule [11], shown in Table 1. The factor of $1/\sqrt{2}$ is introduced to keep the total transmit power from two antennas the same as in the single transmit antenna case (no STTD).

The frequency-domain STTD encoding can be implemented in the time-domain using the following relationship [7]:

$$\begin{cases} \dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1} S_{u,e}^*(k)\exp\left(j2\pi t\dfrac{k}{N_c}\right) = s_{u,e}^*((N_c - t) \bmod N_c) \\ \dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1} S_{u,o}^*(k)\exp\left(j2\pi t\dfrac{k}{N_c}\right) = s_{u,o}^*((N_c - t) \bmod N_c) \end{cases}. \tag{3}$$

Equivalent time-domain STTD encoding is shown in Table 2.

Table 1: Frequency-domain STTD encoding.

Time (in chip-block)	Antenna #0	Antenna #1
Even	$\frac{1}{\sqrt{2}}S_{u,e}(k)$	$\frac{1}{\sqrt{2}}S_{u,o}(k)$
Odd	$-\frac{1}{\sqrt{2}}S_{u,e}^*(k)$	$\frac{1}{\sqrt{2}}S_{u,o}^*(k)$

Table 2: Equivalent time-domain STTD encoding.

Time (in chip-block)	Antenna #0	Antenna #1
Even	$\frac{1}{\sqrt{2}}s_{u,e}(t)$	$\frac{1}{\sqrt{2}}s_{u,o}(t)$
Odd	$-\frac{1}{\sqrt{2}}s_{u,o}^*((N_c - t) \bmod N_c)$	$\frac{1}{\sqrt{2}}s_{u,e}^*((N_c - t) \bmod N_c)$

C. Block-level spreading

The STTD encoded N_c-chip blocks are spread by using the block-level spreading code $\{c_u^{SF_t}(t); t = 0 \sim SF_t - 1\}$ with the spreading factor SF_t. In the block-level spreading, each N_c-chip bock is repeated SF_t times and each copy is multiplied by a chip from the orthogonal block-level spreading code $\{c_u^{SF_t}(t); t = 0 \sim SF_t - 1\}$. The frequency-domain STTD encoded signal to be transmitted during the even and odd time periods can be expressed as

$$\begin{cases} \hat{s}_{u,e}(t) = \sqrt{\dfrac{2E_c}{T_c}} s_{u,e}(t \bmod N_c) c_u^{SF_t}(\lfloor t/N_c \rfloor) \\ \hat{s}_{u,o}(t) = \sqrt{\dfrac{2E_c}{T_c}} s_{u,e}(t \bmod N_c) c_u^{SF_t}(\lfloor t/N_c \rfloor) \end{cases}$$
$$\text{for } t = 0 \sim SF_t \times N_c - 1, \tag{4}$$

where E_c is the average chip energy and T_c is the chip duration. Before the transmission, an N_g-chip guard interval (GI) is inserted in front of each N_c-chip block to avoid the inter-block interference (IBI). The GI-inserted signal from the u-th user is transmitted over a frequency-selective fading channel.

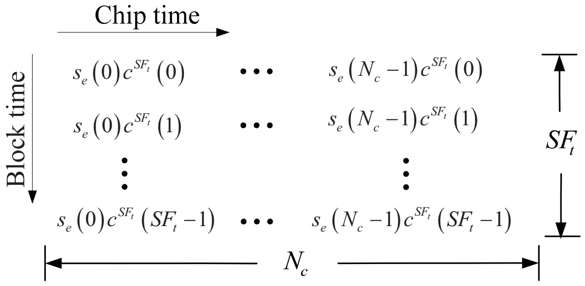


Figure 2: 2D block spreading.

D.Received signal

The channel is assumed to be composed of chip-spaced L independent paths and its impulse response $h_u(\tau)$ is expressed as

$$h_u(\tau)=\sum_{l=0}^{L-1} h_{u,l}\delta(\tau-\tau_{u,l}), \qquad (4)$$

where $h_{u,l}$ and $\tau_{u,l}$ are respectively the complex valued path gain and delay time of the l-th path for the u-th user's channel. We have assumed that the channel gain $h_{u,l}$ stays unchanged during block interval $T=T_c\left(N_c+N_g\right)$, while it changes block by block. $\tau_{u,l}$ is assumed to be T_c-spaced time delay and equal to $\tau_{u,l}=\tau_u+l\cdot T_c$, $l=0\sim L-1$, and τ_u is the u-th user's transmit timing offset. The maximum delay time of $\left\{\tau_{u,l}\right\}$ is assumed to be shorter than the GI.

