Adaptive Multistage Parallel Interference Cancellation for CDMA over Multipath Fading Channels

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Abstract

In this paper, we propose an *adaptive* multistage parallel interference cancellation (PIC) structure for multipath fading channel. Similarly to the previous partial interference cancellation (IC) approach suggested in [1], only part of the multiaccess interference (MAI) estimate is canceled at each stage. However, the weights employed in this proposed scheme are derived from an LMS algorithm which tries to minimize the mean-square error between the actual signal received and its replica. The complexity of the proposed *adaptive* multistage PIC scheme is much lower than that of linear multiuser detectors. Performance of the proposed structure in single-path Rician and multipath Rayleigh fading channels is evaluated by simulations. Our results show that the proposed technique outperforms the existing interference cancellation methods in multipath fading channels.

1 Introduction

It is well known that the performance of a CDMA system is interference-limited. Multiuser detection can greatly increase the system capacity.

Parallel interference cancellation (PIC) is attractive for its potential capacity increases and simplicity. Ideally, when all multiaccess interference (MAI) are known *a priori*, a single stage PIC is equivalent to the optimum detector in a maximum-likelihood (ML) sense [1]. In practical applications, the MAI estimates are used due to the lack of an exact knowledge of MAI. By introducing multistage [2], MAI estimation can be improved in an iterative way. However, this is not always true for a conventional multistage PIC, especially, when the BER in the previous stage is sufficient high. A wrong estimation used in MAI cancellation will largely increase the interference power, hence introducing further degradation.

Divsalar *et al.* [1] suggested a partial cancellation of MAI at each stage to reduce the cost of wrong MAI estimation, the amount of interference to be cancelled is decided by a weighting factor at each stage for all users. This method can ensure a performance improvement after partial interference cancellation. Since the bit decisions become more reliable when more MAI is canceled, they also propose to increase the weighting factor for each successive stage. Their results show a considerable capacity increase in an AWGN channel over conventional multistage PIC [3, 1].

In Divsalar *et al.*'s partial cancellation approach [1], a constant weight is used for all users at each stage throughout the cancellation. For a CDMA system operating in a multipath fading channel, the MAI varies from one user to another and from bit to bit according to the PN cross-correlation as well as the power level of each user at a particular time instant. Hence, adaptive weights that reflect the reliability of data estimation can offer a better solution.

Motivated by the above thought, we propose a new cost function in this paper which takes the weighting factors into account. Our objective is to minimize the mean-square error between the received signal and the weighted sum of the estimates of all users' signal during a bit interval with respect to the weights. The optimum weights can be obtained through an adaptive LMS algorithm. An LMS multistage PIC structure is presented for multipath fading channels, the proposed structure also incorporates RAKE diversity. Performance of this technique and other PIC methods is investigated by means of simulation.

The rest of the paper is organized as follows. Transmitter and channel models are described in Section 2. Section 3 presents the proposed adaptive multistage PIC structure for multipath fading channels. Performance comparisons of various PIC schemes in single-path Rician and multipath Rayleigh fading channels are discussed in Section 4. Section 5 concludes the paper.

2 System Model

We consider a synchronous DS-CDMA system using QPSK. For the ith user, the transmitted signal can be written as

$$s_i(t) = \sqrt{P_i} b_i(t) c_i(t) \tag{1}$$

where P_i is the signal power. $b_i(t) = \sum_{m=-\infty}^{\infty} a_i^{(m)} p(t - mT_b)$ represents the data signal, $a_i^{(m)}$ is a binary sequence taking values ± 1 with equal probability. $p(t)$ is a rectangular chip waveform with duration T_b. $c_i(t)$ represents a complex form PN sequence that is defined as

$$c_i(t) = PN_i(t)[PN^{(I)}(t) + jPN^{(Q)}(t)] \tag{2}$$

where $PN^{(I)}(t)$, $PN^{(Q)}(t)$ are the PN waveforms used in the in-phase and quadrature components of the QPSK modulated signal. $PN_i(t)$ is the signature waveform of the ith user.

