Frequency-domain Pre-equalization Transmit Diversity for MC-CDMA

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Abstract— **Recently, multi-carrier code division multiple access (MC-CDMA) has been attracting much attention for the broadband wireless access in the next generation mobile communications systems. In the case of uplink transmissions, the orthogonality property among users' signals is lost since each user's signal goes through different fading channel and hence, multi-access interference (MAI) is produced, thereby significantly degrading the transmission performance compared to the downlink case. The use of frequency-domain equalization (FDE) at the receiver cannot sufficiently suppress the MAI. 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 receiver to the frequency-nonselective channel. The BER performance with proposed frequency-domain pre-equalization transmit diversity is evaluated by computer simulation.**

Keywords— **Pre-equalization, transmit diversity, MC-CDMA, frequency-domain equalization, frequency-selective channel**

I. Introduction

High speed and high quality data transmissions 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 transmission performance degrades due to severe inter-symbol inference (ISI) [1]. Recently, multi-carrier code division multiple access (MC-CDMA), which uses a number of lower rate subcarriers to reduce the ISI resulting from frequency-selective channel, has been attracting much attention [2,3]. Multiple access capability is attained by frequency-domain spreading using user-specific orthogonal spreading codes. In the case of downlink, a good bit error rate (BER) performance can be achieved by using frequency-domain equalization (FDE) at the receiver [4]. However, in the case of uplink, each user's signal goes through different fading channel, and the orthogonality property among users is lost, resulting in multi-access interference (MAI), and hence, the BER performance degrades [3]. The BER performance cannot be sufficiently improved by using only FDE at the receiver.

Recently, frequency-domain pre-equalization at a transmitter has been under study to improve the MC-CDMA uplink transmission performance [5-7]. In [5-7], a single antenna is used and FDE similar to the frequency-domain equalization used at the receiver is applied at the transmitter. Unlike the previous works [5-7], in this paper, we apply transmit antenna diversity [8-11] to each subcarrier of MC-CDMA signal and propose a frequency-domain pre-equalization transmit diversity (FPTD) to effectively suppress the MAI for MC-CDMA uplink transmissions. In the proposed FPTD, subcarrier-by-subcarrier pre-equalization achieved by antenna diversity transmission is employed and orthogonal spreading codes are used by different users unlike the conventional MC-CDMA uplink transmission. For performing FPTD, the knowledge of the uplink fading channel is required. The uplink channel can be estimated using the downlink channel for the case of time division duplex (TDD) [12]. In this paper, FPTD is presented for MC-CDMA/TDD and then, the BER performance of MC-CDMA/TDD uplink with FPTD is evaluated by computer simulation.

II. Proposed FPTD for MC-CDMA uplink transmission

Figure 1 illustrates the transmitter and receiver structure employing the proposed FPTD for the *j*th user. At the transmitter, a sequence of modulated data symbols to be transmitted is spread in time-domain by an orthogonal spreading code with the spreading factor *SF* to obtain the chip sequence (we assume that orthogonal spreading codes are used unlike the conventional uplink transmission of MC-CDMA, where pseudo-random spreading codes are used by different users). After serial-to-parallel (S/P) conversion, the chip sequence is converted into N_c (N_c is the number of subcarriers) parallel streams, 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 fast Fourier transform (IFFT) is applied to transform the time-domain spread signal into the frequency-domain spread signal, which is the pre-equalized MC-CDMA signals to be transmitted from N_t transmit antennas after insertion of the guard interval (GI). N_t pre-equalized MC-CDMA signals transmitted over a frequency-selective channel are superimposed and received at a base station receiver. At the base station receiver, after removal of GI from the received MC-CDMA signal, N_c-point FFT is applied to decompose it into the N_c subcarrier components. After parallel-to-serial (P/S) conversion, despreading is carried out, followed by data demodulation. Note that no FDE is required at the base station receiver, while it is needed at the mobile terminal receiver for the downlink signal reception.

In what follows, without loss of generality, we assume a transmission of N_c/SF data symbols $\{d_j(m);\ m=0\sim N_c/SF\text{-}1\}$ over one MC-CDMA signaling interval.

