DS-CDMA and MC-CDMA with Per-User MMSE Frequency Domain Equalization

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Abstract

The future wireless mobile communication systems will be required to support high-speed transmission rate. Direct sequence code-division multiple access (DS-CDMA) and multicarrier (MC-) CDMA are two important CDMA schemes for high rate wireless communication. A novel linear per user minimum mean square error (PU-MMSE) detection technique for DS-CDMA with frequency domain equalization (FDE) based on the MMSE criterion applied per user is presented. It is shown by computer simulation that PU-MMSE outperforms conventional per carrier (PC-) MMSE for DS-CDMA with FDE in frequency selective block fading channel. Especially, in case of uplink PU-MMSE gains better performance than conventional MMSE not only for non-full-load DS-CDMA with FDE but also for full-load DS-CDMA with FDE. The performance of DS-CDMA with PU-MMSE FDE can be further promoted by successive interference cancellation (SIC). Comparing to MC-CDMA with PU-MMSE FDE, DS-CDMA with PU-MMSE FDE has no performance loss and has much lower peak-to-average power ratio (PAPR).

1. Introduction

The future wireless mobile communication systems will be required to support high-speed transmission rate. The high data rate requires broad frequency bands. Unfortunately in broadband wireless channel, the severe frequency-selectivity due to the more number of resolvable multiple paths fading degrades the BER performance.

MC-CDMA, based on the combination of orthogonal frequency division multiplexing with CDMA, is one important candidate techniques for future wireless communication system [1-2]. Using a given spreading code, the MC-CDMA transmitter spreads the original data stream over different subcarriers in frequency domain. MC-CDMA scheme is robust to frequency selective fading. For MC-CDMA system, there are some detection techniques such as equal gain combining (EGC), orthogonal restoring combining (ORC), maximum ratio combining (MRC) and MMSE. The MMSE scheme can achieve better performance [1][3].

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In the past literatures of MC-CDMA with MMSE FDE, which mostly only consider downlink, the MMSE equalization criterion is applied independently to each subcarrier in frequency domain, which we call per carrier MMSE (PC-MMSE) in this paper. However, the subcarriers have different amplitude levels and different phase shifts in frequency selective fading channel, which causes a loss of orthogonality among users and severe MAI. A new MMSE detection technique for MC-CDMA was proposed [3]. This technique apply MMSE criterion to per user and achieve performance improvement mainly for non-full-load systems. Taking advantage of the dispreading process, the new MMSE detection scheme outperforms the PC-MMSE MC-CDMA system.

However, MC-CDMA is composed of a lot of subcarriers with their overlapping power spectra and exhibits a non-constant nature in its envelope, which causes a high PAPR problem. Recently, it was shown that DS-CDMA using MMSE FDE can achieve good performance comparable to MC-CDMA with MMSE FDE [4]. And as a kind of single-carrier systems, DS-CDMA with FDE transmitter has much lower PAPR and transmitter complexity. Hence DS-CDMA with FDE is more suitable for uplink transmission than MC-CDMA.

In this paper, we propose an improved FDE based on applying MMSE criterion jointly on all subcarriers for the user, called per-user MMSE (PU-MMSE) FDE, for DS-CDMA system. It is evaluated that the BER performances of DS- and MC-CDMA with PU-MMSE FDE in frequency selective fading channel both downlink and uplink (uplink channel condition are not considered in existing papers on MMSE FDE for DS-CDMA and [3]).

The outline of this paper is as follows. After presenting the MC-CDMA with PC- and PU-MMSE FDE in Section 2, the DS-CDMA with PU-MMSE detection algorithm is derived in Section 3, followed by the performance simulation and comparison in Section 4. Conclusions are drawn in Section 5.

2. MC-CDMA with PC- and PU-MMSE FDE system

The MC-CDMA transmitter and receiver is shown in Fig.1. Each data symbol x_j of user j, is multiplied with a user specific L-chip spreading code and scrambled by a long code at the transmitter. Then each chip signal is assigned to a subcarrier and transformed to time domain through using serial-to-parallel (S/P) conversion and L-point inverse fast Fourier transform (IFFT). A cyclic prefix (CP) is inserted at the beginning of each transmitted data block. In order to avoid inter-block interference (IBI), the length of CP must exceed the maximum channel delay in downlink, or the maximum delay between first and last paths of all users in uplink. Without loss of generality, user 1 is denoted as the desired user in this paper.

