Frequency-domain Multi-stage MAI Cancellation for DS-CDMA Uplink with Transmit/Receive Antenna Diversity

Koichi Ishihara+, Kazuaki Takeda+, and Fumiyuki Adachi++
Dept. of Electrical and Communications Engineering, Graduate School of Engineering
Tohoku University, Sendai, Japan
+{ishihara, takeda}@mobile.ecei.tohoku.ac.jp, ++adachi@ecei.tohoku.ac.jp

***Abstract*— As the number of resolvable propagation paths increases, the bit error rate (BER) performance of DS-CDMA with rake combining degrades due to increasing inter-path interference. Recently, we have shown that the use of frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion can significantly improve the downlink BER performance. However, for the uplink transmissions, MAI (multi-access interference) is produced due to orthogonality destruction among users and the uplink BER performance severely degrades. In this paper, we propose a frequency-domain multi-stage MAI cancellation for DS-CDMA uplink with transmit/receive antenna diversity and evaluate the achievable BER performance by computer simulation.**

Keywords- *DS-CDMA, Frequency-domain equalization(FDE), MAI cancelation, Transmit/receive antenna diversity.*

I. INTRODUCTION

Wideband direct sequence code division multiple access (DS-CDMA) with rake combining is adopted in the 3rd generation mobile communication systems that provide a variety of data services of up to a few Mbps transmissions [1]. Next generation wireless communication systems require much higher rate data transmissions, e.g., close to 1 Gbps, over a severely frequency-selective fading channel. As the transmission data rate increases, the number of resolvable propagation paths increases and therefore, the bit error rate (BER) performance of DS-CDMA with rake combining degrades due to increasing inter-path interference (IPI).

So far, multi-carrier CDMA (MC-CDMA) has been attracting much attention [2]. However, recently DS-CDMA has been considered over again with the application of frequency-domain equalization (FDE) [3]. FDE based on minimum mean square error (MMSE) criterion [4] can replace rake combining to significantly improve the BER performance of DS-CDMA [5], [6]. Unlike rake combining, the computational complexity of FDE does not depend on the degree of channel frequency-selectivity.

However, in the uplink case, different users' transmit signals go through different channels and thus, the orthogonality between users is lost; the uplink BER performance is severely degraded due to the multi-access interference (MAI) [3]. To improve the uplink BER performance, the use of MAI cancellation technique [7]-[9] is inevitable. To further improve the uplink performance, transmit/receive antenna diversity can be used together with MAI cancellation technique. For transmit/receive antenna diversity, space-time block coded (STBC) transmit antenna diversity [10] and receive antenna diversity can be used.

In this paper, we propose frequency-domain multi-stage parallel interference cancellation (FD-MS-PIC) and successive interference cancellation (FD-MS-SIC) and evaluate by computer simulation the BER performance in a frequency-selective Rayleigh fading channel. The remainder of this paper is organized as follows. Uplink transmission system model of DS-CDMA with FDE is presented in Sect. II. FD-MS-PIC and -SIC are proposed in Sect. III. In Sect. IV, the computer simulation results for the BER performance using the proposed interference cancellation schemes are presented. The paper is concluded in Sect. V.

II. UPLINK TRANSMISSION SYSTEM MODEL

Transmitter/receiver structure for the DS-CDMA uplink is illustrated in Fig. 1. FD-MS-PIC/SIC is jointly used with 2-antenna STBC transmit diversity and N_r-antenna receive diversity. Throughout the paper, the chip-spaced discrete time representation is used.

At a mobile station transmitter, a binary data sequence of the uth user (u=0~(U−1)) is transformed into QPSK-modulated symbol sequence $d^u(n)$, n=0~(N_c/SF−1), and then spread by multiplying the long pseudo noise (PN) sequence $c^u(t)$, where N_c is the size of fast Fourier transform (FFT). The resultant DS-CDMA signal $s^u(t)$, t=0~(N_c−1), can be expressed using the equivalent baseband representation as

$$s^u(t)=\sqrt{\frac{2E_c}{T_c}}d^u\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)\cdot c^u(t)\text{ , (1)}$$

where E_c and T_c represent the chip energy and the chip length, respectively, SF represents the spreading factor and $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x.