A. Pre-equalization

Using the pre-equalization weight vector $\mathbf{w}_j(k) = [w_j(0,k), w_j(1,k),..., w_j(N_t\text{-}1,k)]^{\mathrm{T}}$, the transmit signal vector of the *j*th user at the *k*th subcarrier can be expressed as

$$\begin{aligned}\mathbf{s}_j(k) &= [s_j(0,k), s_j(1,k),..., s_j(N_t-1,k)]^{\mathrm{T}} \\ &= \sqrt{\frac{2S}{SF}}\mathbf{w}_j(k)c_j(k \bmod SF)d_j(m)\end{aligned} \quad (1)$$

with

$$\left\|\mathbf{w}_j(k)\right\|^2 = 1, \quad (2)$$

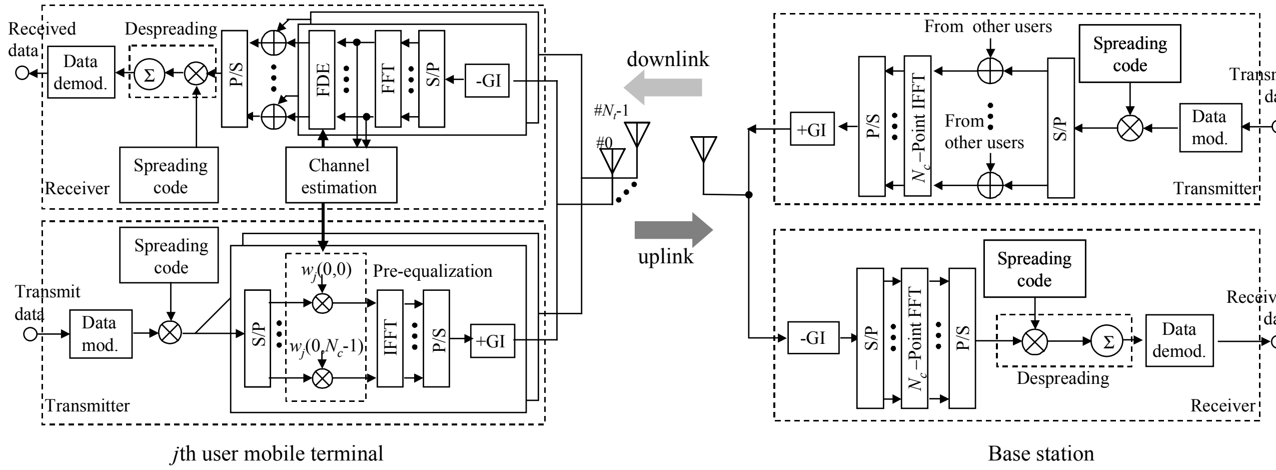


Fig. 1 Transmitter and receiver structure of MC-CDMA using FPTD

where S, $c_j(k)$, and $d_j(m)$ denote the transmit signal power, the kth chip of the orthogonal spreading code with spreading factor SF, and the mth data-modulated symbol, respectively, and $\|\cdot\|$ represents the vector norm operation. We use subcarrier-by-subcarrier pre-equalization schemes based on the well-known diversity combining schemes [1], i.e., maximal ratio combining (MRC), equal gain combining (EGC), and selection combining (SC). The nth element of $\mathbf{w}_j(k)$ is given by

$$w_j(n,k)=\begin{cases}\dfrac{H_j^*(n,k)}{\sqrt{\sum_{n=0}^{N_t-1}|H(n,k)|^2}}, & \text{MRC}\\[2ex] \dfrac{1}{\sqrt{N_t}}\dfrac{H_j^*(n,k)}{|H_j(n,k)|}, & \text{EGC}\\[2ex] \begin{cases}\dfrac{H_j^*(n,k)}{|H_j(n,k)|}, \text{if } |H_j(n,k)|=\arg\max_{n'}\{|H_j(n',k)|\}\\ 0, \quad \text{otherwise}\end{cases}, & \text{SC}\end{cases} \quad ,(3)$$

where $H_j(n,k)$ represents the nth element of the channel gain vector of $\mathbf{H}_j(k)=[H_j(0,k), H_j(1,k),..., H_j(N_t\text{-}1,k)]^{\mathrm{T}}$ of the jth user. It can be understood from Eq. (3) 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.

MRC pre-equalization maximizes the instantaneous received signal-to-noise power ratio (SNR) at the mobile receiver, while EGC pre-equalization equalizes the phase only. In SC, one of the N_t transmit antennas providing the strongest channel gain is selected to transmit each subcarrier after phase equalization. The difference of our SC pre-equalization from the transmit antenna diversity scheme presented in Ref. [11] is that in our proposed scheme, phase equalization is used in order to make all subcarrier components arrive at the receiver in phase.

