A Robust Adaptive MMSE Rake Receiver for DS-CDMA System in a Fast Multipath Fading Channel

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Abstract. *In this paper, we propose a robust adaptive minimum mean square error (MMSE) Rake receiver for asynchronous DS-CDMA systems. The receiver uses the modified MMSE criterion that incorporates the differential detection and the amplitude compensation for interference cancellation in a time-varying multipath fading channel. We investigate that the proposed Rake receiver can achieve the higher output signal to interference plus noise ratio (SINR) than the conventional adaptive Rake receiver, since the modified MMSE criterion does not attempt to track the time-varying MMSE solution. Computer simulations verify that the performance of the proposed Rake receiver is better than those of the conventional and the adaptive Rake receiver.*

Keywords

DS-CDMA, modified MMSE, time-varying multipath fading, Rake receiver.

1. Introduction

In direct sequence code division multiple access (DS-CDMA) communication systems, all transmissions occupy the same time and frequency, but they use distinct code sequences to allow signal separation at the receiver. The performance of a conventional receiver (i.e. matched filter) depends critically on the multiple access interference (MAI) and the near-far problem [1], [2]. Moreover, a multipath fading channel is encountered in most mobile wireless situations. Multipath fading not only increases the MAI by introducing extra interfering paths but also distorts the desired signal component. As the number of simultaneous users in the system becomes large, the performance of the conventional Rake receiver is degraded due to the detrimental effect of the MAI [3].

The minimum mean square error (MMSE) detection has attracted considerable attention because it can suppress the MAI, and needs only the spreading sequence and timing of the desired signal [4]. An alternative solution to suppress the MAI without the aid of any training sequence is the blind minimum output energy (MOE) detection [5]. To overcome the MAI and the near-far problem, some adaptive interference cancellation Rake receivers have been proposed [6]–[8]. A linear MMSE receiver was applied to each resolvable path to remove the interferences [6]. A modified version of a blind adaptive multiuser detector was proposed in [7] to avoid deep fading impairments and the distortion of the desired signal due to signature sequence mismatch. In [8], a linearly constrained minimum variance Rake receiver was proposed to enhance the decorrelating Rake receiver which used the assumption of a quasi-synchronous channel. Most of evaluations of these receivers have been performed under assumption of perfect channel estimation. This is not valid in practice. A time-varying fading significantly degrades the performance of these receivers due to less reliable channel estimation [9].

A differential detection, which can be used for demodulation if the fading channel is difficult to estimate, was analyzed in time-varying multipath fading channels [10]. This analysis has not considered in the context of suppressing the MAI and the inter-symbol interference (ISI) arising from the existence of different transmission paths. In [11], an adaptive interference canceller (AIC) on differential detection was proposed for removing the fast phase variation. A modified adaptive MMSE receiver was proposed [12] to achieve the performance improvement of MAI cancellation for a fast flat fading channel. However, the adaptive interference cancellation characteristics in time-varying multipath fading channels need to be considered, because time-varying fading causes significant performance degradation when the adaptive algorithms are applied.

In this paper, we propose a robust adaptive MMSE Rake receiver for a time-varying multipath fading channel. Specifically this receiver provides immunity to the near-far problem as well. We investigate that the proposed scheme can improve the BER performance and robustness, resulting in the improved performance in a time-varying multipath fading channel.

The rest of this paper is organized as follows. In Section 2, the DS-CDMA system model in a time-varying multipath fading channel is described. The robust adaptive Rake receiver is introduced in Section 3, and the BER performance and the output signal to interference plus noise ratio (SINR) of the proposed scheme are compared to those of the conventional and the adaptive interference canceller on differential detection Rake one based on simulation results in Section 4. Finally, conclusions are made in Section 5.

We define notations as follows: matrices are denoted by boldface upper case letters and vectors are denoted by boldface lower case letters; superscripts $(.)^T$ and $(.)^H$ denote the transpose and Hermitian transpose, respectively; $E\{.\}$ denotes the statistical expectation; finally, $\|.\|$ denotes the Euclidian norm.