An SFxN_c-chip block interleaver, as shown in Fig 2, is used in order to reduce the error propagation produced by decision feedback for the interference replica generation. The resulting chip sequence is divided into a sequence of blocks, each with N_c chips. The even and odd chip blocks, $\{s_e^u(t)\}$ and $\{s_o^u(t)\}$, are STBC-encoded as shown in Fig. 3 [11]. After insertion of guard interval (GI) of N_g chips, the STBC-encoded chip blocks are transmitted simultaneously from two antennas during the time interval of consecutive two (even and odd) chip blocks.

U users' transmitted signals go through different fading channels and are received by N_r antennas at a base station. The transmission channel is assumed to be a chip-spaced L-path frequency-selective fading channel. The lth path gain and time delay of the channel between the nth transmit antenna and the mth received antenna for the uth user are denoted by $h^u_{n,m,l}$ and τ^u_l, respectively, with $\sum_{l=0}^{L-1}E[|h_{n,m,l}|^2]=1$. The STBC-encoded even and odd chip blocks received on the mth antenna, m=0~N_r–1, can be expressed as

$$\begin{cases} r_{e,m}(t)=\sum_{u=0}^{U-1}\sum_{l=0}^{L-1}\left\{h_{0,m,l}^u s_e^u(t-\tau_l^u)+h_{1,m,l}^u s_o^u(t-\tau_l^u)\right\}+\eta_{e,m}(t) \\ r_{e,m}(t)=-\sum_{u=0}^{U-1}\sum_{l=0}^{L-1}\left\{h_{0,m,l}^u s_o^{u*}(N_c-t-\tau_l^u)+h_{1,m,l}^u s_e^{u*}(N_c-t-\tau_l^u)\right\}+\eta_{o,m}(t) \end{cases} ,(2)$$

where $\eta_m(t)$ represents the zero-mean additive white Gaussian noise (AWGN) process having variance $2N_0/T_c$ with N_0 representing the single-sided power spectrum density. Here, we have assumed block fading, where path gains remain constant over the time interval of $t= -N_g$~(N_c-1).

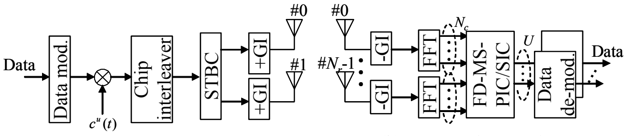
After the removal of GI, the received signal is decomposed into N_c frequency components $\{R_{e(\text{or }o),m}(k);k=0\sim(N_c-1)\}$ by applying N_c-point FFT. $R_{e(\text{or }o),m}(k)$ is given by

$$\begin{cases} R_{e,m}(k)=\sum_{t=0}^{N_c-1}r_{e,m}(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ \qquad =\sum_{u=0}^{U-1}H_{0,m}^u(k)S_e^u(k)+\sum_{u=0}^{U-1}H_{1,m}^u(k)S_o^u(k)+\Pi_{e,m}(k) \\ R_{o,m}(k)=\sum_{t=0}^{N_c-1}r_{o,m}(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ \qquad =-\sum_{u=0}^{U-1}H_{0,m}^u(k)S_o^{u*}(k)+\sum_{u=0}^{U-1}H_{1,m}^u(k)S_e^{u*}(k)+\Pi_{o,m}(k) \end{cases} ,(3)$$

where $S_{e(\text{or }o)}^u(k)$ is the kth frequency component of $s_{e(\text{or }o)}^u(t)$ and $H_{0(\text{or }1),m}^u(k)$ and $\Pi_{e(\text{or }o),m}(k)$ are respectively the channel gain and the noise component at the kth frequency due to the AWGN. $s_{e(\text{or }o)}^u(t)$, $H_{0(\text{or }1),m}^u(k)$ and $\Pi_{e(\text{or }o),m}(k)$ are given by

