Frequency-domain Differential Detection and Equalization for DS-CDMA Mobile Radio

Le Liu[†] *and Fumiyuki Adachi*[‡]
Dept. of Electrical and Communication Engineering, Graduate School of Engineering,
Tohoku University, 6-6-05, Aza-Aoba, Aramaki, Aoba-ku Sendai 980-8580, JAPAN
†liule@mobile.ecei.tohoku.ac.jp, ‡adachi@ecei.tohoku.ac.jp

Abstract—In this paper, we show that differential detection of DS-CDMA signals transmitted over a severe frequency-selective fading channel is possible. Joint frequency-domain differential detection and equalization (FDDDE) based on the minimum mean square error (MMSE) criterion is proposed. A simple decision feedback filter is used to provide a reliable reference signal for MMSE-FDDDE. It is confirmed by computer simulation that MMSE-FDDDE provides good BER performance close to coherent MMSE-FDE and shows high robustness against the Doppler spread.

Key words: DS-CDMA, frequency-domain differential detection, frequency-domain equalization.

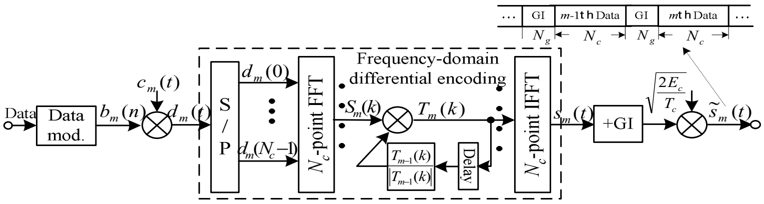
1. INTRODUCTION

A very high-speed data transmission of over several 10Mbps is required in the 4th generation mobile communication systems [1]. However, the frequency-selective multipath fading, encountered in a broadband wireless communication system, severely degrades the bit error rate (BER) performance [2], [3]. In direct sequence code division multi-access (DS-CDMA) systems [4], coherent rake combining can exploit the channel frequency-selectivity through path-diversity effect to improve the BER performance [5]. However, in a broadband wireless channel, the BER performance degrades because severe inter-path interference (IPI) offsets the obtainable path-diversity effect by using coherent rake combining [5]. Recently, multi-carrier CDMA (MC-CDMA) [6]-[9] has been attracting much attention. In MC-CDMA, data symbol to be transmitted is spread over a number of subcarriers to attain the frequency-diversity gain by using coherent frequency-domain equalization (FDE) [9].

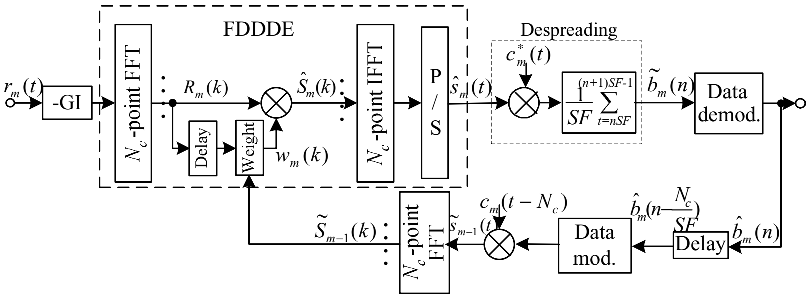
Quite recently, coherent FDE has been drawing a lot of attention to improve the single-carrier wireless transmission performance [10]. Since DS-CDMA is a family of the single-carrier transmission (DS-CDMA is sometimes called single-carrier CDMA), FDE can also be applied. It has been shown [11]~[13] that coherent FDE is more effective than coherent Rake combining for the reception of DS-CDMA signals in a severe frequency-selective fading channel. Coherent FDE requires accurate channel estimation. However, in practical wireless communication systems, the BER performance suffers from channel estimation error. So far, several pilot-assisted channel estimation schemes have been proposed for coherent FDE [14]-[16]. In order to acquire better tracking ability against fast fading, the pilot transmission rate has to be increased, but this results in the loss of transmission efficiency. For applications like mobile radio, differential detection is sometimes preferable because of its simple implementation due to no requirement of channel estimation. But differential detection is inferior to that of coherent detection since a delayed version of the received noisy signal is used as the phase reference. However, in a fast fading channel, differential detection is more attractive, where coherent detection becomes practically infeasible.

