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Frequency-domain equalisation for block CDMA transmission†

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SUMMARY

In next generation wireless network, significantly higher rate data services of close to 1 Gpbs are expected. The wireless channels for such a broadband data transmission become severe frequency-selective. Frequency-domain equalisation (FDE) technique may play an important role for broadband data transmission using multi-carrier (MC)- and direct-sequence code division multiple access (DS-CDMA). The performance can be further improved by the use of multi-input/multi-output (MIMO) antenna diversity technique. The downlink performance is significantly improved with FDE. However, the uplink performance is limited by the multiple access interference (MAI). To remove the MAI while gaining the frequency diversity effect through the use of FDE, two-dimensional (2D) block spread CDMA can be used. 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. Copyright © 2008 John Wiley & Sons, Ltd.

1. INTRODUCTION

The next generation wireless networks are expected to support extremely high-speed packet data services of 100 M–1 Gbps [1]. However, the received signal spectrum is severely distorted due to the frequency-selective fading and thus, the use of advanced equalisation techniques is indispensable. Direct-sequence code division multiple access (DS-CDMA) with coherent rake combining used in the present 3rd generation wireless networks [2] provides very poor performance because of strong inter-chip interference. Multi-carrier CDMA (MC-CDMA) [3–5] with frequency-domain equalisation (FDE) has long time been considered as a broadband multiple access technique since it can take advantage of the channel frequency-selectivity to improve the transmission performance. Single-carrier signal transmission performance in a frequency-selective fading channel can be significantly improved by the use of low-complexity FDE [6]. FDE based on minimum mean square error (MMSE) criterion can also be applied to DS-CDMA to replace the coherent rake combining [7].

In the downlink (base-to-mobile), different users' spread signals are code-multiplexed. MC- and DS-CDMA with MMSE-FDE can achieve almost the same downlink transmission performance. Further performance improvement can be achieved by additional use of multi-input/multi- output (MIMO) antenna diversity [8, 9]. However, in the uplink (mobile-to-base) transmission, different users' signals go through different channels and asynchronously received. This produces the multiple access interference (MAI) and limits the uplink performance. Although multiuser detection (MUD) [10, 11] can be used to mitigate the detrimental effects of MAI, the MUD algorithms are relatively complex and their computational complexity increases exponentially with the number of users. To remove the MAI while gaining the frequency diversity effect through the use of FDE, block spread CDMA can be used [12, 13]. Two-dimensional (2D) block spreading (frequency-time domain block spreading) [14] allows multi-rate transmissions.

For broadband packet access, hybrid automatic repeat request (HARQ) with channel coding and FDE is a promising error control technique to increase the packet throughput

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in a frequency-selective fading channel [15]. Although the target peak data rates in the next generation systems is as high as 1 Gbps, the available bandwidth is limited (e.g. 100 MHz). To increase the throughput without expanding the signal bandwidth, MIMO space division multiplexing (SDM) has been attracting a particular attention [16–18]. In MIMO SDM, the data to be transmitted is transformed into parallel data streams and each stream is transmitted simultaneously from a different transmit antenna with the same carrier frequency. At the receiver, a superposition of different data streams transmitted from different antennas is received. To exploit the channel frequency-selectivity, signal detection needs to be combined with FDE.

Both MC- and DS-CDMA have a high flexibility to provide variable rate transmissions by using multiple spreading codes in parallel (called multicode CDMA), yet retain multiple access capability. FDE is a key technique for both CDMA. So far, many works have been done for improving the transmission performances of MC- and DS-CDMA with FDE. In this paper, we present a comprehensive performance comparison of MC- and DS-CDMA with FDE. In multicode CDMA, different sets of spreading codes are assigned to different users according to their requested data rates. However, in this paper, we only consider the single-user transmission case. The remainder of the paper is organised as follows. In Section 2, we discuss similarity of both CDMA with FDE. MIMO antenna diversity jointly used with FDE is presented in Section 3. Section 4 presents 2D block spread CDMA. Frequency-domain HARQ and MIMO SDM are presented in Sections 5 and 6, respectively. Section 7 concludes the paper.

