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2 次元 OVSF 拡散符号を用いるチップインターリーブ DS-CDMA

劉　楽†　安達 文幸‡

東北大学大学院工学研究科電気・通信工学専攻 〒980-8579 仙台市青葉区荒巻字青葉 6-6-05
E-mail: †liule@mobile.ecei.tohoku.ac.jp, ‡adachi@ecei.tohoku.ac.jp

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，MUI(Multi-user interference)が発生し，特性が大幅に劣化してしまう．そこで本論文では，2 次元 OVSF 拡散とチップインターリーブを用いで MUI を低減する DS-CDMA を提案する．本提案では，MUI 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 等化を用いている．リンク容量を増加することができるとともに，マルチレート伝送も可能である．また，マルチユーザ環境下での周波数選択性フェージングチャネルにおけるビット誤り率(BER)特性を計算機シミュレーションによって明らかにしている．

キーワード　DS-CDMA, multi-rate, uplink transmission, interleaving, OVSF.

Chip-interleaved DS-CDMA with 2-dimensional OVSF spreading code

Le LIU†　Fumiyuki ADACHI‡

Dept. of Electrical and Communication Engineering, Graduate School of Engineering,
Tohoku University, 6-6-05, Aza-Aoba, Aramaki, Aoba-ku Sendai 980-8580, JAPAN
E-mail: †liule@mobile.ecei.tohoku.ac.jp, ‡adachi@ecei.tohoku.ac.jp

Abstract　Multiuser interference (MUI) limits the transmission performance of the DS-CDMA uplink. In this paper, we propose a 2-dimensional (2-D) OVSF spreading and chip-interleaving to transform the multi-user channel into orthogonal single-user channels. Due to MUI cancellation, the chip-interleaved DS-CDMA with 2-D OVSF spreading has ability to increase the link capacity as well as to provide multi-rate services. Single-user frequency-domain equalization based on the minimum mean square error (MMSE) criterion is applied for signal detection. The transmission performance in a multiuser and frequency-selective fading environment is evaluated by computer simulation.

Keyword　DS-CDMA, multi-rate, uplink transmission, interleaving, OVSF.

1. Introduction

Recently, there has been an increasing interest in providing multi-rate services in wireless communications [1], [2]. Examples of such services include text, images, data, and low-to-high rate video with audio. These services entail variable rates and may have different Quality of Service (QoS) requirements. Future wireless communication systems should support flexible QoS and rate-scalability. Multi-rate services can be provided in many ways. Among them code division multiple access (CDMA) systems [3] have attracted much attention due to their design flexibility and potential for improved capacity. Using direct-sequence (DS) CDMA, multi-rate services may be offered by choosing appropriately: chip rate, variable spreading factor (SF), number of multiple codes, and/or modulation format (such as multi-level QAM (MQAM)) [4].

In the downlink transmission, all users' signals are synchronous and go through the same channel; using the orthogonal variable spreading factor (OVSF) spreading codes [5], CDMA systems enable simultaneous transmissions of different data rates for multiple users over the same bandwidth and time. When the chip rate increases, the multipath channel becomes frequency selective; it introduces inter-path interference (IPI), and thus distorts code orthogonality at a receiver. Loss of orthogonality gives rise to the multiuser interference (MUI). However, the use of frequency-domain equalization (FDE) significantly improves the bit error rate (BER) performance [6].

In the uplink transmission, however, since the transmitted signals of different users go through different channels and their transmit timings are asynchronous, severe MUI is produced. Several schemes have been proposed for MUI-resilient multi-rate transmissions. Those include the chip-interleaved DS-CDMA [7] and the generalized mutlicarrier CDMA (GMC-CDMA) [8], [9], which makes use of multiuser detection (MUD) [10] to suppress MUI. However, MUD requires the knowledge of the multipath channels for all users and suppresses MUI at the price of large complexity.