In this paper, joint frequency-domain differential detection and equalization (FDDDE) based on minimum mean square error (MMSE) criterion is proposed. A simple decision feedback filter is used to provide the noise-reduced reference signal. In this paper, we will focus on the uncoded case in order to show the potential of DS-CDMA using FDDDE in a frequency-selective fading channel. The achievable BER performance of DS-CDMA using FDDDE is evaluated by computer simulation and is compared with that of coherent FDE. The proposed FDDDE can also be applied to MC-CDMA. Performance comparison between DS- and MC-CDMA both using FDDDE is presented.

The remainder of this paper is organized as follows. Sect. 2 presents the transmission system model of DS-CDMA using FDDDE. Then, the MMSE equalization weight is derived for FDDDE. Performance comparison between DS- and MC-CDMA is also presented in Sect. 3. Sect. 4 offers concluding remarks and future work.



(a) Transmitter



(b) Receiver

Fig. 1.Transmitter/receiver structure for DS-CDMA using FDDDE.

2. PRINCIPLE OF FDDDE

The transmitter/receiver structure for DS-CDMA using FDDDE is illustrated in Fig.1.

2.1. Transmitted signal

At a transmitter, the data-modulated symbol sequence $\{b_m(n)\}$ to be transmitted during the mth block is spread by the spreading sequence $c_m(t)$ with spreading factor SF. The mth block chip sequence $\{d_m(t);\ t=0\sim(N_c\text{-}1)\}$ constitutes of a block of N_c chips. Then, N_c-point FFT is applied to decompose the mth block chip sequence into N_c frequency components. Block-by-block frequency-domain differential encoding at the kth subcarrier is performed as follows:

$$T_m(k)=S_m(k)\,T_{m-1}(k)\big/\left|T_{m-1}(k)\right| \tag{1}$$

with $m\geq 1$, where $S_m(k)$ is the kth frequency component of the mth block chip sequence with $E[|S_m(k)|^2]=1$ and $T_m(k)$ is the differentially encoded subcarrier component with $|T_m(k)|=|S_m(k)|$. At m=0, the reference chip block $T_0(k)$ known to the receiver is transmitted. Then, N_c-point IFFT is applied to obtain the differentially encoded DS-CDMA signal in the time-domain, to which the N_g-chip guard interval (GI) is inserted. The mth block DS-CDMA signal to be transmitted can be expressed using the equivalent lowpass representation as

$$\tilde{s}_m(t)=\sqrt{\frac{2E_c}{N_cT_c}}\sum_{k=0}^{N_c-1}T_m(k)\exp(j2\pi t\frac{k}{N_c}) \tag{2}$$

for t=-N_g~(N_c-1), where E_c is the average chip energy and T_c is the chip duration.

2.2. Received signal and equalization

At a receiver, GI is removed and then N_c-point FFT is applied to the GI-removed signal to obtain the kth frequency component $R_m(k)$, given by

$$R_m(k)=\sqrt{2E_c/T_c}\,H_m(k)T_m(k)+\Pi_m(k)\,, \tag{3}$$

where $H_m(k)$ is the channel gain at the kth frequency of the mth block and $\Pi_m(k)$ is the noise component due to the AWGN with the variance of N_0/T_c. Then, FDDDE is performed as:

$$\hat{S}_m(k)=w_m^{DS}(k)R_m(k)\,, \tag{4}$$

where $w_m^{DS}(k)$ acts as the reference signal for differential detection as well as an equalization weight.

2.3. Equalization weight

A set of FDDDE weights, $\{w_m(k);\ k=0\sim(N_c\text{-}1)\}$, is derived according to the MMSE criterion [3]. Substituting Eqs. (1) and (3) into Eq. (4), $\hat{S}_m(k)$ can be expressed as

$$\hat{S}_m(k)=\sqrt{\frac{2E_c}{T_c}}w_m(k)H_m(k)S_m(k)\frac{T_{m-1}(k)}{\left|T_{m-1}(k)\right|}+w_m(k)\Pi_m(k)\,. \tag{5}$$

We define the equalization error for the kth frequency component of the mth block as

$$\varepsilon_m(k)=S_m(k)-\hat{S}_m(k)\,. \tag{6}$$

A set of weights that satisfy $\partial E[\left|\varepsilon_m(k)\right|^2]\big/\partial w(k)=0$ is the optimum one in the MMSE sense [3] and is given by

$$w_m^{DS}(k)=\frac{\sqrt{\frac{2E_c}{T_c}}H_m^*(k)\frac{T_{m-1}^*(k)}{|T_{m-1}(k)|}}{\left|\sqrt{\frac{2E_c}{T_c}}H_m(k)\frac{T_{m-1}(k)}{|T_{m-1}(k)|}\right|^2+\frac{2N_0}{T_c}} . \qquad (7)$$

However, $\sqrt{2E_c/T_c}\,H_m(k)T_{m-1}(k)\big/|T_{m-1}(k)|$ is not known to the receiver.