Applying N_c-point IFFT to $\mathbf{s}_j(k)$, the pre-equalized MC-CDMA signal vector is obtained as

$$\begin{aligned}\tilde{\mathbf{s}}_j(t)&=\sum_{k=0}^{N_c-1}\mathbf{s}_j(k)\exp\left(j2\pi t\,k/N_c\right)\\&=[\tilde{s}_j(0,t),\tilde{s}_j(1,t),...,\tilde{s}_j(N_t-1,t)]^{\mathrm{T}} \quad .(4)\\&\quad ,\text{for } t=0\sim N_c-1\end{aligned}$$

After insertion of the GI, the pre-equalized MC-CDMA signal vector is transmitted using N_t transmit antennas.

B. Fading channel

The fading channel composed of L independent propagation paths is assumed. The time delay of the lth path is assumed to be lT_c with T_c representing the FFT/IFFT sampling period. Using path gain vector $\boldsymbol{\xi}_{j,l}=[\xi_{j,l,0}, \xi_{j,l,1},..., \xi_{j,l,N_t\text{-}1}]^{\mathrm{T}}$ of the lth path for the jth user, the channel gain vector $\mathbf{H}_j(k)$ can be expressed as

$$\mathbf{H}_j(k)=\left[\boldsymbol{\xi}_{j,0},...,\boldsymbol{\xi}_{j,l},...,\boldsymbol{\xi}_{j,L-1}\right]\begin{bmatrix}1\\ \vdots\\ \exp\left(-j2\pi k\,l/N_c\right)\\ \vdots\\ \exp\left(-j2\pi k\,(L-1)/N_c\right)\end{bmatrix} \quad .(5)$$

C. Received signal and despreading

Transmit timing control is assumed such that the time delays of all paths of all users are within the GI. The received signal is the superposition of MC-CDMA signals transmitted from U different users and can be expressed as

$$r(t)=\sum_{j=0}^{U-1}\sum_{l=0}^{L-1}\boldsymbol{\xi}_{j,l}^{\mathrm{T}}\tilde{\mathbf{s}}_j(t-l)+n(t) \quad , \quad (6)$$

where $n(t)$ represents the complex-valued additive white Gaussian noise (AWGN) having zero mean and variance $2\sigma^2$. After removal of GI from the received MC-CDMA signal, N_c-point FFT is applied to decompose it into the N_c subcarrier components. The kth subcarrier component $R(k)$ is represented as

$$\begin{aligned}R(k)&=\sum_{j=0}^{U-1}\mathbf{H}_j^{\mathrm{T}}(k)\mathbf{s}_j(k)+N(k)\\&=\sqrt{\frac{2S}{SF}}\sum_{j=0}^{U-1}\tilde{H}_j(k)c_j(k \bmod SF)d_j(m)+N(k)\end{aligned} \quad , \quad (7)$$

where

$$\tilde{H}_j(k)=\mathbf{H}_j^{\mathrm{T}}(k)\mathbf{w}_j(k) \quad (8)$$

is the equivalent channel gain associated with the jth user at the kth subcarrier and $N(k)$ is the noise component at the kth subcarrier owing to the AWGN. The soft decision value $\hat{d}_j(m)$, m=0~N_c/SF-1, for the mth data-modulated symbol of the jth user is obtained by despreading as

$$\hat{d}_j(m)=\frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}R(k)c_j^*(k \bmod SF) \quad . \quad (9)$$

Substituting Eq. (7) into Eq. (9), we have

$$\hat{d}_j(m)=\sqrt{\frac{2S}{SF}}\left(\frac{1}{SF}\sum_{k=mSF}^{(m+1)SF-1}\tilde{H}_j(k)\right)d_j(m)+\mu_{MAI}+\mu_{AWGN} \quad , (10)$$

where the first term represents the desired signal component and the second and third terms denote the MAI component and the noise component due to the AWGN, respectively, and are given by

$$\begin{cases}\mu_{MAI}=\dfrac{1}{SF}\sqrt{\dfrac{2S}{SF}}\displaystyle\sum_{k=mSF}^{(m+1)SF-1}\sum_{\substack{u=0\\u\neq j}}^{U-1}\begin{Bmatrix}\tilde{H}_u(k)c_u(k \bmod SF)\\ \times c_j^*(k \bmod SF)d_u(m)\end{Bmatrix}\\ \mu_{AWGN}=\dfrac{1}{SF}\displaystyle\sum_{k=mSF}^{(m+1)SF-1}N(k)c_j^*(k \bmod SF)\end{cases} . \quad (11)$$