2. System Description

This paper deals with a single user detection scheme in multipath fading channels. We consider a base-band asynchronous K-user DS-CDMA system using differential phase shift keying (DPSK) modulation. The transmitted signal for the k-th user is represented as

$$s_k(t) = \sum_i \sqrt{P_k}\, d_k(i) c_k(t - iT) \tag{1}$$

where $d_k(i) \in \{+1,-1\}$ is the i-th differentially encoded symbol, $c_k(t)$ is the spreading sequence, P_k represents the signal power and T is the symbol period. The spreading sequence is defined as

$$c_k(t) = \sum\nolimits_{n=1}^{N} c_{k,n} p(t-(n-1)T_c) \tag{2}$$

where T_c is the chip period, $T/T_c=N$ is the length of the spreading sequence, and $p(t)$ is the chip waveform. Each user's transmitted signal is assumed to pass through a time-varying multipath Rayleigh fading channel [3] whose impulse response is modeled as

$$h_k(t) = \sum_{l=1}^{L_k} a_{k,l}(t) e^{j\varphi_{k,l}(t)} \delta(t - \tau_{k,l}) \tag{3}$$

where $a_{k,l}(t)$, $\varphi_{k,l}(t)$ and $\tau_{k,l}$, respectively, denote the path amplitude with $\sum\nolimits_{l=1}^{L_k} E\{|a_{k,l}(t)|^2\}=1$, the phase shift and the propagation delay of the l-th path for the k-th user, $\delta(t)$ denotes the Dirac delta function, and L_k denotes the total number of paths of the k-th user.

The received signal can be written as

$$r(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \sqrt{P_k}\, a_{k,l}(t) e^{j\varphi_{k,l}(t)} s_k(t-\tau_{k,l}) + n(t) \tag{4}$$

where $n(t)$ is a complex zero-mean additive white Gaussian noise (AWGN) with a two-sided noise power spectral density of $N_0/2$ at the receiver input.

In the remainder of this paper, it is assumed that the desired user is user 1, the power of desired user is $P_1=1$, $L_k=L$ for all k, and the l-th detector is synchronized to the l-th path. The complex base-band signal (4) is sampled at the chip rate after conventional chip-matched filtering. Similar to previous studies [6]-[8], we define $\tau_{1,l}$ as a multiple of the chip interval T_c, and $T_c \le \tau_{1,2} < \ldots < \tau_{1,L} < T$ is assumed. The received signal vector for the l-th detector is given by

$$\begin{aligned} \mathbf{r}_l(i) = {} & \sqrt{P_1}\, a_{1,l}(i) e^{j\varphi_{1,l}(i)} d_1(i) \mathbf{c}_1 \\ & + \sum_{j=1, l \neq j}^{L} \sqrt{P_1}\, a_{1,j}(i) e^{j\varphi_{1,j}(i)} d_1(i) \tilde{\mathbf{c}}_{1,j} \\ & + \sum_{k=2}^{K} \sum_{l=1}^{L} \sqrt{P_k}\, a_{k,l}(i) e^{j\varphi_{k,l}(i)} d_k(i) \tilde{\mathbf{c}}_{k,l} \\ & + \mathbf{n}_l(i) \end{aligned} \tag{5}$$

where $\mathbf{c}_k=(c_{k,1},c_{k,2},\ldots,c_{k,N})^T$ is the spreading vector of the k-th user and $\tilde{\mathbf{c}}_{k,l}$ is the effective spreading waveform for the l-th path of the k-th user [12] (see also Fig.1).

The received signal of the k-th user in a multipath fading channel is shown in Fig. 1. Due to asynchronous transmissions, two adjacent symbols in each path contribute to $\mathbf{r}_l(i)$.

