FREQUENCY DOMAIN EQUALIZATION TECHNIQUES FOR MULTICODE DS-CDMA IN FREQUENCY SELECTIVE RAYLEIGH FADING CHANNEL

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ABSTRACT

Orthogonal multicode direct sequence code division multiple access (DS-CDMA) has the flexibility in offering high data rate services. However, in a frequency-selective fading channel, the bit error rate (BER) performance is severely degraded since the orthogonality among spreading codes is partially lost. In this paper, frequency-domain equalization (FDE) and space antenna diversity combining are applied to orthogonal multicode DS-CDMA in order to restore the code orthogonality and improve the BER performance of the system. Two methods of FDE are considered, the first method based on fast Fourier transform (FFT), while the second method based on circulant matrices. Moreover, a channel interleaving method, called chip interleaving is used to improve the performance of multicode DS-CDMA system.

KEYWORDS: Multicode Ds-Cdma, Frequency Domain Equalization.

الخلاصة:

تعدد الشفرات المتعامدة لنظام تقسيم الشفرات متعدد المداخل ذي المتتابعة المباشرة (DS-CDMA) يعطي مرونة في خدمات نقل البيانات بسرعة عالية. مع ذلك في قناة الخفوت الترددية الاختيارية فان اداء النظام سيقل بشدة وذلك لان التعامد بين شفرات النشر سيفقد جزئيا. في هذا البحث، معادلة مجال التردد (FDE) مع تنوع الهوائيات المكانية ستطبق على نظام (DS-CDMA) متعدد الشفرات المتعامدة وذلك لاستعادة التعامد بين الشفرات وبالتالي تحسين اداء النظام. طريقيتين من طرق معادلة مجال التردد ستعتمد في هذا البحث، الطريقة الاولى تعتمد على تحويل فورير السريع (FFT) بينما الطريقة الثانية تعتمد على طريقة تدوير المصفوفات (circulant matrices) . بالاضافة الى ذلك سيتم استخدام طريقة لبعثرة القناة تدعى بعثرة الشريحة (Chip Interleaving) لتحسين اداء نظام (DS-CDMA) متعدد الشفرات المتعامدة.

INTRODUCTION

In direct sequence code division multiple access (DS-CDMA), one way to achieve high speed data transmission is to use orthogonal multicode multiplexing. However, frequency selective multipath fading encountered in a broadband wireless communication system severely degrades the bit error rate (BER) performance of multicode DS-CDMA, (T. Itagaki etal, 2004). An effective way to improve the BER performance is to apply frequency-domain equalization (FDE) to multicode DS-CDMA signal reception, (F. Adachi etal, 2003).

Frequency domain equalization (FDE) is an effective technique for improving the single carrier (SC) transmission performance in a frequency selective fading channel, (D. Falconer etal, 2002). Minimum mean square error (MMSE)-FDE based on fast Fourier transform (FFT) was applied to multicode DS-CDMA to obtain a good BER performance similar to that of multi carrier code division multiple access (MC-CDMA), (F. Adachi etal, 2003 and F. Adachi etal, 2005). The distinctive point of this technique is the use of Cyclic Prefix (CP), in order to prevent degradation of transmission characteristics caused by multipath interference, which become more apparent during broadband transmission. CP copies multiple data symbols at the end of a frame to the head part of a frame. Moreover, the equalization is performed on a block of data at a time and the operations on this block involve fast Fourier transform (FFT), (D. Falconer etal, 2002).

Space antenna diversity technique can be used to improve the system performance in a fading channel. Instead of transmitting and receiving the desired signal through one channel, several copies of the desired signal are obtained through different channels, (H. Hourani, 2004-2005).

Chip interleaving is a form of channel interleaver that exploits the spreading process in DS-CDMA and thus improves the BER performance in a frequency selective fading channel. Chip interleaver scrambles the chips and transforms the transmission channel into highly time selective or highly memoryless channel, (D. Garg etal, 2002 and D. Garg etal, 2005).

In this paper, two additional FDE techniques are used; maximum ratio combining (MRC-FDE) and zero forcing (ZF-FDE). Moreover, MMSE-FDE (based on FFT) which was applied in (F. Adachi etal, 2003), will be used too. All the above FDE techniques are applied to multicode DS-CDMA with their performance are compared by simulation.

Finally, two methods of FDE techniques based on FFT and circulant matrices are illustrated. Since FDE based on FFT consumes less time compared with circulant matrices method, it will be used in this work.