2. SIMILARITY OF MC- AND DS-CDMA

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 $\{c_u(t);\ t=0\sim(\mathrm{SF}-1)\}$, $u=0\sim(U-1)$, with spreading factor SF, and further multiplied by a scrambling sequence $c_{\mathrm{scr}}(t)$. For MC-CDMA, N_c-point inverse fast Fourier transform (IFFT) is applied to generate the time-domain 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 $\{R(k);\ k=0\sim(N_\mathrm{c}-1)\}$. FDE is carried out as $\hat{R}(k)=w(k)R(k)$ for $k=0\sim(N_\mathrm{c}-1)$, where $w(k)$ is the MMSE-FDE weight given by

$$w(k)=\frac{H^*(k)}{|H(k)|^2+(U/\mathrm{SF})^{-1}(E_s/N_0)^{-1}} \tag{1}$$

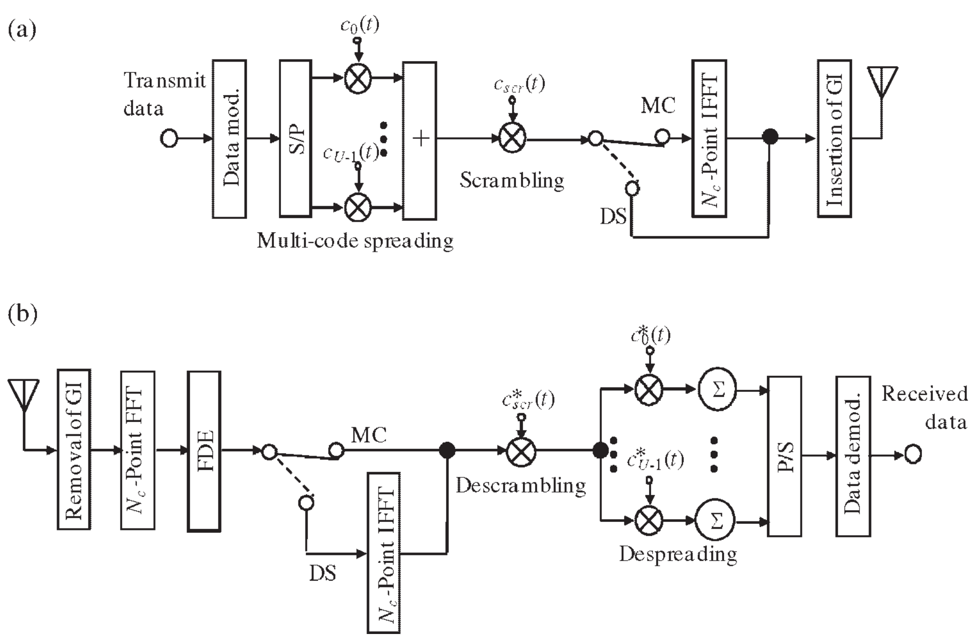

Figure 1. CDMA transmitter/receiver structure. (a) Transmitter, (b) Receiver.

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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 Figure 1, the difference between MC- and DS-CDMA is the 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 and DS-CDMA.

The uncoded BER performances of MC- and DS-CDMA are plotted in Figure 2 when SF $= U = 1$, 16 and 256 (full code-multiplexing). MC-CDMA using SF $= 1$ corresponds to OFDM. As SF increases, larger frequency diversity effect is obtained in MC-CDMA, and hence, the BER performance improves even without channel coding. In DS-CDMA, on the other hand, since one data symbol is spread over all the subcarriers and the channel frequency-selectivity is fully exploited by MMSE-FDE, a good BER performance is obtained irrespective of SF. Application of channel coding significantly improves the BER performance. For $R = 1/2$-rate turbo coding with $i = 8$ iterations of Log-MAP decoding, MC- and DS-CDMA with MMSE-FDE provide a slightly worse BER performance than OFDM. This slight performance degradation is mainly due to the presence of residual inter-code interference/inter-chip interference (ICI) after MMSE-FDE. The introduction of ICI cancellation into CDMA can improve the throughput performance and will be discussed in later sections.