Assuming a very slow fading (i.e., $H_m(k)\approx H_{m-1}(k)$), we replace $\sqrt{2E_c/T_c}H_m(k)T_{m-1}(k)$ and $|T_{m-1}(k)|$ in Eq. (7) by $\sqrt{2E_c/T_c}H_{m-1}(k)T_{m-1}(k)$ and $\left|\tilde{S}_{m-1}(k)\right|$, respectively, where $\tilde{S}_{m-1}(k)$ is the kth frequency component of the previous chip block obtained by the decision feedback. Therefore, $w_m^{DS}(k)$ based on MMSE criterion is given by

$$w_m^{DS}(k)=\frac{X_{m-1}^*(k)}{|X_{m-1}(k)|^2+2N_0/T_c}, \qquad (8)$$

where $X_{m-1}(k)=R_{m-1}(k)\big/\left|\tilde{S}_{m-1}(k)\right|$.

Since $X_{m-1}(k)$ is noisy, we apply infinite impulse response (IIR) filtering to improve the reliability of the FDDDE weight. Using $\frac{T_{m-1}(k)}{|T_{m-1}(k)|}=\frac{S_{m-1}(k)}{|S_{m-1}(k)|}\frac{T_{m-2}(k)}{|T_{m-2}(k)|}$ from Eq. (1), we have

$$\hat{X}_{m-1}(k)=\alpha\hat{X}_{m-2}(k)\frac{\tilde{S}_{m-1}(k)}{\left|\tilde{S}_{m-1}(k)\right|}+(1-\alpha)X_{m-1}(k) \qquad (9)$$

with $m\geq 2$, where α ($0\leq\alpha\leq 1$) is the forgetting factor. In Eq. (9), $\hat{X}_0(k)=X_0(k)$ $=R_0(k)/|T_0(k)|$, where $R_0(k)$ is the kth frequency component of the received reference chip block. $X_{m-1}(k)$ in Eq. (8) is replaced by the filter output $\hat{X}_{m-1}(k)$. α is an important design parameter to determine the tracking ability against fading. The optimum value of α depends on the channel condition.

2.4. Application to MC-CDMA

The above FDDDE with decision feedback can also be applied to MC-CDMA. Since always $|S_m(k)|=1$ for QPSK data modulation, the following equalization weight can be used:

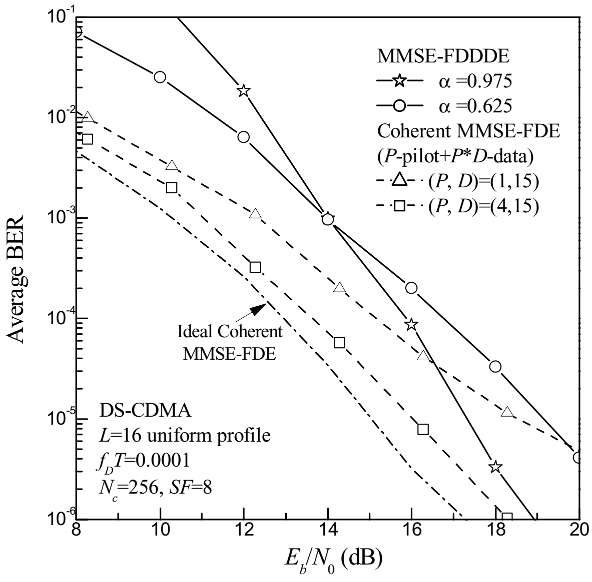
$$w_m^{MC}(k)=\frac{\hat{R}_{m-1}^*(k)}{\left|\hat{R}_{m-1}(k)\right|^2+2N_0/T_c}, \qquad (10)$$