III. COMPUTER SIMULATION

D. Simulation conditions

The average BER performance of MC-CDMA uplink with FPTD is evaluated by computer simulation. Table 1 summarizes the simulation conditions. Quadrature phase shift keying (QPSK) data modulation, N_c=256, N_g=32, and a sample-spaced L-path frequency-selective Rayleigh fading channel having an exponential power delay profile with decay factor α dB are assumed. Ideal channel estimation is assumed.

E. BER performance with frequency-domain equalization reception (no pre-equalization)

First of all, the BER performance with no transmit diversity but MRC-, MMSE-, and EGC-FDE at a receiver are evaluated by computer simulation. Figure 2 shows the average BER performance with FDE reception as a function of the received E_b/N_0 (=0.5(E_s/N_0)(1+N_g/N_s)) with the number U of users as a parameter, where E_s(=SN_cT_c) is the transmit symbol energy. The FDE weight is given by [3], [13]

$$w_j(k)=\begin{cases}H_j^*(k) & ,\text{MRC}\\ \dfrac{H_j^*(k)}{\displaystyle\sum_{j=0}^{U-1}\left|H_j(k)\right|^2+\left(\dfrac{E_s/N_0}{SF}\right)^{-1}} & ,\text{MMSE}\\ H_j^*(k)/\left|H_j(k)\right| & ,\text{EGC}\end{cases} \quad , (12)$$

where $H_j(k)$ is the kth subcarrier channel gain between the jth user and the base station. When U>1, the BER floor is produced due to the MAI. It is only seen that the uplink BER performance cannot be improved with FDE reception only. In the following sub-sections, we present the average BER performance when the proposed FPTD is used.

Tab. 1. Simulation conditions.

Data modulation		QPSK
MC-CDMA	No. of subcarriers	N_c=256
	Guard interval	N_g=32
FPTD	Pre-equalization weights	MRC, EGC, SC
	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, 8 (dB)
	Normalized maximum Doppler frequency	f_DT=0.01 (T=(N_c+N_g)T_c)
Channel estimation		Ideal