At the receiver, the L_p-length CP is first discarded. Then every block with L chips is decomposed by fast Fourier transform (FFT) into L subcarrier components. The frequency-selective fading distortion is compensated using a one-tap FDE with equalization vector given by $\boldsymbol{w}^H = [w_1^* \quad w_2^* \quad \ldots \quad w_L^*]$, where $(\cdot)^H$ denotes the conjugate transpose and $(\cdot)^*$ denotes the complex conjugate operation. After FDE, the signal is despread and demodulated.

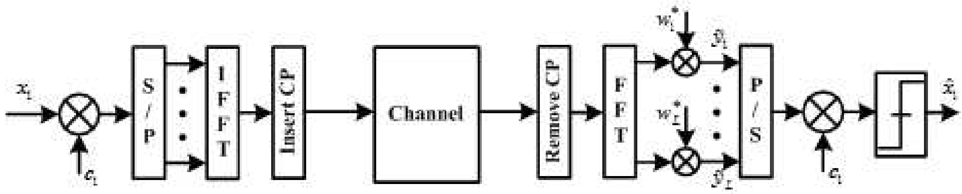

Figure 1. MC-CDMA with FDE system

With conventional PC-MMSE FDE, the equalization coefficients for the ith subcarrier of desired user can be represented as [3-4]

$$w_i^* = \frac{\tilde{h}_{1i}}{\left|\tilde{h}_{1i}\right|^2 + \rho^{-1}} \tag{1}$$

where $\tilde{h}_{1i}$ denotes ith subcarrier of user 1 fading gain and ρ denotes the subcarrier signal to noise ratio.

The equalization vector of MC-CDMA with PU-MMSE FDE [3] can be written as

$$\boldsymbol{w} = L\left(\sum_{j=1}^{N_u}\left(\boldsymbol{\gamma}_j \boldsymbol{\gamma}_j{}^H\right) + \frac{\left(L+L_p\right)}{E_s/N_0}\boldsymbol{I}\right)^{-1}\tilde{\boldsymbol{h}}_1 \tag{2}$$

where $\boldsymbol{\gamma}_j = \mathrm{diag}\left(\tilde{\boldsymbol{h}}_j\right)\mathrm{diag}\left(\boldsymbol{c}_j\right)\boldsymbol{c}_1$, $\boldsymbol{c}_j$ is the scrambled spreading code for jth user, $\boldsymbol{I}$ is the identity matrix, E_s/N_0 is the average symbol energy to additive white Gaussian noise (AWGN) power spectrum density ratio of the desired user.

3. DS-CDMA with PC- and PU-MMSE FDE system

Recently, it was shown that the DS-CDMA with FDE transmission should be more suitable than multi-carrier transmission for uplink wireless communication system since lower PAPR and shifting the complexity of signal processing from transmitter to receiver [3-6]. The block diagram of a DS-CDMA with FDE is shown in Fig.2. At the transmitter of DS-CDMA with FDE, a difference from a MC-CDMA transmitter is the absence of L-point IFFT after spreading and scrambling. A repetition of the last several chips in a data block after spreading and scrambling as a CP is inserted at the beginning of each transmitted data block.

At the receiver, the CP is discarded firstly. The received data block is decomposed by FFT into L subcarrier components. Then FDE is carried out. After FDE, the frequency domain signal is transformed back to time domain through L-point IFFT, and then dispread the user's scrambled spreading code. The equalization coefficients of DS-CDMA with PC-MMSE FDE can be also represented by Eq.(1) [4].

The conventional PC-MMSE FDE does not take into account the spreading and despreading, hence the mean square error between the transmitted symbol x_1 and the estimated symbol $\hat{x}_1$ is not minimal. We will next derive the expression of the PU-MMSE for DS-CDMA with FDE.

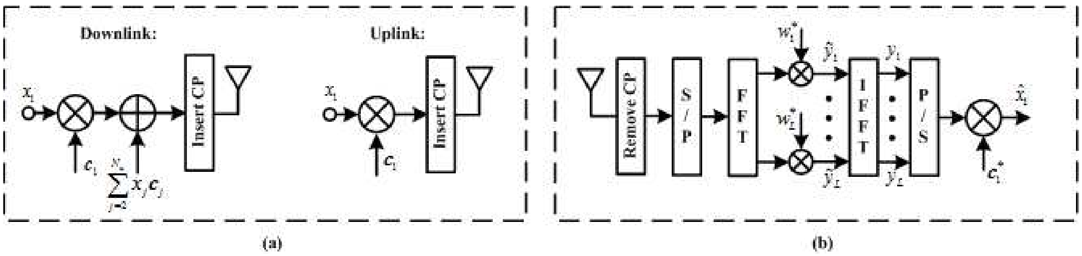

Figure 2. The transmitter/receiver structure of DS-CDMA with FDE: a) transmitter; b) receiver

