Frequency-domain Pre-equalization Transmit Diversity for DS-CDMA Mobile Radio

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***Abstract*—Recently, frequency-domain equalization has been attracting an attention for improving the single-carrier transmission (i.e. DS-CDMA) performance in a frequency-selective fading channel. In the case of uplink transmissions, the orthogonality among users' signals is lost since each user's signal goes through a different fading channel and hence, the use of frequency-domain equalization at the receiver cannot sufficiently improve the uplink transmission performance. In this paper, we propose frequency-domain pre-equalization transmit diversity (FPTD), which employs pre-equalization using multiple transmit antennas with transmit power constraint, in order to transform a frequency-selective channel seen at a base station receiver to a close-to-frequency-nonselective channel. The BER performance with proposed frequency-domain pre-equalization transmit diversity is evaluated by computer simulation.**

Keywords-component;DS-CDMA, transmit-diversity, frequency-domain equalization, frequency-selective channel

I. INTRODUCTION

High speed data transmissions of over 100Mbps are required for the next generation mobile communications systems. However, mobile channel is composed of many propagation paths with different time delays, producing severe frequency-selective fading channel, and therefore, the bit error rate (BER) performance significantly degrades due to severe inter-symbol inference (ISI) [1]. Recently, direct sequence code division multiple access (DS-CDMA) with rake combining has been applied to improve the BER performance. However, for a transmission of more than 100 Mbps, the number of resolvable propagation paths increases and thus, the transmission performance of DS-CDMA with rake combining substantially degrades due to the severe inter-path-interference (IPI).

Frequency-domain equalization (FDE) is an effective technique for improving the single-carrier (SC) transmission performance in a frequency-selective fading channel [2]. FDE can be applied to DS-CDMA to obtain a good BER performance similar to that of multi-carrier code division multiple access (MC-CDMA) [3, 4]. However, in uplink transmissions, each user's signal goes through a different fading channel and the orthogonality among users is lost, producing large multi-access interference (MAI), and hence, the BER performance significantly degrades.

Recently, frequency-domain pre-equalization at a transmitter has been attracting attention for improving the MC-CDMA uplink transmission performance [5-7]. Frequency domain pre-equalization can also be applied to SC transmissions [8, 9]. In this paper, we consider DS-CDMA uplink transmissions and apply frequency-domain pre-equalization to reduce the MAI, thereby improving the uplink performance in a multi-user environment. DS-CDMA signal is decomposed by fast Fourier transform (FFT) into frequency components, to each of which the transmit diversity technique [10-13] is applied, similar to MC-CDMA. This is called frequency-domain pre-equalization transmit diversity (FPTD) in this paper. By applying transmit diversity technique on each frequency component, a frequency-selective channel can be transformed into a close-to-frequency-nonselective channel, and thus, the MAI can be effectively suppressed.

For performing FPTD, the knowledge of the uplink fading channel is required. The uplink fading channel can be estimated using the downlink channel in the time division duplex (TDD) systems, which uses the same carrier frequency for both uplink and downlink channels. TDD can flexibly assign the limited channel resources to uplink and downlink. Another advantage of TDD is that channel reciprocity (fading is highly correlated between the uplink and downlink), due to the same carrier frequency being used for both uplink and downlink, facilitates adaptive communication techniques. Therefore, TDD is considered as a promising duplex technique in the next generation mobile communications systems [14]. The complexity of the mobile terminals increases with the use of FPTD. However, at the cost of increasing complexity of a mobile terminal, the use of FPTD can significantly improve the DS-CDMA uplink transmission performance in a multi-user environment.

In this paper, we evaluate the effect of the proposed FPTD on the uplink BER performance of DS-CDMA using TDD. The remainder of this paper is organized as follows. Sect. II describes the proposed FPTD for the DS-CDMA uplink transmission. In Sect. III, the average BER performance is evaluated by computer simulation. Sect. IV offers some conclusions.