$$\begin{cases} S_{e(\text{or }o)}^u(k)=\sum_{t=0}^{N_c-1}s_{e(\text{or }o)}^u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ H_m^u(k)=\sum_{l=0}^{L-1}h_{m,l}^u\exp\left(-j2\pi k\frac{\tau_l^u}{N_c}\right) \\ \Pi_m(k)=\sum_{t=0}^{N_c-1}\eta_m(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \end{cases} .(4)$$

Then, frequency-domain STBC-decoding is carried out, followed by PIC and SIC for MAI cancellation to obtain a sequence of decision variables $\{\tilde{d}_{i-1}^u(n);n=0\sim(N_c/SF-1),u=0\sim(U-1)\}$.



(a) Mobile station transmitter (b) Base station receiver

Fig. 1 Transmitter/receiver structure.

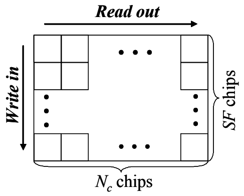


Fig. 2 Chip interleaver.

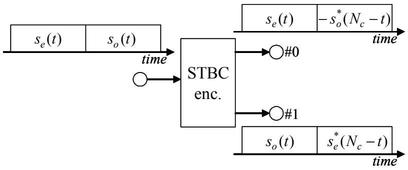


Fig. 3 STBC-encoding.

III. JOINT STBC-DECODING AND MAI CANCELLATION

At the 0th stage of FD-MS-PIC, all users' data sequences are detected after performing one-tap MMSE-FDE taking into account the MAI power. For the 1st stage onwards, MAI replicas are generated and subtracted from the received signal to obtain the MAI-reduced signal and then, MMSE-FDE taking into account the residual MAI power is carried out again. This is repeated a sufficient number of times. On the other hand, in FD-MS-SIC, a series of MMSE-FDE, MAI replica generation and subtraction is carried out at each stage for users in the descending order of their equivalent channel gains. This is repeated a sufficient number of times. The cancellation structure at the ith stage structure is illustrated in Fig. 4 and 5 for FD-MS-PIC and SIC, respectively.

A. Frequency-domain PIC

The soft symbol replica $\bar{d}_{i-1}^u(n)$ of the uth user is generated by using the decision variable $\tilde{d}_{i-1}^u(n)$ at the (i–1)th stage as follows [12]:

$$\bar{d}_{i-1}^u(n)=\frac{1}{\sqrt{2}}\left[\tanh\left(\beta_{i-1}\frac{\text{Re}[\tilde{d}_{i-1}^u(n)]}{\sqrt{2E_c/T_c}}\right)+j\tanh\left(\beta_{i-1}\frac{\text{Im}[\tilde{d}_{i-1}^u(n)]}{\sqrt{2E_c/T_c}}\right)\right] ,(5)$$

where $\beta_{i\text{-}1}$ is a parameter that controls the extent to which the soft decision contributes to the replica generation. The soft symbol replica $\bar{d}_{i-1}^u(n)$ is re-spread and then decomposed into N_c frequency components $\{\bar{S}_{i-1}^u(k);k=0\sim(N_c-1)\}$ by applying N_c-point FFT:

$$\bar{S}_{i-1}^u(k)=\sum_{t=0}^{N_c-1}\left\{\sqrt{\frac{2E_c}{T_c}}\bar{d}_{i-1}^u\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)\cdot c^u(t)\right\}\exp\left(-j2\pi k\frac{t}{N_c}\right).(6)$$