Remainder of this paper is organized as follows. Section 2, presents the transmission system model for a multicode DS-CDMA using FDE and antenna diversity combining. MMSE-FDE, MRC-FDE and ZF-FDE based on FFT and circulant matrices methods are presented. Moreover, chip interleaver is presented in this section. In section 3, the BER performance of the system in 3-paths frequency selective Rayleigh fading channel is evaluated by computer simulation. Finally, section 4, offers some conclusions.

- MULTICODE DS-CDMA WITH FDE AND ANTENNA DIVERSITY

Transmission System Model

Transmission system model for multicode DS-CDMA using FDE and antenna diversity combining is illustrated in Fig.(1). At the transmitter, the data modulated symbol sequence is serial-to-parallel (S/P) converted into U parallel data streams {$d_i(t)$; i=0~U-1} which are then spread using U orthogonal spreading sequences {$c_i(t)$; i=0~U-1} having a spreading factor of *SF*. The Resultant U chip sequences are summed to form the orthogonal multicode DS-CDMA signal, which then divided into blocks of N_c chips each and then, the last N_g chips of each block is copied as a cyclic prefix and inserted into the guard interval (GI) at the beginning of each block to form a frame of (N_c+N_g) chips. Figure (2) illustrates the frame structure, (T. Itagaki etal, 2004 and K. Takeda etal, 2004).

The GI-inserted chip sequence is transmitted over a frequency-selective fading channel and is received by N_r diversity antennas at the receiver. After the removal of GI, the received chip sequence on each antenna is decomposed by N_c-point FFT into N_c subcarrier components. Then, joint FDE and antenna diversity combining is carried out. Finally, inverse FFT (IFFT) is applied to obtain the equalized and diversity combined time-domain chip sequence for multicode despreading and parallel-to-serial (P/S) converted for data demodulation , (T. Itagaki etal, 2004 and K. Takeda etal, 2004).