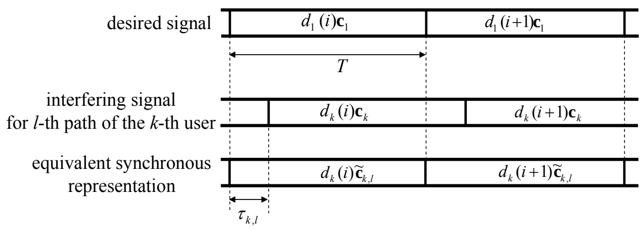

Fig. 1. Relationship between the desired signal and the interfering signal for detecting the l-th path signal.

3. A Robust Adaptive MMSE Detector

We develop a robust adaptive Rake receiver that incorporates the differential detection and the amplitude compensation to achieve the output SINR improvement and robustness in a time-varying multipath fading channel. The block diagram of the proposed receiver is shown in Fig. 2. Considering a structure using individual L-detectors and a Rake combiner, each received signal vector (5) is fed to the adaptive interference cancellation filter. The l-th filter output of the k-th user at the i-th bit can be written as

$$z_l(i) = \mathbf{x}_l^H(i)\mathbf{r}_l(i) \qquad \text{subject to} \quad \mathbf{x}_l^H(i)\mathbf{c}_1 = 1 \tag{6}$$

where $\mathbf{x}_l(i)$ is a vector of the weight coefficient of the adaptive filter. Let us define a demodulated symbol as $b_1(i)=d_1(i)d_1(i-1)$. Thus, the decision variable for detecting the i-th bit of the desired user can be expressed by

$$y(i) = \sum_{l=1}^{L} g_l \left(\mathbf{x}_l^H(i)\mathbf{r}_l(i)\right)\left(\mathbf{r}_l^H(i-1)\mathbf{x}_l(i-1)\right) \tag{7}$$

where g_l a positive combining gain, and the bit estimate is made $b_1(i)=sgn\{Re[y(i)]\}$. If the weight vector equals to the spreading code of the desired user, that is, $\mathbf{x}_l(i)=\mathbf{c}_1$ for all l and i, it is obvious that the receiver is equivalent to a conventional Rake receiver [10].

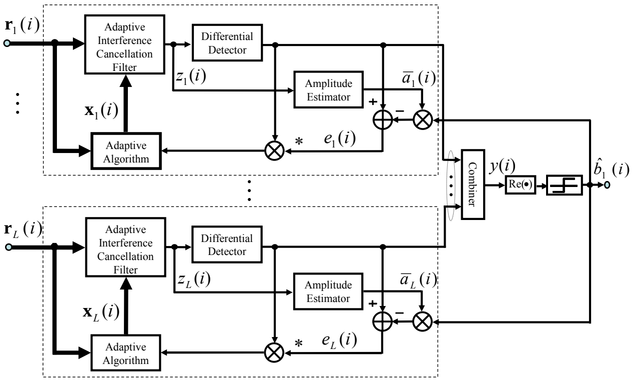

Fig. 2. Block diagram of the proposed receiver.

3.1 Adaptive Implementation

Assuming that the sequence $b_1(i)=d_1(i)d_1(i-1)$ is known in a training mode and can be estimated in a decision-directed mode. The error signal $e_l(i)$ is defined as the difference between the adaptive interference cancellation filter output and the amplitude compensated desired signal for the l-th path, that is

$$e_l(i) = z_l(i)\frac{z_l^*(i-1)}{|z_l(i-1)|} - \bar{a}_l(i)b_1(i) \tag{8}$$

where $\bar{a}_l(i)$ is an amplitude estimate for the i-th bit of the l-th path. In order to estimate the amplitude variation, we use the moving average for past Q bits, it can be readily computed as

$$\bar{a}_l(i) = \frac{1}{Q}\sum_{q=0}^{Q-1}|z_l(i-q)| \tag{9}$$

where the optimal length of Q will be evaluated in Section 4. The modified MMSE criterion incorporated with the amplitude compensation is given by

