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FREQUENCY-DOMAIN EQUALIZATION FOR BLOCK CDMA TRANSMISSION

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Abstract: Frequency-domain equalization (FDE) technique may play an important role for broadband packet transmission using MC- and DS-CDMA. The downlink performance is significantly improved with FDE; however, the uplink performance is limited by the multi-access interference (MAI). To remove the MAI while gaining the frequency diversity effect through the use of FDE, frequency-domain block spread CDMA can be used. The performance can be further improved by the use of multi-input/multi-output (MIMO) antenna technique. Recently, particular attention has been paid to MIMO space division multiplexing (SDM) to significantly increase the throughput without expanding the signal bandwidth. In this paper, we present a comprehensive performance comparison of MC- and DS-CDMA using FDE.

Key words: MC-CDMA, DS-CDMA, frequency-domain equalization, MIMO, HARQ

1. INTRODUCTION

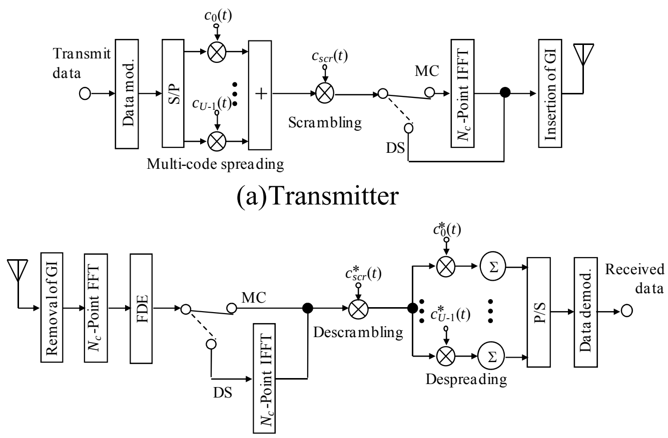
The deployment speed of 3rd generation (3G) wireless networks based on direct-sequence code division multiple access (DS-CDMA) technique[1] has accelerated. 3G wireless networks will be continuously evolving for providing packet data services of 50~100Mbps. The evolution of 3G wireless networks will be followed by the development of 4th generation (4G) wireless networks that can support extremely higher-speed packet data services of e.g., 100M~1Gbps[2]. The received signal spectrum is severely distorted due to frequency-selective fading and thus, equalization techniques are indispensable. Since DS-CDMA using coherent rake combining provides very poor performance in a strong frequency-selective fading channel, multi-carrier CDMA (MC-CDMA)[3] with frequency-domain equalization (FDE) has long time been considered as a broadband multi-access technique. However, it was recently shown[4] that FDE can replace the coherent rake combining to improve the DS-CDMA downlink (base-to-mobile) transmission performance. The uplink (mobile-to-base) performance is limited by the multi-access interference (MAI). To remove the MAI while gaining the frequency diversity effect through the use of FDE, frequency-domain block spread CDMA can be used. Some form of error control technique is indispensable for broadband packet transmission. Frequency-domain hybrid ARQ (HARQ), which is a combination of HARQ and FDE, will be a promising error control technique. Further throughput improvement is possible by the multi-input/multi-output (MIMO) antenna technique. Recently, particular attention has been paid to MIMO space division multiplexing (SDM) to increase the throughput without expanding the signal bandwidth[5]. To exploit the channel frequency-selectivity, signal separation/detection can be combined with FDE. In this paper, first, we discuss similarity of both CDMA techniques and then, show that both are comparable and can remain as a promising wireless access.

2. SIMILARITY OF MC- AND DS-CDMA

FDE based on minimum mean square error (MMSE) criterion can exploit the channel frequency-selectivity to improve the bit error rate (BER) performance. Figure 1 illustrates the transmitter/receiver structure of multicode CDMA using MMSE-FDE. A data-modulated symbol sequence to be transmitted is serial-to-parallel (S/P) converted to U parallel symbol streams, and then, multicode spreading is done using U orthogonal spreading codes $\{c_u(t);\ t=0\sim(SF-1)\}$, $u=0\sim(U-1)$, with spreading factor SF, and further multiplied by a scrambling sequence $c_{scr}(t)$. For MC-CDMA, N_c-point inverse fast Fourier transform (IFFT) is applied to generate the MC-CDMA signal with N_c subcarriers. In DS-CDMA transmission, however, no IFFT is required. Each signal block is transmitted after inserting a cyclic prefix of N_g samples into the guard interval (GI). At the receiver, the received signal block is transformed by N_c-point FFT into N_c subcarrier components $\{R(k);\ k=0\sim(N_c-1)\}$. FDE is carried out as $\hat{R}(k) = w(k)R(k)$ for $k=0\sim(N_c-1)$, where $w(k)$ is the MMSE-FDE weight given by