As shown in Fig.2, the signal after equalization can be expressed as

$$\begin{aligned}\tilde{\boldsymbol{y}} &= [\tilde{y}_1 \quad \tilde{y}_2 \quad \dots \quad \tilde{y}_L] \\ &= \boldsymbol{w}^H\left(\sum_{j=1}^{N_u}\left(x_j \operatorname{diag}\left(\tilde{\boldsymbol{h}}_j\right)\operatorname{diag}\left(\tilde{\boldsymbol{c}}_j\right)\right)+\operatorname{diag}\left(\tilde{\boldsymbol{n}}\right)\right)\end{aligned} \tag{3}$$

where $\operatorname{diag}(\boldsymbol{v})$ denotes a diagonal matrix whose main diagonal elements are the elements of vector $\boldsymbol{v}$, $\tilde{\boldsymbol{c}}_j$ is the L-point FFT of $\boldsymbol{c}_j$, $\tilde{\boldsymbol{n}}$ is the L-point FFT of the AWGN vector $\boldsymbol{n} = [n_1 \quad n_2 \quad \dots \quad n_L]^T$. Note $\tilde{\boldsymbol{c}}_j$ that can be written as $\tilde{\boldsymbol{c}}_j = \boldsymbol{\Psi}\boldsymbol{c}_j, j = 1, \dots, N_u$, where

$$\boldsymbol{\Psi} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & \exp\left(-j2\pi\frac{1}{L}\right) & \dots & \exp\left(-j2\pi(L-1)\frac{1}{L}\right) \\ \dots & \dots & \dots & \dots \\ 1 & \exp\left(-j2\pi\frac{L-1}{L}\right) & \dots & \exp\left(-j2\pi(L-1)\frac{L-1}{L}\right)\end{bmatrix} \tag{4}$$

and $\boldsymbol{c}_j$ is the product of spread code and a part of long scramble code.

After IFFT, the equalized time domain signal $\boldsymbol{y}$ is despread and descrambled with $\boldsymbol{c}_1^*$. So the estimated symbol $\hat{x}_1$

$$\hat{x}_1 = \frac{1}{L}\cdot \boldsymbol{y}\cdot \boldsymbol{c}_1^* = \boldsymbol{w}^H\boldsymbol{r} \tag{5}$$

where

$$\boldsymbol{r} = \frac{1}{L^2}\left(\sum_{j=1}^{N_u}\left(\operatorname{diag}\left(\tilde{\boldsymbol{h}}_j\right)x_j \operatorname{diag}\left(\tilde{\boldsymbol{c}}_j\right)\right)+\operatorname{diag}\left(\tilde{\boldsymbol{n}}\right)\right)\tilde{\boldsymbol{c}}_1^* \tag{6}$$

According to Wiener filtering, the equalization vector is given by

$$\boldsymbol{w} = \mathbf{R}_{r,r}^{-1}\mathbf{R}_{r,x_1} \tag{7}$$

where $\mathbf{R}_{r,r}$ and $\mathbf{R}_{r,x_1}$ denote the autocorrelation of $\boldsymbol{r}$ and the cross correlation of $\boldsymbol{r}$ and x_1, respectively

$$\begin{aligned}\mathbf{R}_{r,x_1} &= \mathrm{E}\left\{\boldsymbol{r}\cdot x_1^*\right\} \\ &= \frac{E_s}{L^2\left(L+L_p\right)}\operatorname{diag}\left(\tilde{\boldsymbol{h}}_1\right)\operatorname{diag}\left(\tilde{\boldsymbol{c}}_1\right)\tilde{\boldsymbol{c}}_1^*\end{aligned} \tag{8}$$

$$\begin{aligned}\mathbf{R}_{r,r} &= \mathrm{E}\left\{\boldsymbol{r}\boldsymbol{r}^H\right\} \\ &= \frac{1}{L^4}\left(\frac{E_s}{L+L_p}\sum_{j=1}^{N_u}\left(\boldsymbol{u}_j\boldsymbol{u}_j^{\,H}\right)+LN_0\mathrm{diag}\left(\tilde{\boldsymbol{c}}_1^*\right)\mathrm{diag}\left(\tilde{\boldsymbol{c}}_1\right)\right)\end{aligned} \tag{9}$$

