Chip-interleaved Multi-rate CDMA with 2-dimensional OVSF Spreading

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Abstract—**Chip interleaving technique has been proposed for DS-CDMA to eliminate the multiple-access interference (MAI). In this paper, we develop this technique to provide the single- or multicarrier CDMA with flexible low-to-high bit rate transmission by jointly using 2-dimensional (2D) OVSF spreading and chip interleaving for quasi-synchronous uplink transmissions in time- and frequency-selective fading channels. Through appropriate design of 2D spreading code assignment, not only the maximum time- and frequency-domain diversity can be achieved but also users are equipped with multi-rate services. The complexity of receivers is greatly reduced since single-user frequency-domain equalization (FDE) based on the MMSE criterion can be applied for signal detection. Computer simulation results show that the multi-rate transmission is possible for the 2D OVSF spread/chip-interleaved CDMA uplink and the bit error rate (BER) performance with turbo coding is very robust against Doppler spread.**

Keywords - CDMA, multi-rate, uplink transmission, chip interleaving, 2-dimensional OVSF spreading.

I. INTRODUCTION

Code division multiple access (CDMA) technique [1], can support low-to-high data rate of multimedia services [2]. Two popular approaches are single-carrier direct sequence (DS)-CDMA [3] using time-domain spreading and multicarrier (MC)-CDMA [4], [5] using frequency-domain spreading. In the downlink transmission, where all users share the same channel, the orthogonal variable spreading factor (OVSF) spreading codes can be used in MC-CDMA downlink [6]. Also, it has been shown that DS-CDMA downlink can achieve almost the same BER performance as MC-CDMA by using frequency-domain equalization (FDE) [7] based on the minimum mean square error (MMSE) criterion in a severe frequency-selective fading channel. However, in the MC- and DS-CDMA uplink transmissions, different users' signals go through different channels and are asynchronously received, which produces multiple-access interference (MAI) and limits the uplink capacity.

Although multiuser detection (MUD) [8], [9] 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. MUD receivers at the base station also require the knowledge of all users' channels. In practice, however, the users' channel information needs to be estimated from the received signals and are prone to the MAI and noise.

On the other hand, chip interleaving has been proposed for DS-CDMA to cancel the MAI in a quasi-synchronous multipath channel [10], [11]. Provided that the propagation channel delays and transmit timings of different users are within the guard interval (GI), an MAI-free transmission is guaranteed in slow fading channels. Recently, we have introduced 2-dimensional (2D) OVSF spreading into the chip-interleaved DS-CDMA uplink transmission [12]. A joint use of 2D OVSF spreading and chip-interleaving makes it possible to realize multi-rate transmissions while avoiding high-complexity MUD processing.

In this paper, we extend this concept to a generalized chip-interleaved multi-rate (DS- or MC-) CDMA with 2D OVSF spreading for quasi-synchronized uplink transmissions. We consider multi-rate, single-code CDMA uplink transmissions in a multiuser environment and present the optimum design of 2D OVSF spreading factors for the given overall spreading factor $SF=SF_t \text{x} SF_f$, where SF_f is the spreading factor of the 1st OVSF code for multi-rate services per user and SF_t is the spreading factor of the 2nd one for orthogonal multiuser multiplexing. Through appropriate code assignment of 2D spreading, not only the maximum time- and frequency-domain diversity can be achieved but also users are equipped with a flexible support for the low-to-high bit rate of multimedia services. Most of the previous work about MAI cancellation focused on the uncoded case. However, analyses of different schemes without coding do not always properly predict the performances of those with coding. In this paper, the turbo-coded BER performances of our proposed 2D OVSF spread/chip-interleaved DS- and MC-CDMA are evaluated and also compared with that of optimal MUD scheme. Computer simulation results show that the uplink MAI-free CDMA with multi-rate multiuser transmissions can be realized by using low-complexity single-user FDE and the bit error rate (BER) performance with turbo coding is very robust against Doppler spread.