Then, STBC-encoded received signal replica $\bar{R}_{e(\text{or }o),m,i}^u(k)$ is generated as

$$\begin{cases} \bar{R}_{e,m,i}^u(k)=H_{0,m}^u(k)\bar{S}_{e,i}^u(k)+H_{1,m}^u(k)\bar{S}_{o,i}^u(k) \\ \bar{R}_{o,m,i}^u(k)=-H_{0,m}^u(k)\bar{S}_{o,i}^{u*}(k)+H_{1,m}^u(k)\bar{S}_{e,i}^{u*}(k) \end{cases} .(7)$$

PIC is carried out as

$$\tilde{R}^{u}_{e(\text{or }o),m,i}(k) = R_{e(\text{or }o),m}(k) - \sum_{\substack{u'=0\\ \neq u}}^{U-1} \bar{R}^{u'}_{e(\text{or }o),m,i-1}(k)\ . \ (8)$$

Next, joint STBC-decoding, antenna diversity combining and MMSE-FDE is carried out as follows [11]:

$$\begin{cases} \tilde{S}^{u}_{e,i}(k) = \sum_{m=0}^{N_r-1}\left[w^{u*}_{0,m,i}(k)\tilde{R}^{u}_{e,m,i}(k) + w^{u}_{1,m,i}(k)\tilde{R}^{u*}_{o,m,i}(k)\right] \\ \tilde{S}^{u}_{o,i}(k) = \sum_{m=0}^{N_r-1}\left[w^{u*}_{1,m,i}(k)\tilde{R}^{u}_{e,m,i}(k) - w^{u}_{0,m,i}(k)\tilde{R}^{u*}_{o,m,i}(k)\right] \end{cases}, \ (9)$$

where $w^{u}_{0(\text{or }1),m,i}$ is the MMSE weight. $w^{u}_{0(\text{or }1),m,i}$ is given by

$$w^{u}_{0(\text{or }1),m,i}(k) = \frac{H^{u}_{0(\text{or }1),m}(k)}{\sum_{n=0}^{1}\sum_{m=0}^{N_r-1}\left[|H^{u}_{n,m}(k)|^2 + \sum_{\substack{u'=0\\ \neq u}}^{U-1}\rho^{u'}_{i-1}|H^{u'}_{n,m}(k)|^2\right] + \left(\frac{1}{2}\frac{E_c}{N_0}\right)^{-1}}\ , \ (10)$$

where

$$\rho^{u'}_{i-1} = \frac{1}{N_c}\sum_{t=0}^{N_c-1}\left[1 - \left(\frac{2E_c}{T_c}\right)^{-1}\left|\bar{s}^{u'}_{i-1}(t)\right|^2\right] \ (11)$$

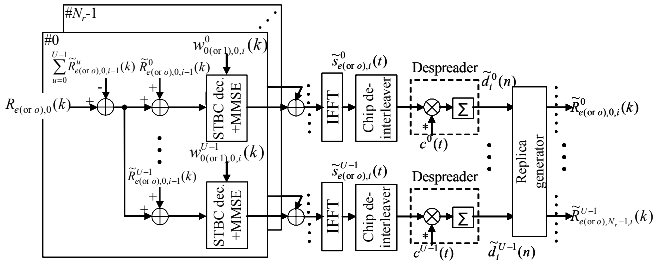
is the contribution from the residual MAI and E_c/N_0 is the average chip energy-to-AWGN power spectrum density ratio. In Eq. (11), $\bar{s}^{u'}_{i-1}(t)$ is the replica of the u'th user's transmitted DS-CDMA signal, given by

$$\bar{s}^{u'}_{i-1}(t) = \sqrt{\frac{2E_c}{T_c}}\bar{d}^{u'}_{i-1}\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)\cdot c^{u'}(t)\ . \ (12)$$

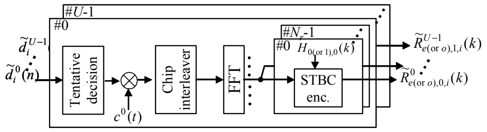
After carrying out joint STBC-decoding and MMSE-FDE, N_c-point inverse FFT (IFFT) is performed on $\{\tilde{S}^{u}_{i}(k); k = 0 \sim (N_c-1)\}$ to produce the uth user's chip stream $\tilde{s}^{u}_{i}(t)$ and despreding is carried out to obtain the decision variable $\tilde{d}^{u}_{i}(n)$:

$$\tilde{d}^{u}_{i}(n) = \frac{1}{SF}\sum_{t=nSF}^{(n+1)SF-1}\tilde{s}^{u}_{i}(t)c^{u*}(t)\ . \ (13)$$

The above procedure is carried out for all U users.



