Application of Cyclic Delay Transmit Diversity to uplink 2-Dimensional Block Spread CDMA with Frequency-Domain Equalization

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Abstract—**The presence of the multi-access interference (MAI) limits the uplink performance of code division multiple access (CDMA). 2-dimensional (2D) block spread CDMA makes it possible to achieve MAI free uplink transmission while obtaining the frequency diversity gain by using low-complexity single-user frequency-domain equalization (FDE). To further improve the uplink transmission performance, the transmit diversity technique can be used. Cyclic delay transmit diversity (CDTD) can strengthen the frequency-selectivity of the channel. In this paper, we apply CDTD to 2D block spread CDMA with MMSE-FDE. The achievable uplink BER performance is evaluated by computer simulation for both direct sequence CDMA and multi-carrier CDMA. It is shown that CDTD can offer improved uplink BER performance in a frequency-selective uplink channel.**

Keywords-fading channel; MAI; 2-Dimensional block CDMA; CDTD

I. INTRODUCTION

In a broadband wireless communication system, high-speed and high-quality data transmissions are demanded [1],[2]. However, the wireless channel is composed of many propagation paths with different time delays, producing frequency-selective fading which significantly degrades the bit error rate (BER) performance. Frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can obtain the frequency diversity gain and significantly improve the BER performance [3]. MMSE-FDE can be applied to both direct sequence code division multiple access (DS-CDMA) and multi-carrier CDMA (MC-CDMA).

To further improve the BER performance, the use of transmit diversity technique is effective [4],[5]. Delay transmit diversity (DTD) [6],[7] transmits the same signal from different antennas with different time delays; however, the use of DTD limits the performance improvement due to inter-block interference (IBI) caused by the time delay added to the transmitter. To avoid IBI, cyclic delay transmit diversity (CDTD) was proposed for DS-CDMA and MC-CDMA [8],[9]. With CDTD, the same signal is simultaneously transmitted from different antennas after adding different cyclic delays. CDTD can obtain a larger frequency diversity gain and achieve better BER performance than DTD. The joint use of CDTD and MMSE-FDE can improve the BER performance in a weak frequency-selective fading channel [10],[11].

However, for the uplink (from mobile-to-base) transmission, since 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. 2-dimensional (2D) block spread CDMA makes it possible to achieve MAI free uplink transmission while obtaining the frequency diversity gain by using MMSE-FDE [12]~[14]. In this paper, CDTD is applied to the uplink using 2D block spread CDMA.

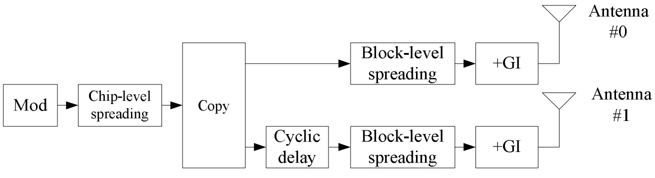
The remainder of the paper is organized as follows. Section 2 describes the uplink transmission system model of 2D block spread CDMA using CDTD. The achievable uplink BER performance is evaluated by computer simulation in Sect. 3. Finally, Sect. 4 offers some concluding remarks.

II. TRANSMISSION SYSTEM MODEL

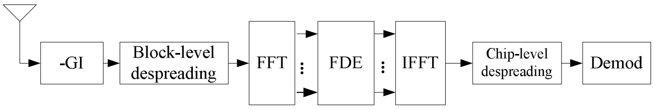
A. Overall Transmisson System

The uplink transmission systems model for 2D block spread CDMA using two-antenna CDTD is shown in Fig.1. 2-dimensinal 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 chip-level spreading is the same as traditional DS-(or MC-) CDMA. The chip-level spreading is used to achieve the frequency diversity gain while the block-level spreading is used to remove the MAI. CDTD is carried our between the chip-level spreading and block-level spreading.

