A Novel Finger Assignment Algorithm for RAKE Receivers in CDMA Systems

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***Abstract*— In CDMA systems, assignment of the RAKE fingers to the correct multipath components is crucial for the receiver to combat fading and to take advantage of the multipath diversity. This is particularly important since the number of fingers available is normally limited in order to maintain low receiver complexity. In this paper, we introduce a new RAKE receiver finger assignment algorithm (FAA) based on estimates of the signal-to-interference ratio (SIR) per path, as opposed to signal strength in the conventional schemes. We also introduce a simple algorithm to produce these SIR estimates. A performance comparison between the proposed scheme and already existing schemes is presented. We show that the proposed scheme provides a significant performance improvement relative to that of the conventional schemes. In terms of BER, the proposed scheme provides a gain upto 3.0 dB at bit error rate 10^{-4}, relative to the conventional one.**

I. INTRODUCTION

Code Division Multiple Access (CDMA) is a leading candidate for the proposed third generation (3G) wireless communication systems. In such systems, the signals transmitted are wideband in nature, which gives rise to multipath fading. Although multipath fading may seem harmful because different replicas of the same signal may add destructively at the receiver, it can be exploited to improve the performance relative to the case when there is no multipath fading. A key issue to dealing with multipath fading is to first identify the potential paths at the front end of the receiver. Then, a RAKE receiver is used to coherently combine the energy from these multipath components. A RAKE receiver consists of several correlators called *fingers* that are time-aligned with the different paths. Each finger is intended to de-spread the corresponding path and then the outputs of these fingers are properly combined to maximize the signal-to-interference ratio (SIR) at the output of the RAKE receiver. The criterion by which a finger is assigned to a multipath component is very crucial as it significantly impacts the overall performance of the receiver.

Normally, deciding on what paths to combine at the RAKE receiver depends on several factors, including the available number of fingers, energy content per path, and the inter-path separation. For instance, if the number of available fingers is greater than the number of resolvable paths, it may not be a good idea to combine weak paths since they will contribute more noise to the combiner output and hence may degrade the bit-error-rate (BER) performance of the system. In this case, however, it may be useful to combine strong paths that are within a fraction of a chip apart (i.e. correlated paths) if extra fingers are available at the receiver.

There are two strategies available in the literature for assigning RAKE fingers to multipath components [1]. The first strategy assigns the paths with the largest instantaneous amplitudes to the available fingers. This strategy is well suited for cases when the channel coefficients are slowly changing during the search process for new paths. The second strategy assigns the paths with the largest average powers to the available fingers, which is applicable when the fade rate is comparable to or larger than the search rate. In both strategies, the finger assignment is based upon the assumption that the multipath interference at all fingers are mutually uncorrelated and have equal energy. However, this is not always the case. For instance, if we consider the forward link in CDMA systems, the multipath interferences may differ in energy magnitude from one finger to another as illustrated in [2] and [3]. Therefore, finger combining based on signal strength alone does not achieve maximal-ratio combining [4].

Moreover, the energy-based assignment strategies ignore the interference contaminating the measured signal power. Consequently, the conventional strategies suffer from low probability of detection at low SIR where the actual delays are masked by the interference [5] [6]. Thus, a better assignment strategy should consider the SIR in each path as the assignment metric. To this end, the SIR in each multipath component should be estimated at the receiver side.

Most of the algorithms available in the literature consider estimation of the total SIR [7]-[9]. In [10], however, the SIR is estimated for each assigned path with the intention of estimating the total received SIR. For finger assignment purposes, the SIR must be estimated for all resolvable paths impinging at the receiver front end, and hence the per-path SIR estimator should be implemented at the acquisition stage. To the best of our knowledge, the estimation of the SIR per multipath component has not been considered yet.

In this paper, we consider a new finger assignment strategy that is based on estimates of the SIR per path as opposed to signal-strength in the conventional strategies. In particular, we

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estimate the SIR values for the resolvable paths and select those paths that correspond to the largest SIR values. The selected paths are then assigned to the available RAKE fingers. In estimating the SIR values, we use a simple algorithm, similar to the one proposed in [10], that utilizes already existing results obtained from the acquisition circuit used to find the multipath components over a given window of delay offsets, i.e., delay spread. We provide a performance comparison between the proposed scheme and that of the conventional one, and show that the performance of the former is superior to that of the latter.