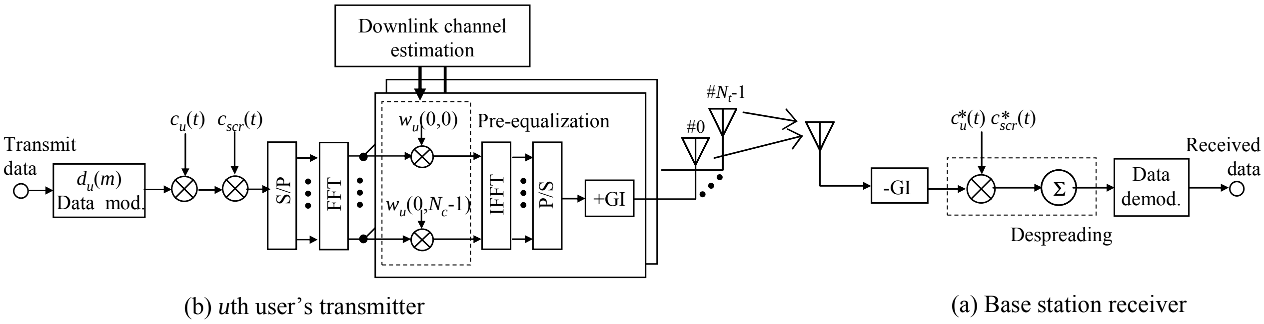

Fig. 1 Transmitter and receiver structure of DS-CDMA using FPTD.

II. PROPOSED FPTD FOR DS-CDMA UPLINK TRANSMISSION

A. Over all transmission system

We assume that U users are simultaneously communicating with a base station. Figure 1 illustrates the mobile terminal transmitter and base station receiver employing the proposed FPTD for the uth user. At the uth user's transmitter, a data-modulated symbol sequence to be transmitted is spread by an orthogonal spreading code $c_u(t)$ to obtain the chip sequence and is multiplied by a scramble sequence $c_{scr}(t)$. The resultant DS-CDMA chip sequence is divided into a sequence of chip blocks of N_c chips each. Then, each chip block is decomposed by N_c-point fast Fourier transform (FFT) into N_c frequency components, each of which is multiplied by N_t pre-equalization weights, where N_t represents the number of transmit antennas. Then, N_c-point inverse FFT (IFFT) is applied to generate the pre-equalized DS-CDMA signals, which are transmitted from N_t transmit antennas after insertion of the guard interval (GI). N_t pre-equalized DS-CDMA signals transmitted over a frequency-selective channel are superimposed and received at the base station receiver. After removal of GI from the received signal, despreading is carried out, followed by data demodulation. Note that no FDE is required at the base station receiver.

Through out the paper, chip-spaced discrete time representation of the transmitted signal is used. In what follows, without loss of generality, we assume a transmission of one chip block with N_c/SF data symbols $\{d_u(m);\ m=0\sim N_c/SF\text{-}1\}$.

B. Pre-equalization

The uth user's DS-CDMA chip sequence $\{s_u(t);t=0\sim N_c\text{-}1\}$ can be expressed as

$$s_u(t)=\sqrt{\frac{2E_c}{T_c}}c_u(t \bmod SF)c_{scr}(t)d_u\left(\left\lfloor\frac{t}{SF}\right\rfloor\right) \quad , \qquad (1)$$

where E_c, T_c, $c_u(t)$ and $c_{scr}(t)$ denote the transmit signal energy per a chip, the chip duration, the orthogonal spreading code with spreading factor SF with $|c_u(t)|=1$, and the scramble code, respectively. $\lfloor x\rfloor$ is the largest integer smaller than or equal to x. $s_u(t)$ is decomposed by N_c-point FFT into N_c frequency components $\{S_u(k);k=0\sim N_c\text{-}1\}$:

$$S_u(k)=\sum_{t=0}^{N_c-1}s_u(t)\exp\left(-j2\pi t\frac{k}{N_c}\right),\quad k=0\sim N_c-1\quad . \qquad (2)$$

The pre-equalized signals in the frequency-domain can be expressed, using the vector representation, as

$$\tilde{\mathbf{S}}_u(k)=[\tilde{S}_u(0,k),\tilde{S}_u(1,k),\ldots,\tilde{S}_u(N_t-1,k)]^{\mathrm{T}}=S_u(k)\mathbf{w}_u(k)\quad , (3)$$