$$w(k) = H^*(k) \Bigg/ \left(|H(k)|^2 + \left(\frac{U}{SF} \frac{E_s}{N_0} \right)^{-1} \right), \qquad (1)$$

where $H(k)$ is the channel gain at the kth subcarrier and E_s/N_0 is the average received signal energy per data symbol-to-AWGN power spectrum density ratio. For DS-CDMA, the time-domain chip sequence is recovered by applying N_c-point IFFT to $\{\hat{R}(k); k = 0 \sim (N_c - 1)\}$, while it is not required for MC-CDMA. Descrambling and multicode despreading are carried out to get a soft-decision symbol sequence for data demodulation. As seen from Fig. 1, the difference between MC- and DS-CDMA is a location of IFFT function; IFFT is required at the transmitter for MC, while it is required at the receiver for DS. This leads to a new transceiver, based on software-defined radio technology, which can flexibly switch between MC-CDMA (or OFDMA) and DS-CDMA.



(a)Transmitter

(b) Receiver

Fig. 1 CDMA transmitter/receiver structure.

3. FREQEUNCY-DOMAIN TRANSMIT DIVERSITY

Antenna diversity is a well-known technique to improve the transmission performance. Space-time block coded joint transmit/receive diversity (STBC-JTRD) was proposed[6] that can use an arbitrary number of transmit antennas while limiting the maximum number of receive antennas to 4. Frequency-domain pre-equalization[7] can be introduced to STBC-JTRD for both CDMA[8]. At the transmitter, the multicode CDMA signal is divided into a sequence of G information blocks. For DS-CDMA, N_c-point FFT is applied to decompose the gth chip block, g=0~(G-1), into N_c subcarrier components

$\{S_g(k);\ k=0\sim(N_c-1)\}$, while it is not required for MC-CDMA. The resulting G consecutive components $\{S_0(k),...,S_g(k),..,S_{G-1}(k)\}$ of the kth subcarrier are encoded into N_t parallel codewords as shown in Fig. 2; the n_tth codeword consisting of a sequence of Q subcarrier components $\{\tilde{S}_{0,n_t}(k),...,\ \tilde{S}_{q,n_t}(k),...,\tilde{S}_{Q-1,n_t}(k)\}$ is transmitted from the n_tth transmit antenna after performing N_c-point IFFT. Table 1 shows the number G of information chip blocks per codeword, the number Q of coded chip blocks per codeword, and the code rate R for N_r=1~4. A superposition of N_t codewords is received via a frequency-selective fading channel. A simple STBC-JTRD decoding is carried out by using N_r parallel received codewords $\{r_{q,n_r}(t);\ q=0\sim(Q-1),\ n_r=0\sim(N_r-1)\}$[8]. For MC-CDMA, after transforming the decoder output $\{\hat{r}_g(t);\ t=0\sim(N_c-1)\}$ into the N_c subcarrier components by N_c-point FFT, the descrambling and despreading are carried out to get a sequence of the decision variables. For DS-CDMA, FFT is not required.

STBC-JTRD encoding for N_r=2 is represented as

$$\begin{pmatrix}\tilde{S}_{0,n_t}(k)\\ \tilde{S}_{1,n_t}(k)\end{pmatrix}=\sqrt{\frac{N_c}{\sum_{n_r=0}^{N_r-1}\sum_{n_t=0}^{N_t-1}\sum_{k=0}^{N_c-1}|w_{n_r,n_t}(k)|^2}}\begin{pmatrix}S_0(k)w_{0,n_t}(k)+S_1(k)w_{1,n_t}(k)\\ S_0^*(k)w_{1,n_t}(k)-S_1^*(k)w_{0,n_t}(k)\end{pmatrix},\quad(2)$$

where $w_{n_r,n_t}(k)$ is the MMSE pre-equalization weight, given as

$$w_{n_r,n_t}(k)=H^*_{n_r,n_t}(k)\Bigg/\left(\frac{1}{N_r}\sum_{n_r=0}^{N_r-1}\sum_{n_t=0}^{N_t-1}|H_{n_r,n_t}(k)|^2+\left(\frac{U}{SF}\frac{E_s}{N_0}\right)^{-1}\right),\qquad(3)$$

