Adaptive Step Size RAKE Receiver for DS/CDMA Communications Over a Rayleigh Fading Channel

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Abstract: Despite its simplicity, the stochastic gradient method used by the majority of adaptive algorithms, e.g. the LMS algorithm, has a slow convergence speed, thus limiting its use in mobile applications operating in a time-varying channel. A blind adaptive step size algorithm has been proposed in [3] in order to enhance the convergence speed of a stochastic gradient based adaptive algorithm in an AWGN channel. In this paper, the blind adaptive step size algorithm is incorporated into a RAKE receiver in order to harness the energies of the multipath signals in a fading channel. The performance of the proposed multipath combiner with respect to detector complexity in terms of the number of fingers involved in the detection process is investigated. Simulation results show that the proposed RAKE receiver with reduced number of fingers achieves improved frame error rate over the standard RAKE receiver whose fingers consist of the classical match filters.

1. Introduction

Although centralised multiuser detectors (MUDs) [1] alleviate the MAI limitation and near-far problem of the classical match filter (CMF), the improvement in performance is achieved at the expense of high detector complexity. In addition, most MUDs require side information such as code sequences and timing of users and channel parameters, in order to be functional. The need for side information makes this kind of detection scheme impractical for cellular mobile applications in a fast-varying multipath channel. Moreover, the MUD is susceptible to interference from unknown users as in the case of intercell interference. In contrast, low detector complexity and the ability of a blind adaptive single user detector (SUD) to adjust its detector coefficients in response to changes in the received signal make it an attractive alternative to the highly complex MUD for DS/CDMA communications. For simplicity, most of the adaptive SUDs employ stochastic gradient techniques in order to achieve convergence. It is well known that adaptive algorithms based on this technique, e.g. the LMS algorithm, are subject to the tradeoff between convergence speed and adaptation noise. In particular, the convergence of the LMS algorithm struggles in a fading channel due to the need to frequently update the rapidly changing channel parameters. In view of this, a stochastic gradient technique based blind adaptive algorithm with adjustable step size has been proposed in order to enhance the convergence speed. In an environment where the signal parameters do not change rapidly, the proposed algorithm achieves an accelerated convergence and small misadjustment. In an environment where the signal parameters change rapidly, the proposed algorithm offers a fast tracking capability. The algorithm is blind in the sense that only information of the desired user is required. The beneficial properties of the adaptive step size algorithm, termed Gradient Adaptive Step Size Constant Modulus Algorithm (GASCMA), in an AWGN channel have been demonstrated in [2]. In this paper, the performance of the adaptive step size algorithm in a multipath fading channel is investigated by incorporating the GASCMA into a RAKE receiver in order to effect diversity combining. Of particular interest is the performance of the RAKE with respect to the its complexity in terms of the number of fingers involved in the detection process. The performance of the standard RAKE receiver whose fingers consist of the CMF will also be included as a benchmark. The layout of the rest of the paper is as follows. The multipath channel model, signal representations and notations are explained in Section 2. The proposed multipath combiner is presented in Section 3 and its Frame Error Rate (FER) performance in a fading channel are given in Section 4. Finally, concluding remarks and recommendations for future work are discussed in Section 5.

2. Channel Model and Signal Representation

In a K-user DS/CDMA system where each user transmits baseband signals in an AWGN channel, the received signal is given by,

$$r(t) = \sum_{k=1}^{K} A_k b_k(t - t_k) a_k(t - t_k) + w(t) \quad (1)$$

where A_k is user amplitude, $b_k(t)$ is an unit amplitude bipolar square pulse of period T_b; $a_k(t)$ is an unit amplitude bipolar spreading code of N chips each of duration T_c where $N = T_b / T_c$, t_k is the user delay and $w(t)$ is AWGN of variance s_w^2. The subscript 'k' in the equation denotes the k-th user in the system. Without loss of generality, the first user is considered to be the desired user and all the $b_k(t)$, $k = 1,2,3,\ldots,K$ are assumed to be independent and identically distributed (i.i.d) random variables. Assuming that the timing of the desired user is known, a one-shot detection where the detection interval is equal to the code sequence period, is considered. Employing one-shot detection allows the chip sampled received signal to be represented by N-by-1 column vectors, given by,

$$\boldsymbol{r}(m)=\sum_{k=1}^{K} A_k b_k(m-t_k)\boldsymbol{a}_k(m-t_k)+\boldsymbol{w}(m) \qquad (2)$$

where $\boldsymbol{r}(m)$, $\boldsymbol{a}_k(m)$ and $\boldsymbol{w}(m)$ are the received signal, code sequence and noise vectors at discrete time m, respectively, and t_k is assumed to be a multiple integer of T_c (mod T_b). In this paper, the convention where bold lower case denotes vector quantity and bold upper case denotes matrix quantity is adopted. In an asynchronous system where the detection interval overlaps two consecutive data bits of the interfering users with arbitrary delays, the received signal may equivalently be represented by the sum of $2K$ 'effective' users given by,