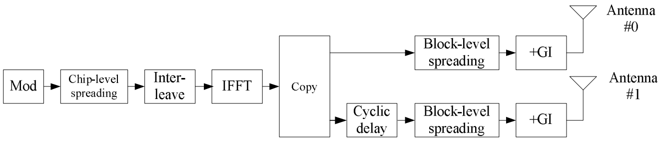
In this paper, we assume the square-root Nyquist chip shaping filter at the transmitter and the same filter at the receiver as the chip-matched filter. Ideal chip sampling timing is assumed at the receiver. Therefore, the chip-spaced discrete-time signal representation is used throughout the paper. In this paper, Δ is the cyclic time delay, $\lfloor a \rfloor$ represents the largest integer smaller than or equal to the real-valued variable a and $\lceil a \rceil$ represents the smallest integer larger than or equal to a.



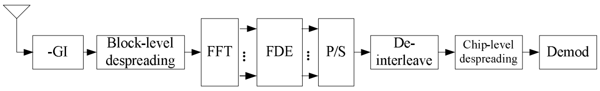
(a) DS-CDMA transmitter for one user



(b) DS-CDMA receiver for one user



(c) MC-CDMATransmitter for one user



(d) MC-CDMA receiver for one user

Figure 1. Uplink transmission system model for 2D block spread CDMA using two-antenna CDTD.

B. Transmitted signal

Assume that U users are simultaneously accessing the same base station. The data symbol sequence to be transmitted from the u-th (u=0~U-1) user is denoted by $\{d_u(n); n=0 \sim N_c/SF_f-1\}$, where SF_f is the chip-level spreading factor and N_c is the size of fast Fourier transform (FFT). The data symbol sequence $\{d_u(n); n=0 \sim N_c/SF_f-1\}$ is spread by chip-level spreading code $\{c_u^{SF_f}(t); t=0 \sim SF_f-1\}$ with $\left|c_u^{SF_f}(t)\right|=1$ and is further multiplied by a binary scramble sequence $\{c_u^{scr}(t); t=0 \sim N_c-1\}$ to make the resulting DS-CDMA chip sequence $\{s_u^{DS}(t); t=0 \sim N_c-1\}$ white-noise like. $s_u^{DS}(t)$ can be expressed as

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

In the case of MC-CDMA, N_c-point IFFT is applied to chip sequence $\{s_u^{DS}(t); t=0 \sim N_c-1\}$ to generate an MC-CDMA signal $\{s_u^{MC}(t); t=0 \sim N_c-1\}$. In order to make better use of the channel frequency-selectivity, a block interleaving of size $SF_f \times \left(N_c/SF_f\right)$ is performed before applying IFFT. $s_u^{MC}(t)$ can be expressed as

$$s_u^{MC}(t)=\frac{1}{\sqrt{N_c}}\sum_{n=0}^{N_c/SF_f-1}\sum_{i=0}^{SF_f-1}\left[s_u^{DS}\left(n\cdot SF_f+i\right)\times\exp\left\{j2\pi\frac{t}{N_c}\cdot\left(n+i\frac{N_c}{SF_f}\right)\right\}\right]. \tag{2}$$

The CDMA signal, $\{s_u^{DS}(t); t=0 \sim N_c-1\}$ for DS and $\{s_u^{MC}(t); t=0 \sim N_c-1\}$ for MC, is then copied into two streams, one of which is given the cyclic time delay Δ as shown in Fig. 2, where the case of N_c=8 and Δ=2 is shown as an example.

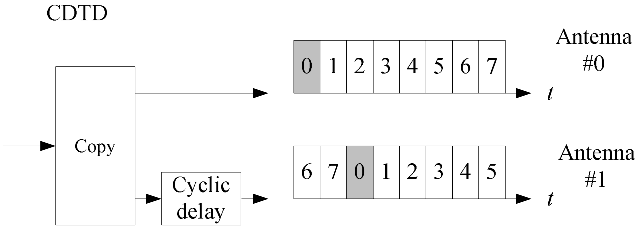


Figure 2. Cyclic time delay addition processing (N_c=8, Δ=2)

