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2次元 OVSF 拡散符号を用いてマルチレート/マルチ接続を実現する一般化チップインターリーブ CDMA

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あらまし 複数ユーザが同時に基地局にアクセスする上りリンクでは，ユーザ間の直交性が保たれず，マルチアクセス干渉（MAI）が発生し，伝送特性が大幅に劣化してしまう．本論文では，2 次元 OVSF 拡散とチップインターリーブを用いて MAI を低減する CDMA（GCI-CDMA）を提案している．本提案方式では，MAI を低減できるので信号判定にシングルユーザの周波数領域 MMSE 等化を用いることができる．GCI-CDMA では，DS-CDMA または MC-CDMA を用いた柔軟なマルチレート/マルチ接続通信を行うことができるのが特徴である．伝送も可能である．本論文では，時間と周波数選択性にフェージングチャネルにおける伝送時性を計算機シミュレーシュンによって明らかにしている．

キーワード CDMA，マルチレート，上りリンク伝送，インターリーブ，2 次元 OVSF 拡散．

Generalized chip-interleaved CDMA with multi-rate/multi-connection using 2-dimensional OVSF spreading

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Abstract The multiple-access interference (MAI) limits the transmission performance of the CDMA uplink transmission. In this paper, we propose a generalized chip-interleaved (GCI)-CDMA with 2-dimensional (2D)-OVSF spreading. Since MAI can be removed, single-user frequency-domain equalization based on the MMSE criterion can be applied for signal detection. The GCI-CDMA allows flexible multi-rate/multi-connection data transmission using either DS- or MC-CDMA. The transmission performance in a time- and frequency-selective fading multiuser environment is evaluated by computer simulation.

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

1. Introduction

In multimedia wireless communications, a flexible support for the low-to-high bit rate of multimedia services upon a specific user's request is desirable [1]. Using code division multiple access (CDMA) technique [2][3], multi-rate services can be offered by changing the spreading factor (*SF*), the number of multiple codes, and/or modulation format (such as multi-level QAM (MQAM)). The well-known multiple access techniques include single-carrier direct sequence (DS)-CDMA [2], [4] using time-domain spreading and multicarrier (MC)-CDMA [5], [6] using frequency-domain spreading. With the aid of frequency-domain equalization (FDE), DS-CDMA can achieve similar downlink performance to MC-CDMA in a severe frequency-selective fading channel [7], [8]. However, in the uplink, different users' signals are asynchronous and go through different channels, resulting in multiple-access interference (MAI). Suppression of MAI to increase the link capacity while providing multimedia services is a challenging task for the realization of future wireless communication systems [16].

Multicarrier DS-CDMA (MC/DS-CDMA) has been attracting attention for uplink transmissions [3], [9]-[14], where broad bandwidth is first divided into many non-overlapping subcarriers and signal on each subcarrier is spread similar to narrowband DS-CDMA. Time- and frequency-domain (TF)-spreading is introduced in MC/DS-CDMA [3], [11], [12]. The total number of supportable users in TF-spread MC/DS-CDMA is determined by the time- and frequency-domain spreading factors and the correlation characteristics of the spreading codes employed. This TF-spread MC/DS-CDMA can reduce multiuser detection (MUD) complexity [10], [13]. L-L. Yang, et al. have evaluated the achievable performance of TF-spread MC/DS-CDMA in an AWGN channel [11] and extended this scheme to quasi-synchronous transmissions [12] by using user-specific spreading codes with interference-free window (IFW) [15]. However, the small value of IFW length limits its application in a practical multiuser multipath fading environment.

On the other hand, chip-interleaving technique was proposed for single-carrier DS-CDMA to cancel the MAI in a quasi-synchronous multipath environment [16], [17]. Provided that the propagation delays and transmit timings of different users are within the guard interval (GI), an MAI-free transmission is guaranteed. Recently, we have introduced 2-dimensional (2D)-OVSF spreading into chip-interleaved DS-CDMA uplink transmission [18], [19]. The combination of 2D-OVSF spreading and chip-interleaving makes it possible to get both the time- and frequency-domain diversity gains. The 2D-OVSF spread DS-CDMA can achieve good BER performance, while accommodating users with multi-rate services.