where $H_{n_r,n_t}(k)$ is the channel gain between the n_tth transmit antenna and the n_rth receive antenna at the kth subcarrier. The corresponding STBC-JTRD decoding is represented as

$$\begin{pmatrix}\hat{r}_0(t)\\ \hat{r}_1(t)\end{pmatrix}=\begin{pmatrix}r_{0,0}(t)+r_{1,1}^*(N_c-t)\\ r_{0,1}(t)-r_{1,0}^*(N_c-t)\end{pmatrix},\ \text{for } t=0\sim(N_c-1)\quad.\qquad(4)$$

The turbo-coded BER performance using frequency-domain STBC-JTRD is plotted in Fig. 3 as a function of the average total transmit energy per information bit-to-AWGN power spectrum density ratio E_b/N_0. For comparison, the BER performance of the space-time transmit diversity (STTD)[9] jointly used with FDE (called frequency-domain STTD) is also plotted. Almost the identical BER performance can be achieved for MC- and DS-CDMA. As N_t increases, frequency-domain STBC-JTRD consistently improves the BER performance while frequency-domain STTD provides the same BER performance irrespective of N_t. The use of frequency-domain STBC-JTRD is advantageous for the downlink applications, where the allowable number of receive antennas at a mobile terminal is limited. Frequency-domain STTD is a good option for the uplink applications.

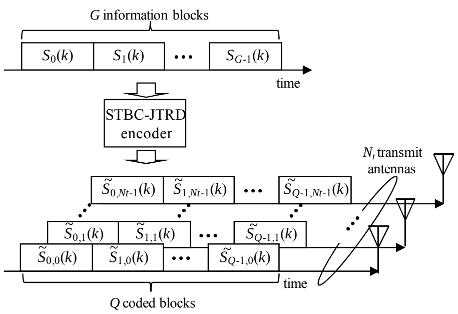


Fig. 2 STBC-JTRD encoding.

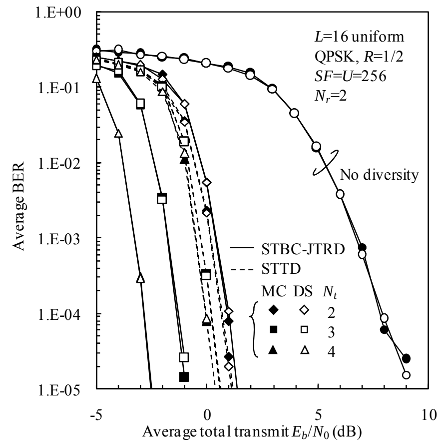


Fig. 3 BER performance of frequency-domain STBC-JTRD with N_r=2.

Table 1 G, Q and R for N_r=1~4

N_r	G	Q	R
1	1	1	1
2	2	2	1
3	3	4	3/4
4	3	4	3/4

4. TIME/FREQUENCY-DOMAIN BLOCK SPREAD CDMA

Using MMSE-FDE, users of different data rates can be code-multiplexed without causing significant performance difference in the downlink case. However, as the number of users increases, the BER performance degrades since the inter-code interference (ICI) gets stronger due to orthogonality distortion in a severe frequency-selective fading channel. This can be avoided to certain extent by introducing 2-dimensional (2D) spreading (frequency-time domain spreading) to MC-CDMA[10]. This 2D spreading can also be applied to DS-CDMA, resulting in 2D block spread DS-CDMA[11]. In the uplink case, the orthogonality among different users is always distorted, resulting in MAI. 2D block spreading can be applied to both MC- and DS-CDMA in order to remove the MAI while gaining the frequency diversity effect by MMSE-FDE. As shown in Fig. 4, each data symbol to be transmitted is spread in both frequency- and time-domain using 2D block spreading code. The 2D block spreading code is a product code of two orthogonal spreading codes. It is represented in a matrix form as $\mathbf{C}_u = \mathbf{c}_u^t(\mathbf{c}_u^f)^T$ with $SF_u = SF_u^t \times SF_u^f$ for the uth user, where $\mathbf{c}_u^t$ and $\mathbf{c}_u^f$ are the column vectors representing time-domain and frequency-domain spreading codes with spreading factor SF_u^t and SF_u^f , respectively. The time-domain spreading code is used to remove the MAI; up-to-as many as SF_u^t users can be multiplexed without causing MAI. The frequency-domain spreading code can be used to gain the frequency diversity effect through MMSE-FDE. The optimum choice of (SF_u^t , SF_u^f) for the given spreading factor SF_u is (U, SF_u/U), where U should be a power of 2.