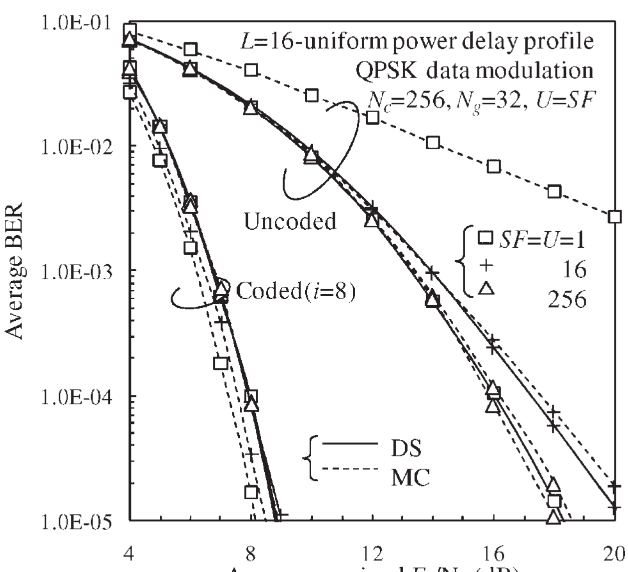

Figure 2. Uncoded BER performance comparison of MC- and DS-CDMA with MMSE-FDE.

3. FREQEUNCY-DOMAIN MIMO ANTENNA 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 [19] that can use an arbitrary number of transmit antennas while limiting the maximum number of receive antennas to four. In a frequency-selective channel, the frequency-selectivity can be exploited to improve the performance by introducing the frequency-domain pre-equalisation [20] to STBC-JTRD for both CDMA [21].

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, $g = 0 \sim (G-1)$, 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 $\{S_0(k), \cdots, S_g(k), \cdots, S_{G-1}(k)\}$ of the kth subcarrier are encoded into N_t parallel codewords; the n_tth codeword consisting of a sequence of Q subcarrier components $\{\tilde{S}_{0,n_t}(k), \cdots, \tilde{S}_{q,n_t}(k), \cdots, \tilde{S}_{Q-1,n_t}(k)\}$, $n_t = 0 \sim (N_t - 1)$, is transmitted from the n_tth transmit antenna after performing N_c-point IFFT. For $N_r = 2$, 3 and 4, $(G, Q) = (2, 2)$, (3, 4) and (3, 4) and the corresponding code rates are $R = 1$, 3/4 and 3/4, respectively. 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 $\{r_{q,n_r}(t);\ q = 0 \sim (Q-1),\ n_r = 0 \sim (N_r - 1)\}$ [21]. 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.

Below, the encoding/decoding algorithm is presented for the case of $N_r = 2$ only. $G = 2$ information symbol blocks are encoded into two codewords, each consisting of $Q = 2$ consecutive blocks $\{\tilde{S}_{q,n_t}(k);\ q = 0 \sim 1\}$ given as

$$\begin{pmatrix} \tilde{S}_{0,n_t}(k) \\ \tilde{S}_{1,n_t}(k) \end{pmatrix} = \sqrt{C_2}\begin{pmatrix} S_0(k)w_{0,n_t}(k) + S_1(k)w_{1,n_t}(k) \\ S_0^*(k)w_{1,n_t}(k) - S_1^*(k)w_{0,n_t}(k) \end{pmatrix} \tag{2}$$