The remainder of the paper is outlined as follows. Section II presents the CDMA system model. The proposed finger assignment algorithm (FAA) and the per-path SIR estimation are discussed in Section III. In Section IV, we present simulation results. Finally, Section V concludes the paper.

II. CDMA SYSTEM MODEL

We consider a CDMA system that uses a code-multiplexed pilot channel, similar to the proposed third generation CDMA 2000 system, where a low-power pilot channel is always transmitted along with the data channel [11]. The pilot channel is used for code synchronization (acquisition and tracking), channel estimation, and signal strength measurement. More specifically, we consider a direct-sequence spread-spectrum (DS-SS) system where the baseband BPSK transmitted signal from the desired user is modeled as

$$s_1(t) = \sqrt{P_1}\sum_i \left(d_{1i}W_t + \sqrt{G_p}\right)\sum_{k=0}^{N-1} c_{1k}g(t - iT_b - kT_c) \quad (1)$$

where P_1 is the transmitted average power, $d_{1i} \in \{\pm 1\}$ is the i^{th} information bit, W_t is a Walsh code used to separate the pilot channel from the traffic channel, G_p is the pilot channel power gain relative to the traffic channel, $c_{1k} \in \{\pm 1\}$ is the spreading pseudo random (PN) code of the desired user, N is the PN code spreading factor which is the same as the number of chips per bit, $g(t)$ is the chip pulse shape, T_b is the bit duration, and T_c is the chip duration. The transmitted signal passes through a mobile radio channel with L time varying paths. These paths are represented by the channel coefficients $\{\alpha_l : l = 1, 2, \ldots, L\}$, modeled as independent and identically distributed (i.i.d.) complex Gaussian random variables, with zero mean and variance 0.5 per dimension, i.e. $|\alpha_l|$ is Rayleigh distributed and the phase is uniformly distributed in $[0, 2\pi)$.

The received baseband signal is then given by

$$u(t) = \sum_{m=1}^{M}\sum_{l=1}^{L} \alpha_{ml}s_m(t - \tau_{ml}) + n(t) \quad (2)$$

where M is the number of active users. α_{ml} and τ_{ml} are the channel gain and path delay for the l^{th} path of the m^{th} user, respectively, and $n(t)$ is an additive white Gaussian noise (AWGN) with zero mean and power spectral density $N_0/2$ per dimension. The received baseband signal is sampled at a multiple of the chip rate such that there are N_s samples per chip.

III. PROPOSED FINGER ASSIGNMENT ALGORITHM

A block diagram of the CDMA receiver is depicted in Fig.1. As shown in the figure, the received spread spectrum signal is applied to a search block that performs correlation with a locally generated PN code for different delays. The search results are used to estimate the SIR for every possible delay examined by the searcher. Based on the SIR estimates, the FAA provides the delays to the RAKE receiver for demodulation and coherent combining. This process repeats for every frame of the received data. Next, we shall outline the algorithms that we use for the multipath delays estimation, per-path SIR estimation, and finger assignment.

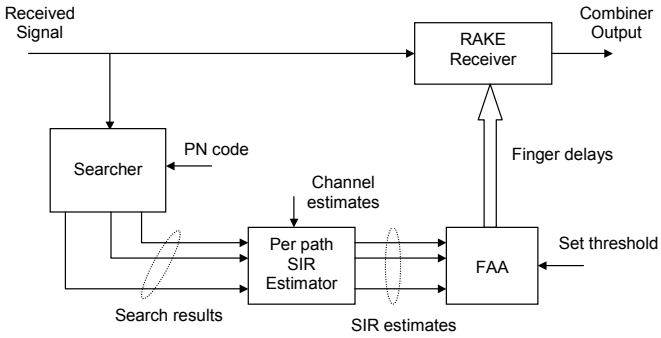


Fig. 1. Block diagram of the proposed scheme.