In this paper, we present a generalized chip-interleaved CDMA (GCI-CDMA) with 2D-OVSF spreading to provide DS- or MC-CDMA with multi-rate/multi-connection while avoiding the MAI. By adopting 2D-OVSF spreading and chip interleaving at the transmitter, single-user FDE with low complexity is applied for signal detection at the receiver due to the MAI-free uplink transmission.

Most of the previous work on MAI cancellation focused on the uncoded case. However, analyses of different schemes without coding do not always properly predict the performance of those with coding. The BER performance of our proposed GCI-CDMA with turbo coding is evaluated and compared with that of optimal turbo-decoded MUD scheme [20]. Impact of the Doppler fading rate on the BER performance is also evaluated for uncoded and coded GCI-CDMA.

2. Transmission System Model

The GCI-CDMA uplink transmission model is illustrated in Fig.1, where only the *u*th user is shown (this scheme can also be applied to the downlink transmission). Here, we assume 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. Therefore, the chip-spaced discrete-time signal representation is used throughout the paper.

2.1. Transmitted signal

We assume V multi-rate connections per user. The vth data-modulated symbol sequence of the uth user $\{d_{u,v}(n);\ n=0\sim(N_c/SF_f-1)\}$ is spread using the 1st OVSF spreading code $\{c_v^{SF_f}(t); t=0\sim SF_f-1\}$ with spreading factor SF_f. The resultant V chip sequences are summed up and further multiplied by a binary scramble sequence $\{c_u^{scr}(t); t=0\sim N_c-1\}$ to produce a sequence of N_c chips (N_c is the FFT/IFFT block size for FDE). The resultant signal is a DS-CDMA signal and can be expressed as

$$s_u^{DS}(t)=c_u^{scr}(t)\sum_{v=0}^{V-1}d_{u,v}(\lfloor t/SF_f\rfloor)c_v^{SF_f}(t \bmod SF_f), \quad (1)$$

where $\lfloor x\rfloor$ is the largest integer smaller than or equal to x.

If N_c-point IFFT is applied to $s_u^{DS}(t)$, then, an MC-CDMA signal $s_u^{MC}(t)$ is generated. In order to make better use of frequency diversity, the frequency-domain interleaving can be performed before IFFT. Assuming an $SF_f\times(N_c/SF_f)$ -chip interleaving, the spread data is distributed with equal distance of SF_f subcarriers. $s_u^{MC}(t)$ is given by

$$s_u^{MC}(t)=\frac{1}{\sqrt{N_c}}\sum_{n=0}^{(N_c/SF_f-1)}\sum_{m=0}^{(SF_f-1)}\Big[s_u^{DS}(nSF_f+m)\times \exp\{\frac{j2\pi t}{N_c}(n+m\frac{N_c}{SF_f})\}\Big] \quad (2)$$