Figure 5 plots the uplink BER performance of rate-1/2 turbo-coded 2D block spread CDMA with SF_u=16. The BER performance of conventional CDMA is also plotted. MC- and DS-CDMA using 2D block spreading can achieve almost the same BER performance. As U increases, the uplink BER performance degrades. This is because the frequency diversity effect decreases due to reduced spreading factor SF_u^f in the frequency-domain. However, the BER performance of 2D block spread CDMA is significantly better than that of the conventional CDMA.

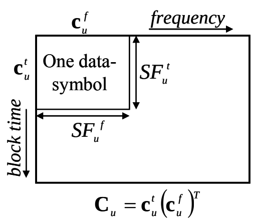


Fig. 4 2D block spreading for MC-CDMA.

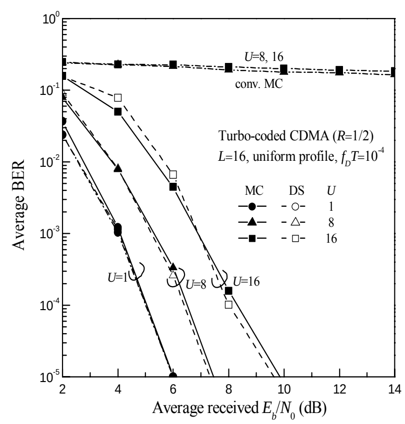


Fig. 5 BER performance.

5. FREQUENCY-DOMAIN HARQ

We consider turbo-coded type II HARQ S-P2[12], as shown in Fig. 6. Rate-1/3 turbo encoder outputs the systematic bit sequence and two parity bit sequences, each has a length of K bits. The 1st transmit packet consists of the systematic bit sequence only and the 2nd and 3rd are taken from two punctured parity bit sequences. Because of the uncoded transmission of the first packet, the throughput performance of full code-multiplexed CDMA is higher than that of OFDM in a higher E_s/N_0 region owing to the frequency diversity effect obtained through MMSE-FDE. However, in a lower E_s/N_0 region, the throughput performance of full code-multiplexed CDMA is worse than that of OFDM owing to the presence of residual ICI after

MMSE-FDE. To reduce the residual ICI, iterative frequency-domain ICI cancellation (FDICIC) technique can be applied (see Fig. 7). MMSE-FDE for the ith iteration is performed as $\hat{R}^{(i)}(k) = w^{(i)}(k)R(k)$ for k=0~(N_c−1), where $w^{(i)}(k)$ is the MMSE-FDE weight and can be derived as

$$w^{(i)}(k) = H^*(k) \Bigg/ \left(|H(k)|^2 + \left\{ \frac{1}{SF} \frac{E_s}{N_0} \sum_{u=0}^{U-1} \rho_u^{(i)} \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) \right\}^{-1} \right) \quad , (5)$$

where $\rho_u^{(i)}(n)$ represents the contribution from the residual ICI $I^{(i)}(k)$. $I^{(i)}(k)$ should be removed for improving the throughput performance. FDICIC is carried out as

$$\tilde{R}^{(i)}(k) = \hat{R}^{(i)}(k) - \tilde{I}^{(i)}(k) \quad , (6)$$

where $\tilde{I}^{(i)}(k)$ is the residual ICI replica generated from *a-posteriori* log likelihood ratio (LLR) of turbo decoder output. After performing multicode despreading and turbo decoding, the soft symbol replica is generated using the decoder output (*a-posteriori* LLR). This replica is fed back to update the MMSE-FDE weight and to generate the residual ICI replica for the (i+1)th iteration.

The use of six iterations (i=6) achieves a sufficient performance improvement. The throughput performance of full code-multiplexed (U=SF) CDMA with FDICIC is plotted in Fig. 8 as a function of the average received E_s/N_0. The achievable throughput is higher than that of OFDM.

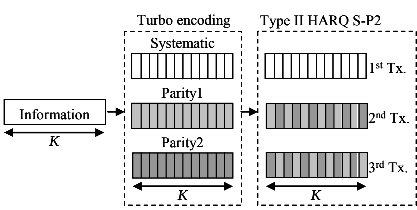


Fig. 6 Type II HARQ S-P2.