Finally, the CDMA signal is block spread by the block-level spreading code $\{c_u^{SF_t}(t); t=0 \sim SF_t-1\}$ with spreading factor SF_t. Before transmission, an N_g-chip guard interval (GI) is inserted every N_c-chip block to avoid the IBI. To keep the same total transmitted power as the single transmit antenna case, the transmit power from each antenna is halved. The 2D block spread CDMA signals to be transmitted from the two antennas can be expressed using the equivalent lowpass representation as

$$\begin{cases} \widehat{s}_u(t)=\dfrac{1}{\sqrt{2}}\cdot\sqrt{\dfrac{2E_c}{T_c}}s_u\left(t \bmod N_c\right)\cdot C_u^{SF_t}\left(\left\lfloor\dfrac{t}{N_c}\right\rfloor\right) & antenna\#0 \\ \widehat{s}_u^{\Delta}(t)=\dfrac{1}{\sqrt{2}}\cdot\sqrt{\dfrac{2E_c}{T_c}}s_u\left(\left(t-\Delta\right) \bmod N_c\right)\cdot C_u^{SF_t}\left(\left\lfloor\dfrac{t}{N_c}\right\rfloor\right) & antenna\#1 \end{cases} \tag{3}$$

for $t=-N_g \sim SF_t\left(N_c+N_g\right)-N_g-1$, where E_c is the average total chip energy and T_c is the chip duration.

C. Channel

The GI inserted signal is transmitted over a frequency- and time- selective fading channel; however the channel gain stays unchanged during one block interval $T=T_c\left(N_c+N_g\right)$ while it changes block by block. Assuming that the channel is composed of chip-spaced L independent paths, its impulse response $h_u(\tau)$ during the reception of one block is expressed as

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

where $h_{u,l}$ and $\tau_{u,l}$ are respectively the complex valued path gain and time delay of the l-th path of the u-th user's channel. $\tau_{u,l}$ is assumed to be $\tau_{u,l}=\tau_u+l\cdot T_c$, $l=0 \sim L-1$, and τ_u is the u-th user's transmit timing offset. The maximum time delay of $\{\tau_{u,l}\}$ is assumed to be shorter than the GI.

D. Received signal

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

$$r(t)=\sum_{u=0}^{U-1}\sum_{l=0}^{L-1}\left\{h_{u,0,l}\hat{s}_u(t-\tau_{u,0,l})+h_{u,1,l}\hat{s}_u^{\Delta}\left(t-\tau_{u,1,l}\right)\right\}+n(t) \quad (5)$$

where $n(t)$ is the zero-mean complex-valued additive white Gaussian noise (AWGN) sample with variance $2N_0/T_c$ (N_0 is the one-sided power spectrum density. The block despreading is applied as

$$\begin{aligned}\hat{r}_u(t)&=\frac{1}{SF_t}\sum_{i=0}^{U-1}r(t+iN_c)\left\{c_u^{SF_t}\right\}^*\\&=\sum_{l=0}^{L-1}\left\{h_{u,0,l}\hat{s}_u(t-\tau_{u,0,l})+h_{u,1,l}\hat{s}_u^{\Delta}\left(t-\tau_{u,1,l}\right)\right\}+n_u(t)\end{aligned} \quad (6)$$

for t=0~N_c-1. If the fading is very slow so that the path gains stay almost constant over at least SF_t consecutive blocks, the MAI can be completely removed since the block-level spreading codes $\{c_u^{SF_t}(t);t=0\sim SF_t-1\}$, u=0~U-1, are orthogonal.

E. FDE

The received N_c-chip block obtained after block despreading is decomposed into N_c subcarrier components $\{R_u(k):k=0\sim N_c-1\}$ by applying an N_c-point FFT. $R_u(k)$ is given as

$$\begin{aligned}R_u(k)&=\frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1}\hat{r}_u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right),\\&=S_u(k)\cdot H_u(k)+\Pi_u(k)\end{aligned} \quad (7)$$

with

$$H_u(k)=H_{u,0}(k)+H_{u,1}(k)\exp\left(-j2\pi k\frac{\Delta}{N_c}\right) \quad (8)$$

where

$$\begin{cases}S_u(k)=\dfrac{1}{\sqrt{N_c}}\displaystyle\sum_{t=0}^{N_c-1}s_u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\H_{u,0(1)}(k)=\dfrac{1}{\sqrt{N_c}}\displaystyle\sum_{t=0}^{L-1}h_{u,0(1),l}(t)\exp\left(-j2\pi k\frac{\tau_{u,0(1),l}}{N_c}\right).\\\Pi_u(k)=\dfrac{1}{\sqrt{N_c}}\displaystyle\sum_{t=0}^{N_c-1}n_u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases} \quad (9)$$

In the above, $H_{u,0}(k)$ ($H_{u,1}(k)$) represents the k-th subcarrier channel gain between the BS receive antenna and the 0th (1st) transmit antenna of MS; $H_u(k)$ is the composite channel gain obtained by applying CDTD; and $\Pi(k)$ represents the zero-mean noise component.