II. Transmission System Model

We assume the multi-rate, single-code CDMA uplink with U active users. The transmission model is illustrated in Fig.1, where only the uth user, u=0~U-1, is shown. Here, we assume

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the square-root Nyquist chip shaping filter at the transmitter and the same filter at the receiver as the chip-matched filter. Ideal chip sampling timing is assumed at the receiver. Throughout the paper, T_c-spaced discrete-time signal representation is used, where T_c represents the chip duration. In the following, $\lfloor x \rfloor$ is the largest integer smaller than or equal to x, $\lceil x \rceil$ is the smallest integer larger than or equal to x, and $E[\cdot]$ denotes the ensemble average.

A. Transmitter

We consider a block data transmission of N_c/SF_f^u symbols using 2D OVSF spreading with the overall spreading factor of the uth user being $SF^u=SF_t^u \times SF_f^u$, where SF_f^u is the spreading factor of the 1st OVSF spreading code $c_f^u(t)$, SF_t^u is the spreading factor of the 2nd OVSF spreading code $c_t^u(t)$ and N_c is the FFT/IFFT block size for FDE. The uth user's symbol sequence $\{d_u(n);\ n=0\sim(N_c/SF_f^u-1)\}$ is spread by $\{c_f^u(t); t=0\sim SF_f^u-1\}$ and is further multiplied by a binary scrambling sequence $\{c_{scr}^u(t); t=0\sim N_c-1\}$ to produce the chip sequence $\{x_u(t);\ t=0\sim N_c-1\}$, which can be expressed as

$$x_u(t)=c_u^{scr}(t)d_u(\lfloor t/SF_f^u \rfloor)c_f^u(t \bmod SF_f^u)\,. \tag{1}$$

Next, $\{x_u(t);\ t=0\sim N_c-1\}$ is spread by the 2nd OVSF spreading code $\{c_t^u(t); t=0\sim SF_t^u-1\}$. As shown in Fig. 2, the 1st OVSF spreading is the row-wise chip spreading and the 2nd OVSF spreading is the column-wise symbol spreading and the 2D spread DS-CDMA signal is expressed as

$$s_u^{DS}(t)=x_u(t \bmod N_c)c_t^u(\lfloor t/N_c \rfloor) \tag{2}$$

with $E[|s_u^{DS}(t)|^2]=1$.

If N_c-point IFFT is applied to $s_u^{DS}(t)$, an MC-CDMA signal $s_u^{MC}(t)$ is generated. In order to make better use of the channel frequency-selectivity, the $SF_f^u \times (N_c/SF_f^u)$-chip interleaving is performed before IFFT so that the data symbol is distributed, with an equal distance of (N_c/SF_f^u) subcarriers, over N_c subcarriers. $s_u^{MC}(t)$ is expressed as

$$\begin{aligned}s_u^{MC}(t)=\frac{1}{\sqrt{N_c}}\sum_{n=0}^{(N_c/SF_f^u-1)}\sum_{m=0}^{(SF_f^u-1)}\Big[&s_u^{DS}(nSF_f^u+m)\times\\ &\exp\{j2\pi t/N_c\cdot(n+m(N_c/SF_f^u))\}\Big]\end{aligned} \tag{3}$$

with $E[|s_u^{MC}(t)|^2]=1$.

Before transmission, an N_g-chip GI is inserted every N_c-chip block to avoid inter-block interference (IBI). The transmitted signal can be expressed using equivalent lowpass representation as

$$s_u(t)=\sqrt{2E_c/T_c}\,s_u(t \bmod (N_c+N_g)-N_g) \bmod N_c)\,, \tag{4}$$

for $t=0\sim SF_t^u(N_g+N_c)-1$, where E_c is the average chip energy.