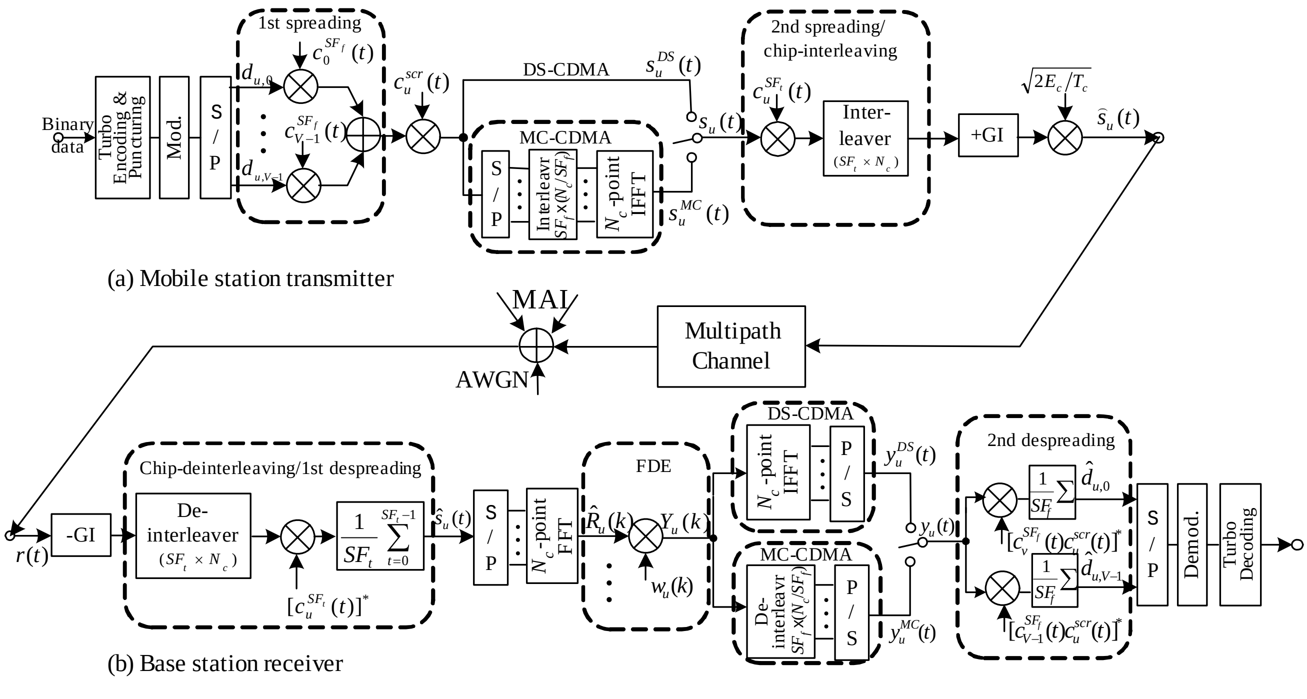


Fig.1. Transmitter and receiver structure for the uplink.

with $E[|s_u^{MC}(t)|^2]=1$. Next, the N_c-chip time-domain signal $s_u(t)$ is spread by the 2nd OVSF spreading code $\{c_u^{SF_t}(t); t=0\sim SF_t-1\}$ with spreading factor SF_t. After that, the chip interleaving is performed with column-wise input and row-wise output, as shown in Fig. 2.

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

$$\hat{s}_u(t)=\sqrt{2E_c/T_c}\, s_u(t \bmod N_c)\, c_u^{SF_t}(\lfloor t/N_c \rfloor) . \qquad (3)$$

where E_c is the average chip energy and T_c is the chip duration of the 2nd OVSF spreading codes.

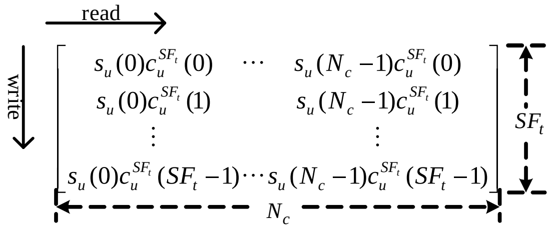
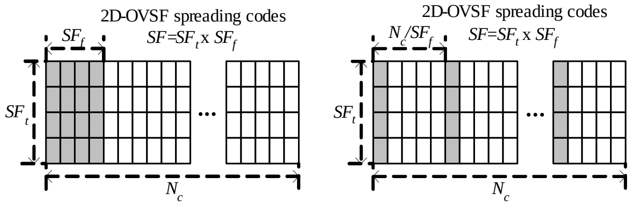


Fig. 2. Chip-interleaving.



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

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

As shown in Fig. 3, the overall spreading factor of 2D-OVSF codes is $SF=SF_t$xSF_f. The 1st OVSF spreading code is for multi-connection per user and SF_f can be arbitrarily selected, independent of the FFT block size N_c, but $SF_f \le N_c$. The 2nd OVSF spreading code is for orthogonal multiuser multiplexing and SF_t is chosen according to the number of active users. If there are U users, $SF_t=2^{\lceil \log_2 U \rceil}$ can be used to allow them access to the base station without causing MAI, if the channel is time-nonselective. Here, $\lceil x \rceil$ is the smallest integer larger than or equal to x.