where $\mathrm{E}\{\cdot\}$ stands for expectation, $\boldsymbol{u}_j = \mathrm{diag}\left(\tilde{\boldsymbol{h}}_j\right)\mathrm{diag}\left(\tilde{\boldsymbol{c}}_j\right)\tilde{\boldsymbol{c}}_1^*$. From (7) to (9), the PU-MMSE FDE coefficients can be shown by

$$\boldsymbol{w} = L^2\mathbf{R}^{-1}\boldsymbol{u}_1 \tag{10}$$

where

$$\mathbf{R} = \left(\sum_{j=1}^{N_u}\left(\boldsymbol{u}_j\boldsymbol{u}_j^{\,H}\right)+\frac{L\left(L+L_p\right)}{E_s/N_0}\mathrm{diag}\left(\tilde{\boldsymbol{c}}_1^*\right)\mathrm{diag}\left(\tilde{\boldsymbol{c}}_1\right)\right) \tag{11}$$

4. Simulation and Comparison

In our simulations, we consider a 16-path Rayleigh block fading channel with uniform power delay profile, and assume that the perfect channel state information in frequency domain can be estimated at the receiver. The number of FFT point is 64 ($L = 64$). Quaternary phase shift keying (QPSK) data modulation is used. 64-chip Walsh-Hadamard codes are chosen as the spreading codes and a long pseudo noise (PN) sequence is used as scramble code. For downlink, we assume that the channel is quasi-synchronous. So the length of CP is 16, which equal to the maximum channel delay. In the uplink simulation, it is assumed that all the user signals arrive quasi-asynchronously at the base station (BS), where the maximum delay between first and last paths of all users is not larger than the CP length. The CP length is 32 in the uplink simulation.

The Fig.3 shows the BER performance against the number of active users at 10dB E_b/N_0 for DS-CDMA with conventional PC-MMSE FDE and proposed PU-MMSE FDE in downlink and uplink. Except for fully loaded downlink system, it can be found that the PU-MMSE FDE achieves lower BER than the conventional PC-MMSE FDE for DS-CDMA. In full-load downlink DS-CDMA system (64 users), the matrix **R** in (11) is a diagonal matrix, which results in that the PU-MMSE equalizer coefficients (10) are equal to the PC-MMSE equalizer coefficients in (1). Thus, PU-MMSE has the same performance as PC-MMSE In full-load downlink DS-CDMA with FDE system. From Fig.3, it can be found that the performance improvement is more pronounced for uplink than downlink, because the time and phase asynchronism among the users leads to severe loss of orthogonality and multiple access interference (MAI), which is more detrimental to PC-MMSE FDE as it does not equalize all subcarriers jointly.

It is well known that SIC could be effective way to decrease MAI. The performance of SIC DS-CDMA with PU-MMSE FDE is shown in Fig.4 for downlink and Fig.5 for uplink. The SIC DS-CDMA with PU-MMSE FDE can achieve much better performance.

In Fig.6, we compare the BER performances of DS- and MC-CDMA with PU-MMSE FDE for different cases in downlink. Especially, the performances of uplink DS- and MC-CDMA with PU-MMSE FDE are shown in Fig.7. It can be found that the proposed PU-MMSE FDE for DS-CDMA has no performance loss comparing to MC-CDMA with PU-MMSE FDE both downlink and uplink. It is well known that DS-CDMA has much lower PAPR than MC-CDMA. Thus, DS-CDMA is more suitable for uplink wireless communication system.

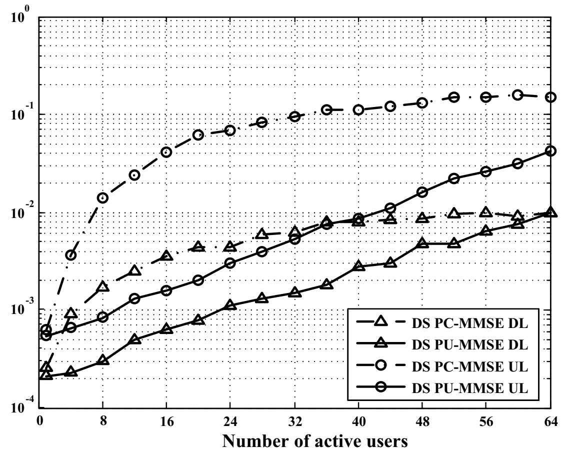

Figure 3. BER of DS-CDMA with PU- and PC-MMSE FDE vs. number of active users at E_b/N_0=10dB in downlink (DL) and uplink (UL)