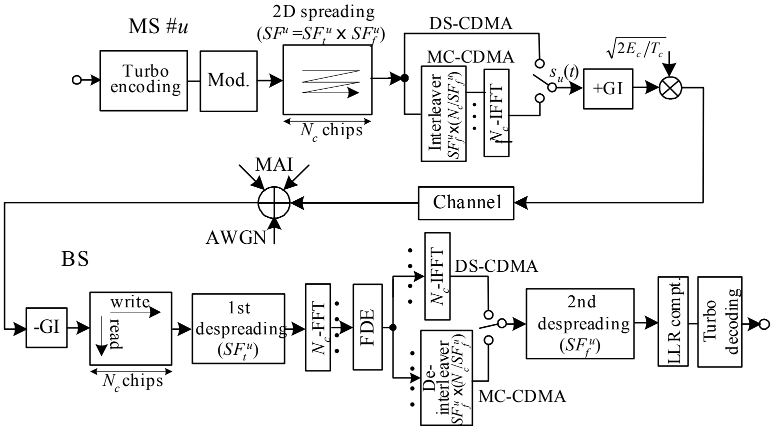


Fig.1. Transmitter and receiver structure for the uplink.

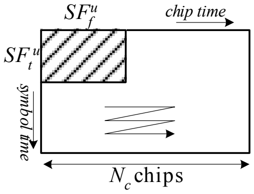


Fig. 2. 2D OVSF spreading.

B. Channel

The GI-inserted uth user's signal is transmitted over its frequency- and time-selective fading channel $h_u(\tau, t)$, which is an L-path Rayleigh fading channel, expressed as [13]

$$h_u(\tau,t)=\sum_{l=0}^{L-1}h_{u,l}(\lfloor t/(N_c+N_g)\rfloor)\delta(\tau-\tau_{u,l})\,, \tag{5}$$

where $h_{u,l}$ and $\tau_{u,l}$ are respectively the lth path gain and time delay with $\sum_{l=0}^{L-1}E[|h_{u,l}(t)|^2]=1$ and $\delta(x)$ is the delta function. We assume a block fading with the maximum Doppler frequency f_D, where the path gains $h_{u,l}(\lfloor t/(N_c+N_g)\rfloor)$ remain constant over one block interval $T=T_c(N_c+N_g)$, but vary block-by-block. $\tau_{u,l}$ is assumed to be $\tau_{u,l}=\tau_u+l$, $l=0\sim L-1$, where τ_u is the uth user's transmit timing offset and $\max\{\tau_{u,l}\}$ is assumed to be smaller than N_g.

C. Receiver

The sum of U users' faded signals is received by a base station receiver. The received signal is sampled at the chip rate and the GI is removed first. The GI-removed received signal can be written as

$$r(t)=\sum_{u=0}^{U-1}h_{u,l}(\lfloor t/(N_c+N_g)\rfloor)s_u(t-\tau_{u,l})+n(t)\,, \tag{6}$$

where $n(t)$ is a zero-mean additive white Gaussian noise (AWGN) with the variance of $2N_0/T_c$ with N_0 being the one-sided power spectrum density.

Then, $r(t)$ is $SF_t^u \times N_c$-chip deinterleaved and the 1st despreading using $\{c_t^u(t); t=0\sim SF_t^u-1\}$ as

$$\hat{s}_u(t) = \frac{1}{SF_t^u} \sum_{i=0}^{SF_t^u-1} r(t+iN_c)\left[c_t^u(i)\right]^* \tag{7}$$

for t=0~N_c-1. After the 1st despreading, an N_c-point FFT is applied to decompose $\{\hat{s}_u(t); t=0\sim(N_c-1)\}$ into N_c frequency components $\{\hat{R}_u(k); k=0\sim(N_c-1)\}$ as

$$\begin{aligned}\hat{R}_u(k) &= \frac{1}{\sqrt{N_c}} \sum_{t=0}^{N_c-1} \hat{s}_u(t)\exp(-j2\pi k\frac{t}{N_c}) \\ &= \sqrt{\frac{2E_c}{T_c}} S_u(k)\hat{H}_u(k) + \sqrt{\frac{2E_c}{T_c}} \sum_{\substack{u'=0\\ \neq u}}^{U-1} S_{u'}(k)Z_{u'}(k) + \hat{\Pi}(k)\end{aligned}, \tag{8}$$

where the 1st, 2nd and 3rd terms represent the desired signal, the residual MAI and AWGN components, respectively, with