The multipath fading channel for the ith user considered in this paper is modeled as

$$h_i(\tau; t) = \sum_{l=0}^{L-1} \alpha_{il}(t) \delta(\tau - \tau_{il}) \tag{3}$$

where L is the number of paths of the channel, assumed to be time-invariant. τ_{il} denotes the relative delay of the lth path. $\alpha_{il}(t)$ represents the time-variant complex channel parameter of the lth path taking the attenuation and phase shift into account.

With the above transmitted signal and channel model, the received signal can be expressed as

$$r(t) = \sum_{l=0}^{L-1} \sum_{i=1}^{K} \alpha_{il}(t) s_i(t - \tau_{il}) + z(t) \tag{4}$$

where K is the number of active users, $z(t)$ is the additive Gaussian noise with double-side spectrum density $N_0/2$.

If we consider the ith user, a RAKE receiver computes at each of its fingers the following

$$y_{il} = \frac{1}{\sqrt{T_b}} \int_{\tau_{il}}^{T_b + \tau_{il}} r(t) c_i^*(t - \tau_{il}) dt \tag{5}$$

We assume the channel fading is slow, or in other words, the channel parameter $\alpha_{il}(t)$ does not change within a bit interval, it is thus denoted as α_{il}. The outputs from these fingers are then combined using maximal ratio rule [4] shown below

$$y_i = \sum_{l=0}^{L-1} \alpha_{il}^* y_{il} \tag{6}$$

For a conventional single-user RAKE receiver, the decision is made as

$$\hat{a}_i = sgn\{Y_i\} \tag{7}$$

where $Y_i = \mathrm{Re}\{y_i\}$.

3 Parallel Interference Cancellation

Without loss of generality, let us focus on the first user. For the multistage PIC [2] operating in multipath environment, the MAI is estimated at the kth stage as follows

$$\hat{I}_1^{(k)} = \sum_{i=2}^{K} \sum_{l=1}^{L} \sqrt{E_{bi}} \alpha_{il} c_i(t) \hat{a}_i^{(k-1)} \tag{8}$$

At the kth stage, the estimated MAI is *completely* removed from the received signal in the conventional multistage PIC, this can be written as

$$r_{c1}^{(k)} = r(t) - \hat{I}_1^{(k)} \tag{9}$$

Rake combining and bit decision can be carried out in the same way as shown in (4)-(6) for single user Rake receiver, the only difference is the $r(t)$ in (4) should be replaced by $r_{c1}^{(k)}$ for conventional PIC.

Partial IC was proposed in [3, 1] to reduce the cost of incorrect MAI estimation. In a multipath fading channel, the procedure of interference cancellation can be described as follows

$$\begin{aligned} \tilde{r}_{p1}^{(k)} &= p^{(k)}[r(t) - \hat{I}_1^{(k)}] + [1 - p^{(k)}] \tilde{r}_{p1}^{(k-1)} \\ \tilde{r}_{p1}^{(0)} &= \sum_{l=1}^{L} y_{il} \end{aligned} \tag{10}$$

where $p^{(k)}$ is the weighting factor for interference cancellation at the kth stage.

Rake diversity is then carried out based on the interference partially removed signal $\tilde{r}_{p1}^{(k)}$.

4 Adaptive Multistage PIC

In Divsalar's *et al.*'s partial cancellation scheme, the weight for each stage remains constant. Intuitively, it is more reasonable to have a set of weights that can reflect the reliability of the bit estimations from the previous stage. In this section we propose an adaptive multistage PIC approach where the weights are updated by an LMS algorithm. In order to incorporate the adaptive algorithm, the received signal must be sampled. In our case, the received signal $r(t)$ is sampled once per chip, the discrete form received signal is denoted by $r(m)$, where