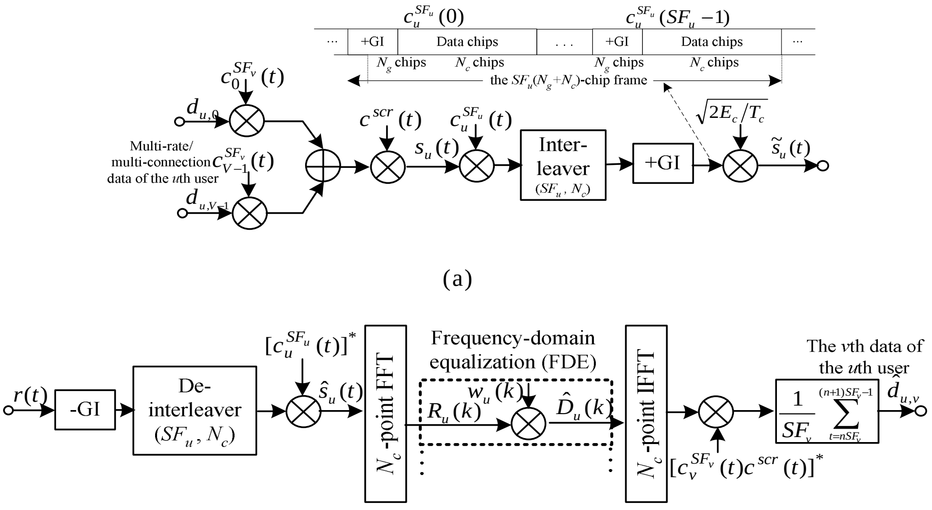
In this paper, we propose a MUI-cancellation scheme for multi-rate/multi-connection DS-CDMA uplink transmissions adopting 2-dimensional (2-D) OVSF spreading and chip interleaving. The 2-D OVSF spread/chip-interleaved DS-CDMA system has low complexity and flexible multi-rate transmission capability. The data symbol to be transmitted is spread by 2-D OVSF spreading code at a transmitter and then chip-interleaved. The 2-D OVSF code is a product code of two 1-D OVSF codes; one is for orthogonal multiuser multiplexing and the other for orthogonal multi-connection per user. After insertion of guard interval (GI), the 2-D OVSF spread/chip-interleaved DS-CDMA signal is transmitted over a frequency-selective channel.

At a receiver, user de-multiplexing is first performed by chip de-interleaving and despreading using 1-D OVSF code. By doing so, the multi-user channel is transformed into orthogonal single-user channel and the MUD can be converted into a set of equivalent single-user equalization problems. This suggests that FDE [11] for single-carrier transmission can also be applied. At each user's receiver, fast Fourier transform (FFT) is applied to decompose the received multi-rate/multi-connection DS-CDMA signal into a number of subcarrier components and FDE is carried out subcarrier by subcarrier. Despreading can be done using 1-D OVSF code for multi-rate connection after performing inverse FFT (IFFT) to recover the data stream of each connection.

The spreading factor for 2-D OVSF codes can be arbitrarily chosen, independent of the FFT block size [6]. Unlike MUD, 2-D OVSF spread/chip-interleaved DS-CDMA is robust against the channel estimation error, and the imperfect power control as well, which means that stringent power control is not necessary as required in the MUD. Moreover, quasi-synchronous transmissions are only required; the transmit timings of all users need to only be kept within GI.

The proposed 2-D OVSF spread/chip-interleaved DS-CDMA has the following features:

1. Multi-rate/multi-connection services
2. Orthogonality among different users maintained by using OVSF spreading codes
3. Single-user FDE exploiting the channel frequency-selectivity to improve the BER performance with low complexity
4. Quasi-synchronous transmission
5. No peak-to-average power ratio (PAPR) problem
6. No strict power control



(a)

(b)

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

2. Transmission System Model

The DS-CDMA uplink transmission system model is illustrated in Fig.1, where only one user (the uth user out of a maximum number of U users) is shown. Although uplink transmission is considered here, this scheme can also be applied to the downlink. 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 time is assumed at the receiver. Therefore, the chip-spaced discrete-time signal representation is used throughout the paper.