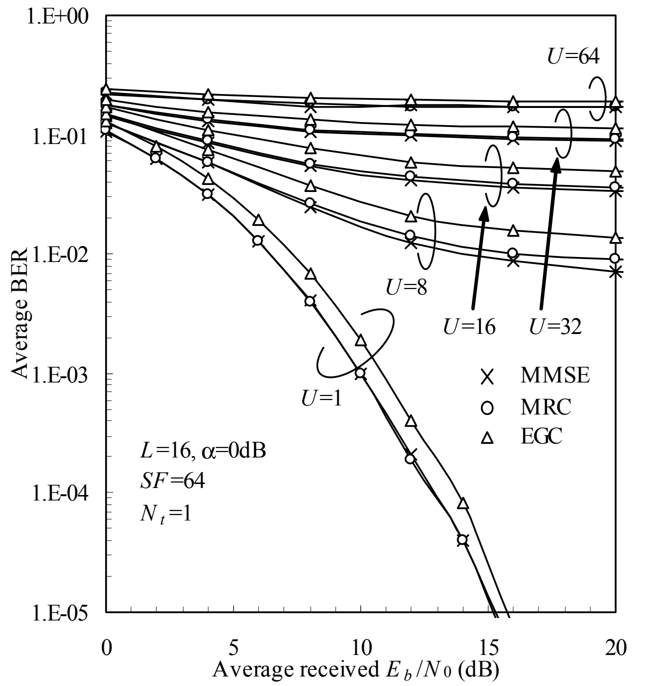


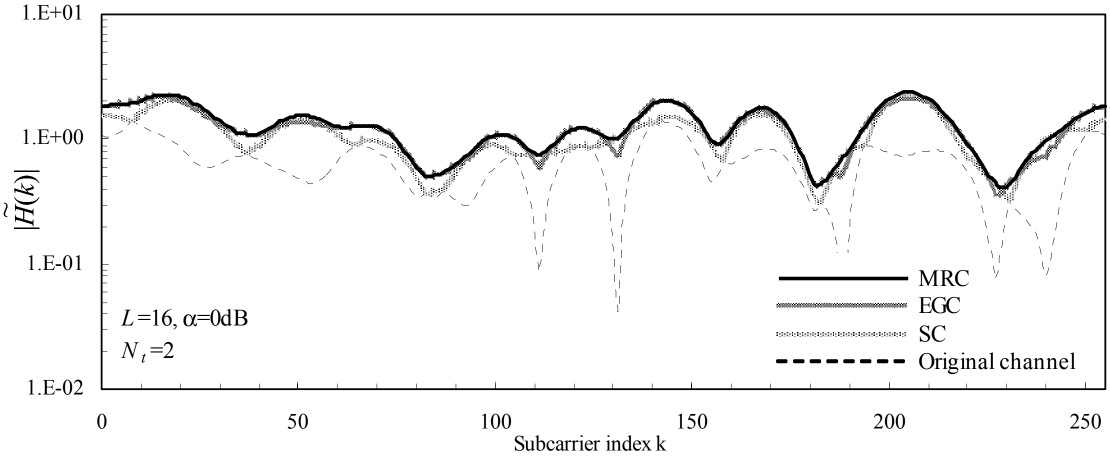
Fig. 2. Simulated average BER performance with FDE reception only.

F. Equivalent channel gain with FPTD

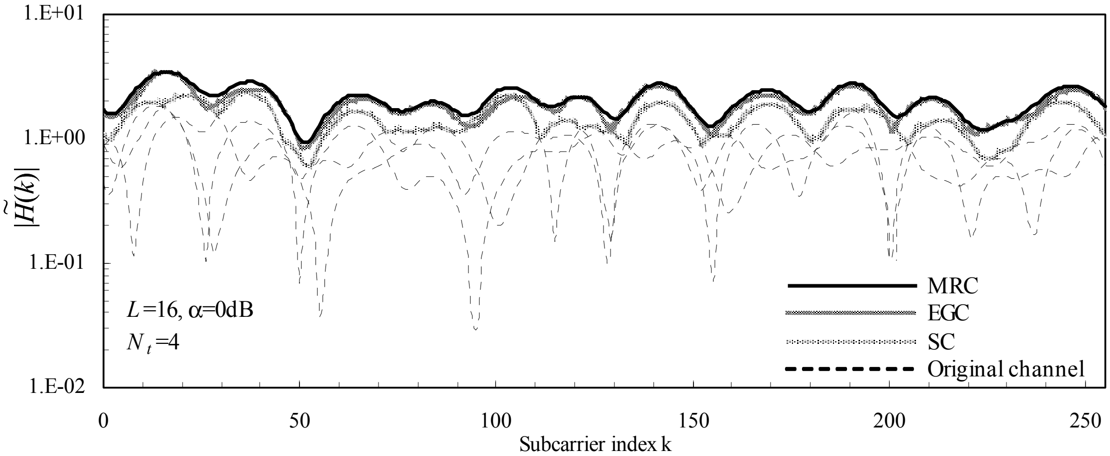
In this section we discuss how FPTD transforms the pre-equalized channel to be close a frequency non-selective channel as possible. Figure 3 shows a one-shot observation of the equivalent channel gain $\tilde{H}(k)$ observed at the base station receiver with FPTD. Without pre-equalization, large variations in $\tilde{H}(k)$ are seen. However, as the number N_t of transmit antennas increases, variations in $\tilde{H}(k)$ are suppressed and the resultant channel approaches the frequency non-selective channel. Hence, the destruction in orthogonality is reduced, resulting in less MAI.

G. Comparison of FPTD using MRC, EGC, and SC pre-equalization weights

Figure 4 compares the average BER performances achievable with FPTD using MRC, EGC, and SC pre-equalizations weights when N_t=4 and α=0 dB. The MRC pre-equalization provides the best BER performance among the three pre-equalization weights since the MRC maximizes the instantaneous SNR while



(a) N_t=2



(b) N_t=4

Fig. 3. Equivalent channel gain with FPTD.