The sum of U users' faded signals is received at a base-station. The GI is removed first. The GI-removed received signal can be expressed as

$$\begin{cases} r_e(t)=\sum\limits_{u=0}^{U-1}\begin{pmatrix}\sum\limits_{l=0}^{L-1} h_{u,0,e,l}\hat{s}_{u,0,e}(t-\tau_{u,l}) \\ +\sum\limits_{l=0}^{L-1} h_{u,1,e,l}\hat{s}_{u,1,o}(t-\tau_{u,l})\end{pmatrix}+n_{u,e}(t) \\ r_o(t)=\sum\limits_{u=0}^{U-1}\begin{pmatrix}-\sum\limits_{l=0}^{L-1} h_{u,0,o,l}\hat{s}^*_{u,0,o}\left(t-\tau_{u,l}\right) \\ +\sum\limits_{l=0}^{L-1} h_{u,1,o,l}\hat{s}^*_{u,1,e}\left(t-\tau_{u,l}\right)\end{pmatrix}+n_{u,o}(t) \end{cases} \qquad (5)$$

for $t=0\sim N_c\cdot SF_t-1$, where $n_e(t)$ and $n_o(t)$ are the zero-mean complex-valued additive white Gaussian noise (AWGN) samples with variance $2N_0/(T_c/SF_t)$ (N_0 is the AWGN one-sided power spectrum density and T_c is the chip duration after the chip-level spreading (or equivalently the chip duration after block despreading).

After the GI removal, the block despreading is applied as

$$\begin{cases} s'_{u,e}(t)=\dfrac{1}{SF_t}\sum\limits_{i=0}^{U-1} r_u(t+iN_c)\left\{c_u^{SF_f}\right\}^* \\ s'_{u,o}(t)=\dfrac{1}{SF_t}\sum\limits_{i=0}^{U-1} r_o(t+iN_c)\left\{c_u^{SF_f}\right\}^* \end{cases} \qquad (6)$$

for $t=0\sim N_c-1$.

If the fading is very slow such that the path gains stay almost constant over at least SF_t consecutive blocks, the MAI can be completely removed.

E. Frequency-domain STTD decoding

The even and odd received signal blocks $\{s'_{u,e}(t);t=0\sim N_c-1\}$ and $\{s'_{u,o}(t);t=0\sim N_c-1\}$, obtained by the block-level despreading, are decomposed by an N_c-point FFT into the frequency-domain signals, $\left\{R_{u,e}(k):k=0\sim N_c-1\right\}$ and $\left\{R_{u,o}(k):k=0\sim N_c-1\right\}$, respectively. $R_{u,e}(k)$ and $R_{u,o}(k)$ are given as

$$\begin{cases} R_{u,e}(k)=\sqrt{\dfrac{2E_c}{T_c}}H_{u,0}(k)S_{u,e}(k)+\sqrt{\dfrac{2E_c}{T_c}}H_{u,1}(k)S_{u,o}(k)+\Pi_{u,e}(k) \\ R_{u,o}(k)=-\sqrt{\dfrac{2E_c}{T_c}}H_{u,0}(k)S^*_{u,o}(k)+\sqrt{\dfrac{2E_c}{T_c}}H_{u,1}(k)S^*_{u,e}(k)+\Pi_{u,o}(k) \end{cases}, \qquad (7)$$

where $H_{u,e(o)}(k)$ represents the N_c-point Fourier transform of channel gain between the receive antenna and the 0th (1st) transmit antenna (note that we are assuming a slow fading channel where the channel stays unchanged during the transmission of N_c/SF_f data symbols) and $\Pi_{u,e(o)}(k)$ represents the zero-mean noise component having the variance $2N_0/T_c$ in the received even (odd) chip-block. The frequency-domain STTD decoding is carried out as [7]

$$\begin{cases} \tilde{S}_{u,e}(k)=w^*_{u,0}(k)R_{u,e}(k)+w_{u,1}(k)R^*_{u,o}(k) \\ \tilde{S}_{u,o}(k)=w^*_{u,1}(k)R_{u,e}(k)-w_{u,0}(k)R^*_{u,o}(k) \end{cases}, \qquad (8)$$

where $w_{u,0}(k)$ and $w_{u,1}(k)$ are MMSE weights given by

$$\begin{cases} w_{u,0}(k)=\dfrac{H_{u,0}(k)}{\sum\limits_{n=0}^{1}\left|H_{u,n}(k)\right|^2+\left(\dfrac{1}{2}\cdot SF_t\cdot\dfrac{E_c}{N_0}\right)^{-1}} \\ w_{u,1}(k)=\dfrac{H_{u,1}(k)}{\sum\limits_{n=0}^{1}\left|H_{u,n}(k)\right|^2+\left(\dfrac{1}{2}\cdot SF_t\cdot\dfrac{E_c}{N_0}\right)^{-1}} \end{cases}. \qquad (9)$$