2.1. 2-D OVSF spreading

We assume V multi-rate connections per user. V parallel data streams $\{d_{u,v}(n);\ v=0\sim V\text{-}1\}$ are spread using OVSF spreading codes $\{c_v^{SF_v}(t);\ v=0\sim V\text{-}1\}$ having a spreading factor of SF_v. This is called as the first spreading in this paper. $\sum_{v=0}^{V-1} SF_v^{-1} \le 1$ must be satisfied. The resultant V chip sequences are summed up and further multiplied by a scramble sequence $c^{scr}(t)$ with $|c^{scr}(t)|=1$, which is common to all users. Then the orthogonal multi-code/multi-rate DS-CDMA signal is divided into blocks with N_c spread data. The N_c-length sequence is then spread by another user-specific OVSF spreading code $c_u^{SF_u}(t)$ with length of SF_u and chip duration of T_c.

2.2. Chip-interleaving

Without loss of generality, transmission of $V(N_c/SF_v)$ data-modulated symbols is considered.

The chip-interleaving is performed with column-wise input and row-wise output, which is represented as

$$\text{write}\downarrow\underbrace{\overset{\xrightarrow{\text{read}}}{\begin{bmatrix} s_u(0)c_u^{SF_u}(0) & \cdots & s_u(N_c-1)c_u^{SF_u}(0) \\ s_u(0)c_u^{SF_u}(1) & & s_u(N_c-1)c_u^{SF_u}(1) \\ \vdots & & \vdots \\ s_u(0)c_u^{SF_u}(SF_u-1) & \cdots & s_u(N_c-1)c_u^{SF_u}(SF_u-1) \end{bmatrix}}}_{N_c}\updownarrow SF_u \qquad (1)$$

with

$$s_u(t)=\left[\sum_{v=0}^{V-1} d_{u,v}(\lfloor t/SF_v \rfloor)c_v^{SF_v}(t \bmod SF_v)\right]c^{scr}(t)\,, \quad (2)$$

where $\lfloor x \rfloor$ is the largest integer smaller than or equal to x. The interleaved output can be expressed as

$$\tilde{s}_u(t)=\sqrt{\frac{2E_c}{T_c}}s_u(t \bmod N_c)c_u^{SF_u}(\lfloor t/N_c \rfloor) \qquad (3)$$

for t=0~$SF_u \times N_c$-1, where E_c is the average chip energy per connection. An N_g-sampled GI is inserted every N_c-chip block for FDE at a receiver.

2.3. Fading Channel Model

We assume a block-fading channel having L independent propagation paths with chip-spaced time delays; the path gains remain constant over one block interval of (N_c+N_g) chips, but they vary block-by-block according to the terminal movement. The channel impulse response can be 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 $h_{u,l}$ and $\tau_{u,l}$ are respectively the lth path gain and time delay of the uth user with $E[\sum_{l=0}^{L-1}|h_{u,l}|^2]=1$ (E[.] is the ensemble average operation). We assume that the lth path time delay is $\tau_{u,l}$=τ_u+l, where τ_u is the transmit timing offset for the uth user. The maximum time delay of the channel is assumed to be shorter than GI, i.e., τ_u+L-1<N_g.

2.4. Received signal and chip de-interleaving

The maximal allowable number U of users is U=SF_u to be transmitted simultaneously without causing MUI in the uplink. The received signal is sampled at the chip rate and the GI is removed. The resultant signal is written row by row into the de-interleaver and read out column by column:

$$\text{read}\downarrow\underbrace{\overset{\xrightarrow{\text{write}}}{\begin{bmatrix} r(N_g) & \cdots & r(N_c+N_g) \\ r(N_c+2N_g) & \cdots & r(2N_c+2N_g-1) \\ \vdots & \vdots & \vdots \end{bmatrix}}}_{N_c}\,. \qquad (5)$$

Despreading is performed by multiplying the user specific OVSF code $c_u^{SF_u}(t)$ with each column:

$$\hat{s}_u(t)=\frac{1}{SF_u}\sum_{t'=0}^{N_c-1} r(t+N_g+t'(N_c+N_g))\left[c_u^{SF_u}(t')\right]^* \qquad (6)$$

for t=0~N_c-1.

