Delay-time/Code Division Multi-access for Uplink Transmission in A Frequency-selective Fading Channel

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Abstract— **The downlink bit error rate (BER) performance of direct sequence-code division multi-access (DS-CDMA) in a frequency-selective fading channel can be significantly improved by the use of frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion. In the uplink case, however, the presence of multi-access interference (MAI) significantly degrades the BER performance even if MMSE-FDE is used. In this paper, we propose a new hybrid multi-access technique called delay-time/code division multi-access (DT/CDMA) for the uplink transmission, which can mitigate the MAI while achieving the frequency diversity gain, and evaluate the achievable BER performance by computer simulation.**

Keywords— **Multi-access, delay-time domain, MMSE-FDE**

I. INTRODUCTION

Since the broadband wireless channel is composed of many propagation paths having different time delays, the bit error rate (BER) performance of direct sequence-code division multi-access (DS-CDMA) using coherent rake combining significantly degrades due to strong inter-chip interference (ICI) arising from frequency-selective fading channel [1]. Recently, multi-carrier (MC)-CDMA has been attracting much attention to overcome this problem by the use of a number of orthogonal narrowband subcarriers for signal transmission [2-6]. In multicode MC-CDMA, the downlink (base-to-mobile) BER performance in a frequency-selective channel is significantly improved by the use of frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion. More recently, it was shown that MMSE-FDE can also be applied to DS-CDMA in order to achieve the much improved BER performance by achieving the frequency diversity gain while suppressing the ICI [7-8]. However, in the uplink (mobile-to-base) case, since different users' signals go through different channels, the orthogonality among different orthogonal spreading codes is severely distorted and therefore, strong multi-access interference (MAI) is produced. The uplink BER performance of DS-CDMA significantly degrades due to the MAI even if MMSE-FDE is used [9].

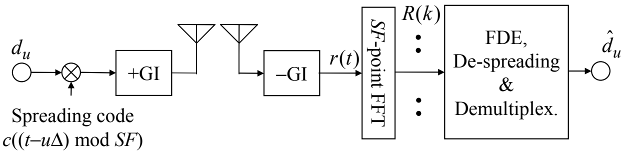
Recently, interleaved frequency division multi-access (IFDMA) [10] and single-carrier (SC)-FDMA [11] were proposed. Chip-repetition CDMA [12] is a combination of IFDMA (or SC-FDMA) and DS-CDMA. Recently proposed frequency-interleaved single-carrier spread-spectrum multi-access (FI-SC-SSMA) [13] is a generalized version of chip-repetition CDMA. All of IFDMA, SC-FDMA, chip-repetition CDMA, and FI-SC-SSMA manipulate the different users' transmit signal spectra so as not to overlap each other (frequency-domain orthogonalization) and therefore, remove the MAI while keeping the SC transmit signal amplitude property intact. Another multi-access technique is block-spread DS-CDMA [14-16], which takes advantage of the time-nonselective fading channel property to remove the MAI in a broadband signal transmission. The above multi-access techniques transform the multi-user detection problem into a set of single-user detection problems and can achieve the frequency diversity gain by the aid of single-user MMSE-FDE.

In this paper, we propose a new hybrid multi-access technique called delay-time/code division multi-access (DT/CDMA) for the uplink transmission. The multi-user orthogonalization is achieved in the delay time-domain; a different user's transmit signal is given a different cyclic time delay so as not to overlap each other in delay time-domain (the cyclic time delay difference among different users is set to be longer than the maximum time delay difference among propagation paths of the channel). Reminder of this paper is organized as follows. Sect. II presents the principle operation of DT/CDMA. The MMSE weight for DT/CDMA is derived in Sect. III. In Sect. IV, the achievable BER performance in a strong frequency-selective channel is evaluated by computer simulation. Sec. V concludes this paper.

II. PRINCIPLE OPERATION OF DELAY-TIME/CODE DIVISION MULTI-ACCESS

In this paper, chip-spaced discrete-time representation is used. The transmitter/receiver structure is illustrated in Fig. 1. U users are simultaneously transmitting their data to a base station. In DT/CDMA, the same partial sequence $\{c(t); t=nSF\sim(n+1)SF-1\}$ taken from a PN sequence $c(t)$ is used as the spreading code to spread the nth data symbol for U users, where SF is the spreading factor.