$$\boldsymbol{r}(m)=\sum_{k=1}^{K} A_k\{b_k(0)\boldsymbol{a}_k'+b_k(-1)\boldsymbol{a}_k''\}+\boldsymbol{w}(m) \qquad (3)$$

where $b_k(0)$, $b_k(-1)$ are the k-th user's current and previous data bits, respectively. The corresponding N-by-1 'effective' code sequences are given by,

$$\begin{aligned}\boldsymbol{a}_k' &= [0,\ldots,0,a_k(1),a_k(2),\ldots,a_k(N-t_k)]^{\mathrm{T}}\\ \boldsymbol{a}_k'' &= [a_k(N-t_k+1),a_k(N-t_k+2),a_k(N),0,\ldots,0]^{\mathrm{T}}\end{aligned} \qquad (4)$$

where $a_k(n)$ denotes the n-th element of $\boldsymbol{a}_k$ and superscript 'T' denotes vector transposition. As the desired user is synchronised, $\boldsymbol{a}_1'=\boldsymbol{a}_1''=\boldsymbol{a}_1$ and $b_1(-1)=0$. In a multipath fading channel where the transmitted signal propagates via L paths of independent attenuation factors and time delays, the complex lowpass equivalent signal when bipolar phase shift keying (BPSK) modulation is used, is given by,

$$\boldsymbol{r}(m)=\sum_{k=1}^{K}\sum_{l=1}^{L} a_{kl}(m)\exp\{-jq_{kl}\}A_k b_k(m-t_{kl})\boldsymbol{a}_k(m-t_{kl})\exp\{jq_k(m-t_{kl})\}+\boldsymbol{w}(m) \qquad (5)$$

where a_{kl} is the Rayleigh distributed attenuation factor of the l-th path of the k-th user, q_{kl} and t_{kl} are the corresponding phase $(0<q_{kl}<2p)$ and delay, respectively, and f_k is the user phase of the BPSK scheme. Likewise, the multipath signals within the detection interval may be expressed in terms of the sum of 'effective' users as given by,

$$\boldsymbol{r}(m)=\sum_{k=1}^{K}\sum_{l=1}^{L} A_k\{g_{kl}(0)b_k(0)\boldsymbol{a}_{kl}'+g_{kl}(-1)b_k(-1)\boldsymbol{a}_{kl}''\}\exp\{jf_k\}+\boldsymbol{w}(m) \qquad (6)$$

where $g_{kl}(m)=a_{kl}(m)\exp\{-jq_{kl}\}$, and $\boldsymbol{a}_{kl}'$ and $\boldsymbol{a}_{kl}''$ are as shown in equation (4). Letting $\boldsymbol{h}_1(m)$ denote the detector coefficient vector, then the detector output, $z_1(m)$, is the inner product between the detector coefficients and the received signal given by,

$$z_1(m)=\boldsymbol{h}_1^{\mathrm{T}}(m)\boldsymbol{r}(m) \qquad (7)$$

3. Adaptive Step Size RAKE Receiver

The diagram of the proposed RAKE receiver is presented in Figure 1. As shown in the figure, the RAKE receiver consists of L fingers, each of which is an independent GASCMA detecting one of the desired multipath signals. The tap spacing between the fingers depends on the timing of the multipath signals. Without loss of generality, it is assumed that the desired user's path delays are in ascending order where $t_{11}<t_{12}<\cdots<t_{1L}$. Neglecting the propagation delay between the transmitter and the receiver, the timing of the first arriving desired signal is taken as the time reference with zero delay, i.e. $t_{11}=0$ and the timing of the l-th path is given by its delay, t_{1l}.

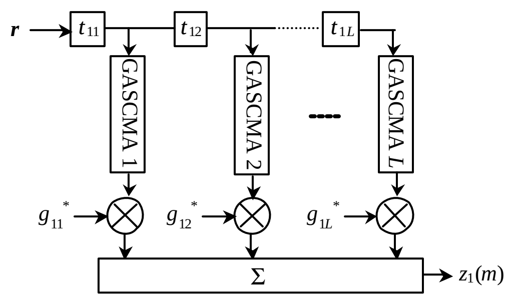

Figure 1 Incorporating GASCMA into the RAKE receiver.