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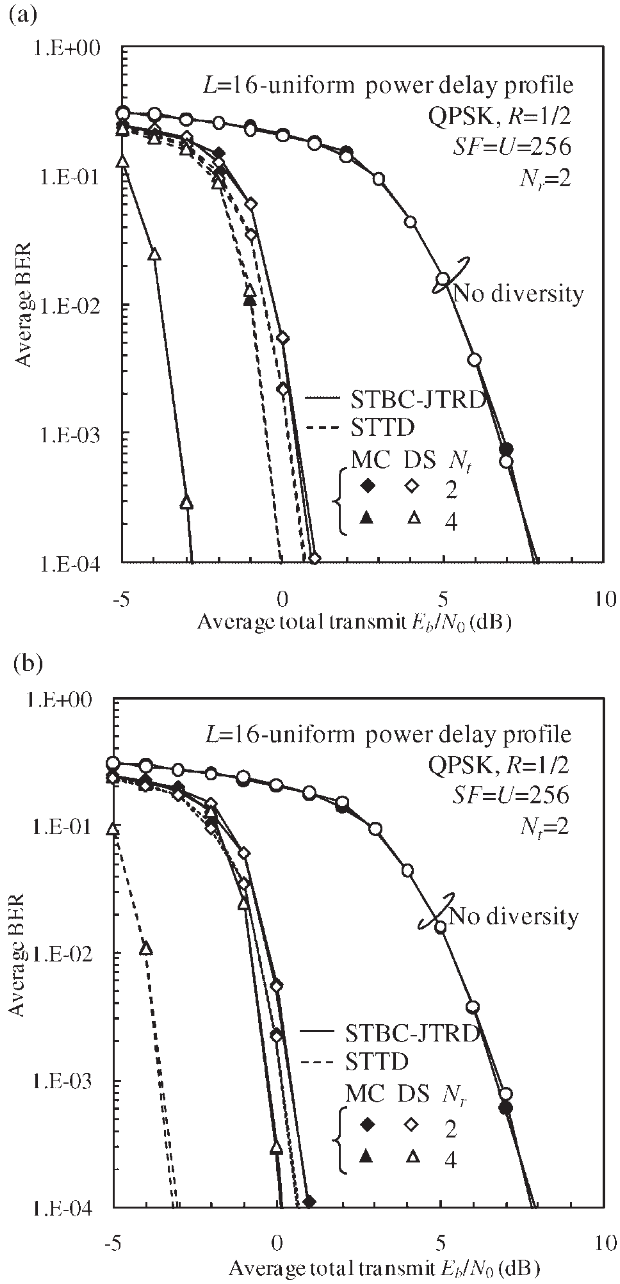

Figure 3. Turbo-coded BER performance of STBC-JTRD. (a) Transmit diversity effect, (b) Receive diversity effect.

where $w_{n_r,n_t}(k)$ is the MMSE pre-equalisation weight, given as [21]

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

with $H_{n_r,n_t}(k)$ representing the channel gain between the n_tth transmit antenna and the n_rth receive antenna at the kth subcarrier. $C_{N_r} = N_c / \sum_{n_r=0}^{N_r-1}\sum_{n_t=0}^{N_t-1}\sum_{k=0}^{N_c-1}|w_{n_r,n_t}(k)|^2$ is the power normalisation coefficient. The corresponding STBC-JTRD decoding is expressed as

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

We consider the full code-multiplexing case (i.e. $\mathrm{SF} = U$) and show how the STBC-JTRD improves the BER performance. The $R = 1/2$-rate turbo-coded BER performance using frequency-domain STBC-JTRD having $N_r = 2$ receive antennas is plotted in Figure 3 as a function of the average total transmit energy per information bit-to-AWGN power spectrum density ratio E_b/N_0. Figure 3(a) shows the effect of transmit diversity with N_t as a parameter for $N_r = 2$. For comparison, the BER performance of the space-time transmit diversity (STTD) [9] jointly used with FDE (called frequency-domain STTD) is also plotted. By increasing N_t from 2 to 4, frequency-domain STBC-JTRD consistently improves the BER performance while frequency-domain STTD provides almost the same BER performance irrespective of N_t. Figure 3(b) shows the effect of receive antenna diversity with N_r as a parameter for $N_t = 2$. It can be seen from Figure 3(b) that when N_r increases, frequency-domain STTD can significantly improve the BER performance, while frequency-domain STBC-JTRD can only slightly improve the performance. This indicates that frequency-domain STTD is a good option for the uplink applications. Frequency-domain STBC-JTRD is advantageous for the downlink applications, where the allowable number of receive antennas at a mobile terminal is limited.