where

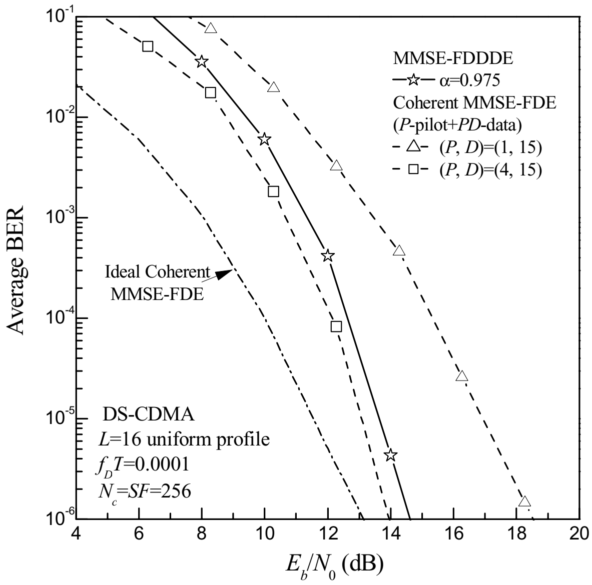
$$\hat{R}_{m-1}(k)=\alpha\hat{R}_{m-2}(k)\tilde{S}_{m-1}(k)+(1-\alpha)R_{m-1}(k). \qquad (11)$$

3. COMPUTER SIMULATION AND DISCUSSION

The BER performance of FDDDE is evaluated by computer simulation. We assume QPSK data modulation and block transmission with N_c=256 and N_g=32. As for the propagation channel, an L=16-path Rayleigh fading channel having the uniform power delay profile (i.e., $E[|h_{m,l}|^2]=1/L$ for all m and l) is assumed. The time delay τ_l of the lth path is assumed to be $\tau_l=l$ and $\max\{\tau_l\}\leq N_g-1$.



(a) SF=8



(b) SF=256

Fig. 2. Comparison between FDDDE and coherent FDE for DS-CDMA.

3.1. Comparison with MMSE-FDE

The simulated BER performance of DS-CDMA with MMSE-FDDDE is compared with that of coherent MMSE-FDE. For coherent FDE, pilot-assisted channel estimation with delay-time domain windowing is used [15], [16]; P pilot blocks are periodically transmitted, followed by $P \cdot D$ data chip blocks. The simulated BER performance of DS-CDMA with FDDDE is plotted for $f_D T=10^{-4}$ in Fig.2 as a function of the average received bit energy-to-the AWGN power spectrum density ratio E_b/N_0, which is defined as $E_b/N_0=0.5SF(E_c/N_0)(1+N_g/N_c)$ for QPSK data modulation. f_D is the maximum Doppler frequency, and $T=(N_c+N_g)T_c$ is the block duration. α=0.625 and 0.975 are used for FDDDE to trade off between the noise reduction and tracking ability against fading. The error propagation due to decision feedback results in the performance degradation for FDDDE. However, it can be seen that when E_b/N_0 is large enough, our proposed FDDDE can achieve the BER performance close to that of coherent FDE with $(P,D)=(4,15)$.

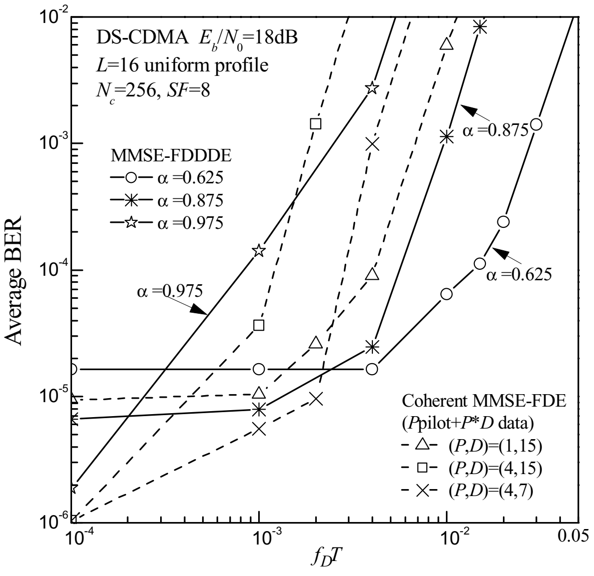
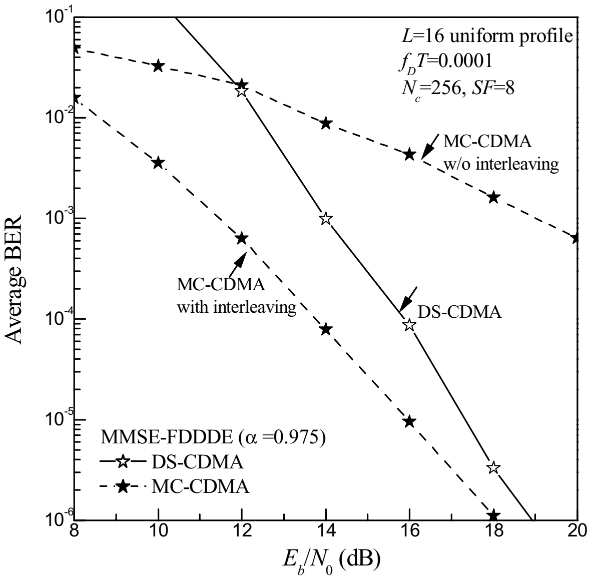