where $\tilde{S}_u(n,k)$ is the kth frequency component of the pre-equalized signal to be transmitted from the nth antenna and $\mathbf{w}_u(k)=[w_u(0,k), w_u(1,k),\ldots, w_u(N_t\text{-}1,k)]^{\mathrm{T}}$ is the pre-equalization weight vector with $\|\mathbf{w}_u(k)\|^2=1$ ($\|\cdot\|$ represents the vector norm operation). In this paper, we propose a FPTD using controlled equalization transmit (CET) weight. In CET-FPTD pre-equalization, a threshold is introduced; equal gain transmit (EGT) weight, which provides the same transmit power for all transmit antennas, is used if the equivalent transmit channel gain after pre-equalization is above the threshold and maximal-ratio transmit (MRT) weight is used otherwise. The nth element $w_u(n,k)$ of $\mathbf{w}_u(k)$ is given by

$$w_u(n,k)=\begin{cases}\dfrac{H_u^*(n,k)}{\sqrt{\sum_{n=0}^{N_t-1}|H_u(n,k)|^2}}=w_{u,\mathrm{MRT}}(n,k) & \text{if } \left|\tilde{H}_{\mathrm{MRT},u}(k)\right|<\gamma_0\\[2ex] \dfrac{1}{\sqrt{N_t}}\dfrac{H_u^*(n,k)}{|H_u(n,k)|}=w_{u,\mathrm{EGT}}(n,k) & \text{otherwise}\end{cases}\quad , (4)$$

where $H_u(n,k)$ represents the nth element of the channel gain vector $\mathbf{H}_u(k)=[H_u(0,k), H_u(1,k),\ldots, H_u(N_t\text{-}1,k)]^{\mathrm{T}}$ of the uth user and $\tilde{H}_{\mathrm{MRT},u}(k)$ is the equivalent channel gain observed at the receiver (defined in Sect II.D). It can be understood from Eq. (4) that since the complex conjugation of the channel gain is used in the pre-equalization weight, all users' signals are received in phase and hence the MAI can be reduced.

MRT pre-equalization maximizes the received instantaneous signal-to-noise power ratio (SNR) at the base station receiver. CET acts as EGT (or MRT) when the MRT equivalent channel gain is larger (or smaller) than the prescribed threshold value γ_0. By doing so, the frequency-selectivity of the pre-equalized channel seen at the receiver can be suppressed well compared with MRT pre-equalizations.

Applying N_c-point IFFT to $\widetilde{\mathbf{S}}_u(k)$, the pre-equalized chip sequence vector $\{\widetilde{\mathbf{s}}_u(t); t=0\sim N_c-1\}$ is generated by

$$\widetilde{\mathbf{s}}_u(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\widetilde{\mathbf{S}}_u(k)\exp\left(j2\pi k\frac{t}{N_c}\right) \quad . \qquad (5)$$

After insertion of the GI, the pre-equalized chip sequence vector is transmitted using N_t transmit antennas.

C. Received signal and despreading

Perfect transmit timing control is assumed such that all user's signals arrive at the base station antenna at the same timing. It is assumed that fading channel is composed of L independent propagation paths with the lth path time delay of lT_c. Using path gain vector $\mathbf{h}_{u,l}=[h_{u,l,0}, h_{u,l,1},..., h_{u,l,Nt-1}]^{\mathrm{T}}$ of the lth path for the uth user, the channel gain vector $\mathbf{H}_u(k)$ can be expressed as

$$\mathbf{H}_u(k)=\left[\mathbf{h}_{u,0},...,\mathbf{h}_{u,l},...,\mathbf{h}_{u,L-1}\right]\begin{bmatrix}1\\ \vdots\\ \exp(-j2\pi k\, l/N_c)\\ \vdots\\ \exp(-j2\pi k(L-1)/N_c)\end{bmatrix}. \quad (6)$$

The received signal is given by

$$r(t)=\sum_{u=0}^{U-1}\sum_{l=0}^{L-1}\mathbf{h}_{u,l}^{\mathrm{T}}\widetilde{\mathbf{s}}_u(t-l)+n(t) \quad , \qquad (7)$$

where $n(t)$ represents the complex-valued zero-mean additive white Gaussian noise (AWGN). After removal of GI from the superimposed received DS-CDMA signal, the decision variable $\hat{d}_u(m)$, m=0~ N_c/SF-1, is obtained by despreading for the mth data-modulated symbol $d_u(m)$ of the uth user as

$$\hat{d}_u(m)=\frac{1}{SF}\sum_{t=mSF}^{(m+1)SF-1}r(t)c_u^*(t \bmod SF)c_{scr}^*(t) \quad , \qquad (8)$$

based on which data-demodulation is carried out.