2.2. Channel

The GI-inserted GCI-CDMA signal is transmitted over a frequency- and time-selective Rayleigh fading channel. Assuming that the channel has L independent propagation paths, the discrete-time impulse response $h_u(t)$ of the uth user is expressed as

$$h_u(t)=\sum_{l=0}^{L-1} h_{u,l}\,\delta(t-\tau_{u,l}) , \qquad (4)$$

where $\delta(x)$ is the delta function and $h_{u,l}$ is the lth path gain with $\sum_{l=0}^{L-1} E[|h_{u,l}|^2]=1$. We assume block fading with the maximum Doppler frequency f_D, where the path gains remain constant over one block interval $T=T_c(N_c+N_g)$, but vary block-by-block. The lth path time delay $\tau_{u,l}$ 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. The maximum time delay of $\{\tau_{u,l}\}$ is assumed to be shorter than GI.

2.3. Received signal

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

$$r(t)=\sum_{u=0}^{U-1} h_u(t)\otimes \hat{s}_u(t)+n(t) , \qquad (5)$$

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

2.4. Chip-deinterleaving/1st despreading

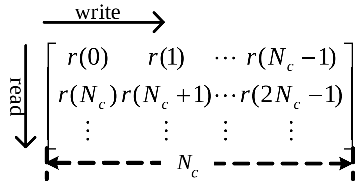


Fig. 4. Chip-deinterleaving.

As shown in Fig. 4, $r(t)$ is deinterleaved and then the 1st despreading is performed using the 2nd OVSF code $c_u^{SF_t}(t)$ as

$$\hat{s}_u(t)=\frac{1}{SF_t}\sum_{i=0}^{SF_t-1} r(t+iN_c)\left[c_u^{SF_t}(i)\right]^* \qquad (6)$$

for $t=0\sim N_c-1$. The MAI is cancelled due to the orthogonal property of OVSF spreading codes $\{c_u^{SF_t}(t); u=0\sim U-1\}$. Hence, the multiuser channel is transformed into a set of orthogonal single-user channels and the MUD problem can be converted into a set of equivalent single-user equalization problems [13], [15].

2.5. MMSE-FDE

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

$$\hat{R}_u(k)=\frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1}\hat{s}_u(t)\exp(-j2\pi k\frac{t}{N_c}) . \qquad (7)$$

Then, one-tap MMSE-FDE is carried out on each frequency component as

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

where $w_u(k)$ is the MMSE-FDE weight given by [7], [8]

$$w_u(k) = \frac{H_u^*(k)}{|H_u(k)|^2 + (SF_t \cdot E_c/N_0)^{-1}} \,. \quad (9)$$

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

$$y_u^{DS}(t) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{N_c-1} Y_u(k) \exp(j2\pi t \frac{k}{N_c}) \,. \quad (10)$$

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

$$y_u^{MC}(t) = Y_u[(t \bmod SF_f) \cdot \frac{N_c}{SF_f} + \lfloor t/SF_f \rfloor] \quad (11)$$

for $t=0\sim N_c-1$.

2.6. 2nd despreading

The 2nd despreading using the 1st OVSF spreading code $c_u^{SF_f}(t)$ is performed to get the decision variable $\hat{d}_{u,v}(n)$ for the detection of $d_{u,v}(n)$ as

$$\hat{d}_{u,v}(n) = \frac{1}{SF_f} \sum_{t=nSF_f}^{(n+1)SF_f-1} y_u(t) \left[c_u^{SF_f}(t) c_u^{scr}(t) \right]^* , \quad (12)$$

based on which data symbol demodulation and turbo decoding are carried out.

2.7. LLR

The soft value for turbo decoding can be generated using the log-likelihood ratio (LLR) for each bit [21]. The LLR values should be calculated for each bit taking into account its equivalent channel gain and residual MAI after FDE. As shown in [22], the distribution of the residual interference-plus-noise at the output of a linear MMSE-FDE can be well approximated by a Guassian distribution. We assume that $\hat{d}_{u,v}(n)$ in Eq. (12) represents the output of an equivalent AWGN channel having $d_{u,v}(n)$ as its input symbol. This equivalent channel can be represented as

$$\hat{d}_{u,v}(n) = \mu_{u,v}(n) \cdot d_{u,v}(n) + \eta_{u,v}(n) \,, \quad (13)$$