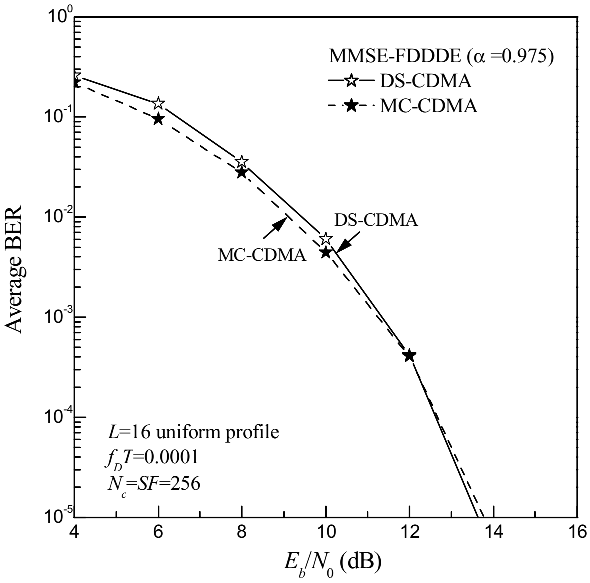
Fig. 3. Impact of $f_D T$.

Fig. 3 shows the impact of f_D on the BER for MMSE-FDDDE and coherent MMSE-FDE when E_b/N_0=18dB and SF=8. For coherent MMSE-FDE, $(P,D)=(1,15)$, (4,7), and (4,15) are used. As D decreases, the tracking ability against fading improves, but the energy loss of $10\log(1+D)/D$ dB due to the pilot insertion becomes larger. As the $f_D T$ value increases (or fading becomes faster), coherent FDE tends to lose the tracking ability, thereby significantly degrading the performance. Although FDDDE is inferior to coherent FDE for small $f_D T$ values, it becomes superior for large $f_D T$ values by reducing α from 0.975 to 0.625.

3.2. Performance comparison with MC-CDMA



(a) SF=8



(b) SF=256

Fig.4. Performance comparison between DS- and MC-CDMA.

The simulated BER performances of DS- and MC-CDMA both using MMSE-FDDDE are plotted in Fig.4 for $f_D T=10^{-4}$. It can be seen that, when $SF \ll N_c$ DS-CDMA with MMSE-FDDDE achieves better BER performance than MC-CDMA with MMSE-FDDDE. This is because, in DS-CDMA, each data symbol is always spread over all subcarriers and hence, full frequency-diversity gain can always be obtained irrespective of SF. On the other hand, in MC-CDMA, each data symbol is spread over less number of frequencies and hence the frequency-diversity gain is smaller. However, it should be pointed out that if frequency-domain interleaving is used, the BER performance of MC-CDMA can be improved as shown in Fig. 4(a). When $SF=N_c$, both DS-CDMA and MC-CDMA provide almost identical BER performances.

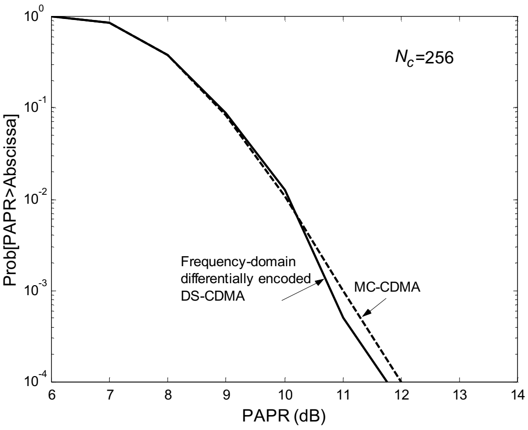


Fig.5. PAPR comparison between MC- and DS-CDMA with FDDDE.