DT/CDMA is a block transmission of SF chips (equivalent to one data symbol length). We assume the transmission of the n=0th data symbol and omit the index n for the simplicity purpose. The uth user is given a cyclic time delay of $u\Delta$ chips, $u=0\sim U-1$, as shown in Fig. 2, where Δ is the cyclic prefix length. Before the transmission of the spread signal, the cyclic prefix of Δ chips is inserted into the guard interval (GI) to carry out MMSE de-spreading at the receiver [7].



(a)Transmitter (b)Receiver

Fig. 1. Transmitter/receiver structure.

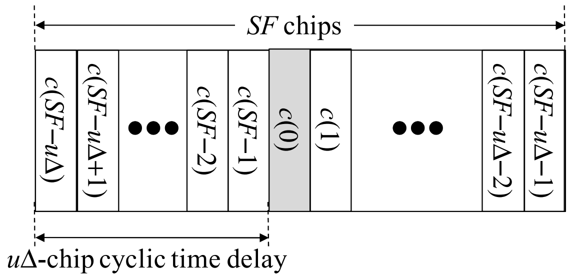


Fig. 2. Spreading code of *u*th user.

A. Transmit and received signal representation

The *u*th users' transmit signal $s_u(t)$, t=0~SF−1, using the equivalent lowpass representation, is expressed as

$$s_u(t)=\sqrt{2P_u}\,d_u c((t-u\Delta)\bmod SF),\quad t=0\sim SF-1,\tag{1}$$

where d_u is the *u*th user's data symbol with $E[|d_u|^2]=1$. $s_u(t)$ is transmitted after the GI insertion from a mobile station to its communicating base station. The channel is assumed to be composed of L distinct propagation paths, each having an integer multiple of chip length T_c. The impulse response $h_u(\tau)$ of the channel between the base station and the *u*th user can be expressed as

$$h_u(\tau)=\sum_{l=0}^{L-1}h_{u,l}\delta(\tau-\tau_{u,l}),\tag{2}$$

where $h_{u,l}$ and $\tau_{u,l}$ are respectively the complex-valued path gain with $\sum_{l=0}^{L-1}E[|h_{u,l}|^2]=1$ and the time delay of the *l*th path.

A superposition of U users' signals is received at the base station antenna. The received signal {$r(t)$; t=0~SF−1} after the GI removal can be expressed as

$$r(t)=\sum_{u=0}^{U-1}\sqrt{2P_u}\,d_u\sum_{l=0}^{L-1}h_{u,l}c((t-\tau_{u,l}-u\Delta)\bmod SF)+\eta(t),\tag{3}$$

where $\eta(t)$ represents a zero-mean additive white Gaussian noise (AWGN) with the variance $2N_0/T_c$ with N_0 denoting the one-sided power spectrum density.

B. Frequency-domain signal representation

The received signal {$r(t)$; t=0~SF−1} is transformed by SF-point fast Fourier transform (FFT) into the frequency-domain signal {$R(k)$; k=0~SF−1} as

$$\begin{aligned}R(k)&=\sum_{t=0}^{SF-1}r(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\\&=\sum_{u=0}^{U-1}\sqrt{2P_u}\,d_u\sum_{l=0}^{L-1}h_{u,l}\\&\quad\times\sum_{t=0}^{SF-1}c\big((t-\tau_{u,l}-u\Delta)\bmod SF\big)\exp\left(-j2\pi k\frac{t}{SF}\right)\\&\quad+\sum_{t=0}^{SF-1}\eta(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\end{aligned}.\tag{4}$$

Using

$$\begin{aligned}&\sum_{t=0}^{SF-1}c\big((t-\tau_{u,l}-u\Delta)\bmod SF\big)\exp\left(-j2\pi k\frac{t}{SF}\right)\\&=C(k)\exp\left(-j2\pi k\frac{\tau_{u,l}+u\Delta}{SF}\right)\end{aligned},\tag{5}$$

Eq. (4) can be rewritten as

$$R(k)=\sum_{u=0}^{U-1}\sqrt{2P_u}\,d_u H_u(k)\left\{C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)\right\}+\Pi(k),\tag{6}$$

where $C(k)$, $H_u(k)$, and $\Pi(k)$ respectively represent the *k*th frequency component of the spreading code, channel gain, and noise, given by

$$\begin{cases}C(k)=\sum_{t=0}^{SF-1}c(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\\H_u(k)=\sum_{l=0}^{L-1}h_{u,l}\exp\left(-j2\pi k\frac{\tau_{u,l}}{SF}\right)\\\Pi(k)=\sum_{t=0}^{SF-1}\eta(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\end{cases}.\tag{7}$$

C. Signal detection

In DT/CDMA, de-spreading is carried out in frequency-domain as

$$\hat{R}_u(k)=w_u(k)R(k),\tag{8}$$

where $w_u(k)$ is the de-spreading weight. Then, the frequency-domain signal {$\hat{R}_u(k)$; k=0~SF−1} is transformed by SF-point inverse FFT (IFFT) into the delay time-domain signal {$y_u(\tau)$; t=0~SF−1} for channel equalization. The user separation and equalization are performed in delay-time domain.