A. Search Algorithm

The search algorithm (henceforth referred to as *searcher*) is basically an acquisition circuit used to perform the correlation between the received signal and different replicas of the desired user code. The algorithm examines a window of K possible delays for a period of time and the correlation results are stored for further processing. The search step size, denoted by S, is typically a fraction of a chip, e.g., $1/2$ a chip. Hence, the search results, which we call the search delay profile, will consist of SK values given by

$$h_n(k) = f_{1n}(k) + f_{In}(k) + N_k \quad (3)$$

where the index k represents the k^{th} delay offset within the search window and n is the search index within the n^{th} bit duration in a data frame. $f_{1n}(k)$ is the contribution of the desired user signal, $f_{In}(k)$ the interference component, and N_k is the contribution of the AWGN noise. The first two components can be shown to be

$$f_{1n}(k) = \sqrt{P_1}\sum_{l=1}^{L_1} \alpha_{1l}(n)\left[A_{11}(l,k)d_{1n} + B_{11}(l,k)\right] \quad (4)$$

and

$$f_{In}(k) = \sum_{m=2}^{M}\sqrt{P_m}\sum_{l=1}^{L_m} \alpha_{ml}(n)\left[A_{1m}(l,k)d_{mn} + B_{1m}(l,k)\right], \quad (5)$$

where P_m is the m^{th} user power,

$$A_{1m}(l,k) = \frac{1}{\sqrt{T_b}} \int_{T_b} W_t c_m c_1 g(t-\tau_l) g(t-\tau_k) dt, \quad (6)$$

and

$$B_{1m}(l,k) = \frac{1}{\sqrt{T_b}} \int_{T_b} c_m c_1 g(t-\tau_l) g(t-\tau_k) dt. \quad (7)$$

Obviously, the terms in (6) and (7) depend on the auto- and cross-correlation properties of the shifted versions of the PN sequences assigned to different users. Therefore, the searcher should detect an effective path for the first user whenever l equals k, i.e., $(\tau_l = \tau_k)$, where the autocorrelation function will be at its maximum. In this case, (4) can be re-written as

$$f_{1n}(k) = \sqrt{E_{b1}} \sum_{l \neq k}^{L_1} \alpha_{1l}(n) \left[A_{11}(l,k) d_{1n} + B_{11}(l,k) \right] + \sqrt{E_{b1}} \alpha_{1k}(n) \quad (8)$$

where E_{b1} is the energy per bit for the first user. Substituting (8) into (3) yields the following.

$$h_n(k) = \sqrt{E_{b1}} \alpha_{1k}(n) + I_n(k) \quad (9)$$

where

$$I_n(k) = \sqrt{E_{b1}} \sum_{l \neq k}^{L_1} \alpha_{1l}(n) \left[A_{11}(l,k) d_{1n} + B_{11}(l,k) \right] + f_{In}(k) + N_k. \quad (10)$$

The term $I_n(k)$ in (10) represents the total interference that is coming from other paths with respect to the desired user, interference from other users along with their multipath, and the noise seen by the k^{th} delay offset. Determination of the total interference strictly requires full knowledge of other users' channel coefficients and spreading codes. Although at the base station we may know some of these parameters, information about interference from users outside the serving base station is normally unknown. Furthermore, in the forward link, the mobile station has no knowledge of these parameters at all. Thus, an algorithm for estimating the total interference seen by a particular path is needed to implement the FAA. This is explained in the following subsection.

B. Per Path SIR Estimation Algorithm

As we will demonstrate later, the FAA algorithm requires knowledge of the estimates of the SIR for each multipath component in order to function properly. In this section we develop a simple SIR estimator per path using the search delay profile. As we mentioned previously, the searcher provides the search results for a group of delay offsets using the received signal over one bit duration. Multiple estimation bits in the same data frame are used to provide new independent search results for the same delay offset. These search results (from all estimation bits) are then averaged, leading to averaging out, to a large extent, the noise and interference. Furthermore, choosing the estimation bits such that they are spaced in time within a given frame would provide time diversity against channel fading, and, hence, improve the performance. We would like to remark that such averaging is possible because the code-multiplexed pilot channel with no data modulation is used by the searcher. Now, suppose that we have N_A results for each delay offset that were obtained from N_A independent searches, then the search delay profile will consist of $N_A \times SK$ values of $h_i(k) = \sqrt{E_{b1}} \alpha_{1k}(i) + I_i(k)$ for $i = 1, 2, \ldots, N_A$ and $k = 1, 2, \ldots, SK$, where k is the delay offset index. In vector notation, $h_i(k)$ for all i can be expressed as