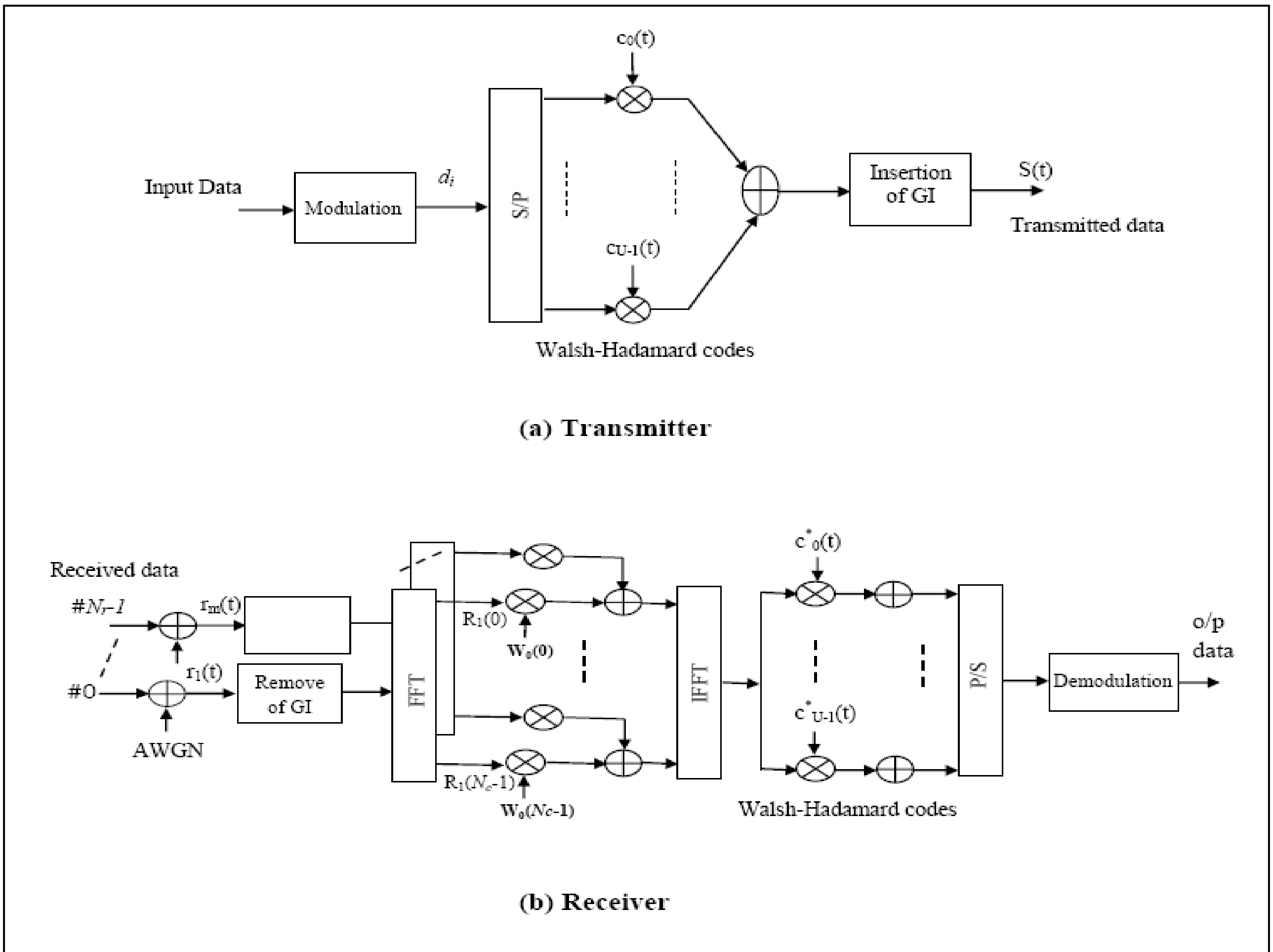


Fig. (1) Transmission system model for multicode DS-CDMA with Joint FDE and antenna diversity combining.

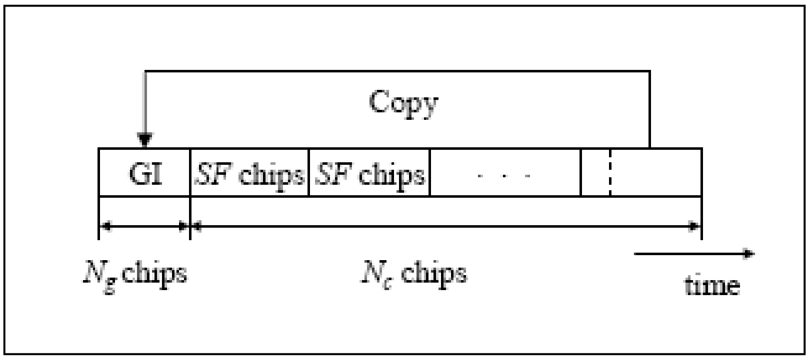


Fig.(2) Frame structure.

Received Signal

The propagation channel is assumed to be a frequency-selective fading channel having L discrete paths, each subjected to independent fading, where the time delay of the lth path (l = 0 ~ L-1) is assumed to be τ_l. The chip sequence $\{r_m(t);\ m=0\sim N_r-1,\ t=-N_g\sim N_c-1\}$ received on the mth antenna can be represented as (T. Itagaki etal, 2004 and K. Takeda etal, 2004):

$$r_m(t) = \sum_{l=0}^{L-1} h_{m,l}\, s(t-\tau_l) + n_m(t), \qquad (1)$$

where, $h_{m,l}$ is the complex path gain of the lth path experienced at the m-th antenna and , s(t) is the transmitted chip sequence ($t = -N_g \sim N_c$ -1), and $n_m(t)$ is the additive white Gaussian noise (AWGN).

After removal of GI from the received chip sequence $\{r_m(t)\}$, N_c-point FFT is applied to decompose $\{r_m(t);\ t = 0 \sim N_c-1\}$ into N_c subcarrier components $\{R_m(k);\ k=0\sim N_c-1\}$. The kth subcarrier component $R_m(k)$ can be written as (T. Itagaki etal, 2004 and K. Takeda etal, 2004):

$$R_m(k) = H_m(k)S(k) + n_m(k), \qquad (2)$$

Where, $S(k)$, $H_m(k)$ and $n_m(k)$ are the kth subcarrier components of the transmitted N_c-chip signal sequence $\{s(t);\ t=0 \sim N_c-1\}$, the channel gain and noise component due to the AWGN, respectively. They are given by (T. Itagaki etal, 2004 and K. Takeda etal, 2004):

$$\begin{cases} S(k) = \sum_{t=o}^{N_c-1} s(t)\exp(-j2\pi k\frac{t}{N_c}) \\ H_m(k) = \sum_{l=o}^{L-1} h_{m,l}\exp(-j2\pi k\frac{\tau_l}{N_c}), \\ n_m(k) = \sum_{t=o}^{N_c-1} n_m(t)\exp(-j2\pi k\frac{t}{N_c}) \end{cases} \qquad (3)$$

Then, joint one-tap FDE and antenna diversity combining is carried out to obtain (T. Itagaki etal, 2004 and K. Takeda etal, 2004):

$$R\square_m(k) = \sum_{m=0}^{N_r-1} R_m(k)\, W_m(k), \quad (4)$$

where $W_m(k)$ is the equalization weight. MMSE equalization, MRC equalization and ZF equalization are used in this work.