$$\begin{cases} S_u(k) = \dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{t=0}^{N_c-1} s_u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ \hat{H}_u(k) = \dfrac{1}{SF_t^u} \displaystyle\sum_{i=0}^{SF_t^u-1} \sum_{l=0}^{L-1} h_{u,l}(i)\exp\left(-j2\pi k\frac{\tau_{u,l}}{N_c}\right) \\ Z_{u'}(k) = \dfrac{1}{SF_t^u} \displaystyle\sum_{i=0}^{SF_t^u-1} \begin{bmatrix} c_t^{u'}(i)\left[c_t^u(i)\right]^* \times \\ \displaystyle\sum_{l=0}^{L-1} h_{u',l}(i)\exp\left(-j2\pi k\frac{\tau_{u',l}}{N_c}\right) \end{bmatrix} \\ \hat{\Pi}(k) = \dfrac{1}{SF_t^u}\dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{i=0}^{SF_t^u-1} \sum_{t=0}^{N_c-1} \begin{bmatrix} n[i(N_c+N_g)+t+N_g] \\ \times\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \end{bmatrix} \end{cases}. \tag{9}$$

If $\sum_{u=0}^{U-1}(SF_t^u)^{-1} > 1$ and the fading is so slow that the path gains stay almost constant over at least SF_t^u consecutive blocks, the MAI can be cancelled owing to the orthogonal spreading codes $\{c_t^u(t); u=0\sim U-1\}$. Next, one-tap MMSE-FDE is carried out on each frequency component as

$$Y_u(k) = w_u(k)\hat{R}_u(k), \tag{10}$$

where $w_u(k)$ is the MMSE-FDE weight given by [7]

$$w_u(k) = \frac{\hat{H}_u^*(k)}{\left|\hat{H}_u(k)\right|^2 + \left(SF_t^u \cdot E_c/N_0\right)^{-1}}. \tag{11}$$

On the other hand, if $\sum_{u=0}^{U-1}(SF_t^u)^{-1} > 1$, the same 2nd OVSF spreading code is allocated to more than one users. Users with the same OVSF spreading code belong to the same group and they are interference-free from other groups with different 2nd OVSF spreading codes. However, due to the MAI within each group, we apply MMSE-MUD [8], [9] to minimize the residual MAI.

For DS-CDMA, an N_c-point IFFT is applied to $\{Y_u(k)$; k=0~N_c-1$\}$ to get the time-domain chip sequence:

$$y_u^{DS}(t) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{N_c-1} Y_u(k)\exp(j2\pi t\frac{k}{N_c}) \tag{12}$$

for t=0~N_c-1. On the other hand, as shown in Fig. 1, the MC-CDMA signal $y_u^{MC}(t)$ is obtained directly from the frequency-domain deinterleaver as

$$y_u^{MC}(t) = Y_u\left((t \bmod SF_f^u)\cdot(N_c/SF_f^u) + \lfloor t/SF_f^u \rfloor\right) \tag{13}$$

for t=0~N_c-1. The 2nd despreading is performed to get the decision variable $\hat{d}_u(n)$ associated with $d_u(n)$ as

$$\hat{d}_u(n) = \frac{1}{SF_f^u} \sum_{t=nSF_f^u}^{(n+1)SF_f^u-1} y_u(t)\left[c_f^u(t)c_{scr}^u(t)\right]^*, \tag{14}$$

based on which the log-likelihood ratio (LLR) [14] is computed to get a sequence of soft values associated with the transmitted turbo-coded bit sequence for turbo decoding.

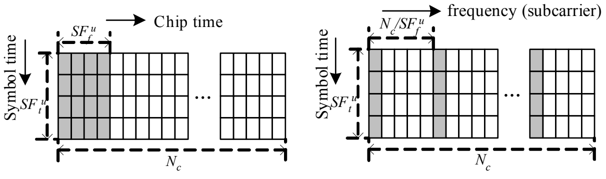
The LLR value should be computed taking into account the equivalent channel gain and residual MAI after FDE. Even if all users are allocated different 2nd OVSF spreading codes, the MAI cannot be cancelled completely when the channel is time-selective due to the fading Doppler spread. According to [9], the residual interference-plus-noise can be treated as a Guassian process. We can show that Eq. (14) can be rewritten as