$$\begin{aligned} J_l(i) &= E\left\{|e_l(i)|^2\right\} \\ &= E\left\{e_l^*(i)e_l(i)\right\} \\ &= E\left\{e_l^*(i)\left(z_l(i)\frac{z_l^*(i-1)}{|z_l(i-1)|} - \bar{a}_l(i)b_1(i)\right)\right\} \\ &= E\left\{e_l^*(i)\left(\mathbf{x}_l^H(i)\mathbf{r}_l(i)\frac{\mathbf{r}_l^H(i-1)\mathbf{x}_l(i-1)}{|\mathbf{x}_l^H(i-1)\mathbf{r}_l(i-1)|}\right.\right. \\ &\qquad \left.\left. - \bar{a}_l(i)b_1(i)\right)\right\} \end{aligned} \tag{10}$$

To minimize $J_l(i)$ with respect to $\mathbf{x}_l(i)$, we set the derivate equal to the null:

$$\frac{\partial J_l(i)}{\partial \mathbf{x}_l^*(i)} = e_l^*(i)\mathbf{r}_l(i)\frac{\mathbf{r}_l^H(i-1)\mathbf{x}_l(i-1)}{|\mathbf{x}_l^H(i-1)\mathbf{r}_l(i-1)|} = \mathbf{0}. \tag{11}$$

Thus, this results in the update equation for the normalized least mean square (NLMS) algorithm given by

$$\mathbf{x}_l(i+1) = \mathbf{x}_l(i) + \mu(i)\mathbf{r}_l(i)\frac{z_l^*(i-1)}{|z_l(i-1)|}e_l^*(i) \tag{12}$$

where $\mu(i)$ is the time-variant step size parameter which is approximated as $\mu(i) = \tilde{\mu} / \|\mathbf{r}_l(i)\|^2;\ 0 < \tilde{\mu} < 2$ [14].

3.2 Multipath Combining

In our analysis, the fading processes among the L-diversity channels are assumed to be mutually statistically independent [3]. Thus, it can be shown that the output signal of the interference cancellation for the l-th path may be decomposed into

$$z_l(i) = a_l(i)e^{j\varphi_l(i)}d_1(i) + m_l(i),\ l = 1,\cdots,L \tag{13}$$

where $m_l(i)$ consists of noise and residual interferences (MAI and ISI), $a_l(i)$ and $\varphi_l(i)$ are the channel amplitude and phase variation for the i-th bit of the l-th path, respectively.

In order to understand that the performance improvement of the proposed scheme can be achieved as a result of the convergence of the modified MMSE, we make following assumptions:

$$a_l(i) \approx a_l(i-1) \text{ and } \varphi_l(i) \approx \varphi_l(i-1). \tag{14}$$

It is shown that the differentially detected signal for the l-th path satisfies

$$\begin{aligned} z_l(i)z_l^*(i-1) &= a_l(i)a_l(i-1)e^{j(\varphi_l(i)-\varphi_l(i-1))} \\ &\quad \times d_1(i)d_1^*(i-1) + m_l'(i) \\ &\approx |a_l(i)|^2 b_1(i) + m_l'(i) \end{aligned} \tag{15}$$

where

$$\begin{aligned} m_l'(i) &= m_l(i)a_l(i-1)e^{-j\varphi_l(i-1)}d_1^*(i-1) \\ &\quad + m_l^*(i-1)a_l(i)e^{j\varphi_l(i)}d_1(i) \\ &\quad + m_l(i)m_l^*(i-1) \end{aligned}. \tag{16}$$

We may define the output SINR as the ratio of the desired signal power to the power of interferences and noise for Eq. (15) under the above assumptions. This leads to

$$SINR = \frac{E\left\{\left|\sum_{l=1}^{L}|a_l(i)|^2 b_1(i)\right|^2\right\}}{E\left\{\sum_{l=1}^{L}|m_l'(i)|^2\right\}}. \tag{17}$$

From Eq. (8), the error signal for the l-th path can be expressed as

$$\begin{aligned} e_l(i) &= a_l(i)b_1(i) + residual\ ISI,\ MAI\ and\ noise \\ &\quad - \bar{a}_l(i)b_1(i) \\ &\approx residual\ ISI,\ MAI\ and\ noise \end{aligned} \tag{18}$$

where the adaptive filter does not attempt to track the channel amplitude when the channel amplitude is perfectly compensated $a_l(i) = \bar{a}_l(i)$. However, the error signal without amplitude compensation results in the higher mean square error (MSE), because the adaptive filter attempts not only to cancel the residual interferences but also to track the channel amplitude variation $a_l(i)$.