Two methods of FDE are considered in this work to calculate the equalization weight; the first method is based on FFT (T. Itagaki etal, 2004 and K. Takeda etal, 2004), while the second method is based on circulant matrices (Y. YANG, 2003).

2.2.1 FDE Based on FFT

FDE based on FFT is much faster than FDE based on circulant matrices. The frequency domain MMSE equalization weight $W_m(k)$ for kth subcarrier is given by, (F. Adachi etal, 2003):

$$W_m(k) = \frac{H_m^*(k)}{\sum_{m=0}^{Nr-1} |H_m(k)|^2 + \left[\frac{U}{SF}\left(\frac{E_s}{N_o}\right)\right]^{-1}} \quad (5)$$

where, (E_s/N_o) is the average received signal energy per symbol to-single-sided power spectrum density of AWGN process ratio and * denotes complex conjugation.

In this work, the below two FDE methods, (T. Itagaki etal, 2004 and K. Takeda etal, 2004) are used in addition to MMSE-FDE, (F. Adachi etal, 2003).

$$W_m(k) = \begin{cases} H_m^*(k) & \text{, MRC-FDE} \\ \dfrac{H_m^*(k)}{\sum_{m=0}^{Nr-1} |H_m(k)|^2} & \text{, ZF-FDE} \end{cases} \quad (6)$$

FDE Based on Circulant Matrices

Let h = [$h(0)$, $h(1)$, …..$h(L\text{-}1)$] is the equivalent discrete time channel impulse response (CIR). The $N \times N$ channel matrix H is circulant with its (k,l)th entry given by $h((k\text{-}l) \; mod \; N)$; or looks like (Y. YANG, 2003):

$$H = \begin{bmatrix} h(0) & 0 & \cdots & h(L\text{-}1) & \cdots & h(1) \\ h(1) & h(0) & \cdots & 0 & & \vdots \\ \vdots & h(1) & & & & h(L\text{-}1) \\ h(L\text{-}1) & \vdots & & h(0) & & 0 \\ \vdots & h(L\text{-}1) & & \vdots & & \vdots \\ 0 & \cdots & \cdots & h(L\text{-}2) & \cdots & h(0) \end{bmatrix} \quad (7)$$

Since H is a circulant matrix, it can be expressed in term of its eigenvalues and associated eigenvectors, i.e., eigen-decomposition, as follows (Y. YANG, 2003):

$$H = F_N^H \; \Lambda \; F_N \quad (8)$$

where, F_N is the orthonormal discrete Fourier transform (DFT) matrix whose (k,l)th entry is given by $F_{k,l} = N^{-1/2} \exp(-j2\pi kl/N)$, where $0 \leq k,l \leq N\text{-}1$; and Λ is a diagonal matrix with its (k,k) element equal to the kth DFT coefficient of the channel impulse response, i.e., $\Lambda_{k,k} = \sum_{n=0}^{N-1} h(n) \exp(-j2\pi nk/N)$. It is also noteworthy that the $N \times N$ matrix F_N is unitary, i.e., $F_N^{-1} = F_N^H$. Here, the superscript H denotes complex conjugate transpose. The diagonal of Λ contains uniformly sampled samples of channel frequency response (Y. YANG, 2003).

After discarding CP at the receiver, the received time domain block is transformed to frequency domain by means of N-point DFT operations. Then, based on the eigen-decomposition property of circulant matrix H, the input-output relationship can be described as (Y. YANG, 2003):

$$R(i) = F_N \; r(i) = F_N \; F_N^H \Lambda \; F_N \; s(i) + F_N \; n(i)$$

$$= \Lambda \; S(k) + n(k) \quad (9)$$

where, s(i), and n(i) are the ith transmitted block and corresponding noise vector, both of them of size N.

The coefficients of FDE based on circulant matrices are given by (Y. YANG, 2003):

$$W(k) = \begin{cases} \Lambda^H \left(\Lambda \Lambda^H + \frac{1}{SNR} I_N\right)^{-1}, & \text{MMSE-FDE} \\ \Lambda^H, & \text{MRC-FDE} \\ \frac{1}{\Lambda}, & \text{ZF-FDE} \end{cases} \tag{10}$$

where, SNR is a signal-to-noise ratio.