where $\mu_{u,v}(n)$ is the equivalent channel gain for the uth user's vth connection signal and $\eta_{u,v}(n)$ is a zero-mean Gaussian noise with variance $2\sigma_{u,v}^2(n)$. Assuming the quaternary phase shift keying (QPSK) data-modulation, the LLRs for the 1st bit and 2nd bit belonging to QPSK symbol are given as [20]

$$\begin{cases} LLR_0 = \dfrac{\mathrm{Re}\{\mu_{u,v}^*(n) \cdot \hat{d}_{u,v}(n)\}}{2\sigma_{u,v}^2(n)} \\ LLR_1 = \dfrac{\mathrm{Im}\{\mu_{u,v}^*(n) \cdot \hat{d}_{u,v}(n)\}}{2\sigma_{u,v}^2(n)} \end{cases} \quad (14)$$

with $\mu_{u,v}(n)$ and $\sigma_{u,v}^2(n)$ updated for each symbol.

3. Simulation Results

The computer simulation condition is shown in Table 1. An L=16-path frequency-selective block Rayleigh fading channel having the uniform power delay profile is assumed. The transmit timing offsets $\{\tau_u;\ u=0\sim(U-1)\}$ are uniformly distributed over $[-\Delta/2, \Delta/2]$ with $\Delta<(N_g-L)$ so that the maximum time delay difference is less than GI. Also ideal channel estimation is assumed.

Table 1. Simulation condition

Trans-mitter	Turbo encoder	Data bit length 1018
		Coding rate R=1/2
		(13,15) RSC component encoder
		S-random interleaver
	Modulation	QPSK
	Spreading code	2D-OVSF spreading code SF_f=1~256,SF_t=1~16
	Chip interleaving	$SF_t \times N_c$ block interleaver
	Block length	N_c=256
	GI	N_g=32
Recei-ver	Equalization	MMSE-FDE
	Channel esti.	Ideal
	Turbo decoder	Log-MAP
		8 iterations

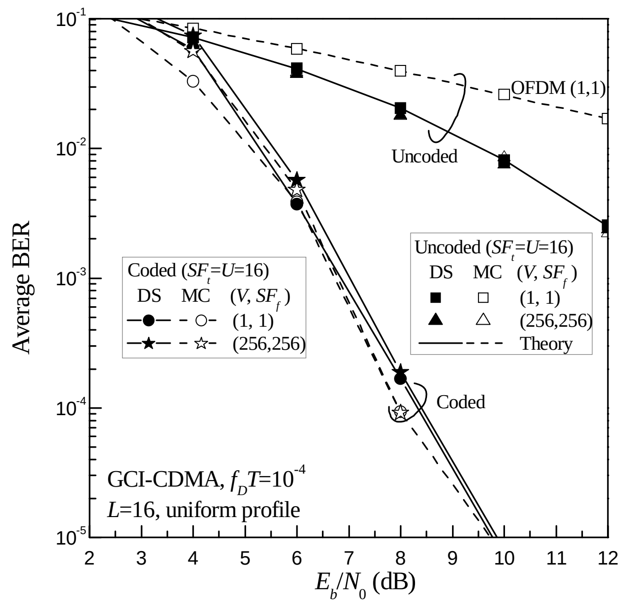
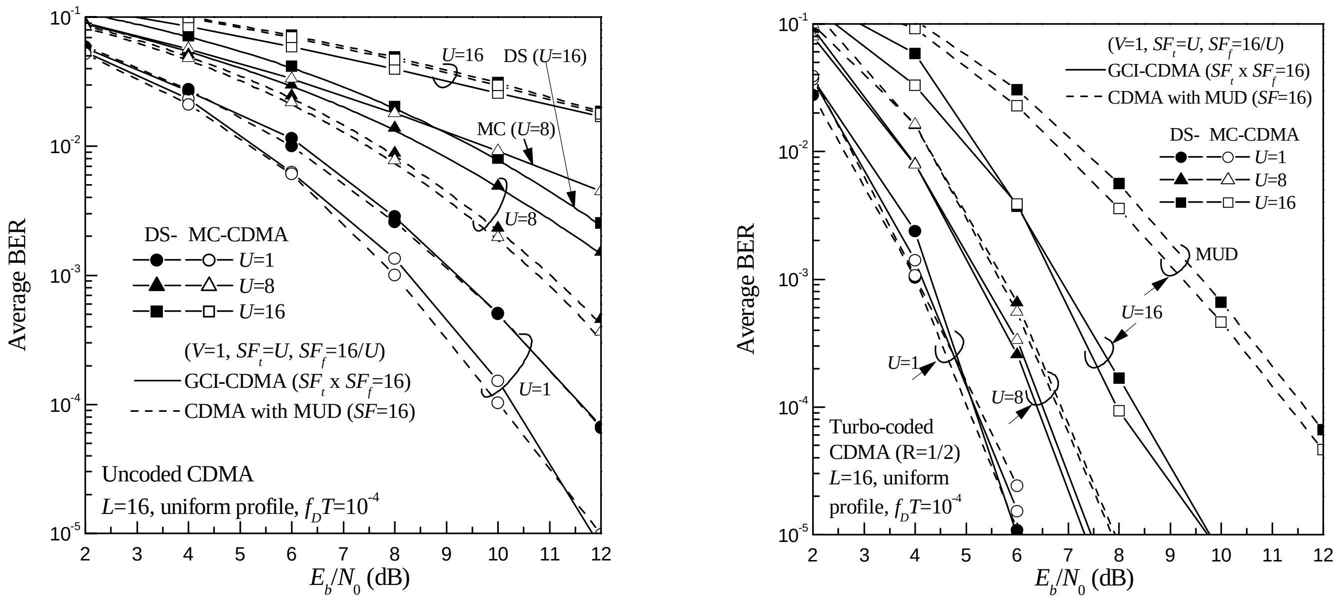