$$\hat{d}_u(n) = \mu_u(n)\cdot d_u(n) + \xi_{SI}(n) + \xi_{MAI}(n) + \xi_{noise}(n), \tag{15}$$

where $\mu_u(n)$ is the equivalent channel gain for the uth user's signal, $\xi_{SI}(n)$, $\xi_{MAI}(n)$ and $\xi_{noise}(n)$ represent the self interference (SI), MAI and noise components, respectively. The sum of last three terms is approximated as a zero-mean random process with variance $2\sigma_u^2(n)$. Assuming the quaternary phase shift keying (QPSK) data-modulation, the LLRs for the 1st bit and 2nd bit belonging to the nth QPSK symbol are given as [9], [14]

$$LLR = \begin{cases} \mathrm{Re}\left\{\mu_u^*(n)\cdot\hat{d}_u(n)\right\}/2\sigma_u^2(n) & \text{for the 1st bit} \\ \mathrm{Im}\left\{\mu_u^*(n)\cdot\hat{d}_u(n)\right\}/2\sigma_u^2(n) & \text{for the 2nd bit} \end{cases}. \tag{16}$$

III. CODE ASSIGNMENT FOR 2D OVSF SPREADING



(a) DS-CDMA (b) MC-CDMA

Fig. 3. 2D OVSF spreading/chip-interleaving.

As shown in Fig. 3, the overall spreading factor of the uth user's 2D OVSF codes is SF^u=SF_t^uxSF_f^u. The total data rate normalized by the chip (or sample) rate for the multi-rate and multiuser case is defined as [15]

$$R_{total} = \sum_{u=0}^{U-1} (SF_t^u \times SF_f^u)^{-1} \le 1. \qquad (17)$$

The 1st OVSF spreading code with spreading factor SF_f^u is for multi-rate services per user and SF_f^u can be arbitrarily set according to the requested data rate, independently of the FFT block size N_c, but $SF_f^u \le N_c$. The 2nd OVSF spreading code is for orthogonal multiuser multiplexing. The MAI is cancelled due to the orthogonality of the 2nd OVSF spreading codes. In order to maintain the orthogonality of the 2nd OVSF spreading codes over SF_t^u consecutive blocks in a time-selective fading channel, SF_t^u should be smaller than the maximum permitted value SF_t, which is decided by the fading Doppler frequency.

If $U<SF_t$ and $U=2^k$ (k=0,1,…), all users can be assigned $SF_t^u=2^k$. An MAI-free channel is constructed after the chip-deinterleaving/1st despreading. The MUD problem is converted into a set of equivalent single-user detection problems. If $U<SF_t$ but $2^{k-1}<U<2^k$, (2^k-U) users among U users can be assigned $SF_t^u=2^{k-1}$ and then the other $(2U-2^k)$ users can use $SF_t^u=2^k$. By doing so, all U users are orthogonal.

If $U>SF_t$, users are partitioned into SF_t groups first. Each group uses a different OVSF spreading code with the spreading factor SF_t. Users with the same 2nd OVSF spreading code belong to one group. Users of one group are interference-free from other groups. We then apply MUD per group, which is practically feasible since the number of users per group is at least SF_t times smaller than U. In contrast, MUD for the conventional DS- or MC-CDMA needs to consider all active users, and thus has prohibitive complexity.

After setting the value of SF_t^u for each user, SF_f^u can be set equal to SF^u/SF_t^u, where the overall spreading factor SF^u is decided by the uth user's data rate. Therefore, our proposed code assignment achieving MAI-free uplink transmissions is very flexible for multi-rate services.

IV. SIMULATION MODEL

For computer simulation, we assume QPSK modulation and N_c=256, N_g=32. An L=16-path frequency-selective block Rayleigh fading channel having the uniform power delay profile is assumed. The transmit timing offsets $\{\tau_u;\ u=0\sim(U\text{-}1)\}$ are uniformly distributed over $[-\Delta/2,\Delta/2]$ with $\Delta<(N_g\text{-}L)$ so that the maximum time delay difference is less than the GI. A rate-1/3 turbo encoder consists of two (13,15) recursive systematic convolutional (RSC) encoders connected in parallel with an S-random interleaver between them. The two parity bit sequences of the two RSC encoders are punctured to increase the coding rate to R=1/2. Log-MAP decoding with eight iterations is carried out at the receiver.