3.3. Consideration on PAPR

The DS-CDMA signal amplitude after frequency-domain differential encoding is not any more constant. Large amplitude fluctuations may appear in the transmitted signal waveform, similar to MC-CDMA. The statistical property of amplitude variations in terms of peak-to-average power ratio (PAPR) is investigated. The PAPR of the mth block transmitted signal $\tilde{s}_m(t)$ in Eq. (2) is defined as the ratio of the instantaneous peak power to the ensemble average power:

$$PAPR_m = \max\{|\tilde{s}_m(t)|^2\} \big/ E[|\tilde{s}_m(t)|^2] \qquad (12)$$

for t=0~(N_c-1). The PAPR is a random variable. We measured the PAPRs of more than 1 million blocks and computed the its probability distribution. The probability of PAPR exceeding a certain level is plotted in Fig. 5. It is seen that the frequency-domain differentially encoded DS-CDMA signal has almost the same PAPR distribution as MC-CDMA signal.

In this paper, we have shown that the differential encoding and detection can also be applied to DS-CDMA in a frequency-selective fading channel; however, this is only possible at the cost of increased PAPR.

4. CONCLUSIONS

In this paper, it was shown that differential detection of DS-CDMA signals transmitted over a frequency-selective fading channel is possible. Joint frequency-domain differential encoding and detection (FDDDE) based on the MMSE criterion was proposed and the average BER performance was evaluated by computer simulation. It was confirmed that the proposed MMSE-FDDDE is very robust against the Doppler spread and outperforms coherent MMSE-FDE for large Doppler spreads. The proposed FDDDE can also be applied to MC-CDMA.

REFERENCES

[1] F. Adachi, "Wireless past and future-Evolving mobile communications systems," IEICE Trans. Fundamentals, vol. E84-A, no.1, pp. 55–60, Jan. 2001.

[2] W. C. Jakes, and Jr., ed., *Microwave mobile communications*, Wiley, New York, 1974.

[3] J. G. Proakis, *Digital communications*, 2nd ed. McGraw-Hill, 1995.

[4] A. J. Viterbi, *CDMA: Principles of spread spectrum communications*, Addison Wesely, 1995.

[5] F. Adachi, M. Sawahashi, and H. Suda, "Wideband DS-CDMA for next generation mobile communications systems," IEEE Commun. Mag., vol.36, no.9, pp.56-69, Sep. 1998.

[6] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun., Mag., vol.35, no.12, pp.126-144, Dec. 1997.

[7] S. Hara and R. Prasad, Multicarrier Techniques for 4G Mobile Communications, Artech House, 2003.

[8] R. Van Nee and R. Prasad, OFDM for Wireless Multimedia Communications, Artech House, 2000.

[9] N. Yee, J. -P. Linnarts and G. Fettweis, "Multi-carrier CDMA in indoor wireless radio networks," Proc. IEEE PIMRC'93, pp. 109-113, May 1993.

[10] D. Falconer, S. L. Ariyavisitakul, A. Benyamin -Seeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., vol.40, no.4, pp.58-66, Apr. 2002.

[11] F. Adachi, T. Sao, and T. Itagaki, "Performance of multicode DS-CDMA using frequency domain equalisation in frequency-selective fading channel," Electron. Lett., vol.39, no.2, pp.239-241, Jan. 2003.

[12] F. Adachi, and K. Takeda, "Bit error rate analysis of DS-CDMA with joint frequency-domain equalization and antenna diversity combining," IEICE Trans. Commun., vol.E87-B, no.10, pp.2991-3002, Oct. 2004.

[13] F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Mag. Wireless Commun., vol.2, no.2, pp. 2- 13, Apr. 2005.

[14] D. N. Kalofonos, M. Stojanovic, and J. G. Proakis, "Performance of adaptive MC-CDMA detectors in rapidly fading Rayleigh channels," IEEE Trans. Wireless Commun., vol.2, no.2, pp. 229- 239, March 2003.

[15] J. -J. van de Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Borjesson, "On channel estimation in OFDM systems," Proc. IEEE VTC'95, pp. 815-819, Chicago, Illisnois, USA, July 1995.

[16] T. Fukuhara, H. Yuan, Y. Takeuchi, and H. Kobayashi, "A novel channel estimation method for OFDM transmission technique under fast time-variant fading channel," Proc. IEEE VTC'03-Spring, pp. 2343-2347, Jeju, Korea, April 2003.