D. Equivalent channel gain

The kth frequency component of the received signal is given by

$$\begin{aligned}R(k)&=\sum_{t=0}^{N_c-1}r(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ &=\sum_{u=0}^{U-1}\widetilde{H}_u(k)S_u(k)+N(k)\end{aligned} \quad , \qquad (9)$$

where

$$\widetilde{H}_u(k)=\mathbf{H}_u^{\mathrm{T}}(k)\mathbf{w}_u(k) \qquad (10)$$

is the equivalent channel gain after pre-equalization and $N(k)$ is the noise component due to the AWGN.

III. SIMULATION RESULTS

Table 1 summarizes the simulation condition. Quaternary phase shift keying (QPSK) data-modulation and a chip-spaced L=16-path frequency-selective Rayleigh fading channel having an exponential power delay profile with decay factor α dB are assumed. For comparison, the BER performance achievable with MMSE-FDE reception using a single transmit antenna and N receive antennas (N_t=1 and N_r=N) [4] and the BER performance achievable with MC-CDMA using N_t-transmit antennas FPTD and a single receive antenna are also shown.

Firstly, we consider the BER performance for single-user case (U=1). Figure 2 shows the performance comparison between N (=N_t)-transmit antenna FPTD and N-receive antenna MMSE-FDE reception. For FPTD, only MRT weight is considered since CET weight provides almost the same BER performance in the case of U=1. The BER performance can be significantly improved by increasing N. The BER performance of N-transmit antenna MRT-FPTD is slightly worse than that of N-receive antenna MMSE-FDE reception. However, the E_b/N_0 degradation for BER=10^{-4} is 0.8 dB, 0.4 dB and 0.2 dB with MRT-FPTD when N=1, 2 and 4, respectively.

Next, we consider the multi-user case (U=64). The BER performances with MRT and CET are plotted with N_t as a parameter in Fig. 3, where γ_0 for CET is optimized at the transmit E_b/N_0=10dB. For comparison, the BER performance of MMSE-FDE reception is also plotted. It is seen that although the BER performance with MMSE-FDE reception is

Table 1 Simulation conditions.

Data modulation		QPSK
DS-CDMA	No. of FFT points	N_c=256
	Guard interval	N_g=32
FPTD	Pre-equalization weight	MRT, CET
	No. of transmit antennas	N_t=1, 2, 4
	Spreading factor	SF=64
Channel model	No. of paths	L=16
	Power delay profile	Exponential with decay factor α=0, 4, 8 (dB)
	Time delay	τ_l=lT_c, l=0~L-1
	Normalized maximum Doppler frequency	f_DT=0.001 (T=(N_c+N_g)T_c)
Channel estimation		Ideal

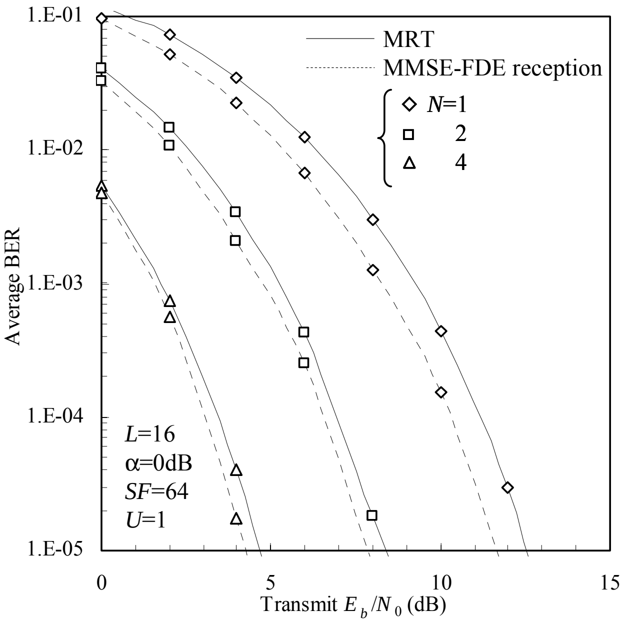

Fig. 2 BER performance comparison with MMSE-FDE reception. Single-user case (U=1).