$$r(m) = \sum_{i=1}^{K} \sum_{l=0}^{L-1} \alpha_{il} s_i(m-l) + z(m) \tag{11}$$

We try to estimate $r(m)$ at the kth stage from the PN sequence $c_i(m)$, the bit estimate from the previous stage $\hat{a}_i^{(k-1)}$ and the weight $\{\lambda_{il}(m), l = 0, \cdots, L-1\}$. The estimation is carried out as following

$$\hat{r}^{(k)}(m) = \sum_{i=1}^{K} \sum_{l=0}^{L-1} \hat{s}_i(m-l)\lambda_{il}(m) \tag{12}$$

where $\hat{s}_i(m)$ is defined as

$$\hat{s}_i^{(k)}(m) = c_i(m)\hat{a}_i^{(k-1)} \tag{13}$$

Our objective is to minimize the mean-square error (MSE) between the received signal $r(m)$ and its estimate $\hat{r}(m)$ with respect to the weights. The cost function can be expressed as

$$E\left[\left|r(m) - \hat{r}^{(k)}(m)\right|^2\right] \quad 0 \le m \le N-1 \tag{14}$$

A normalized LMS algorithm is used to search for the optimum weights during each bit interval and on a chip basis. The weights update is given by

$$\boldsymbol{\lambda}^{(k)}(m+1) = \boldsymbol{\lambda}^{(k)}(m) + \frac{\mu}{\|\hat{\boldsymbol{s}}^{(k)}(m)\|^2}\hat{\boldsymbol{s}}^{(k)}(m)[e^{(k)}(m)]^* \tag{15}$$

where μ is a step size. $e^{(k)}(m)$ represents the error between the desired response and the output of the LMS filter of the kth stage

$$e^{(k)}(m) = r(m) - \hat{r}^{(k)}(m) \tag{16}$$

The dimension of vector $\boldsymbol{\lambda}$ is $L \times K$. The block diagram of the weight estimation via an LMS algorithm is depicted in Figure 1. The same concept can be used to develop an adaptive multistage parallel interference cancellation structure for applications in an AWGN environment as shown in Figure 2 of [5].

With the weights provided by the LMS algorithm, the interference cancellation at the kth stage for the ith user is performed as

$$y_{ci}^{(k)}(m) = r(m) - \sum_{\substack{j=1 \\ j\neq i}}^{K} \sum_{l=0}^{L-1} \lambda_{jl}^{(k)}(N-1)\hat{s}_j^{(k)}(m-l) \tag{17}$$

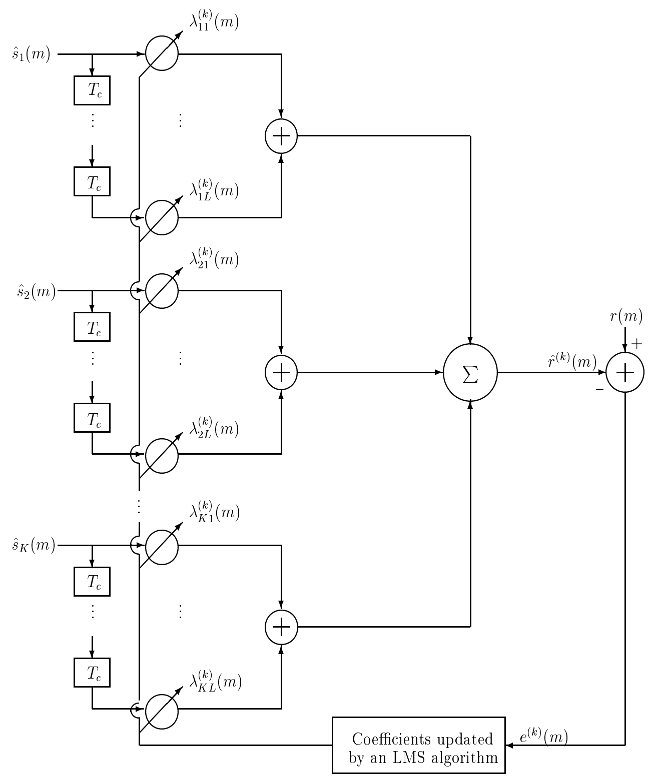

Figure 1: Adaptive PIC using an LMS algorithm in multipath fading channel

RAKE diversity is then carried out based on the less interfered signal $y_{ci}^{(k)}(m)$, i.e.