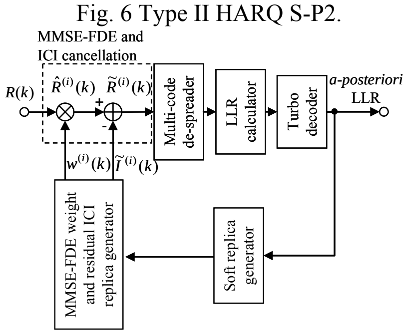


Fig. 7 Iterative FDICIC.

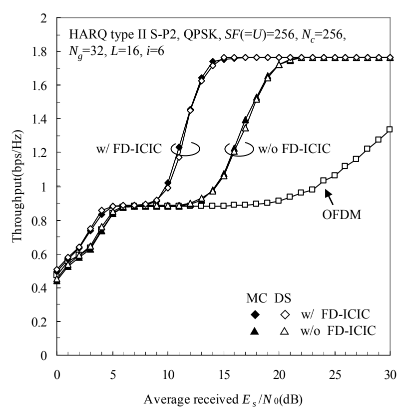


Fig. 8 Throughput performance.

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6. FREQUENCY-DOMAIN MIMO SDM

We consider (N_t, N_r) MIMO SDM using the iterative frequency-domain interference cancellation (FDIC) combined with MMSE-FDE[13,14]. A data-modulated symbol sequence is S/P converted into N_t parallel symbol streams $\{d_{n_t,u}(n); n=0\sim(N_c/SF-1), u=0\sim(U-1)\}$, n_t=0~(N_t–1). Then, multicode spreading using U orthogonal spreading codes with spreading factor SF is applied to each symbol stream to obtain the multicode chip sequence. Each resultant sequence is transformed by N_c-point IFFT into the MC-CDMA signal $\{s_{n_t}(t)$; t=0~(N_c–1)$\}$. In the case of DS-CDMA, IFFT is not required. After inserting the GI, N_t CDMA signals are transmitted simultaneously from N_t transmit antennas. After the removal of GI, the received CDMA signal $\{r_{n_r}(t)$; t=0~N_c–1$\}$ at the n_rth receive antenna is decomposed by N_c-point FFT into N_c subcarrier components $\{R_{n_r}(k)$; k=0~N_c–1$\}$ as

$$R_{n_r}(k)=\sqrt{\frac{2E_s}{SF\cdot T_c}}\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)S_{n_t}(k)+\Pi_{n_r}(k), \qquad (7)$$

where $S_{n_t}(k)$ is the kth frequency component of the multicode CDMA signal transmitted from the n_tth transmit antenna and $\Pi_{n_r}(k)$ is the noise.

In iterative FDIC (see Fig. 9), 2D-MMSE FDE is first carried out as $\hat{R}^{(i)}_{n_t}(k)=\mathbf{w}^{(i)}_{n_t}(k)\mathbf{R}(k)$ to suppress the inter-antenna interference (IAI) and ICI simultaneously, where $\mathbf{R}(k)=[R_0(k),\cdots,R_{N_r-1}(k)]^T$ is N_r-by-1 received signal vector and $\mathbf{w}^{(i)}_{n_t}(k)=[w^{(i)}_0(k),\cdots,w^{(i)}_{N_r-1}(k)]^T$ is 1-by-N_r 2D-MMSE weight vector. $\mathbf{w}^{(i)}_{n_t}(k)$ is given as

$$\mathbf{w}^{(i)}_{n_t}(k)=\mathbf{H}^H_{n_t}(k)\left[\mathbf{H}(k)\mathbf{G}^{(i)}(k)\mathbf{H}^H(k)+\left(\frac{E_s}{SF\cdot N_0}\right)^{-1}\mathbf{I}_{N_r}\right]^{-1}, \qquad (8)$$

where $\mathbf{I}_{N_r}$ is N_r-by-N_r identity matrix, $\mathbf{H}_{n_t}(k)$ and $\mathbf{H}(k)$ are respectively N_r-by-1 channel gain vector and N_r-by-N_t channel gain matrix, and $\mathbf{G}^{(i)}(k)=diag[g^{(i)}_0(k),\cdots,g^{(i)}_{N_t-1}(k)]$ is N_t-by-N_t matrix with $g^{(i)}_{n'_t}(k)$ reflecting the contribution of interference from the n'_tth antenna[14]. Note that $g^{(i)}_{n_t}$ and $g^{(i)}_{n'_t}$ ($n'_t \neq n_t$) correspond to the residual ICI and IAI, respectively. The residual IAI and ICI replicas $\{\tilde{S}^{(i-1)}_{n'_t}(k)\}$ are generated by feeding back the (i–1)th iteration result and subtracted from $\hat{R}^{(i)}_{n_t}(k)$ as