Then, MMSE-FDE is carried out as

$$R_u'(k)=R_u(k)\cdot w_u(k) \quad (10)$$

where $w_u(k)$ is the MMSE weight given by [12]

$$w_u(k)=\frac{H_u^*(k)}{\left|H_u(k)\right|^2+\left(SF_t\cdot\dfrac{E_c}{N_0}\right)^{-1}}. \quad (11)$$

For DS-CDMA, an N_c-point IFFT is applied to $R_u'(k)$ to get the time-domain chip sequence

$$r_u^{DS}{}'(t)=\frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1}R_u'(k)\exp\left(-j2\pi k\frac{t}{N_c}\right) \quad (12)$$

for t=0~N_c-1. In the case of MC-CDMA, application of N_c-point IFFT is not necessary and the signal $r_u^{MC}{}'(k)$ is obtained directly after the block deinterleaver as

$$r_u^{MC}{}'(t)=R_u'\left(\left(t\bmod SF_f\right)\cdot\left(N_c/SF_f\right)+\left\lfloor t/SF_f\right\rfloor\right) \quad (13)$$

Finally, the chip-level despreading is carried out on $r_u'(t)$ ($=r_u^{DS}{}'(t)$ for DS and $r_u^{MC}{}'(t)$ for MC) to obtain

$$d_u'(n)=\frac{1}{SF_f}\sum_{t=n\cdot SF_f}^{(n+1)\cdot SF_f-1}r_u'(t)\left[c_u^{SF_f}(t)\cdot c_u^{scr}(t)\right]^*, \quad (14)$$

which is the decision variable associated with $\{d_u(n)\}$, $n=0\sim N_c/SF_f-1$.

III. SIMULATION RESULTS

The achievable BER performance of the uplink 2D spread CDMA using CDTD is evaluated by the computer simulation. The simulation condition is summarized in Table 1. In our computer simulation, the constant spreading factor of $SF(=SF_f\cdot SF_t)=16$ is assumed. The lowest block-level spreading factor sufficient to remove the MAI is SF_t =U; therefore, $(SF_f,SF_t)=(SF/U,U)$ is used. f_D stands for maximum Doppler frequency and T(=T_c(N_c+N_g)) represnets one block length.

TABLE I. 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
	Cyclic time delay	Δ=16 chips
	Spreading factor	$SF(=SF_f\cdot SF_t)=16$
Channel	Type of fading	Rayleigh
	Power delay profile	L=16-path uniform
	f_DT	0.01, 0.001, and 0.0001
	Channel estimation	Ideal
Receiver	Equalization	MMSE-FDE

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 ration E_b/N_0 with the number U of users as a parameter.

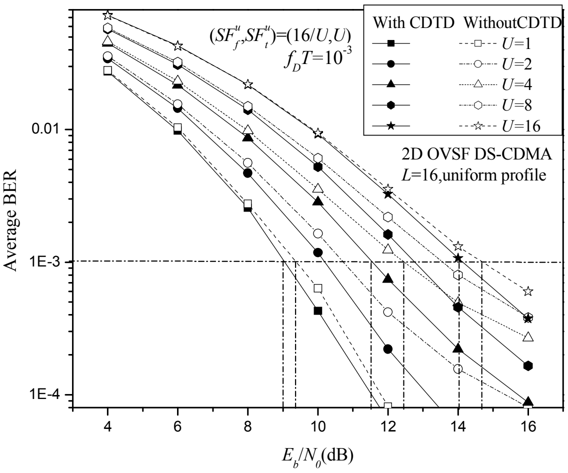


Figure 3 BER performance of 2D block spread DS-CDMA with CDTD.

It can be seen from Fig.3 that the 2D block spread CDMA with CDTD can improve the BER performance in DS-CDMA. When U=1 and BER=10^{-3}, the situation with CDTD has over 0.3dB increasing; while when U=16 and BER=10^{-3}, the improvement is about 0.7dB. Thus, the BER performance, which is with CDTD, is slight improvement with U increasing. It is because when U is large, SF_f is smaller, so at this time the affection of the diversity gain becomes stronger.