(a) Overall structure



(b) Replica generator

Fig. 4 *i*th stage structure of FD-MS-PIC.

B. Frequency-domain SIC

The equivalent channel gain $\bar{H}^{u}$ for the uth user is given by [6]

$$\bar{H}^{u} = \frac{1}{N_c}\sum_{n=0}^{1}\sum_{m=0}^{N_r-1}\sum_{k=0}^{N_c-1}\left|H^{u}_{n,m}(k)\right|^2\ . \ (14)$$

At first, $\{\bar{H}^{u}; u = 0 \sim (U-1)\}$ are compared and users are sorted in the descending order. In this paper, we assume $\bar{H}^{0} \geq \bar{H}^{1} \geq \ldots \geq \bar{H}^{u} \geq \ldots \geq \bar{H}^{U-1}$ without loss of generality.

The MAI subtraction for the uth user at the ith stage is expressed as

$$\begin{aligned}\tilde{R}^{u}_{e(\text{or }o),m,i}(k) = R_{e(\text{or }o),m}(k) &- \sum_{\substack{u'=0\\ \neq u}}^{U-1}\bar{R}^{u'}_{e(\text{or }o),m,i-1}(k) \\ &- \sum_{u'=0}^{u-1}\left\{\bar{R}^{u'}_{e(\text{or }o),m,i}(k) - \bar{R}^{u'}_{e(\text{or }o),m,i-1}(k)\right\}\end{aligned}\ , \ (15)$$

where $\bar{R}^{u}_{e(\text{or }o),m,i}(k)$ and $\bar{R}^{u}_{e(\text{or }o),m,i-1}(k)$ are the MAI replicas generated at the ith stage and (i–1)th stage, respectively. Then, joint STBC-decoding and MMSE-FDE is carried out as shown in Eq. (9). The MMSE weight $w^{u}_{0(\text{or }1),m,i}$ is given by

$$w^{u}_{0(\text{or }1),m,i}(k) = \frac{H^{u}_{0(\text{or }1),m}(k)}{\sum_{n=0}^{1}\sum_{m=0}^{N_r-1}\left[\begin{aligned}&|H^{u}_{n,m}(k)|^2 + \sum_{u'=0}^{u-1}\rho^{u'}_{i}|H^{u'}_{n,m}(k)|^2 \\ &+ \sum_{u'=u+1}^{U-1}\rho^{u'}_{i-1}|H^{u'}_{n,m}(k)|^2\end{aligned}\right] + \left(\frac{1}{2}\frac{E_c}{N_0}\right)^{-1}}\ . \ (16)$$

After joint STBC-decoding and MMSE-FDE, N_c-point IFFT is performed on $\{\tilde{S}^{u}_{i}(k); k = 0 \sim (N_c-1)\}$ to produce the time-domain signal $\tilde{s}^{u}_{i}(t)$ and despreding is carried out to obtain the decision variable $\tilde{d}^{u}_{i}(n)$. The soft symbol replica $\bar{d}^{u}_{i}(n)$ for the uth user is generated by using $\tilde{d}^{u}_{i}(n)$ as in Eq. (5). The symbol replica $\bar{d}^{u}_{i}(n)$ is re-spread and decomposed into N_c frequency components $\{\bar{S}^{u}_{i}(k); k = 0 \sim (N_c-1)\}$ by applying N_c-point FFT. Then, the received signal replica $\bar{R}^{u}_{e(\text{or }o),m,i}(k)$ is generated as in Eq. (7).