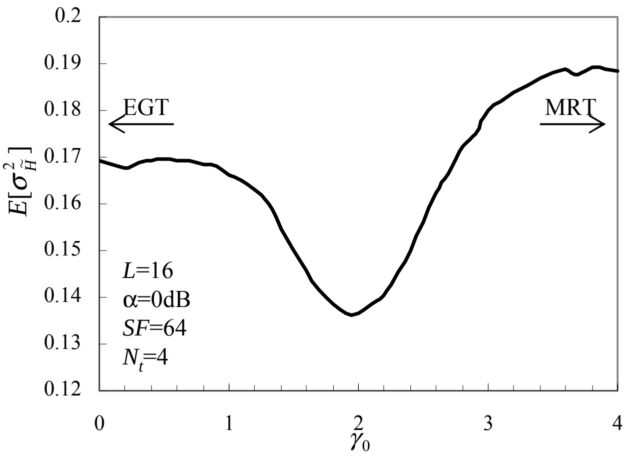

Fig. 4 Dependency of MAI on γ_0.

improved by increasing N, high BER floors are observed. This is because MAI cannot be sufficiently suppressed by MMSE-FDE reception. On the other hand, CET-FPTD and MRT-FPTD can transform the each user's transmit channel to a close-to-frequency-nonselective channel while improving the SNR, and therefore, the orthogonality among different users can be restored to some extent, thereby, a better BER performance than MMSE-FDE reception can be achieved. CET-FPTD provides slightly better BER performance than MRT-FPTD. The reason for this is explained below.

Assuming that all the received DS-CDMA signals transmitted from different users are synchronous, MAI is caused only by the residual variations in the equivalent channel gain. MAI is proportional to the variance $\sigma^2_{\tilde{H}}$ of the equivalent channel gain $\tilde{H}_u(k)$ (see Eq. (10)). $\sigma^2_{\tilde{H}}$ is given by

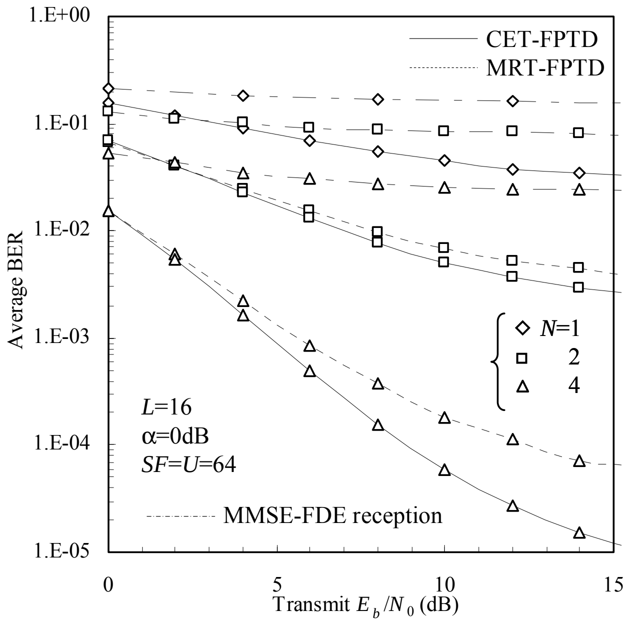

Fig. 3 BER performance comparison with CET-, MRT-FPTD and MMSE-FDE reception. Multi-user case (U=64).

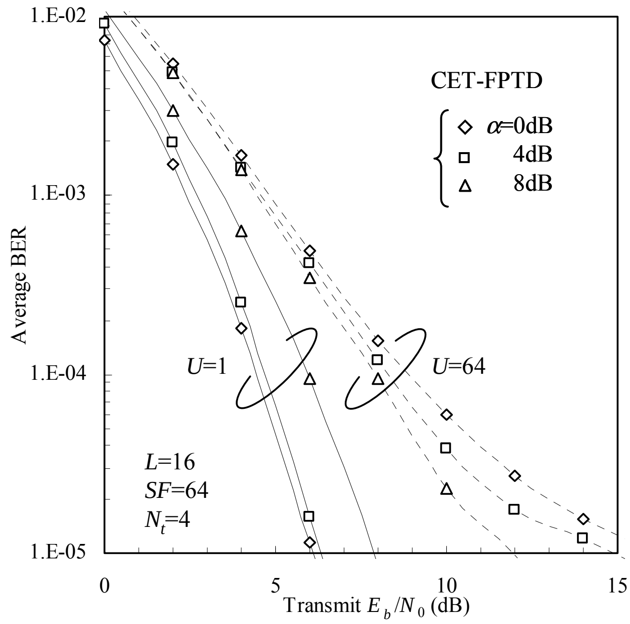

Fig. 5 Impact of decay factor.