4. 2D 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 ICI gets stronger due to orthogonality distortion in a severe frequency-selective fading channel. This can be avoided to certain extent by introducing 2D block spreading to MC-CDMA [22]. This 2D block spreading can also be applied to DS-CDMA, resulting in 2D block spread DS-CDMA [13]. In the uplink case, the orthogonality among

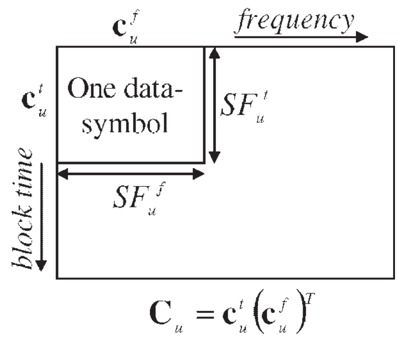

Figure 4. Two-dimensional block spreading for MC-CDMA.

different users is always distorted, resulting in the MAI. The 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 Figure 4, each data symbol to be transmitted is spread in both frequency- and block 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 $\mathrm{SF}_u = \mathrm{SF}_u^t \times \mathrm{SF}_u^f$ for the uth user, where $\mathbf{c}_u^t$ and $\mathbf{c}_u^f$ are the column vectors representing block time-domain and frequency-domain spreading codes with spreading factor SF_u^t and SF_u^f, respectively. The block time-domain spreading code is used to remove the MAI. As many as U users can be multiplexed without causing MAI if the condition $\sum_{u=0}^{U-1}(1/\mathrm{SF}_u^t) \leqslant 1$ is satisfied. The frequency-domain spreading code is 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 two. The 2D block spread DS-CDMA uses the same block time-domain spreading as 2D block spread MC-CDMA, but replaces frequency-domain spreading by DS time-domain spreading (i.e. IFFT is removed from the transmitter).

Figure 5 plots the uplink BER performance of $R = 1/2$-rate turbo-coded 2D block spread CDMA with $\mathrm{SF}_u = 16$. 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 (to keep the spreading factor $\mathrm{SF}_u = \mathrm{SF}_u^t \times \mathrm{SF}_u^f$ the same). However, the BER performance of 2D block spread CDMA is significantly better than that of the conventional CDMA.

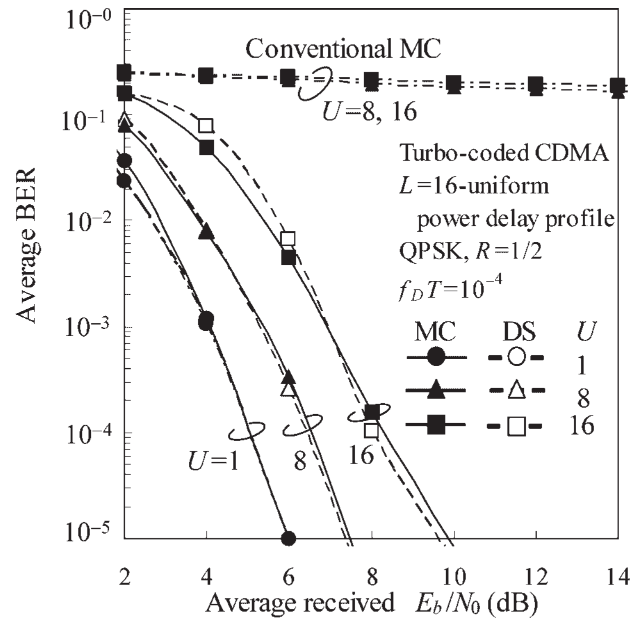

Figure 5. Turbo-coded BER performance.

5. FREQUENCY-DOMAIN HARQ

We consider turbo-coded type II HARQ S-P2 [23]. From the $R = 1/3$-rate turbo encoder outputs (the systematic bit sequence and two parity bit sequences, each has a length of K bits), three transmit packets are constructed. The 1st packet consists of the systematic bit sequence only and the 2nd and 3rd packets are taken from two punctured parity bit sequences. If the transmission of the 1st packet has failed, the 2nd packet is transmitted; then $R = 1/2$-rate turbo decoding is carried out using the received 1st and 2nd packets. If any error remains in the decoded packet, the transmission of the 3rd packet is requested to carry out $R = 1/3$-rate turbo decoding. Because of the uncoded transmission of the 1st 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) [24] technique can be applied (see Figure 6). MMSE-FDE for the ith iteration is performed as $\hat{R}^{(i)}(k) = w^{(i)}(k)R(k)$ for $k = 0 \sim (N_c - 1)$, where $w^{(i)}(k)$ is the MMSE-FDE weight and can be derived as