F. Chip-level despreading

An N_c-point IFFT is applied to $\{\tilde{S}_{u,e}(k);k=0\sim N_c-1\}$ and $\{\tilde{S}_{u,o}(k);k=0\sim N_c-1\}$ to obtain the time-domain chip blocks as

$$\begin{cases} \tilde{s}_{u,e}(t)=\dfrac{1}{\sqrt{N_c}}\sum\limits_{k=0}^{N_c-1}\tilde{S}_{u,e}(k)\exp\left(j2\pi t\dfrac{k}{N_c}\right) \\ \tilde{s}_{u,o}(t)=\dfrac{1}{\sqrt{N_c}}\sum\limits_{k=0}^{N_c-1}\tilde{S}_{u,o}(k)\exp\left(j2\pi t\dfrac{k}{N_c}\right) \end{cases}. \qquad (10)$$

Then, the chip-level despreading using the spreading code $\{c_u^{SF_f}(t);t=0\sim SF_f-1\}$ is performed to get the soft decision variables, $\tilde{d}_{u,e}(n)$ and $\tilde{d}_{u,o}(n)$, $n=0\sim N_c/SF_f-1$, for data demodulation as

$$\begin{cases} \tilde{d}_{u,e}(n)=\dfrac{1}{SF_t}\sum\limits_{t=nSF_f}^{(n+1)SF_f-1}\tilde{s}_{u,e}(t)\left[C_u^{SF_f}(t)\right]^* \\ \tilde{d}_{u,o}(n)=\dfrac{1}{SF_t}\sum\limits_{t=nSF_f}^{(n+1)SF_f-1}\tilde{s}_{u,o}(t)\left[C_u^{SF_f}(t)\right]^* \end{cases}. \qquad (11)$$

III. SIMULATION RESULTS

The achievable BER performance of the uplink 2D spread CDMA using frequency-domain STTD is evaluated by the computer simulation. The simulation condition is summarized in Table 3. The channel gain $h_{u,l}$ is assumed to stay unchanged during the transmission of two chip block (i.e., during the transmission of N_c / SF_f data symbols). A fixed spreading factor of $SF(= SF_f \cdot SF_t) = 16$ is considered. Since the block-level spreading factor $SF_t = U$ is sufficient to remove the MAI, we use $(SF_f, SF_t) = (SF/U, U)$.

Table 3: Simulation condition.

Transmitter	Modulation	QPSK
	Chip-block length (no. of FFT points)	$N_c = 256$
	GI length	$N_g = 32$
	Spreading codes	Walsh sequences
	No. of transmit antennas	2
	Spreading factor	$SF(= SF_f \cdot SF_t) = 16$
Channel	Type of fading	Rayleigh
	Power delay profile	L=16-path uniform
	Channel estimation	Ideal
Receiver	Frequency-domain STTD decoding	MMSE

The computer simulated BER performance is plotted in Fig. 3 as a function of the average signal energy per bit-to-AWGN power spectrum density ratio E_b / N_0 with the number U of users as a parameter. DS-CDMA is assumed. It can be seen from Fig.3 that the use of frequency-domain STTD can significantly improve the BER performance of the uplink 2D block spread CDMA. When U=1, the use of STTD reduces the required E_b/N_0 for achieving BER=10^{-3} by only about 1dB. The BER performance improvement becomes more significant as U increases. When U=16, the E_b/N_0 reduction can be as much as 4dB. The reason for this is discussed below. As U increases, SF_f becomes smaller and therefore, the frequency-diversity gain achievable by MMSE-FDE gets smaller. As a consequence, the relative diversity gain achievable by STTD gets stronger.

However, it is seen from Fig. 3 that as U increases, the BER performance degrades for both cases with and without STTD. This is because the chip-level spreading factor SF_f decreases for the given total spreading factor SF=16 and hence, the residual ISI, which is present after MMSE-FDE, increases. An extreme case is U=16; no ISI suppression is obtained (the spreading is used to remove the MAI only). To improve the BER performance for a large U, some ISI interference cancellation techniques must be incorporated into the frequency-domain STTD decoding.