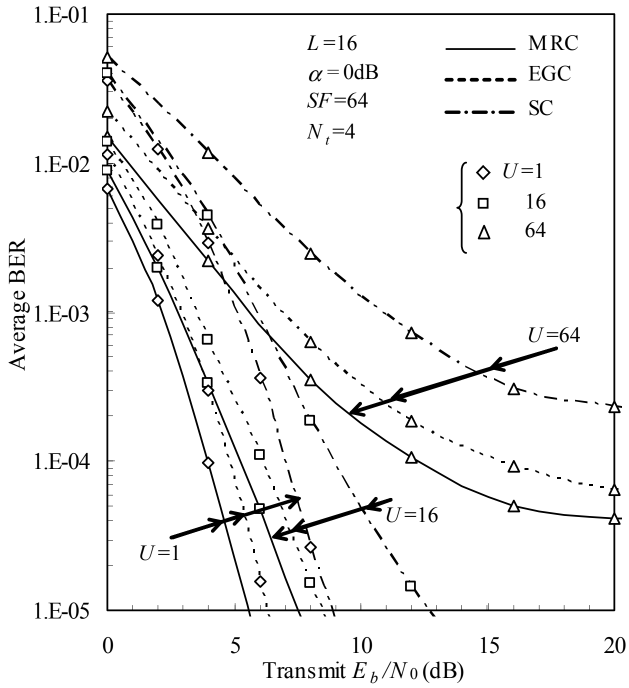


Fig. 4.Performance comparison of MRC, EGC, and SC pre-equalizations.

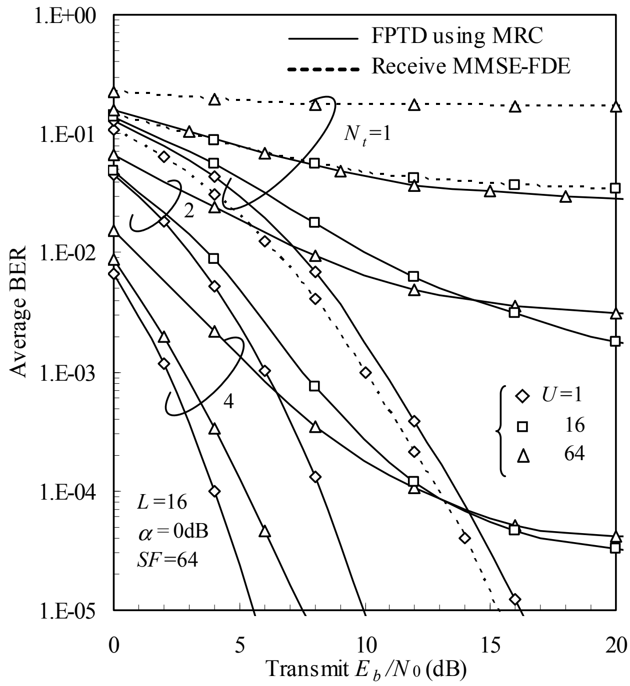


Fig. 5. Effect of no. of transmit antennas.

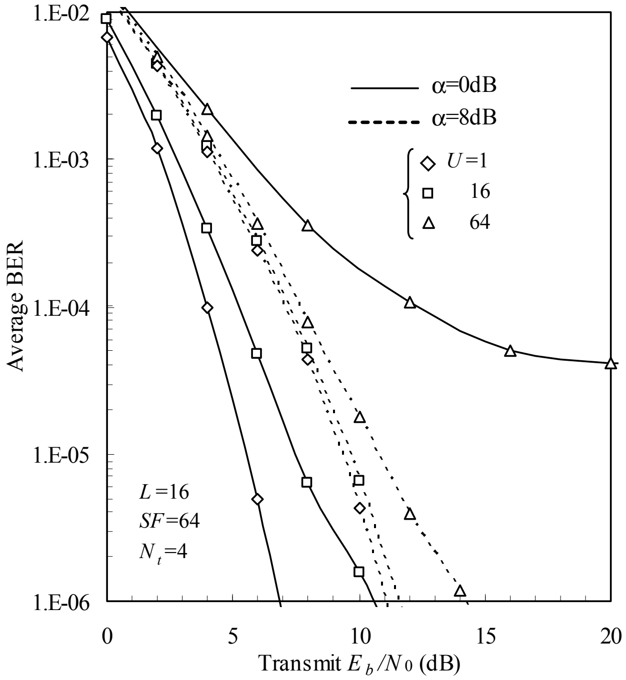


Fig. 6. Effect of decay factor.

suppressing the variations in $\tilde{H}(k)$. Hence, only MRC is considered in the following simulations.