The detection interval of each finger is equal to the code sequence period such that the observed signal vector of the l-th finger is given by $\boldsymbol{r}_l(m)=[r(1+t_{1l}),\ldots,r(N+t_{1l})]$. Assuming that the channel variation is sufficiently slow and that all the users have unit amplitude, the constant modulus being tracked by the algorithm is the fading envelope of the desired user. The update equations of the step size and the detector coefficients of the l-th finger are then given by,

$$m_l(m) = bm_l(m-1) + h\left\{\left|a_{1l}\right|^2 - z_l^2(m)\right\}\left\{\left|a_{1l}\right|^2 - z_l^2(m-1)\right\} z_l(m) z_l(m-1) \boldsymbol{r}_l^{\mathrm{T}}(m-1)\boldsymbol{r}_l(m) \quad (8)$$

$$\boldsymbol{h}_l(m+1) = \boldsymbol{h}_l(m) + m_l(m)\left\{\left|a_{1l}\right|^2 - z_l^2(m)\right\} z_l(m)\boldsymbol{r}_l(m) \quad (9)$$

where $z_l(m)$ denotes the output of the l-th finger [3]. Apart from including the fading envelope in the update equations of $m_l(m)$ and $\boldsymbol{h}_l(m)$, the operation of the GASCMA in each finger is the same as that in [2]. The output of the RAKE receiver when a maximal ratio combining (MRC) scheme is employed, is given by equation (10) where $g_{1l}^*(m)$ denotes the complex conjugate of $g_{1l}(m)$.

$$z(m) = \sum_{l=1}^{L} g_{1l}^*(m) z_l(m) \quad (10)$$

4. Simulation Results

The performance of the RAKE incorporating GASCMA based on a WCDMA signalling format [4] in two channels of contrasting delay spreads and path average power has been presented in [5]. In this paper, the relationship between the complexities of the RAKE and its FER performance is investigated. The complexity of the RAKE receiver is reduced by removing first the finger that corresponds to the weakest path. This is then followed by the finger for the next weakest path and so on. Since the detector complexity is in terms of the number of RAKE fingers, investigations were focused on the channel which offers more path diversity. The channel's delay spread and average power are tabulated in Table 1. For the given channel profile and code chip rate, there are five resolvable paths in the channel. It is assumed that the channel parameters are changed at every frame, but remain unchanged within the frame duration. As the investigations aim at evaluating the blind detection of the GASCMA, the pilot signals in the frames are discarded, i.e. the proposed multipath combiner is not allowed to converge before the FER is computed. Hence, the investigations represent a worst case performance scenario. It is assumed that the detectors have perfect knowledge of the path attenuation factor and delay of the desired user. In addition, forward error correction (FEC) using Viterbi decoding is implemented in order to improve the detectors' performance for a given E_b/N_o value. The system and FEC parameters are :

System parameters :
Frame duration = 10ms.
Spreading bandwidth ≈ 5MHz;
Nominal code chip rate = 4.096 × 10^6 chips/second;

FEC parameters :
Code rate = ½;
Constraint length = 9;
Generator polynomial = [753, 561].

Tap	1	2	3	4	5	6
Rel. Delay (nSec)	0	200	800	1200	2300	3700
Avg. Power (dB)	0	-0.9	-4.9	-8.0	-7.8	-23.9

Table 1 Path average power and relative delay of the Rayleigh fading channel.

The FER performance as a function of E_b/N_o in an asynchronous system for the standard RAKE and the RAKE receiver incorporating GASCMA is presented in Figures 2 and 3, respectively. The spreading sequences used were Orthogonal Gold codes of length N = 32 and the spectral efficiency was kept at 25%. Two cases of reduced complexity configurations were investigated, i.e. 4 and 3 fingers. In addition, the performance of the receivers detecting all the multipath signals, i.e. 5 fingers, is also included for comparison. In general, both detectors show little difference in performance when the number of fingers is reduced from 5 to 4. However, the GASCMA RAKE exhibits significant performance loss if the number of fingers is further reduced to 3. Nevertheless, the GASCMA RAKE at its worst configuration, i.e. 3 fingers still outperforms the standard RAKE in all the complexity configurations. The complexity of the GASCMA RAKE can therefore be reduced at the cost of decreased performance gain over the standard RAKE receiver.

The FER results of the standard RAKE and the GASCMA RAKE for Orthogonal Gold codes of length 64 are presented in Figures 4 and 5, respectively. As in the previous case, the spectral efficiency was maintained at 25%. Again, both detectors are insensitive to the removal of the finger for the weakest path. However, degradation in performance become noticeable in both detectors, particularly the GASCMA RAKE, when the detector complexity is reduced to 3 fingers. Nevertheless, the GASCMA RAKE still outperforms the best performance of the standard RAKE in all the complexity configurations investigated. At the best FER performance of the standard RAKE receiver, i.e. 3%, the GASCMA RAKE offers power gain of almost 5dB for the 3 fingers configuration and around 7.5dB for both 4 and 5 finger configurations.