Chip Interleaver

Chip interleaver is a channel interleaving method used for DS-CDMA mobile radio. Chip interleaver scrambles the chips associated with a data symbols so that the channel gains experienced by neighboring chips are highly uncorrelated. By doing so, the resultant transmission channel can be transformed into highly time-selective or highly memoryless channel, (D. Garg etal, 2002 and D. Garg etal, 2005).

The proposed chip interleaver interleaves the chip sequence obtained after spreading. Figure (3) illustrates the chip interleaver structure, (D. Garg etal, 2002). It is a block interleaver with columns equal to the number of chips to be transmitted (N_c) and rows equal to N_R. The chip sequence to be transmitted is written column-wise and read row-wise. At the receiver, the received chip sequence is written and read in an opposite manner in the chip de-interleaver before despreading. The number of rows in chip interleaver is chosen to be larger than *SF*, which is given by, (D. Garg etal, 2005):

$$N_R = \frac{SF * a}{N_c} \tag{11}$$

where, N_R is the number of rows in chip interleaver and a is the number of data in each substream.

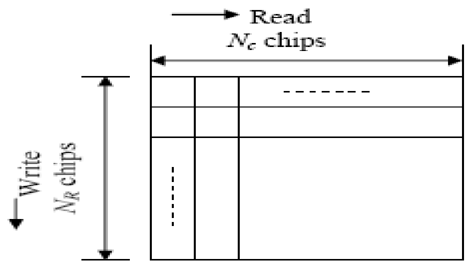


Fig.(3) Chip Interleaver Structure.

- COMPUTER SIMULATION

The parameters that have been used in simulation are listed in Table (1). This system is software implemented with MATLAB 7.0 technical programming language.

Table 1 Simulation Parameters.

Parameter	Value
Data rate	3MHz
No. of transmitted bits	100000
Modulation type	QPSK
Spreading code type	Walsh code
Spreading Factor	*SF*=4, 8, 16, 32
No. of parallel codes	U=4
No. of FFT points	N_c =256
Cyclic prefix interval	N_g=32 (chips)
fading channel model	Rayleigh fading channel (Jakes model)
Doppler Frequency	f_d=10 Hz
No. of channel paths	L=3
No. of receiver antennas	N_r=1, 2, 4
Frequency-Domain Equalization Types	MMSE-FDE, MRC-FDE, ZF-FDE
SNR	(0,2,…,22) dB

BER Performance Comparison of Multicode DS-CDMA with MMSE-FDE Based on FFT and Circulant Matrices Methods:

Figure (4) shows the BER performance versus SNR of multicode DS-CDMA system with MMSE-FDE using FFT method and circulant matrices method, in three paths Rayleigh fading channel, for *SF*=4 and 16. It can be seen that the FFT method gives better BER performance than circulant matrices method. Moreover, FDE based on FFT is much faster than FDE based on circulant matrices.