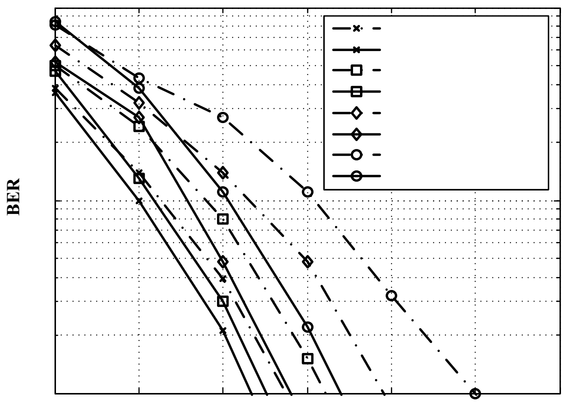

Figure 4. BER of SIC DS-CDMA with PU-MMSE FDE in downlink

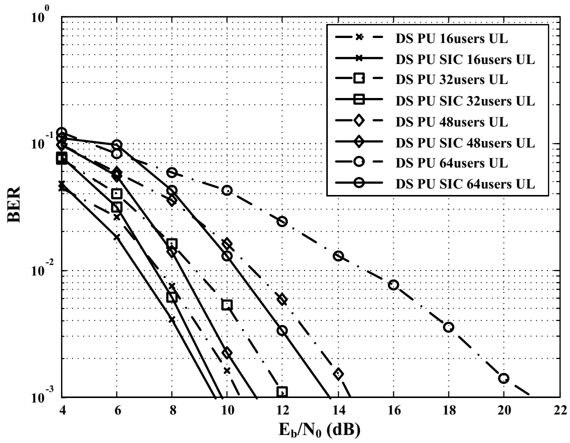

Figure 5. BER of SIC DS-CDMA with PU-MMSE FDE in uplink

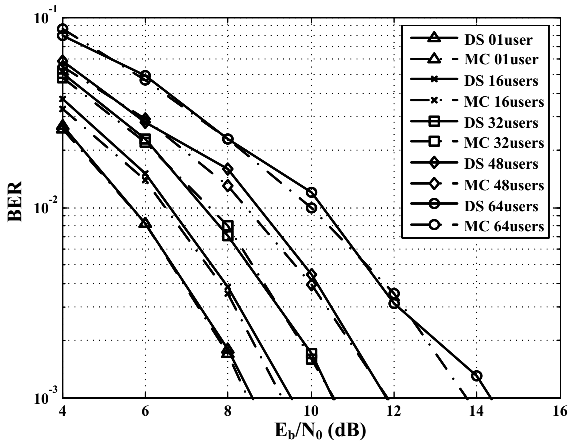

Figure 6. Comparison of DS- and MC-CDMA with PU-MMSE FDE in downlink

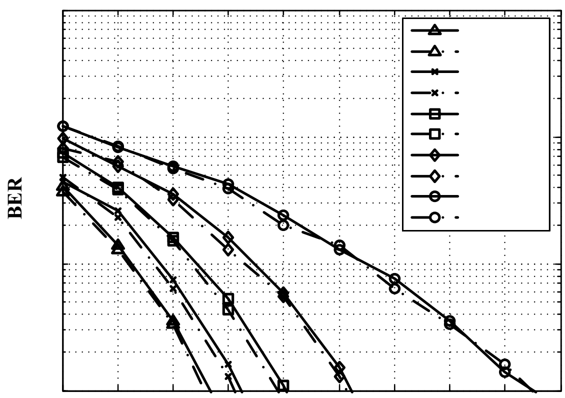

Figure 7. Comparison of DS- and MC-CDMA with PU-MMSE FDE in uplink

5. Conclusions

In this paper, a new linear PU-MMSE FDE detection scheme was proposed for DS-CDMA system. This scheme is based on the MMSE criterion applied per user and taking into account the time domain despreading at receiver, and evidently restores the orthogonality among the spreading sequences and reduces the interference among users, which are caused by multipath delay and asynchrony among users. By comprehensive computer simulation, it is shown that the proposed PU-MMSE method can provide a marked performance improvement than conventional PC-MMSE method for DS-CDMA with FDE in downlink and uplink. With applying SIC in proposed scheme, the better performance can be achieved. It is well known that PAPR reduction is an important problem for MC-CDMA but not for DS-CDMA. The comparison of DS- and MC-CDMA with PU-MMSE FDE shows that the PU-MMSE DS-CDMA with FDE has no performance loss than MC-CDMA with PU-MMSE FDE.

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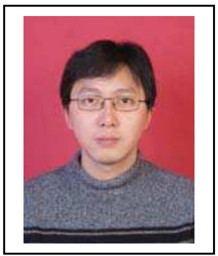

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