For both cases of with and without CDTD, the BER performance degrades as U increases. 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 when U=16; no suppression of ISI is achieved (spreading is used to remove the MAI only). To improve the BER performance for large U, some ISI interference cancellation techniques must be introduced.

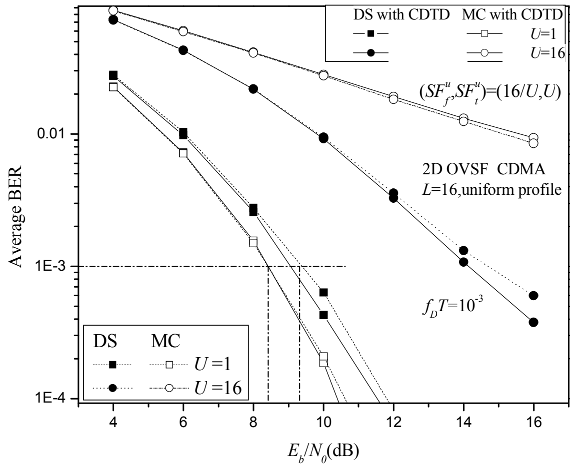


Figure 4 Performance comparison between 2D block spread MC-CDMA and DS-CDMA when CDTD is used.

Comparison between 2D block spread with CDTD is shown in Fig. 4. It is seen that the CDTD improves the BER performance for only DS-CDMA. For MC-CDMA, the performances with or without CDTD are almost the same.

Both with and without CDTD, when U=16, DS-CDMA provides much better performance than MC-CDMA. The reason for this is given below. Since $(SF_f, SF_t) = (SF/U, U)$, SF_f=1 when U=16. In this case, MC-CDMA cannot obtain the frequency diversity gain, while DS-CDMA can obtain it since each data symbol is always spread over all subcarriers irrespective of SF_f. However, as U decreases, SF_f increases and MC-CDMA can also obtain the frequency diversity gain, thereby improving the BER performance as DS-CDMA. For an extreme case of U=1, MC-CDMA reduces the required E_b/N_0 BER=$10^{-3}$by about 1dB compared to DS-CDMA. This is because no ISI exists in MC-CDMA while DS-CDMA suffers from the residual ISI after MMSE-FDE.

In Fig. 5, how f_DT (or the fading rate) affects the achievable BER performance is shown for the case of U=8. When f_DT = 10^{-3} and 10^{-4}, almost the same BER performance can be achieved. CDTD is seen to provide about 1dB gain in the required E_b/N_0 for BER=10^{-3}. This gain is because the path gains stay almost unchanged over SF_t=8 consecutive chip-blocks and hence, orthogonality among users can be maintained. 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.

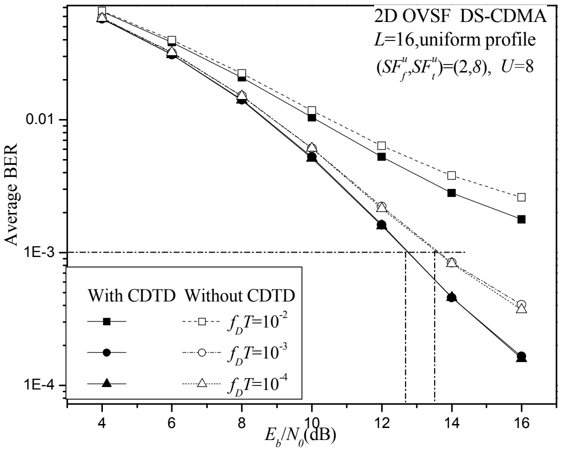


Figure 5 Impact of f_DT.

IV. CONCLUSIONS

In this paper, we applied CDTD to the uplink using 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 CDTD can improve the uplink BER performance in DS-CDMA. The comparison between different f_DT showed that the BER performances are almost the same when the value of f_DT is small enough, however with the increasing of f_DT, the BER performance degrades significantly. For the path gains tend to vary over consecutive chip-blocks and hence, the orthogonality among different users is distorted, so the MAI is partly remained. In the future, we will do research on the problem.

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