It is clear from (17) that if we can use the above assumptions (14) and there are no interferences (ISI and MAI) then the maximum SINR can be achieved, but the residual interference in practice is not negligible then we define the proposed scheme as the near-optimal combining. However, this scheme can achieve significant performance improvement over the AIC Rake receiver (without the amplitude compensation).

In slow fading channels, it is assumed that the fading variations for all users are maintained constant over many bit durations so that the adaptive filter can easily track their parameters. However, in fast fading channels, the fading fluctuations for all users change so rapidly that the adaptive filter can only track the mean values of the fading fluctuations [1]. Because the adaptive algorithm attempts to track the fading fluctuations, the AIC Rake receiver results in the degradation of the diversity combining gain. We will show this degradation under single-user environment (K=1) in Section 4.

4. Simulation Results

Computer simulations were carried out to evaluate the SINR and BER performance of the Rake receivers in a time-varying multipath fading channel. Uniform and exponential distributions of the delay power profiles are considered [9]. The normalized maximum Doppler frequency is $f_{max}T$=0.01. We consider near-far environments without power control. The near-far ratio is defined as NFR_k=P_k/P_1. More detailed parameters used in these simulations are shown in Tab. 1.

Modulation system	**DPSK DS-SS**
Detection method	**Differential detection**
Spreading sequence	**Gold codes (N=31)**
Bit timing	**Asynchronous**
Transmission channel	**2, 4-path Rayleigh fading channel**
Power delay profile	**Uniform, exponential delay profile**

Tab. 1. Simulation parameters.

In the following simulations, we compare the BER performance of the proposed Rake receiver with those of the conventional Rake [10] and the differential adaptive interference cancellation Rake receiver (AIC Rake) [11], which is similar to the proposed scheme without the amplitude compensation.

After 2000 iterations, the adaptive filters reached the steady state, and the gap between the maximum achievable SINR of the proposed and that of the AIC Rake was maintained in the range of convergence. Thus, both adaptive Rake receivers used the same step size $\tilde{\mu}=0.05$ and 2000 training bits. The combining gains, g_1=…=g_L were assumed for simplicity.

From Fig. 3, it can be seen that a minimum BER performance is achieved for $f_{max}T$=0.01 when the window length equals to 3. In the following simulations, we use Q=3 with respect to $f_{max}T$=0.01 for channel estimation in the proposed scheme.

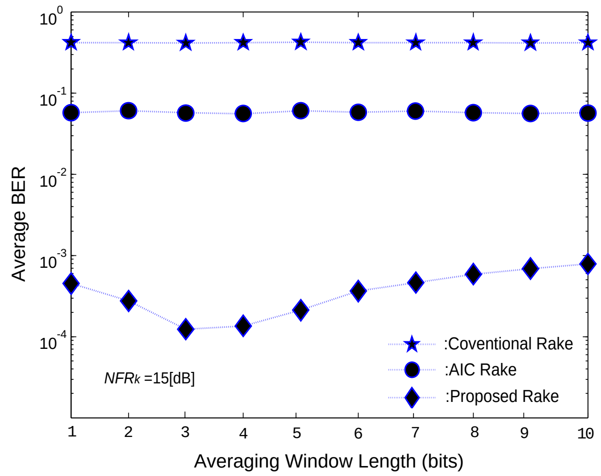

Fig. 3. Average BER performance as a function of window length (Q) with K=5, L=2 (uniform delay profile) and $f_{max}T$=0.01.