$$\begin{aligned}\sigma^2_{\tilde{H}} &= \frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}\left|\tilde{H}_u(k)-\frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}\tilde{H}_u(k)\right|^2 \\ &= \frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}\left|\tilde{H}_u(k)\right|^2-\left|\frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}\tilde{H}_u(k)\right|^2\end{aligned} \quad (11)$$

Figure 4 shows the ensemble average of $E[\sigma^2_{\tilde{H}}]$ as a function of γ_0. For comparison, $E[\sigma^2_{\tilde{H}}]$ is also indicated for MRT in

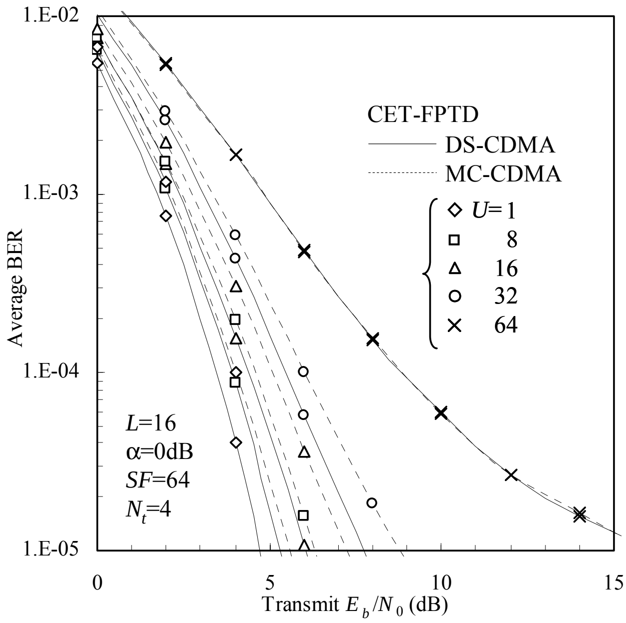

Fig. 6 Comparison of DS-CDMA and MC-CDMA.

Fig. 4 (note that CET with $\gamma_0 \to \infty$ (0) corresponds to MRT (EGT), respectively). It can be seen that CET can reduce the value of $E[\sigma_H^2]$ by optimizing the value of γ_0 and hence reduces the MAI, compared to MRT. The optimum γ_0 is seen to be γ_0=2. By using γ_0=2, CET-FPTD provides a better BER performance than MRT.

Figure 5 shows the impact of the decay factor α on the average BER performance with CET-FPTD as a function of the transmit E_b/N_0 for α=0, 4 and 8 dB. When U is small (U=1), α=0 dB gives better BER performance than for α=8 dB due to larger frequency diversity effect. However, when U is large (U=64), the performance for α=0 dB is worse than that for α=8 dB. This is because, as the frequency-selectivity becomes severer, larger MAI is produced and offsets the frequency diversity effect.

Figure 6 compares DS-CDMA and MC-CDMA both using CET-FPTD as a function of the transmit E_b/N_0 with the number U of users as a parameter for N_t=4. It can be seen that the BER performance of DS-CDMA is slightly better than that of MC-CDMA expect for U=64. This is because in DS-CDMA each data symbol is spread over the entire bandwidth and thereby, larger frequency diversity effect can be achieved than MC-CDMA. When U=64, DS-CDMA and MC-CDMA give almost the same BER performance. This is because a predominant cause of errors is the MAI and difference in the frequency diversity effect between DS- and MC-CDMA can be negligible.

IV. CONCLUSION

In this paper, frequency-domain pre-equalization transmit diversity (FPTD) for improving the BER performance was proposed for DS-CDMA uplink transmission. Frequency-domain equalization (FDE) reception is not necessary at a base station receiver. The average BER performance was evaluated by computer simulation. With FPTD, the equivalent transmit channel of each user can be transformed to a close-to-frequency-nonselective channel for all users, and hence, the orthogonality among different user's signals is retained to some extent (unlike the conventional DS-CDMA uplink transmission, orthogonal spreading codes are used for different users), thereby improving the BER performance. This was confirmed by computer simulation. It was also shown that DS-CDMA provides a slightly better BER performance than MC-CDMA when CET-FPTD is used for both CDMA schemes.

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