Fig. 5. GCI-CDMA with multi-rate/multi-connection

Fig. 5 plots the BER performance of the uplink GCI-CDMA as a function of the average received bit energy-to-the AWGN power spectrum density ratio E_b/N_0, defined by $E_b/N_0=0.5(E_c/N_0)(SF_tSF_f)(1+N_g/N_c)$, when $f_DT=10^{-4}$. BER performances of uncoded and coded GCI-CDMA are compared are shown assuming $SF_t=U=16$ and variable values of (V,SF_f) pair. The multi-rate/multi-connection services can be realized by selecting SF_f and V independently, but $V \le SF_f$.

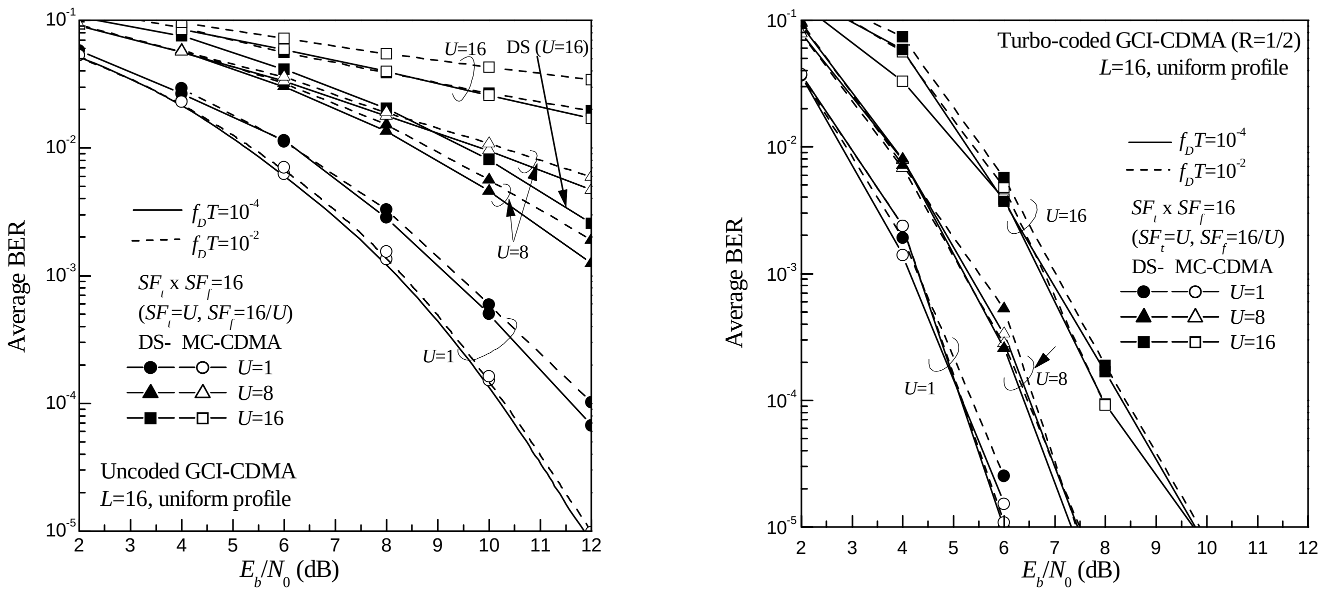
Also shown is the numerical BER performance of uncoded GCI-CDMA, which agrees well with that of the computer simulation. For the uncoded case, full-loaded multi-connection MC-CDMA with (V,SF_f)=(256,256) performs almost the same as DS-CDMA. However, in the case of OFDM, (V,SF_f)=(1,1), it performs the worst since there is no frequency diversity effect without the channel coding. By contrast with the uncoded case, both MC- and DS-CDMA with turbo coding can achieve similar BER performance for multi-rate services.