Below, for easy understanding of the signal detection in DT/CDMA, we neglect the noise and assume the zero-forcing (ZF) weight for de-spreading. ZF weight is given by

$$w_u(k)=\frac{1}{C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)}.\tag{9}$$

Substituting Eqs. (6) and (9) into Eq. (8) gives

$$\hat{R}_u(k)=\sum_{u'=0}^{U-1}\sqrt{2P_{u'}}\,d_{u'}H_{u'}(k)\exp\left(-j2\pi k\frac{(u'-u)\Delta}{SF}\right).\tag{10}$$

Therefore, $y_u(\tau)$ is given by

$$
\begin{aligned}
y_u(\tau) &= \frac{1}{SF}\sum_{k=0}^{SF-1}\hat{R}_u(k)\exp\left(j2\pi k\frac{\tau}{SF}\right)\\
&= \sum_{u'=0}^{U-1}\sqrt{2P_{u'}}d_{u'}\left\{\frac{1}{SF}\sum_{k=0}^{SF-1}H_{u'}(k)\exp\left(j2\pi k\frac{\tau-(u'-u)\Delta}{SF}\right)\right\}\\
&= \sum_{u'=0}^{U-1}\sqrt{2S_{u'}}d_{u'}h_{u'}(\tau-(u'-u)\Delta)
\end{aligned}
\quad . \tag{11}
$$

An example of delay time-domain signal {$y_u(\tau)$; t=0~SF−1} is illustrated in Fig. 3. It can be seen from Eq. (11) and Fig. 3 that different users' modulated impulse responses appear equidistantly with Δ-sample distance. The uth user's signal appears over a delay time interval of [0, Δ−1]. Since the value of Δ is set to be longer than the maximum delay time difference of the channel, the uth user's signal can be separated from other users without MAI. The decision variable $\hat{d}_u$ can be obtained using the delay time-domain combining as

$$
\hat{d}_u = \sum_{\tau=0}^{\Delta-1}y_u(\tau)h_u^*(\tau) = \sqrt{2P_u}d_u\sum_{l=0}^{L-1}\left|h_{u,l}\right|^2 . \tag{12}
$$

It can be understood from Eq. (12) that DT/CDMA can collect all signal powers distributed over L paths and achieve the path diversity gain while removing the MAI.

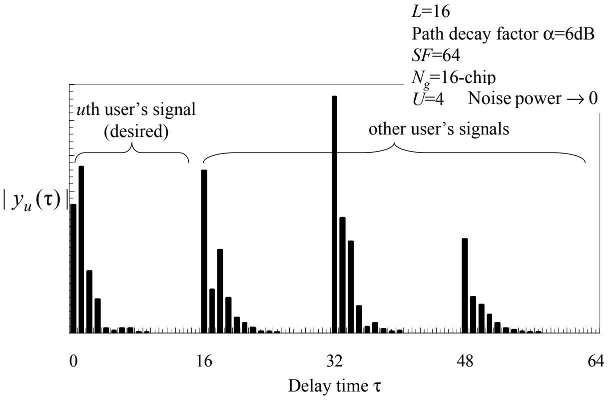


Fig. 3. $|y_u(\tau)|$.

III. MMSE De-spreading Weight

In the previous section, we use the ZF de-spreading weight and delay time-domain combining is carried out after the signal separation. However, since the spectrum $C(k)$ of the spreading code is not constant in frequency-domain, the use of ZF de-spreading weight of Eq. (9) produces the noise enhancement. In this section, we propose three MMSE de-spreading weights that can mitigate the noise enhancement. Note that the MAI cannot be removed when the MMSE de-spreading weight is used.