Fig. 4 plots the average BER performances of the receivers as a function of the average E_b/N_0 with K=1 and L=4 (exponential delay profile). This figure shows that multipath diversity can offer significant improvement in the performance. The results indicate that for multipath diversity, the proposed Rake receiver performs almost as well as the conventional Rake receiver which is the optimal combining when the interference is negligible. However, the AIC Rake receiver degrades as the E_b/N_0 is increased compared with the other receivers. This is because the adaptive algorithm fails to track each fading fluctuation, resulting in multipath combining with degraded gain.

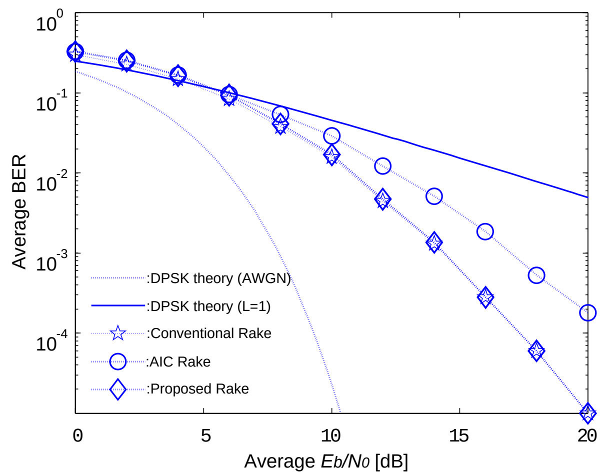

Fig. 4. Average BER performance as a function of the average E_b/N_0 with K=1, L=4 (exponential delay profile) and $f_{max}T$=0.01.

Fig. 5 and 6 plot the achievable SINR averaged over 100 independent runs in 2-path Rayleigh fading channels for uniform delay profile NFR_k=10 and 15[dB], respectively. It can be observed that the AIC Rake receiver cannot sufficiently suppress the strong MAI caused by the near far problem. Whereas the proposed Rake receiver can effectively suppress the strong MAI in a time-varying multipath fading channel.

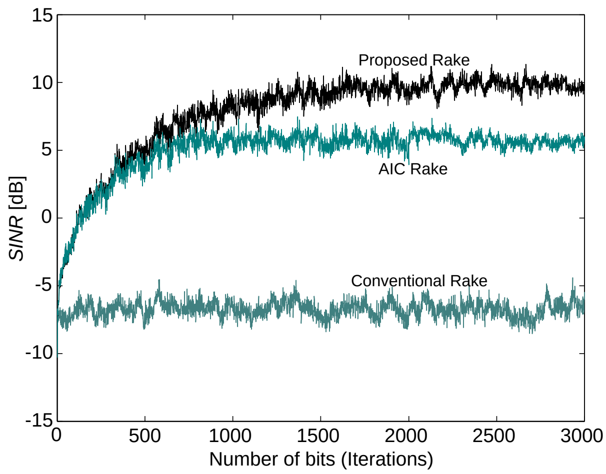

Fig. 5. Comparison of the achievable *SINR* for the proposed adaptive Rake receiver and the adaptive interference cancellation Rake receiver (NFR_k=10[dB], E_b/N_0=30[dB], K=5 and $f_{max}T$=0.01) .

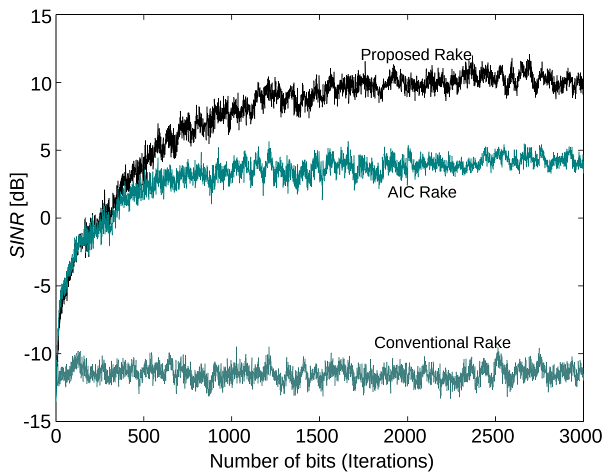

Fig. 6. Comparison of the achievable *SINR* for the proposed adaptive Rake receiver and the adaptive interference cancellation Rake receiver (NFR_k=15[dB], E_b/N_0=30[dB], K=5 and $f_{max}T$=0.01) .