2.5. FDE

Assuming block fading, the orthogonality between different users is preserved even in a frequency-selective fading channel and hence MUI is eliminated. 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 subcarrier components:

$$\begin{aligned} R_u(k) &= \sum_{t=0}^{N_c-1}\hat{s}_u(t)\exp(-j2\pi k\frac{t}{N_c}) \\ &= \sqrt{\frac{2E_c}{T_c}}\hat{S}_u(k)H_u(k)+\Pi_u(k) \end{aligned}\,, \qquad (7)$$

where $H_u(k)$ is the kth subcarrier channel gain of the uth user with $E[|H_u(k)|^2]=1$ and $\Pi_u(k)$ is the noise component due to AWGN with zero-mean and variance of $2N_cN_0/T_c$ (N_0 is the one-sided power spectrum density of the AWGN). They are given by

$$\begin{cases} H_u(k)=\sum_{l=0}^{L-1} h_{u,l}\exp(-j2\pi k\frac{\tau_{u,l}}{N_c}) \\ \Pi_u(k)=\sum_{t=0}^{N_c-1}\eta_u(t)\exp(-j2\pi k\frac{t}{N_c}) \end{cases}. \qquad (8)$$

The single-user FDE is performed subcarrier by subcarrier as

$$Y_u(k)=w_u(k)R_u(k)\,, \qquad (9)$$

where $w_u(k)$ is the equalization weight based on the minimum mean square error (MMSE)given by [12], [13]

$$w_u(k)=\frac{H_u^*(k)}{|H_u(k)|^2+\left(V\cdot SF_u\frac{E_c}{N_0}\right)^{-1}}\,. \qquad (10)$$

2.6. Despreading and data-demodulation

N_c-point IFFT is applied to $\{Y_u(k)\}$ obtain the time-domain chip sequence:

$$y_u(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1} Y_u(k)\exp(j2\pi t\frac{k}{N_c})\,. \qquad (11)$$

Finally, the second despreading is carried out to get the decision variable $\hat{d}_{u,v}(n)$ for the detection of $d_{u,v}(n)$ of the vth connection:

$$\hat{d}_{u,v}(n)=\frac{1}{SF_v}\sum_{t=nSF_v}^{(n+1)SF_v-1} y_u(t)\left[c_v^{SF_v}(t)c^{scr}(t)\right]^*\,, \qquad (12)$$

based on which data demodulation is performed.

3. Simulation Results

The computer simulation condition is shown in Table1. For each user, an L-path frequency-selective block Rayleigh fading channel having the exponential power delay profile with the decay factor γ (in dB) is assumed. The transmit timing offsets $\{\tau_u\}$ are uniformly distributed over [-Δ/2,Δ/2], where Δ<(N_g-L) so that the maximum time delay of the paths is less than GI.

Fig.2 plots the BER performance of uplink DS-CDMA with different number U of active users as a function of the average received bit energy to

Table1. Simulation conditions

Data modulation	QPSK
Spreading code	OVSF spreading code, SF_v=1~256, SF_u=1~16
Scrambling code	Long Gold sequence
Interleaver	$SF_u \times N_c$ block interleaver
Block Length	N_c=256
Guard interval	N_g=32
Equalization	MMSE-FDE
Channel estimation	Ideal

the AWGN power spectrum density ratio E_b/N_0, which is given by E_b/N_0=0.5(E_c/N_0)(SF_uSF_v)(1+N_g/N_c) for QPSK data-modulation. It is assumed that SF_v=V=1 (single connection per user) and SF_u=16; 16 users can be transmitted simultaneously without causing MUI. For comparison, the BER performance of the conventional DS-CDMA with 1-D OVSF (SF_u=1) using single-user detection (SUD) is also given in Fig.2 with Eq. (10) replaced by [13]

$$w_u(k)=\frac{H_u^*(k)}{\sum_{u=0}^{U-1}\left|H_u(k)\right|^2+\left(V\cdot\frac{E_c}{N_0}\right)^{-1}}. \quad (13)$$