A. MMSE weight 1

We define the equalization error $e(k)$ as

$$
e(k) = w_u(k)R(k) - \sqrt{2P_u}d_uH_u(k), \tag{13}
$$

where $\sqrt{2P_u}d_uH_u(k)$ is the reference, and find the MMSE de-spreading weight that minimizes the mean square error $E[|e(k)|^2]$. Since transmit data symbols of different users are independent, solving $\partial E[|e(k)|^2]/\partial w_u(k)=0$ gives

$$
w_u(k) = \frac{\left|H_u(k)\right|^2\left\{C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)\right\}^*}{\frac{\left|C(k)\right|^2}{SF}\sum_{u'=0}^{U-1}\frac{P_{u'}T_c}{N_0}\left|H_{u'}(k)\right|^2+1} . \tag{14}
$$

B. MMSE weight 2

We define the equalization error $e(k)$ as

$$
e(k) = w_u(k)R(k) - \sum_{u'=0}^{U-1}\sqrt{2P_{u'}}d_{u'}H_{u'}(k)\exp\left(-j2\pi k\frac{(u'-u)\Delta}{SF}\right) \quad . \tag{15}
$$

Solving $\partial E[|e(k)|^2]/\partial w_u(k)=0$ gives

$$
w_u(k) = \frac{\sum_{u'=0}^{U-1}\frac{P_{u'}T_c}{N_0}\left|H_{u'}(k)\right|^2\left\{C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)\right\}^*}{\frac{\left|C(k)\right|^2}{SF}\sum_{u'=0}^{U-1}\frac{P_{u'}T_c}{N_0}\left|H_{u'}(k)\right|^2+1} \quad . \tag{16}
$$

C. MMSE weight 3

We use $\sqrt{2P_u}d_u$ as the reference. We define the equalization error $e(k)$ as

$$
e(k) = w_u(k)R(k) - \sqrt{2P_u}d_u . \tag{17}
$$

Solving $\partial E[|e(k)|^2]/\partial w_u(k)=0$ gives

$$
w_u(k) = \frac{\left\{H_u(k)C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)\right\}^*}{\frac{\left|C(k)\right|^2}{SF}\sum_{u'=0}^{U-1}\frac{P_{u'}T_c}{N_0}\left|H_{u'}(k)\right|^2+1} . \tag{18}
$$

Using the above weight, the mean square error between {$y_u(\tau)$; t=0~SF−1} and $\sqrt{2P_u}d_u\delta(\tau)$ can be minimized. This means that de-spreading and frequency-domain equalization can be done simultaneously in frequency-domain.

$y_u(0)$ is the decision variable $\hat{d}_u$, which is given by

$$
\begin{aligned}
\hat{d}_u &= \frac{1}{SF}\sum_{k=0}^{SF-1}\hat{R}_u(k)\exp\left(j2\pi k\frac{\tau}{SF}\right)\Bigg|_{\tau=0}\\
&= \frac{1}{SF}\sum_{k=0}^{SF-1}w_u(k)R(k)
\end{aligned}
\quad . \tag{19}
$$

IV. COMPUTER SIMULATION

The simulation condition is summarized in Table 1. We assume an L=16-path frequency-selective block Rayleigh fading channel having uniform power delay profile. The maximum delay time difference of the channel is assumed to be shorter than N_g=16 and we use Δ=16. QPSK data modulation is used. Spreading factor SF=64 is assumed and a partial sequence $\{c(t);\ t=nSF\sim(n+1)SF\}$ taken from a long PN sequence $c(t)$ is used as the spreading code for the transmission of the nth data symbol for user $u=0\sim SF/\Delta-1$. If U exceeds SF/Δ, we use $\{c(t);\ t=(n+1)SF\sim(n+2)SF\}$ as the spreading code for user $u=SF/\Delta\sim 2SF/\Delta-1$.

Table 1. Simulation condition

Transmitter	Modulation	QPSK
	Spreading sequence	Long PN sequence
	Spreading factor	SF=64
	GI length	$N_g=\Delta$
Channel	Fading type	Frequency-selective block Rayleigh
	Power delay profile	L=16-path uniform power delay profile
Receiver	De-spreading	MMSE
	Channel estimation	Ideal

Figure 4 shows the uplink BER performance as a function of average received bit energy-to-noise power spectrum density ratio $E_b/N_0=0.5(P_uT_c/N_0)(SF+\Delta)$ when U=4. Three de-spreading weights derived in Sect. III are compared. We assume the ideal slow transmit power control (TPC) (i.e., $P_u=P$ for all u). It can be seen from Fig. 4 that the MMSE weight 3 can provide the best BER performance among the three weights. Since the spreading code does not have constant amplitude property in frequency-domain, the delay time-domain signal $\{y_u(\tau);\ t=0\sim SF-1\}$ spreads over entire delay time-domain when the weight 1 and weight 2 are used, resulting in worse BER performance due to the MAI.