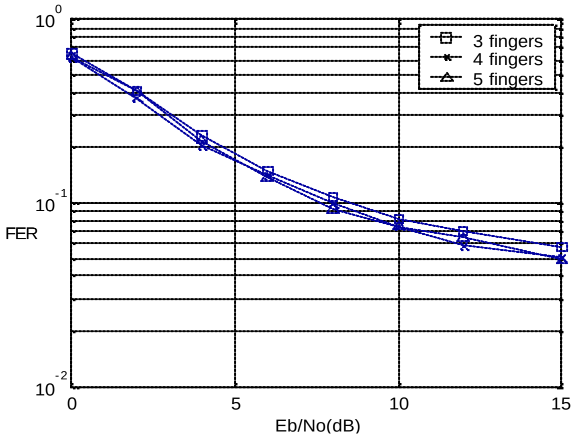

Figure 2 FER vs. E_b/N_o with detector complexity as parameters for RAKE (CMF).

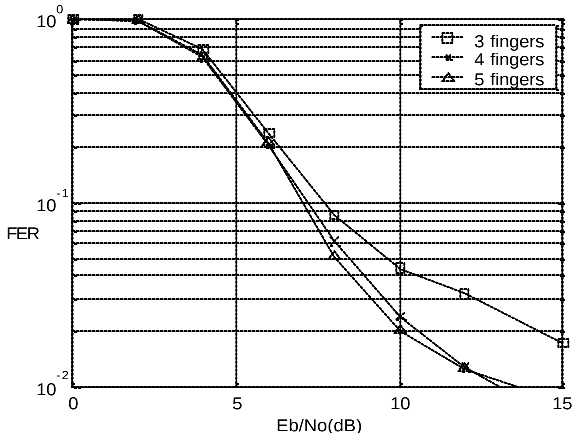

Figure 3 FER vs. E_b/N_o with detector complexity as parameter for RAKE (GASCMA).

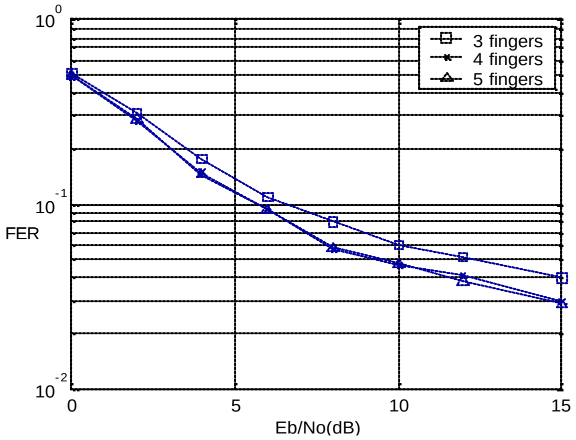

Figure 4 FER vs. E_b/N_o with detector complexity as parameter for RAKE (CMF).

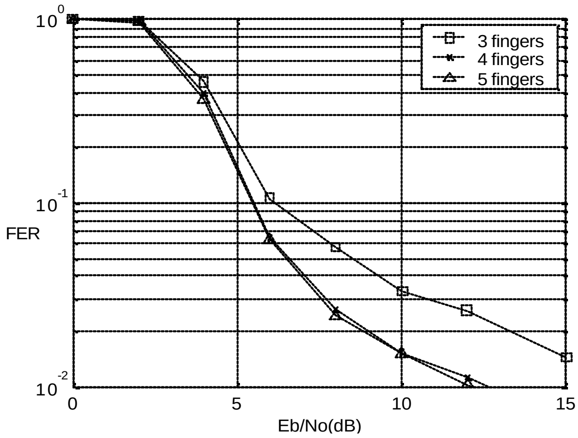

Figure 5 FER vs. E_b/N_o with detector complexity as parameter for RAKE (GASCMA).

5. Conclusions

An adaptive algorithm with adjustable step size for SUD has been proposed for use in DS/CDMA based communications. The performance of the adaptive step size algorithm in a multipath fading channel is investigated by incorporating the proposed algorithm into the RAKE receiver. Investigations were focus on the relationship between the detector performance and its complexity. The FER results obtained by means of computer simulations illustrate the superior MAI resistance of the proposed adaptive step size RAKE receiver as compared to the conventional RAKE receiver. This performance gain is also due to the enhanced convergence speed of the GASCMA and its ability to adjust the step sizes according to chances in the received signal. The additional complexity incurred by adaptation of the step size of the GASCMA can be compensated by reducing the number of fingers involved in the detection process without compromising the performance gain over the standard RAKE receiver to much. Joint blind detection and blind channel parameter estimation and the robustness of the GASCMA to imperfect channel estimation are subjects for future work by the authors.

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