Fig. 6 compares our proposed GCI-CDMA with CDMA using MUD [20]. We assume SF=16 for MUD and the same data rate, SF_txSF_f=16 for 2D-OVSF spread GCI-CDMA, where SF_t=U and SF_f=16/U. First, let's see the uncoded case in Fig. 6(a). When the system is lightly loaded, i.e., U=8, the MUD exhibits better performance since MAI is less severe. However, when the system is moderately or heavily loaded, i.e., $U \approx SF$, large MAI results in a severe BER degradation for DS-CDMA with MUD. Our proposed 2D-OVSF spread DS-CDMA outperforms DS-CDMA with MUD. On the other hand, 2D-OVSF spread MC-CDMA without coding cannot achieve frequency diversity for small SF_f and performs worse than MC-CDMA with MUD. However, for the turbo-coded case, it can be seen from Fig. 6(b) that, both 2D-OVSF spread/ chip-interleaved DS- and MC-CDMA provide much better performance than DS- and MC-CDMA with MUD. Moreover, MMSE-MUD requires the knowledge of the codes and channels of all users at the receiver. Its



(a) Uncoded (b) Turbo-coded

Fig. 6. BER Comparison between GCI-CDMA and CDMA with MUD.



(a) Uncoded (b) Turbo-coded

Fig. 7. Impact of f_DT on GCI-CDMA

computational complexity grows exponentially with the number of users; while the receiver complexity of GCI-CDMA is linear due to the use of single-user FDE.

How the Doppler fading rate influences the BER performance is shown in Fig. 7 for both uncoded and coded cases. We assume each user has the same Doppler spread $f_D^{(q)}T = f_D T$ and the BER performances are compared for $f_D T$=10^{-4} and 10^{-2} (corresponding to the vehicle speed of about 7km/h and 700km/h, respectively, with a carrier frequency of 5GHz and chip data rate 100Mcps). The uncoded GCI-CDMA is shown in Fig. 7(a). For small number of users (i.e., SF_t=U=1 or 8), there is not too much performance degradation seen between $f_D T$=10^{-4} and 10^{-2}. However, for heavy-loaded case (i.e., SF_t=U=16), since the orthogonality among different users cannot be maintained due to the time-selective fading, the performances of both uncoded DS- and MC-CDMA degrade when $f_D T$=10^{-2}. However, when turbo decoding is used, our proposed GCI-CDMA is very robust against large Doppler spread as shown in Fig. 7(b).

4. Conclusions

In this paper, we proposed a 2-dimensional (2D)-OVSF spread/chip-interleaved GCI-CDMA in a frequency-selective fading channel for the multi-rate/multi-connection uplink transmission. Relying on chip-interleaving and 2D-OVSF spreading, 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 sophisticated MUD technique, but also allows a flexible rate-switching capability. The BER performance in a time- and frequency-selective fading channel was evaluated under a quasi-synchronous multiuser environment. When turbo coding is applied, our proposed 2D-OVSF spread/chip-interleaved DS- and MC-CDMA can achieve similar BER performance and also show high robustness against Doppler spread.

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