Fig. 4 plots the BER performance of both DS- and MC-CDMA as a function of the average received bit energy-to-the AWGN power spectrum density ratio E_b/N_0, defined as $E_b/N_0=0.5(E_c/N_0)(SF_t^u SF_f^u)(1+N_g/N_c)$. All users have the same spreading factor pair, i.e., $(SF_t^u,SF_f^u)=(SF_t,SF_f)$. We assume a full loaded case (i.e., $U=SF_t\text{x}SF_f=16$) with the same data rate for all users. Uncoded and coded CDMA performances are shown for various pairs of (SF_t,SF_f). As explained in Sect. III, if $SF_t<U$, users are partitioned into SF_t groups. Groups are interference-free from each other; but the MAI is present in each group and MUD is applied per group. If (SF_t,SF_f)=(1,16), 2D OVSF spread DS-CDMA reduces to the 1D OVSF spread DS-CDMA. It can be seen that severe MAI degrades the MUD performance greatly. For the uncoded case, DS-CDMA with (SF_t,SF_f)=(16,1) performs better than that of $(SF_t,SF_f)\neq(16,1)$; however, MC-CDMA with (SF_t,SF_f)=(16,1) does not get the frequency diversity gain if error-control coding is not used. When turbo coding is used, MC-CDMA can achieve almost the same performance as DS-CDMA. Therefore, SF_t of the 2nd OVSF spreading code should be chosen equal to the number of active users (i.e., $SF_t=U$).

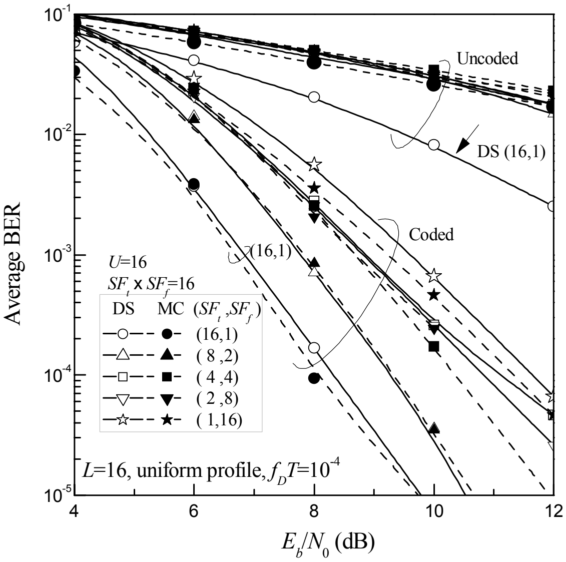


Fig. 4. BER performance of 2D OVSF spread CDMA for various pairs of (SF_t,SF_f).

Fig. 5 plots the turbo-coded BER performance of the mutli-rate case with U=5, R_{total}=0.625 and the lowest data rate R_L=1/16. The data rates of user #0, #1, #2, #3 and #4 are R_L, R_L, $2R_L$, $2R_L$ and $4R_L$, respectively. User #2 with (SF_t^2,SF_f^2)=(8,1) and user #4 with (SF_t^4,SF_f^4)=(4,1) have different data rates but show the same BER performance, which is worse than that of users #0 and #3. User #0 with (SF_t^0,SF_f^0)=(8,2) and user #3 with (SF_t^3,SF_f^3)=(4,2) with different data rates also performs the same, but their BER performances are still worse then user#1 with (SF_t^1,SF_f^1)=(4,4). It can be seen that the BER performance with the same SF_f^u is the same irrespective of data rate. However, as SF_f^u decreases, the BER performances of both 2D OVSF spread DS- and MC-CDMA degrade. In DS-CDMA, since the data symbol is always spread over all subcarriers, yielding large frequency diversity effect irrespective of SF_f^u. The reason for degrading performance of DS-CDMA with decreasing SF_f^u is due only to increasing SI. On the other hand, no SI is present in MC-CDMA; however, since the data symbol is spread over smaller number of subcarriers than in DS-CDMA, the frequency diversity effect is getting smaller as SF_f^u decreases.