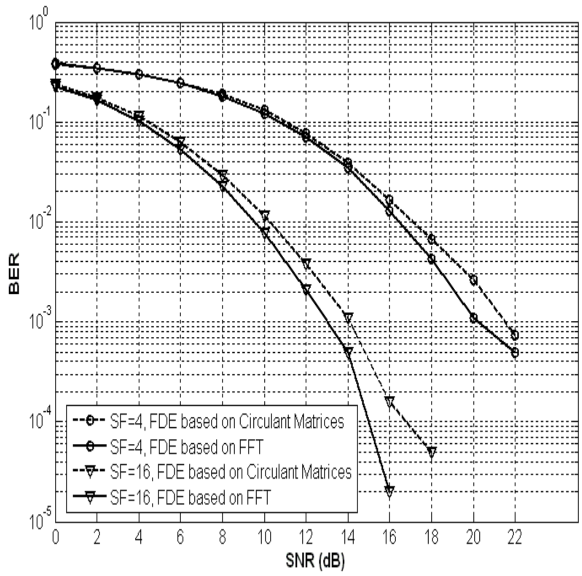


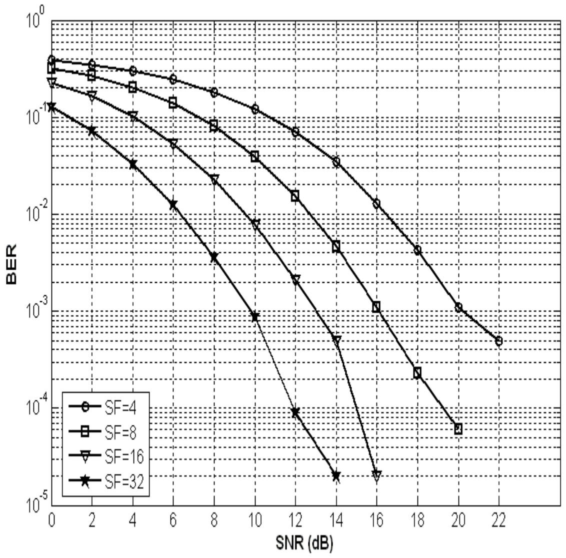
Fig.(4) BER performance of multicode DS-CDMA with MMSE-FDE based on FFT and Circulant Matrices methods in 3-paths Rayleigh fading channel.

Since FDE based on FFT method achieves better BER performance. Hence, in the following results, only this method is used.

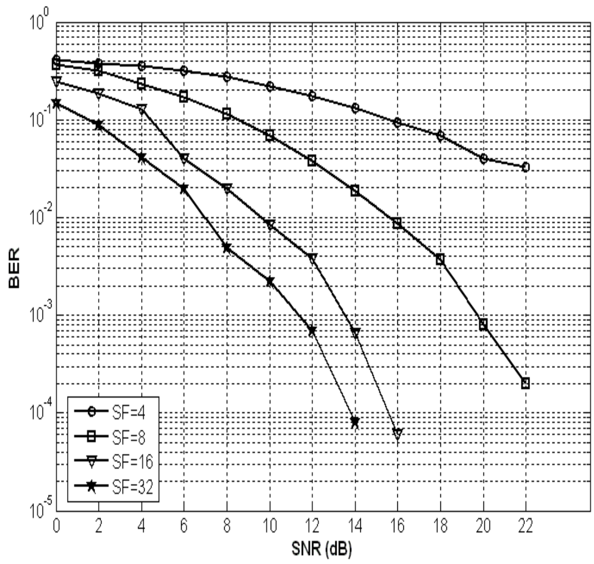
BER Performance Comparison of Multicode DS-CDMA with MMSE-FDE, MRC-FDE and ZF-FDE Techniques:

The BER performances versus SNR of multicode DS-CDMA system using different values of spreading factor (*SF*), with joint MMSE-FDE, MRC-FDE, and ZF-FDE in three paths Rayleigh fading channel are illustrated in Figs.5(a), 5(b), and 5(c), respectively.

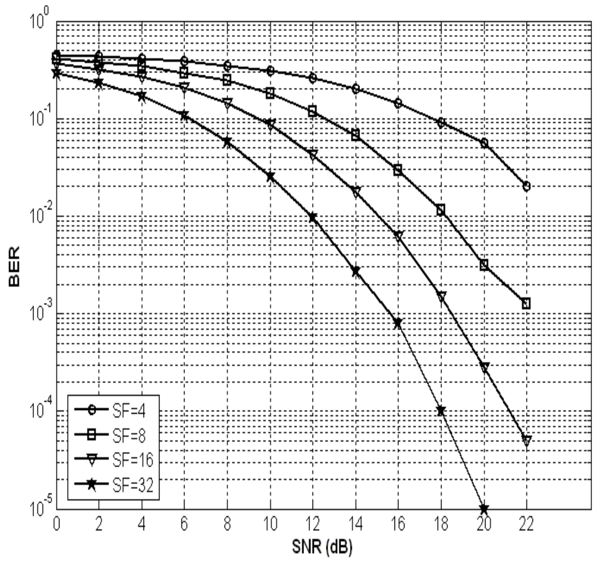
The BER performance is improved when *SF* is increased for all types of FDE. The MMSE equalization always achieves better BER performance as compared to MRC and ZF equalization. The MRC equalization achieves poor performance (BER floor) for *SF*=4, due to the larger ICI (intercode interference) produced by the enhanced frequency-selectivity, but when *SF*=8, 16, and 32, the MRC equalization achieves almost the same BER performance as MMSE equalization since the ICI can be sufficiently suppressed during the despreading process. The ZF equalization achieves good performance at high *SF* and at high SNR values only, because the ZF equalization leads to noise enhancement.



(a) Multicode DS-CDMA with MMSE-FDE



(b) Multicode DS-CDMA with MRC-FDE



(c) Multicode DS-CDMA with ZF-FDE

Fig.(5) BER performances of multicode DS-CDMA using MMSE-FDE, MRC-FDE and ZF-FDE techniques.