The performance comparison between DT/CDMA using MMSE weight 3 and conventional DS-CDMA with MMSE-FDE [9] is shown in Fig. 5. Ideal slow TPC is assumed. When $U\leq 4$, DT/CDMA can mitigate the MAI and achieve the frequency diversity gain while conventional DS-CDMA with MMSE-FDE suffers from the strong MAI. When U=8, since another spreading code is used for a group of four additional users, the delay time-domain signal of a user in the additional user group overlaps with that of the corresponding user in the first user group and hence, the MAI appears. However, DT/CDMA provides still much better BER performance than conventional DS-CDMA.

Fig. 6 plots the uplink BER performance with the signal-to-interference power ratio (SIR) per user as a parameter. The BER performance of conventional DS-CDMA using MMSE-FDE significantly degrades due to the increased MAI as SIR per user decreases. It can be seen from Fig. 6 that when $U\leq 4$ $(=SF/\Delta)$, the BER performance of DT/CDMA is significantly improved since MAI can be sufficiently mitigated in delay time-domain.

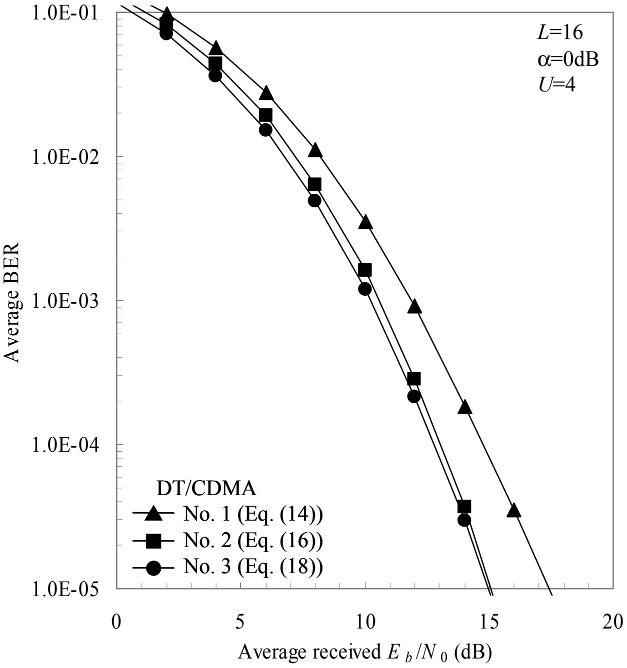


Fig. 4. MMSE weight comparison.

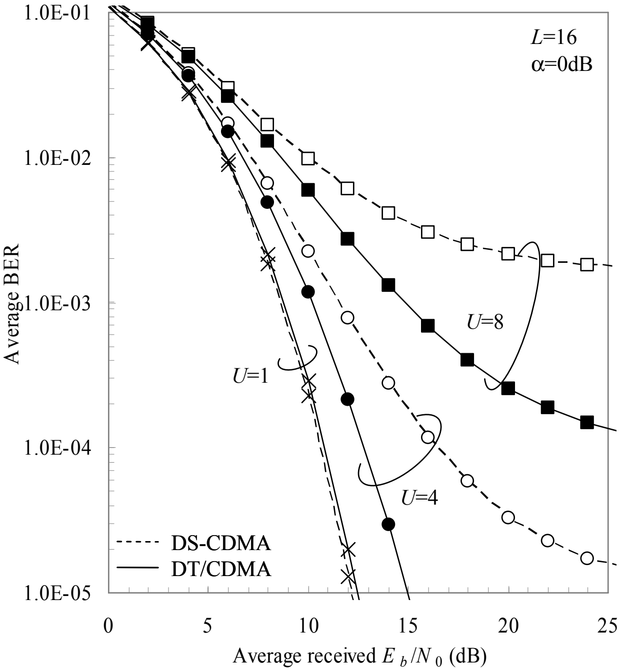


Fig. 5. Impact of number U of users.