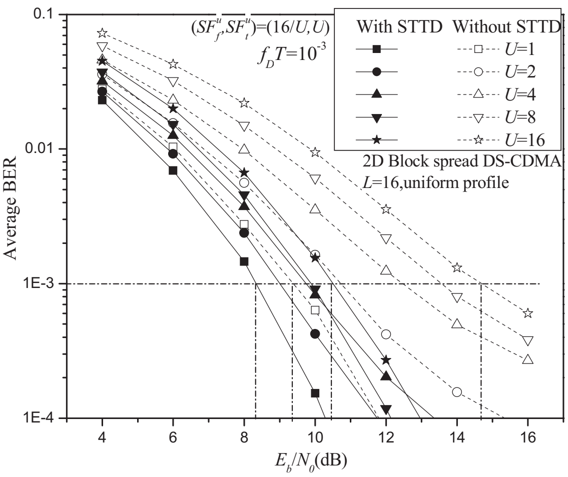


Figure3: BER performance of uplink 2D block spread DS-CDMA using frequency-domain STTD.

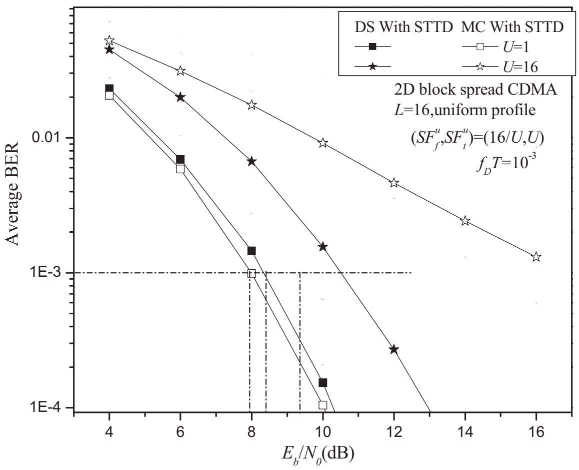


Figure 4: Performance comparison between 2D block spread MC-CDMA and DS-CDMA when frequency-domain STTD is used.

Comparison between 2D block spread MC-CDMA and DS-CDMA when frequency-domain STTD is used is shown in Fig. 4. When U=1, the required E_b/N_0 for achieving BER=10^{-3} is smaller by about 0.5dB with MC-CDMA than with DS-CDMA; however, DS-CDMA provides better performance when U=16.

In Fig. 5, how f_DT (or the fading rate) impacts the achievable BER performance of 2D block spread DS-CDMA using frequency-domain STTD is shown for the case of U=8. Almost the same BER performance can be achieved if f_DT is below 10^{-3}. STTD can provide about 4dB gain in the required E_b/N_0 for BER=10^{-3}. However, when f_DT=10^{-2}, the path gains tend to vary over SF_t=8 consecutive chip-blocks and hence, the orthogonality among different users is distorted. As a consequence, the MAI is produced, thereby significantly degrading the BER performance. In such a fast fading case, the BER performance with STTD is seriously degraded.

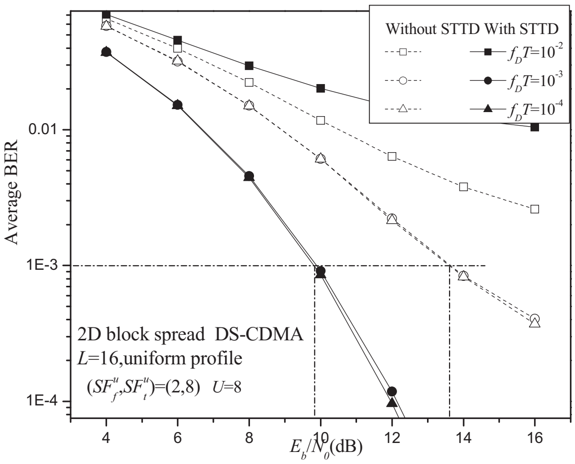


Figure 5: Impact of f_DT on 2D block spread DS-CDMA using frequency-domain STTD.

IV. Conclusions

In this paper, we applied the frequency-domain STTD to the uplink of 2D block spread CDMA and evaluated by the computer simulation the achievable BER performance in a frequency-selective Rayleigh fading channel. It was shown that the frequency-domain STTD can significantly improve the uplink BER performance of 2D block spread CDMA. However, if the channel changes during the signal transmission, the MAI cannot be removed completely and the MAI remains to some extent; to which extent the MAI remains depends on the fading maximum Doppler frequency and this is left as a practically important future research topic.

V. Acknowledgment

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