Error Rate Performance of Multicode DS-CDMA with FDE and Fading Rate as a Parameter:

Figure (6) illustrates the BER performance versus SNR of multicode DS-CDMA system in 3-paths Rayleigh fading channel using *SF*=16, and fading rate (f_d*T_{blk}) as parameter, where f_d=10 Hz and 200 Hz. T_{blk}= ((N_c+N_g)*T_c), here T_c is chip duration. Joint MMSE-FDE, MRC-FDE, and ZF-FDE are used.

In this work, block fading is assumed, where the path gains stay constant over one frame duration. For *SF*=16 and f_d*T_{blk}=4.8e-4, the BER performance is better than f_d*T_{blk}=9.6e-3, because as f_d is increased (fast fading), the path gains of the channel do not stay constant during one frame duration. The MMSE equalization still achieves better BER performance as compared with MRC and ZF equalizations.

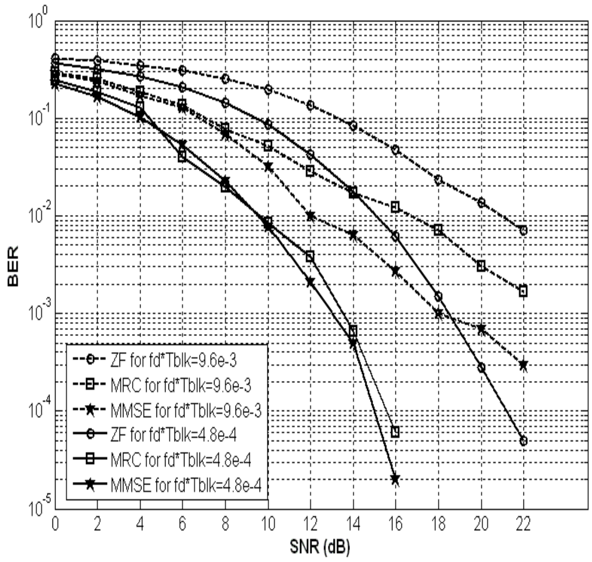


Fig.(6) BER performance of multicode DS-CDMA with frequency domain equalizers and fading rate as a parameter (f_d=10 & 200 Hz).

Since the MMSE equalization always achieves better BER performance. Hence, in the following results, only MMSE equalization is used.

The Effect of Chip Interleaver on the Performance of Multicode DS-CDMA with MMSE-FDE:

Figure (7) shows the BER performance versus SNR of multicode DS-CDMA system using chip interleaver with MMSE-FDE in three paths Rayleigh fading channel, for *SF*=4 and 8. With chip interleaving, the BER performance improves as *SF* increases, when *SF*=4 (8), about 1dB (2dB) improvement is seen in the SNR required for a BER=10^{-3}.

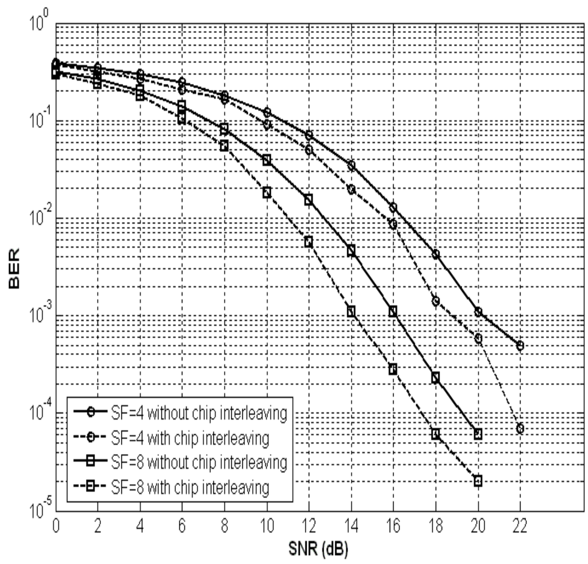


Fig.(7) BER performance of multicode DS-CDMA with MMSE-FDE and chip interleaving in 3-paths Rayleigh fading channel.

- Error Rate Performance of Multicode DS-CDMA with MMSE-FDE and Space Antenna Diversity:

Figure (8) shows the BER performance versus SNR of multicode DS-CDMA system with MMSE-FDE and space antenna diversity (N_r=1,2, and 4) in three paths Rayleigh fading channel for *SF*=4.

It can be clearly seen that the use of antenna diversity combining is always beneficial, where as the number of branches (N_r) is increased, the BER decreases.

It can be seen from Fig.(8) that when BER=10^{-3}, there is about (2.4)dB and (4)dB improvement for N_r=2 and N_r=4, respectively.