$$\mathbf{h}(k) = \sqrt{E_{b1}} \boldsymbol{\alpha}_{1k} + \mathbf{I}(k) \quad (11)$$

where $\mathbf{h}(k)$, $\boldsymbol{\alpha}_{1k}$, and $\mathbf{I}(k)$ are column vectors of length N_A corresponding to the k^{th} delay offset. Thus, the average interference plus noise power seen by the signal at delay k can be estimated as

$$\hat{\sigma}^2_{I+N}(k) = \frac{1}{N_A} \left\| \mathbf{h}(k) - \sqrt{E_{b1}} \boldsymbol{\alpha}_{1k} \right\|^2 \quad (12)$$

where $\|\cdot\|^2$ is the norm squared operator. Therefore, the estimate of the SIR per path is given by

$$SIRp(k) = \frac{E_{b1} \left| \bar{\alpha}_{1k} \right|^2}{\hat{\sigma}^2_{I+N}(k)} \quad (13)$$

where $\bar{\alpha}_{1k}$ is the mean of $\boldsymbol{\alpha}_{1k}$.

The above model assumes only knowledge of the intended user's channel gains for the estimation bits. This is a reasonable assumption since the channel coefficients are needed by the RAKE receiver to implement coherent combining and a channel estimation algorithm is usually implemented in the receiver for that purpose. Once the estimates of the SIR per path are determined, the RAKE fingers are assigned according to the algorithm described below.

C. Finger Assignment Algorithm (FAA)

The proposed algorithm for assigning RAKE fingers to multipath components is outlined as follows:

1) Perform a search over the window of possible delays and obtain the search results for each estimation bit, as per (11).
2) Estimate the SIR per path for every delay, as per (13).
3) According to the desired false alarm probability, e.g. 1%, the delays with SIR greater than the threshold are assigned for RAKE combining.
4) In case none of the delays in the current search window exceeds the threshold, the delay with maximum SIR from the previous search window (corresponding to the previous received frame) is used for demodulation. Otherwise, the delay with maximum SIR in the current search window is assigned.

5) Repeat the above steps for each received frame.

We remark that the SIR-based scheme compares SIR values to a threshold which would result in a certain false alarm probability whereas the conventional algorithm compares the signal-strength search results to a different threshold but for the same desired false alarm probability. As we will demonstrate in the following section, these algorithms result in different detection probability.

IV. SIMULATION RESULTS

The performance of the proposed SIR-based and conventional energy-based finger assignment strategies were evaluated by computer simulation. The bit error probability and the probability of detecting correct multipath delays in both schemes will be presented in this section. A two-user CDMA system with PN spreading codes is considered over a frequency-selective Rayleigh fading channel. The following parameters are used in the simulations:

- Spreading factor (number of chips per bit): $N = 128$,
- Frame duration: 20 ms,
- Number of estimation bits used by searcher: $N_A = 13$,
- Pilot channel gain compared to data channel: 0 dB,
- Number of paths per user: $L = 4$,
- Uniform power delay profile (four paths with equal energy),
- False alarm probability: 1%, and
- Same channel coefficients estimation algorithm is implemented for both schemes.