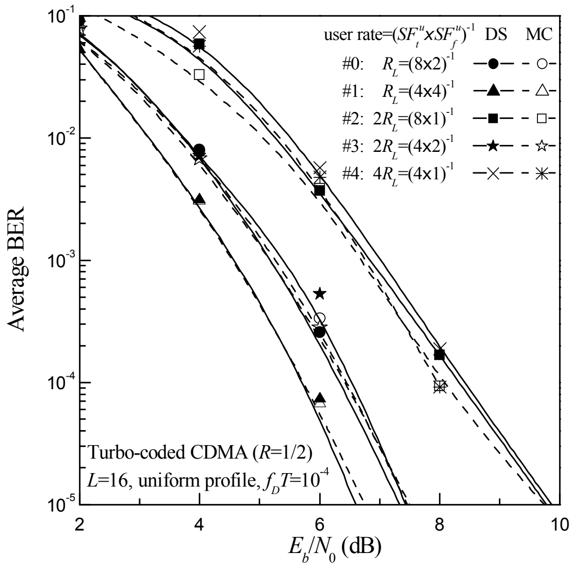


Fig. 5. BER performance of multi-rate 2D OVSF spread CDMA.

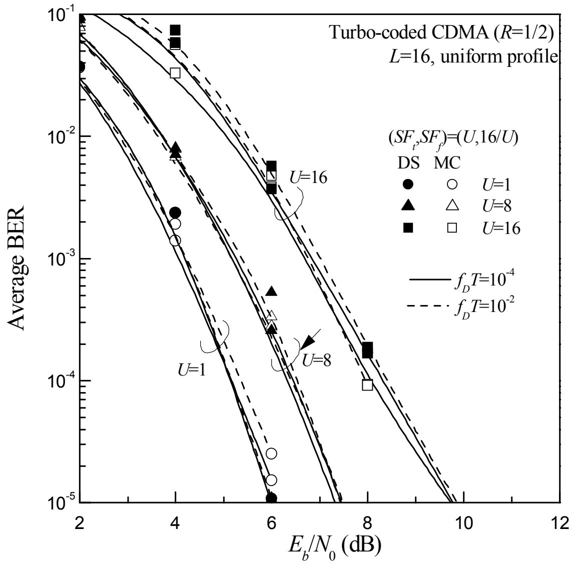


Fig. 6. Impact of f_DT.

How the fading maximum Doppler frequency influences the BER performance is shown in Fig. 6 for turbo-coded DS- and MC-CDMA. Here, SF_t^uxSF_f^u=16 and $(SF_t^u, SF_f^u)=(U, 16/U)$ are used for all users. We assume the same fading Doppler spread $f_DT=10^{-4}$ and 10^{-2} for all users (corresponding to the vehicle speed of about 7.5km/h and 750km/h, respectively, for the carrier frequency of 5GHz and chip data rate 100Mcps). It is seen that when turbo coding is used, our proposed 2D OVSF CDMA is very robust against high Doppler frequency.

V. CONCLUSION

In this paper, we proposed a chip-interleaved multi-rate CDMA with 2-dimensional (2D) OVSF spreading for the uplink multiuser transmission. Relying on 2D OVSF spreading and chip-interleaving, a multiuser detection (MUD) problem is converted into a set of equivalent single-user equalization problems. The suppression of multi-access interference (MAI) not only increases the uplink capacity without applying the sophisticated MUD technique, but also provide a flexible support of the low-to-high data rate transmission. The BER performance in a time- and frequency-selective Rayleigh fading channel was evaluated by the computer simulation under a quasi-synchronous multiuser environment. It was shown that when turbo coding is applied, our proposed 2D OVSF spread/chip-interleaved DS- and MC-CDMA can achieve almost the same BER performance and are very robust against Doppler spread.

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