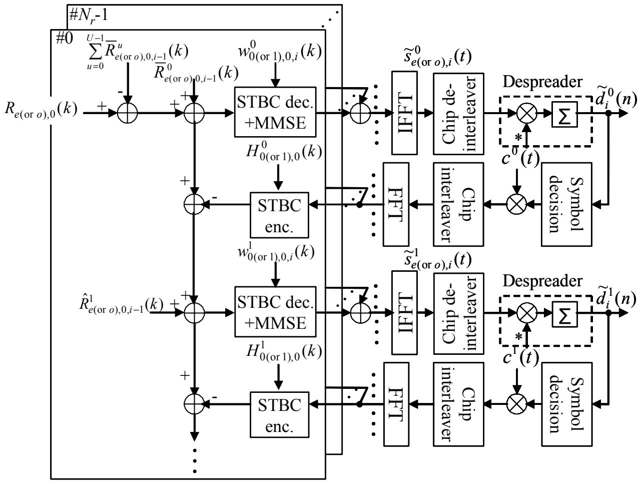


Fig. 5 *i*th stage structure of FD-MS-SIC.

IV. SIMULATION RESULTS

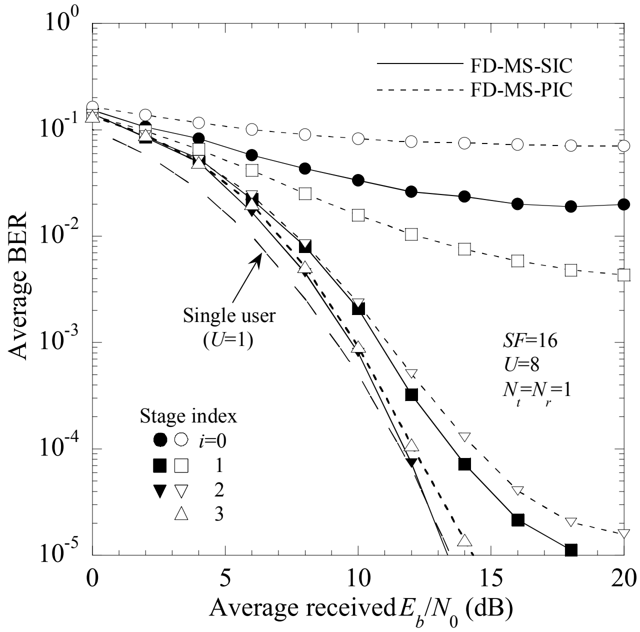
Table 1 shows the computer simulation condition. A chip-spaced 16-path (L=16) frequency-selective block Rayleigh fading channel having the uniform power delay profile are assumed. We assume an FFT block length of N_c=256 chips, a GI length of N_g=32 chips, and a spreading factor of SF=16. We assume ideal channel estimation and all users' transmit timings are kept within GI by the transmit timing control. The MMSE-FDE weight and control parameter β_i for the soft symbol replica generation are optimized in each iteration stage.

Table 1 Simulation condition.