H. Effect of number of transmit antennas and decay factor

Figure 5 plots the average BER performance with FPTD using MRC as a function of the transmit E_b/N_0 with N_t as a parameter. The BER performance can be significantly improved by increasing the number N_t of transmit antennas, although the BER performance degrades with increasing U. Also seen is that the BER performance of FPTD using MRC is superior to that of FDE reception. It is interesting to note that even with N_t=1, FPTD can provide better BER performance than with FDE reception only. This is because, with the FPTD, all the subcarriers are in phase for all users and hence, the code orthogonality among different users is restored to some extent, thus suppressing the MAI. However, without FPTD, different users' subcarriers are out of phase, and hence, the code orthogonality cannot be restored by the use of FDE reception only.

Figure 6 shows the average BER performance with FPTD using MRC as a function of the transmit E_b/N_0 for α=0 and 8 dB. When U is small (U=1, 16), α=0 dB gives a 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 for α=8 dB. This is because, as the frequency-selective becomes severer, larger MAI is produced and offsets the frequency diversity effect

IV. CONCLUSION

In this paper, frequency-domain pre-equalization transmit diversity (FPTD) for improving the uplink BER performance of MC-CDMA was proposed. Unlike the conventional MC-CDMA uplink transmission, orthogonal spreading codes are used by different user. With FPTD, all the subcarriers are in phase for all users and hence, the orthogonality among different users is restored, thereby achieving a better BER performance than using FDE reception at the receiver. We considered various pre-equalization weights of MRC, EGC, and SC, and evaluated by the computer simulation the average BER performances achievable with them to show that MRC provides the best performance.

Reference

[1] W.C., Jakes Jr, Ed, *Microwave mobile communications*, Wiley, New York, 1974.

[2] S. Hara and R. Prasad, "Overview of Multicarrier CDMA," IEEE Commun. Mag., Vol. 35, No. 12, pp. 126-133, Dec. 1997

[3] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels," IEEE Trans. Vehi. Technol., Vol. 48, No. 5, pp. 1584-1595, Sept. 1999.

[4] T. Sao and F. Adachi, "Comparative study of various frequency equalization techniques for downlink of a wireless OFDM-CDMA systems," IEICE Trans. Commun., Vol. E86-B, No. 1, pp. 352-364, Jun. 2003.

[5] D. Mottier and D. Castelain, "SINR-based channel pre-equalization for uplink multi-carrier CDMA systems," Proc. IEEE Int. Symp. On Personal, Indoor and Mobile Radio Commun. (PIMRC2002), Vol. 4, pp. 1488-1492, Sept. 2002.

[6] S. Kaiser, "Space frequency block coding in the uplink of broadband MC-CDMA mobile radio systems with pre-equalization," Proc. IEEE VTC'03 fall, Vol. 3, pp. 1757-1761, Oct. 2003.

[7] I. Cosovic, M. Schnell and A. Springer, "On the performance of different channel pre-compensation techniques for uplink time division duplex MC-CDMA," Proc. IEEE VTC'03 fall, Vol. 2, pp. 857-861, Oct. 2003.

[8] T. Lo, "Maximum ratio transmission," IEEE Trans. Commun., Vol. 47, No. 10, pp. 1458-1461, Oct. 1999.

[9] K. Caver, "Single-user and multiuser adaptive maximal ratio transmission for Rayleigh channels," IEEE Trans. Vehi. Technol., Vol. 49, No. 6, pp. 2043-2050, Nov. 2000.

[10] R. T. Derryberry, S. D. Gray, D. M. Ionescu, G. Mandyam and B. Raghothaman, "Transmit diversity in 3G CDMA systems," IEEE Commun. Mag., Vol. 40, No. 4, pp. 68-75, Apr. 2002.

[11] H. Shi, M. Katayama, T. Yamazato, H. Okada and A. Ogawa, "An adaptive antenna selection scheme for transmit diversity in OFDM systems," Proc. IEEE VTC'01 fall, Vol. 4, pp. 2168-2172, Oct. 2001.

[12] R. Esmailzadeh, M. Nakagawa and A. Jones, "TDD-CDMA for the 4th generation of wireless communications", IEEE Wireless Communications, Vol. 10, No. 4, pp. 8-15, Aug. 2003.

[13] D. Garg and F. Adachi, "STTD decoding combined with MMSE equalization and diversity reception for MC-CDMA in the presence of multiple users," Proc. WPMC03, Vol. 1, pp. 280-284, Oct. 2003.