$$\tilde{R}^{(i)}_{n_t}(k)=\hat{R}^{(i)}_{n_t}(k)-\sqrt{\frac{2E_s}{SF\cdot T_c}}\sum_{n'_t=0}^{N_t-1}H'^{(i)}_{n'_t}(k)\tilde{S}^{(i-1)}_{n'_t}(k) \quad , \qquad (9)$$

where $H'^{(i)}_{n'_t \neq n_t}(k) = \mathbf{w}^{(i)}_{n_t}(k)\mathbf{H}^{(i)}_{n'_t}(k)$ is the equivalent channel gain for IAI and $H'^{(i)}_{n'_t = n_t}(k) = \mathbf{w}^{(i)}_{n_t}(k)\mathbf{H}_{n_t}(k) - \widetilde{H}_{n_t}(\lfloor k/SF \rfloor)$ for ICI with

$$\widetilde{H}_{n_t}(n) = (1/SF)\sum_{k=nSF}^{(n+1)SF-1} \mathbf{w}^{(i)}_{n_t}(k)\mathbf{H}_{n_t}(k) \quad . \tag{10}$$

After descrambling and multicode despreading, the LLR associated with each transmitted bit is computed[15], from which the soft symbol replicas are generated. Then, multicode spreading and scrambling are performed to obtain the CDMA signal replicas $\{\widetilde{S}^{(i)}_{n_t}(k); k = 0 \sim (N_c - 1)\}$, n_t=0~(N_t-1), for the next iteration. The above operations are repeated a sufficient number of times to sufficiently suppress the IAI and ICI.

The HARQ throughput performance of full code-multiplexed (U=SF) MC-CDMA (4,4)SDM with iterative FDIC using i=4 is plotted in Fig. 10 as a function of the average received E_s/N_0 per receive antenna. $N_t \times N_r$ channels are independent Rayleigh fading channels having an L=16-path uniform power delay profile. Iterative FDIC significantly improves the throughput performance. The throughput performance of MC-CDMA is almost as same as that of DS-CDMA and is better than OFDM.

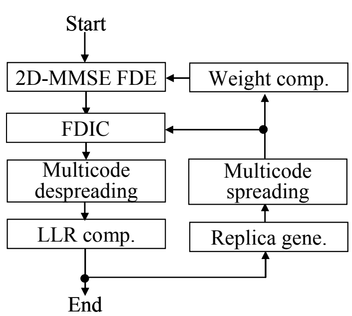

Fig.9 Iterative FDIC.

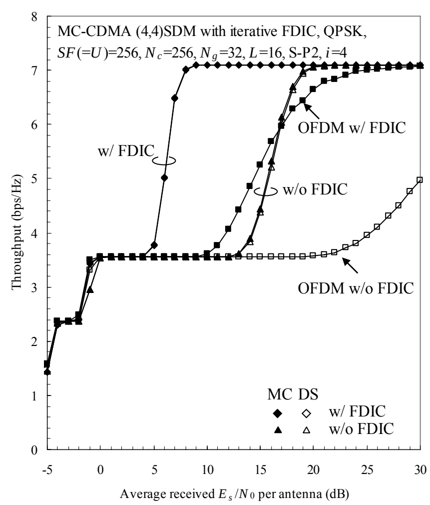

Fig. 10 Throughput performance.

7. CONCLUSION

In this paper, we have presented a comprehensive performance comparison of DS- and MC-CDMA with frequency-domain equalization (FDE). Using FDE, both MC- and DS-CDMA provide almost the identical performance. Since both CDMA transceiver structures are similar, a new CDMA transceiver which can flexibly switch between MC-CDMA (or

OFDMA) and DS-CDMA can be implemented using software defined radio technology. Although OFDMA has recently been attracting attention, CDMA still remains as a promising multi-access technique. Since DS-CDMA signal has less peak-to-average power ratio (PAPR), DS-CDMA is more appropriate for the uplink application than MC-CDMA.

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