To achieve the same data rate, we have assumed SF_v=16, V=1 and U=1~16. To remove MUI, we also simulated MMSE-MUD [14] for DS-CDMA with 1-D OVSF, which requires the knowledge of the spreading codes and channels of all users. When the system is lightly loaded, the MUD exhibits better performance since MUI is less severe in this case. When the system is moderately or heavily loaded, i.e., $U \approx SF_u$, large MUI results in a severe BER degradation. Our proposed 2-D OVSF spread/chip-interleaved DS-CDMA outperforms the MUD and its BER performance remains unchanged for all U. The computational complexity of MUD is greatly increased with the number of users. Also, poor channel estimation accuracy would degrade the BER performance.

Fig.3 shows the average BER performance for a multi-rate DS-CDMA system assuming that the total aggregated data rate normalized by the chip rate, defined as $R_{total}=\sum_{u=0}^{U-1}SF_u^{-1}$, is equal to 0.5 for max{SF_u}=16. The lowest rate R_L corresponds to SF_k=16. Two cases are given: Case1 (4 users with rate R_L and 2 users with rate 2R_L) and Case2 (2 users with rate R_L, 1 user with rate 2R_L and 1 user with rate 4R_L). In the proposed multi-rate DS-CDMA, the same BER performance is obtained irrespective fo the data rate; however, note that the transmit power of lower rate user is lower. As confirmed by Case1 and Case2, the 2-D OVSF spread/chip-interleaved

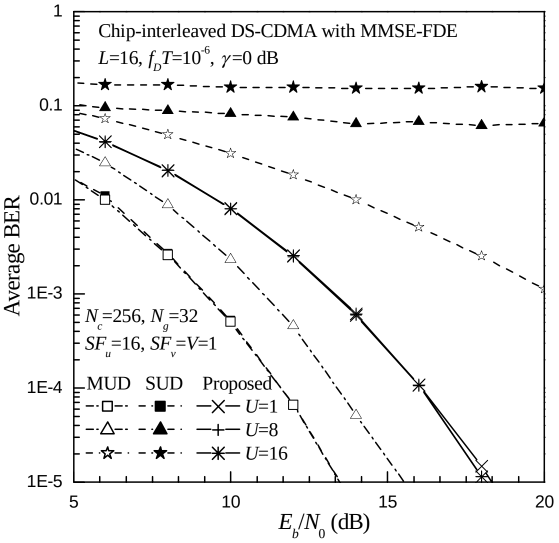


Fig.2. Impact of number U of active users.

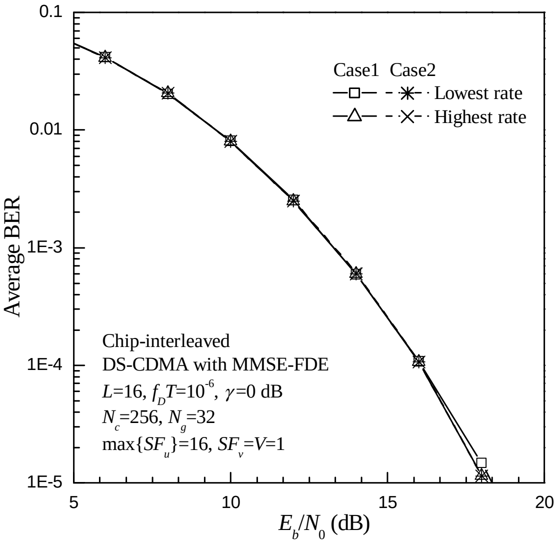


Fig.3. BER performance of multi-rate DS-CDMA.