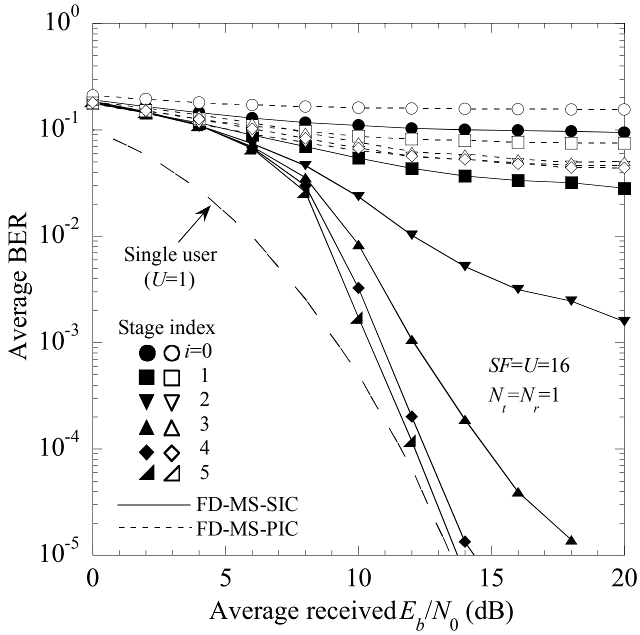
Transmitter	Modulation	QPSK
	FFT block length	N_c=256 chips
	GI length	N_g=32 chips
	Spreading factor	SF=16
	Number of users	U=8, 16
	Number of transmit antennas	N_t=1, 2
Channel	Fading	Frequency-selective block Rayleigh fading
	Number of paths	L=16
	Power delay profile	Uniform
Receiver	Number of receive antennas	N_r=1, 2
	Frequency-domain equalization	MMSE
	Channel estimation	Ideal

Fig. 6 plots the average BER performance as a function of the average received signal energy per bit-to-the AWGN power spectrum density ratio E_b/N_0 (=$0.5SF(1+N_g/N_c)(E_c/N_0)$). For comparison, the single user case (U=1) is also plotted. Without MAI cancellation (i.e., i=0 for PIC), the uplink BER performance is severely degraded. However, it can be seen that the proposed FD-MS-PIC/SIC can significantly improve the BER performance under multi-user environments. When U/SF=0.5, even with i=3rd and 2nd stages, the average BER performance approaches the single user case by about a fractional dB. However, for full load condition (i.e., U/SF=1), PIC cannot improve the BER performance due to the error propagation; but with SIC, the BER performance close to the single-user case can be achieved at the i=5th stage.

The BER performance with transmit/receive antenna diversity (N_t=N_r=2) is plotted in Fig. 7. The joint use of antenna diversity and MAI cancellation can significantly improve the BER performance. Very close-to-single user performance is achieved even in a low E_b/N_0 region at the i=2nd and 3rd stages for SIC and PIC, respectively.