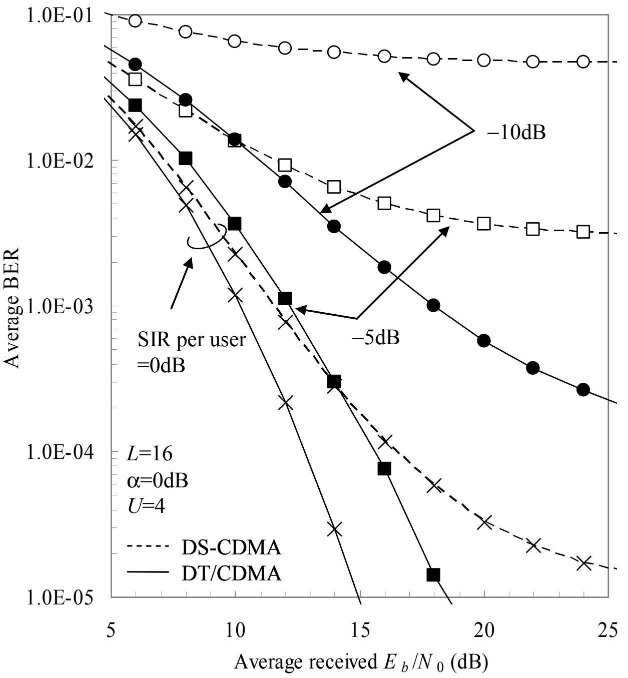


Fig. 6. Impact of SIR per user.

V. CONCLUSION

In this paper, we proposed a new hybrid multi-access technique called DT/CDMA. We evaluated the uplink BER performance by computer simulation. The MMSE weight that can separate different users while obtaining the frequency diversity gain has been derived. It was shown that DT/CDMA provides much better BER performance than conventional CDMA with MMSE-FDE.

REFERENCES

[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., pp. 126-144, Dec. 1997.

[3] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in a frequency-selective Rayleigh fading channels," IEEE Trans. Veh. Technol., Vol. 48, pp. 1584-1595, Sep. 1999.

[4] L. Hanzo, W. Webb, and T. Keller, Single- and multi-carrier quadrature amplitude modulation, John Wiley & Sons, 2000.

[5] M. Helard, R. Le Gouable, J.-F. Helard, and J.-Y. Baudais, "Multicarrier CDMA techniques for future wideband wireless networks," Ann. Telecommun., Vol. 56, pp. 260-274, 2001.

[6] H. Atarashi, S. Abeta, and M. Sawahashi, "Variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) for broadband packet wireless access," IEICE Trans. Commun., Vol. E86-B, No. 1, pp. 291-299, Jan. 2003.

[7] D. Falconer, S. L. Ariyavisitakul, A. Beyamin-Seeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Wireless Commun. Mag., Vol. 40, pp. 58-66, Apr. 2002.

[8] F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Wireless Commun., Vol. 12, No. 2, pp. 8-18, Apr. 2005.

[9] K. Takeda and F. Adachi, "MMSE frequency-domain equalizatoin combined with space-time transmit diversity and antenna receive diversity for DS-CDMA," Proc. 59th IEEE Vehicular Technology Conference (VTC), Italy, 17-19 May 2004.

[10] M. Schnell, I. Broeck, and U. Sorger, "A promising new wideband multiple-access scheme for future mobile communications systems," European Trans. on Telecommun. (ETT), Vol. 10, No. 4, pp. 417-427, Jul.-Aug. 1999.

[11] R. Dinis, D. Falconer, C. T. Lam, and M. Sabbaghian, "A multiple access scheme for the uplink of broadband wireless systems," Proc. IEEE Globecom 2004, pp. 3808-3812, Dallas, Tx, U. S. A., 29 Nov.-3 Dec. 2004.

[12] Y. Goto, T. Kawamura, H. Atarashi, and M. Sawahashi, "Variable spreading and chip repetition factor (VSCRF)-CDMA in reverse link for broadband wireless access," IEEE Personal, Indoor and Mobile Radio Communications (PIMRC2003), pp. 254-259, 7-10 Sep. 2003.

[13] Kazuaki Takeda and Fumiyuki Adachi, "Frequency-interleaved spread spectrum with MMSE frequency-domain equalization," IEICE Trans. Commun., Vol. E90-B, pp. 260-268, Feb. 2007.

[14] S. Zhou, G. B. Giannakis, and C. L. Martret, "Chip-interleaved block-spread code devision multiple accerss," IEEE Trans. Commun., Vol. 50, No. 2, Feb. 2002.

[15] X. Peng, F. Chin, T. T. Tjhung, and A. S. Madhukumar, "A simplified transceiver structure for cyclic extended CDMA system with frequency domain equalization," IEEE VTC2005-Spring, pp. 1565-1569, May 2005.

[16] L. Liu and F. Adachi, "2-Dimensional OVSF spread/chip-interleaved CDMA," IEICE Trans. Commun., Vol. E89-B, No. 12, pp. 3363-3375, Dec. 2006.