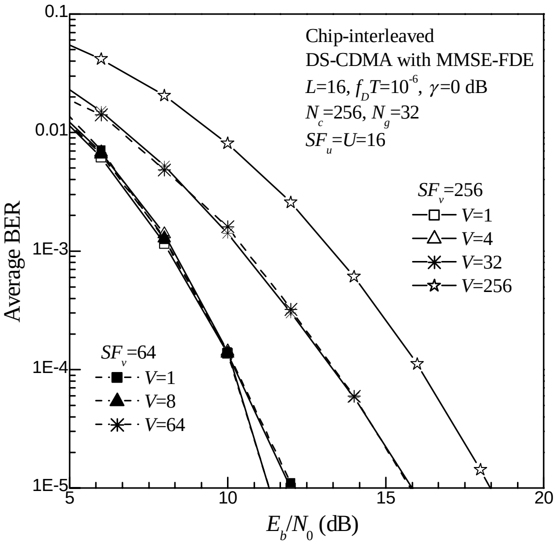
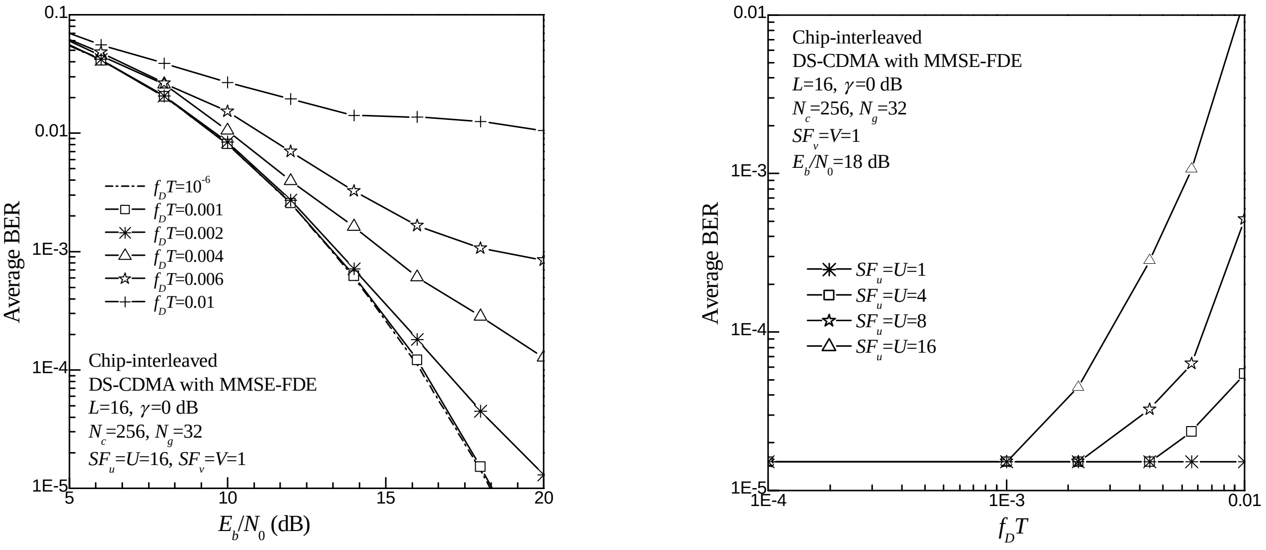


Fig.4. Impact of different SF_v and V



(a) (b)

Fig.5. Impact of f_DT.

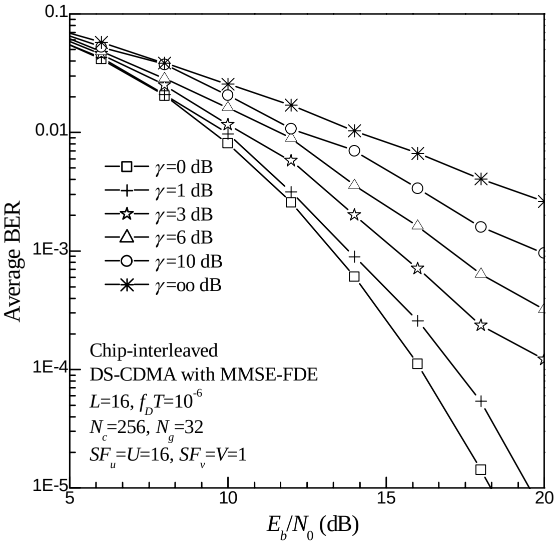


Fig.6. Impact of decay factor γ.