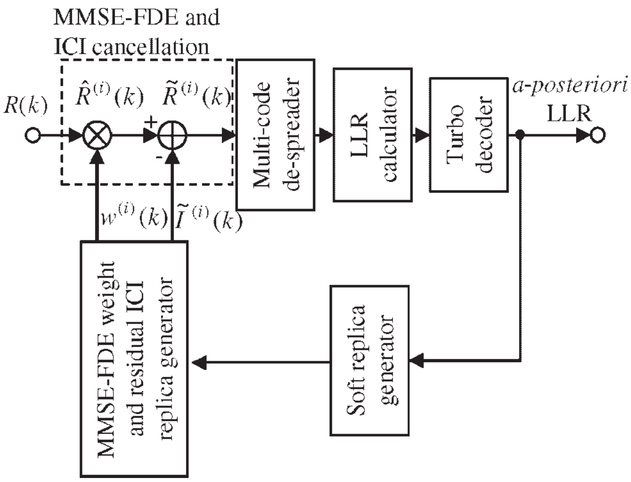

Figure 6. Iterative FDICIC.

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

where $\rho_u^{(i)}(n)$ represents the extent to which the residual ICI remains. $\rho_u^{(i)}(n)$ is given as

$$\rho_u^{(i)}(n) = \left\{E\left[|d_u(n)|^2\right] - \left|\tilde{d}_u^{(i-1)}(n)\right|^2\right\} \quad (6)$$

with $\rho_u^{(0)}(n) = 1$ and $\{\tilde{d}_u^{(i-1)}(n);\ n = 0 \sim (N_c/\mathrm{SF} - 1)\}$ being the soft decision replica of the transmitted symbol block $\{d_u(n)\}$, obtained in the previous iteration. $E[|d_u(n)|^2]$ is the expectation of $|d_u(n)|^2$ for the given received chip block. $\rho_u^{(i)}(n) \to 1$ means that the residual ICI is kept intact, while $\rho_u^{(i)}(n) \to 0$ means that the residual ICI is sufficiently cancelled. The residual ICI should be removed to improve the throughput performance. FDICIC is carried out as

$$\tilde{R}^{(i)}(k) = \hat{R}^{(i)}(k) - \tilde{I}^{(i)}(k) \quad (7)$$

$\tilde{I}^{(i)}(k)$ is the replica of residual ICI $I^{(i)}(k)$ and is given by

$$\tilde{I}^{(i)}(k) = \sqrt{\frac{2E_s}{\mathrm{SF}\cdot T_c}}\left\{\hat{H}^{(i)}(k) - A^{(i)}\left(\left\lfloor\frac{k}{\mathrm{SF}}\right\rfloor\right)\right\} \times \left\{\sum_{u=0}^{U-1}\tilde{d}_u^{(i-1)}\left(\left\lfloor\frac{k}{\mathrm{SF}}\right\rfloor\right)c_u(k)\right\} \quad (8)$$

where T_c is the chip duration, $\hat{H}^{(i)}(k) = w^{(i)}(k)H(k)$ is the equivalent channel gain after MMSE-FDE and $A^{(i)}(n) = (1/\mathrm{SF})\sum_{k=n\mathrm{SF}}^{(n+1)\mathrm{SF}-1}\hat{H}^{(i)}(k)$. After performing multicode despreading and turbo decoding, the soft symbol replica $\tilde{d}_u^{(i)}(n)$ is generated using the *a-posteriori* log-likelihood ratio (LLR) from the decoder output. This replica $\tilde{d}_u^{(i)}(n)$ is fed back to update the MMSE-FDE weight by using Equations (5) and (6), and to generate the residual ICI replica by using Equation (8) for the $(i+1)$th iteration.