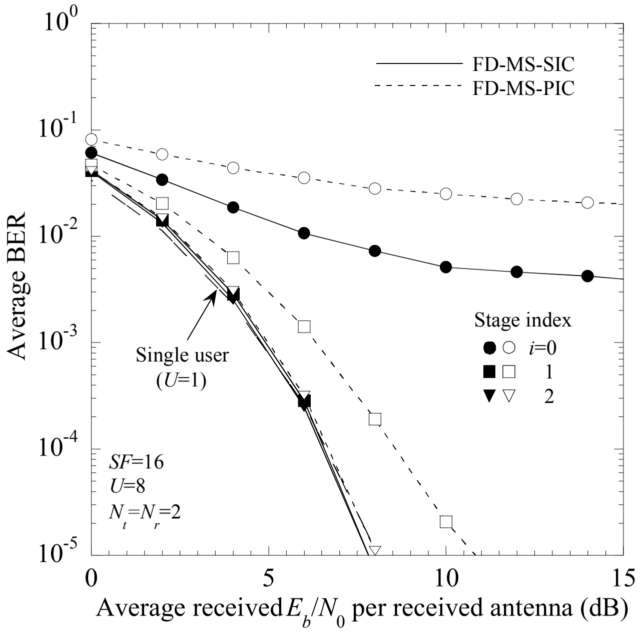


(a) U=8

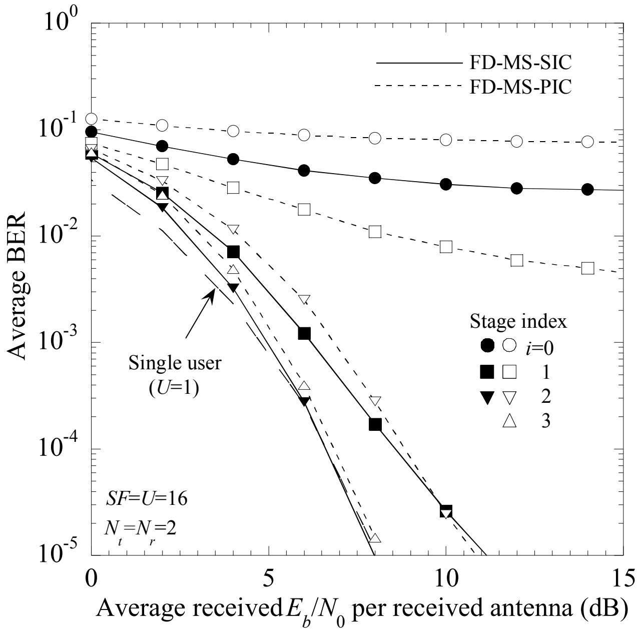


(b) U=16

Fig. 6 BER performance with FD-MS-PIC/SIC (N_t=N_r=1).



(a) U=8



(b) U=16

Fig. 7 BER performance with FD-MS-PIC/SIC and transmit/receive antenna diversity (N_t=N_r=2).

V. CONCLUSION

In this paper, we proposed frequency-domain multi-stage parallel interference cancellation (FD-MS-PIC) and successive interference cancellation (FD-MS-SIC) for DS-CDMA uplink with transmit/receive antenna diversity reception. FD-MS-PIC and SIC operations are carried out in the frequency-domain and then joint STBC-decoding received antenna diversity combining and MMSE-FDE is applied. We have derived the MMSE-FDE weight taking into account the residual MAI power. The MMSE weight and the replica generation control parameter are updated in each cancellation stage. The BER performance with the proposed FD-MS-PIC/SIC in a frequency-selective Rayleigh fading was evaluated by computer simulation. Without antenna transmit/receive diversity, SIC provides a good BER performance at the i=5th stage; however, PIC cannot be used due to the error propagation. With antenna transmit and receive diversity, both PIC and SIC work well and a close-to-single user performance can be achieved at the i=3rd stage for PIC and the i=2nd stage for SIC, respectively.

REFERENCES

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

[2] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., vol. 35, pp. 126-133, Dec. 1997.

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

[4] D. Falconer, et al., "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., vol.40, pp.58-66, Apr. 2002.

[5] F. Adachi, T. Sao, and T. Itagaki, "Performance of multicode DS-CDMA using frequency domain equalization in a frequency selective fading channel," Electronics letters, vol. 39, pp.239-241, Jan. 2003.

[6] 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.

[7] F. Berggren and S. B. Slimane, "Linear successive interference cancellation in DS-CDMA systems," Wirel. Commun. Mob. Comput., vol.3, no.7, pp.847-859, Nov. 2003.

[8] J. G. Andrews and T. H. Y. Meng, "Performance of multicarrier CDMA with successive interference cancellation in a multipath fading channel," IEEE Trans. Commun., vol. 52, no. 5, pp.811-822, May 2004.

[9] S. Tomasin and N. Benvenuto, "Equalization and multiuser interference cancellation in CDMA systems," Proc. 6th International Symposium on Wireless Personal Multimedia Communication (WPMC), vol.1, pp.10-14, Yokosuka, Japan, Oct. 2003.

[10] S. Alamouti, "A simple transmit diversity technique for wireless communications," IEEE Journal on Selected Areas in Commun., vol.16, no.8, pp.1451-1458, Oct. 1998.

[11] K. Takeda and F. Adachi, "MMSE frequency-domain equalization combined with space-time transmit diversity and antenna receive diversity for DS-CDMA," Proc. 59th IEEE Veh. Technol. Conf. (VTC), Milan, Italy, May 2004.

[12] A. Nakajima, D. Garg, and F. Adachi, "Iterative adaptive soft parallel interference canceller for turbo coded MIMO multiplexing," IEICE Trans. Commun., vol.E87-B, no.12, pp.3813-3819, Dec. 2004.