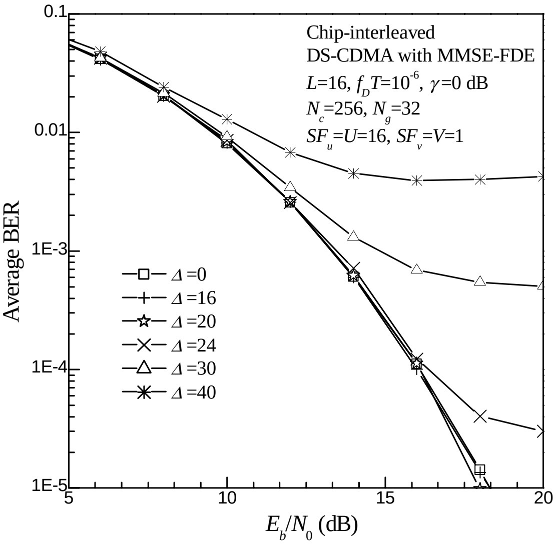


Fig.7. Impact of time offset Δ.

DS-CDMA makes the multi-rate transmissions possible without degrading BER performance in a multi-user environment.

The BER performance of U=16-user multi-rate DS-CDMA with variable SF_v and V is shown in Fig.4. When SF_v=64, V can be selected from 1~64. When SF_v=256, the maximum V can be 256. It has been confirmed by numerical and computer simulation in [15] that with FDE, the same BER performance is obtained for the same value of (V/SF_v). Therefore, 2-D OVSF spread/chip-interleaved DS-CDMA also makes the multi-connection transmissions possible irrespective of the channel conditions.

How the fading rate f_DT influences the BER performance is shown for SF_u=U=16 in Fig.5. It can be seen from Fig.5(a) that no performance degradation is seen if $f_DT<0.001$. However, if $f_DT>0.001$, since the orthogonality among different users cannot be maintained, the performance degrades. Fig.5(b) plots the BER of E_b/N_0=18dB as a function of f_DT. For larger f_DT, the BER performance can be maintained by reducing the data rate. As U decreases, the impact of Doppler spread becomes less due to the shorter length of 1-D OVSF spreading code. Therefore, for very fast fading, we should choose smaller SF_u (higher data rate) by reducing the number of simultaneous users.

So far, we have assumed the uniform power delay profile (γ=0 dB) and no transmit timing offset (Δ=0). Here, we discuss the impacts of γ and Δ. Fig.6 shows the average BER performance with γ as a parameter. As γ increases, the channel frequency-selectivity becomes weaker and the frequency diversity effect reduces, resulting in a degraded BER performance and the worst case is $\gamma \rightarrow \infty$ (corresponding to the L=1-path Rayleigh channel). The impact of Δ is plotted in Fig.7. Since the GI of N_g=32 samples is used, the time delays of all the paths are kept within the GI when $\Delta \leq (N_g\text{-}L)$. It can be seen that our proposed MUI-cancellation scheme works well. Therefore, the BER performance is independent of Δ without exact synchronization as far as $\Delta \leq (N_g\text{-}L)$. However, when $\Delta > (N_g\text{-}L)$, the MUI and IPI will be produced, resulting in the performance degradation.

4. Conclusions

In this paper, we proposed a 2-dimentional (2-D) OVSF spread/chip-interleaved DS-CDMA in a frequency-selective fading channel for the multi-rate/multi-connection uplink transmission. Relying on chip interleaving and 2-D OVSF spreading code, a multiuser detection (MUD) problem is converted into a set of equivalent single-user equalization problems. This simple MUI-cancellation not only increases the uplink capacity, but also allows flexible multi-rate transmissions. It has an easy rate switching capability. Computer simulation results has shown that the proposed DS-CDMA system outperforms the conventional one in the presence of transmit timing offset and multipath fading, and confirmed the capability of multi-rate transmissions in a multi-user environment without sophisticated MUD technique. Compared with MUD, our proposed 2-D OVSF spread/chip-interleaved DS-CDMA using single-user detection is robust against the channel estimation error with low implementation complexity.

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