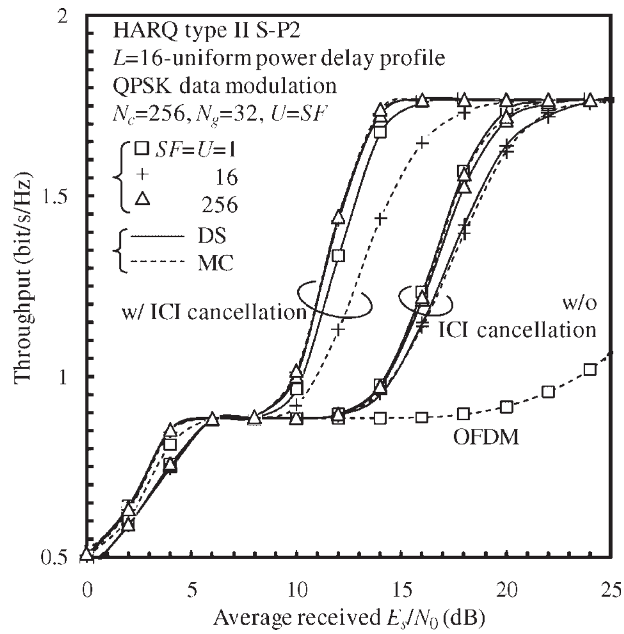

Figure 7. Throughput performance of full code-multiplexed CDMA with iterative FDICIC.

The throughput performance of full code-multiplexed ($U = \mathrm{SF}$) CDMA with iterative FDICIC is plotted in Figure 7 as a function of the average received E_s/N_0 for SF = 1, 16 and 256. The achievable throughput of MC- and DS-CDMA is higher than that of OFDM. The ICI cancellation with eight iterations ($i = 8$) can significantly improve the throughput performance. In MC-CDMA, as SF increases, the throughput gets higher owing to the larger frequency diversity gain. On the other hand, the throughput performance of DS-CDMA is almost insensitive to SF. This is because one data symbol is spread over all the subcarriers and the channel frequency-selectivity can be fully exploited by MMSE-FDE irrespective of SF.

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 [25] for DS- and MC-CDMA. A data-modulated symbol sequence is S/P converted into N_t

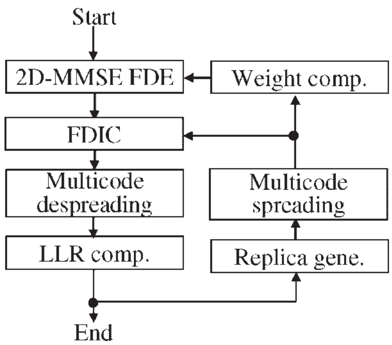

Figure 8. Iterative FDIC.

parallel symbol streams $\{d_{n_t,u}(n);\ n=0\sim(N_c/\mathrm{SF}-1),\ u=0\sim(U-1)\}$, $n_t=0\sim(N_t-1)$. 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 $\{s_{n_t}(t);\ t=0\sim(N_c-1)\}$. 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 $\{r_{n_r}(t);\ t=0\sim N_c-1\}$ at the n_rth receive antenna is decomposed by N_c-point FFT into N_c subcarrier components $\{R_{n_r}(k);\ k=0\sim N_c-1\}$ as

$$R_{n_r}(k)=\sqrt{\frac{2E_s}{\mathrm{SF}\cdot T_c}}\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)S_{n_t}(k)+\Pi_{n_r}(k) \qquad (9)$$

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 Figure 8), 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 $\mathbf{w}^{(i)}_{n_t}(k)=[w^{(i)}_{0,n_t}(k),\cdots,w^{(i)}_{N_r-1,n_t}(k)]^T$ is 1-by-N_r 2D-MMSE weight vector. $\mathbf{w}^{(i)}_{n_t}(k)$ is given as

$$\mathbf{w}^{(i)}_{n_t}(k)=\mathbf{H}^H_{n_t}(k)\left[\mathbf{H}(k)\mathbf{G}^{(i)}(k)\mathbf{H}^H(k)+\left(\frac{E_s}{\mathrm{SF}\cdot N_0}\right)^{-1}\mathbf{I}_{N_r}\right]^{-1} \qquad (10)$$