Throughout the simulation, a predetermined threshold value is used to yield the required false alarm rate. The decision upon the threshold value was assisted using the calibration curves for each assignment algorithm. These curves were produced from an off-line calibration process where the desired user was idle. Fig. 2 shows the BER performance as a function of E_b/N_0 in dB with the SIR as a parameter. A Rayleigh fading channel with a normalized Doppler spread of 10^{-2} is considered. As we observe from the figure, the performance of the proposed SIR-based scheme provides an improvement of about 1 to 2 dB at average $SIR = 10$ dB compared to the conventional scheme. We also observe that the gap between the performances of both schemes increases further at low SIR values. For instance, a gain of 2.0 to 3.0 dB is attainable when the multi-access interferer has the same average power as the desired user–i.e. $SIR = 0$ dB. We attribute such significant improvements to the ability of the proposed scheme to detect more paths and hence provide more diversity gain through RAKE combining compared to the conventional scheme. Note that the improvements reported above are obtained without implementing any error correcting coding schemes. Therefore, the proposed scheme is expected to provide further improvements when used in conjunction with channel coding.

To further illustrate the efficacy of the proposed finger assignment algorithm, we examine the probability of correctly finding the delay of the first path and compare it with that of the conventional system. As shown in Fig. 3, the proposed scheme has better detection probability especially for low SIR range. For instance, at a SIR of -10 dB, the conventional scheme tends to have a detection probability of about 27% at high E_b/N_0 values as compared to 75% achieved by the proposed scheme. Note that this probability is approximately the same for all paths as they have equal energy.

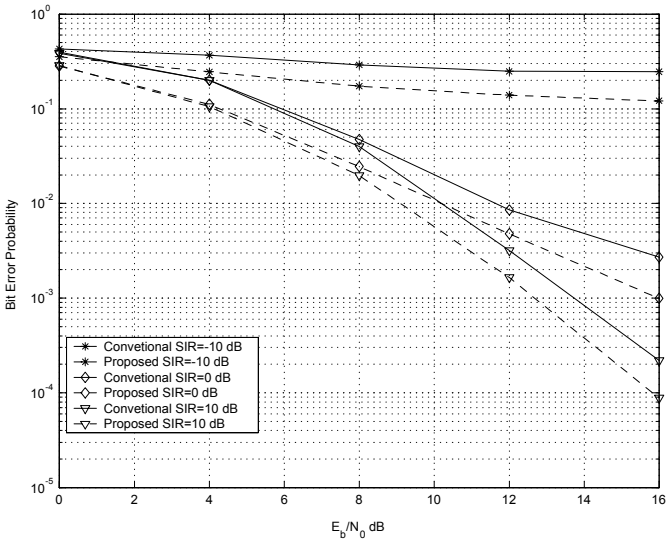


Fig. 2. A BER performance comparison between the proposed scheme and the conventional one

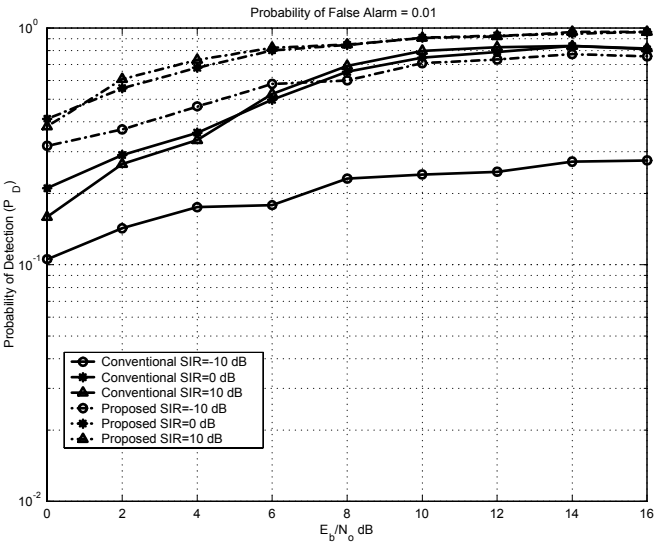


Fig. 3. The probability of detecting the first path using both schemes over a channel with four paths and uniform power delay profile.

In Fig. 4, the probability of simultaneously detecting all four paths is presented. Once again, the proposed scheme shows better detection probability which means that correct delay estimates are provided to the RAKE receiver most of the time

for all paths. On the other hand, the conventional algorithm has a significant reduction in the probability of detecting all paths and only one of the paths will be provided correctly to the RAKE receiver for a small percentage of the time.