We plot the average BER performances of the receivers as a function of the average E_b/N_0 with K=5, L=2 (uniform delay profile), and $f_{max}T$=0.01 in Fig. 7. Both adaptive receivers offer significantly better performance than that of the conventional one. Further, the performance of the proposed Rake receiver is much better than that of the AIC Rake receiver in both NFR_k=10 and 15 [dB]. The results indicate that the proposed scheme provides near far immunity even in multipath conditions and that it performs better than the one proposed in [10].

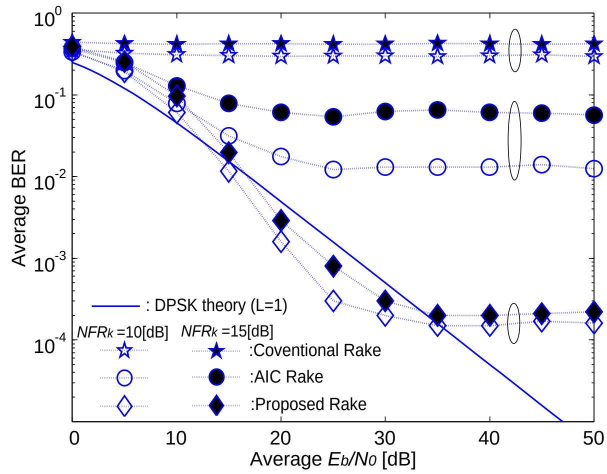

Fig. 7. Average BER performance as a function of the average E_b/N_0 with K=5, L=2 (uniform delay profile) and $f_{max}T$=0.01.

The average BER performance as a function of the average E_b/N_0 for the receivers in 4-path Rayleigh fading channels for the exponential delay profile with K=5 and $f_{max}T$=0.01 is presented in Fig. 8. From these results, it is found that the proposed Rake receiver can effectively remove the interferences (ISI and MAI) in a time-varying multipath fading channel.

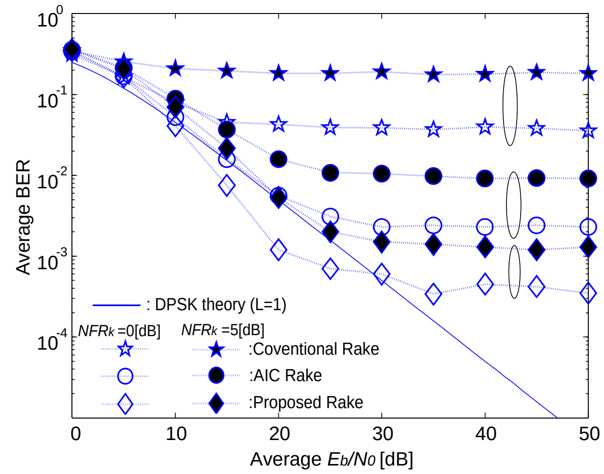

Fig. 8. Average BER performance as a function of the average E_b/N_0 with K=5, L=4 (exponential delay profile) and $f_{max}T$=0.01.

5. Conclusions

In this paper, we have proposed the robust adaptive MMSE Rake receiver for asynchronous DS-CDMA systems to improve the BER degradation caused by the presence of the ISI and the MAI in time-varying multipath fading channels. We have shown that the proposed receiver can achieve the performance improvement and robustness, since the modified MMSE criterion does not attempt to track the fading fluctuations. A comparison with the performance of the AIC Rake receiver and that of the proposed receiver indicates that the proposed receiver provides the better BER performance and the higher maximum achievable SINR. Specifically it provides immunity to the near-far problem as well.

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