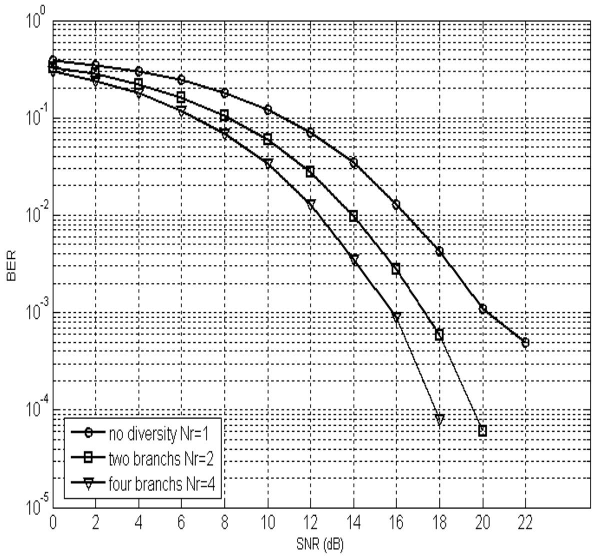


Fig.(8) BER performance of multicode DS-CDMA with MMSE-FDE and space antenna diversity in 3-paths Rayleigh fading channel.

The Effect of Changing the Number of Codes and Spreading Factors on the Performance of Multicode DS-CDMA with MMSE-FDE:

Figure (9) shows the BER performance versus SNR of multicode DS-CDMA system using different number of parallel codes and spreading factors with joint MMSE-FDE in three paths Rayleigh fading channel.

When the value of U/*SF* (which represents intercode interference (ICI)) becomes smaller, the effect of ICI becomes less and less and thus, the achievable BER performance improves. A mathematically extreme case is when (U/*SF*)→ 0 (i.e., ICI is neglected) (K. Takeda etal, 2004).

It can be clearly seen from Fig.(9) that when the amount of ICI is the same for multicode transmission, the BER performance is improved as *SF* is increased.

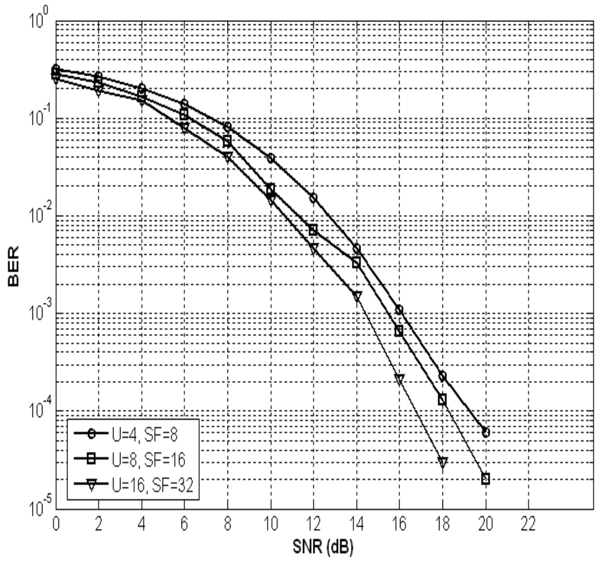


Fig.(9) Performance of multicode DS-CDMA with MMSE-FDE in 3-paths Rayleigh fading channel with different codes and spreading factors as a parameter.

- CONCLUSIONS

In this paper, joint frequency-domain equalization and antenna diversity combining was presented for improving the orthogonal multicode DS-CDMA signal transmission performance in a frequency-selective Rayleigh fading channel and the achievable BER performance was evaluated by computer simulation. It was found that the FDE based on FFT method gives better BER performance than circulant matrices method. Moreover, FDE based on FFT consumes less time and therefore, it is much faster than FDE based on circulant matrices. The BER performance using MMSE, MRC and ZF equalization were compared and the MMSE equalization gives the best BER performance. Also, it was found that as the spreading factor increases, the equalization schemes improve the BER performance since the ICI produced by the frequency-selectivity can be effectively suppressed during the despreading process.

Chip interleaver was also introduced to exploit the time selectivity of the channel in multicode DS-CDMA system with MMSE-FDE. It was shown by computer simulations that the chip interleaving improved the BER performance as *SF* is increased. Finally, space antenna diversity was presented in this paper to improve the BER performance of DS-CDMA with MMSE-FDE. It was shown that the use of antenna diversity is powerful to improve the BER performance, where as the number of branches is increased, the BER performance decreases and the complexity of the system becomes expensive.

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