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 for the n_tth transmit antenna and N_r-by-N_t channel gain matrix, and $\mathbf{G}^{(i)}(k)=\mathrm{diag}[g^{(i)}_0(k),\cdots,g^{(i)}_{N_t-1}(k)]$ is N_t-by-N_t matrix with $g^{(i)}_{n_t'}(k)$ reflecting the contribution of interference from the n_t'th antenna. 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 are generated by feeding back the CDMA signal replicas $\{\tilde{S}^{(i-1)}_{n_t'}(k)\}$ obtained from the $(i-1)$th iteration and subtracted from $\hat{R}^{(i)}_{n_t}(k)$ as

$$\tilde{R}^{(i)}_{n_t}(k)=\hat{R}^{(i)}_{n_t}(k)-\sqrt{\frac{2E_s}{\mathrm{SF}\cdot T_c}}\sum_{n_t'=0}^{N_t-1}H'^{(i)}_{n_t'}(k)\tilde{S}^{(i-1)}_{n_t'}(k) \qquad (11)$$

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 $H'^{(i)}_{n_t'=n_t}(k)=\mathbf{w}^{(i)}_{n_t}(k)\mathbf{H}_{n_t}(k)-\tilde{H}_{n_t}(\lfloor k/\mathrm{SF}\rfloor)$ for ICI with

$$\tilde{H}_{n_t}(n)=\frac{1}{\mathrm{SF}}\sum_{k=n\mathrm{SF}}^{(n+1)\mathrm{SF}-1}\mathbf{w}^{(i)}_{n_t}(k)\mathbf{H}_{n_t}(k) \qquad (12)$$

After descrambling and multicode despreading, the LLR associated with each transmitted bit is computed [26], from which the soft symbol replicas are generated. Then, multicode spreading and scrambling are performed to obtain the CDMA signal replicas $\{\tilde{S}^{(i)}_{n_t}(k);\ k=0\sim(N_c-1)\}$, $n_t=0\sim(N_t-1)$, 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 $(U=\mathrm{SF})$ MC-CDMA (4,4)SDM with iterative FDIC using $i=4$ is plotted in Figure 9 as a function of

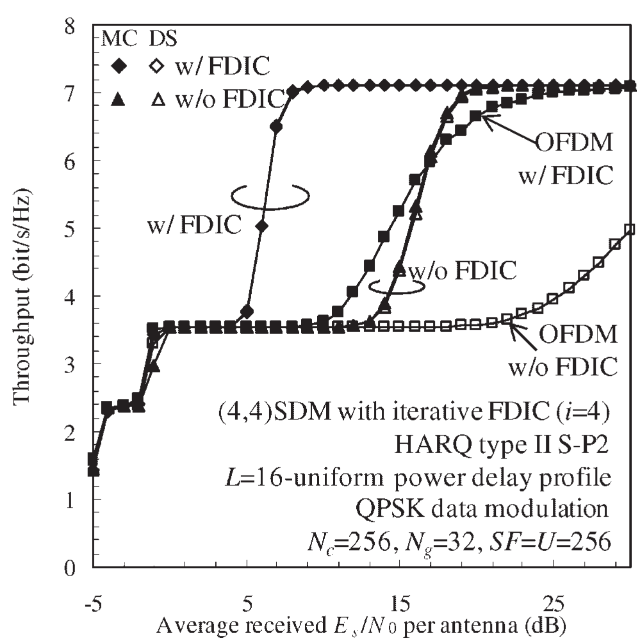

Figure 9. Throughput performance of full code-multiplexed MC-CDMA (4,4)SDM with iterative FDIC.

the average received E_s/N_0 per receive antenna. $N_r \times N_t$ 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.

7. CONCLUSION

In this paper, we have presented a comprehensive performance comparison of MC- and DS-CDMA with 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 and DS-CDMA can be implemented using software defined radio technology. Although OFDMA has recently been attracting attention, CDMA still remains as a promising multiple 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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