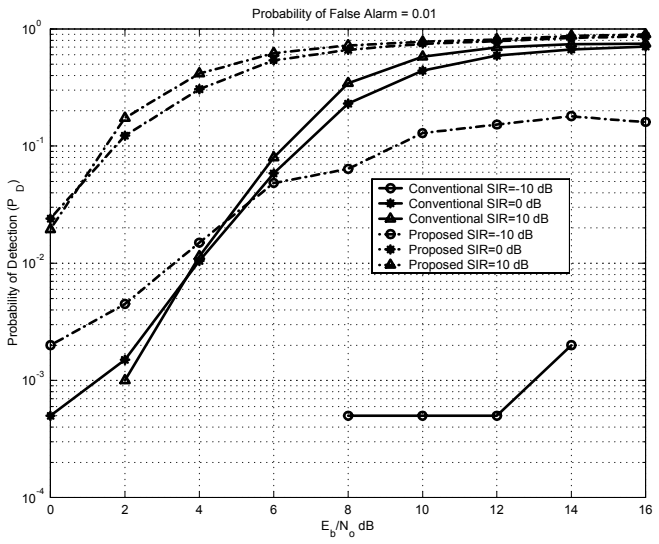


Fig. 4. The probability of simultaneously detecting all four paths using both schemes.

Fig. 5 shows the receiver operating characteristic of both schemes where the probability of detection of the first path is presented against the false alarm probability. Immediately apparent is the fact that the proposed detection scheme extended the operational region of the receiver by reducing the interference effect on the probability of detection.

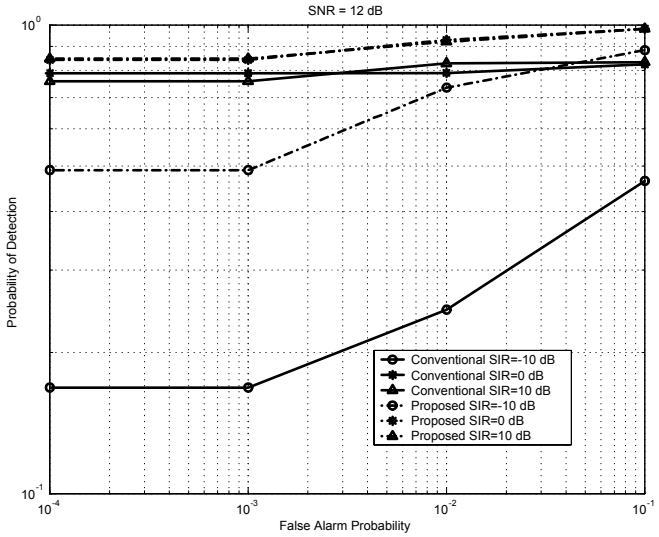


Fig. 5. Probability of first path detection vs. probability of false alarm.

Finally, Table I highlights the effect of threshold setting on the probability of detecting the first path for both assignment schemes. When the threshold is not enforced, the proposed scheme is capable of detecting the first multipath component most of the times. A reduction of about 7% results when the threshold is introduced to yield a false alarm rate of 1%. On the other hand, the conventional assignment scheme suffers from a reduction of about 16% due to the threshold filtering. Hence, the proposed scheme is less sensitive to the threshold setting as apposed to the conventional scheme.

TABLE I

EFFECT OF THE THRESHOLD SETTING ON THE PROBABILLITY OF DETECTING THE FIRST PATH FOR BOTH SCHEMES

	SIR = 0 dB, SNR = 10 dB	
Scheme	Conventional	Proposed
No Threshold	91.05%	99.30%
$\mathbf{P_{FA}= 0.01}$	74.85%	91.85%

V. CONCLUSIONS

In this paper, we have presented a novel scheme for assigning RAKE fingers to multipath components in CDMA systems. The proposed scheme is based on SIR per-path estimates as opposed to signal strength in the conventional schemes. We have also presented a simple algorithm for estimating the SIR per path based on the searcher results**.** The attractive part of this algorithm is that it utilizes already existing results obtained from the acquisition circuit used to estimate the power delay profile of the channel. A thorough performance comparison between the proposed scheme and the conventional scheme has been presented. We have shown that the former scheme provides significant performance improvements over the latter scheme.

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