$$Y_i^{(k)} = \mathrm{Re}\left\{\frac{1}{N}\sum_{l=0}^{L-1}\sum_{m=0}^{N-1} y_{ci}^{(k)}(m)c_i^*(m-l)\alpha_{il}^*\right\} \tag{18}$$

A more reliable decision is made as

$$\hat{a}_i^{(k)} = sgn[Y_i^{(k)}] \tag{19}$$

A conventional single-user RAKE receiver is employed as the initial stage in our method, i.e.

$$\hat{a}_i^{(0)} = sgn(Y_i) \tag{20}$$

where Y_i is as defined in (6). Either exact channel parameters or their estimates can be used as the initial value of the tap coefficients of the LMS filters at each stage. Even if certain MAI estimates are wrong, it is possible for the LMS algorithm to reverse the sign of their corresponding weights, ensuring removal of the interference to some extend.

The step size μ plays an important role in the LMS algorithm. For the normalized LMS algorithm deployed in our approach, μ must satisfy $0 < \mu < 2$ in order to ensure convergence [6]. Generally, a large step size leads to a faster convergence rate, however it will also cause a greater gradient noise.

5 Simulation Results

Simulations have been carried out to evaluate the performance of various interference cancellation schemes discussed in this paper. System model described in Section 2 is used in our simulation. The processing gain is 64 if not otherwise specified. Generating functions for random PN sequences employed in our simulations are identical to those specified in IS-95 for its reverse link.

We evaluated through various simulations the performance of the proposed *LMS PIC*, the *partial PIC* [1], the *conventional PIC* [7], and the *RLS decorrelating* [8] in various fading channels. Perfect amplitude and phase information of all users is assumed. For a single-path Rician fading channel, the power difference between the specular and the diffuse components is 7dB.

Figure 2 shows the performance comparison of various interference cancellation schemes. Figure 2(a) depicts the results of *single-stage* case. At a BER of 0.01, the *conventional* and *partial PIC* schemes can accommodate 18 and 20 users, respectively, while the *RLS decorrelating* and the introduced *LMS PIC* can support 28 users.

With an additional stage, a considerable increase in number of users is observed in Figure 2(b). For a BER of 0.01, the numbers of users can be supported by the *2-stage conventional*, *2-stage partial* and *2-stage LMS PIC* schemes are 27, 37 and 45, respectively.

Performance of various PIC schemes in a two-path Rayleigh fading channel is shown in Figure 3 for E_b/N_o =17dB. The delay of the second path equals to T_c. An even multipath profile is assumed. All PIC schemes show a significant performance improvement over the single-user detector. In particular, at a BER of 10^{-3}, the single-user receiver cannot support more than 10 users. The single-stage *conventional PIC* and *partial PIC* can accommodate 17 and 15 users, respectively, while the single-stage *LMS PIC* can support 20 users.

For 2-stage cancellation as shown in Figure 3(b), the capacity of the *conventional PIC* increases to 34 users for the BER of 10^{-3}. The number of users that can be supported by *2-stage partial PIC* and *2-stage LMS PIC* are 37 and 42 users. *LMS PIC* still outperforms the *partial PIC*.

6 Conclusions

In this paper, we proposed an adaptive multistage PIC structure for multipath fading channels based on the partial PIC approach [3, 1]. The proposed method uses LMS algorithm to search for a set of optimum coefficients which minimize the mean-square error between the received signal and its estimate. These coefficients are used as weights in parallel interference cancellation. Simulation results show that the proposed method outperforms the conventional PIC and the partial PIC schemes in both single-path and multipath fading channels. Its superior performance is also maintained in an AWGN environment as presented in [5].

Acknowledgment

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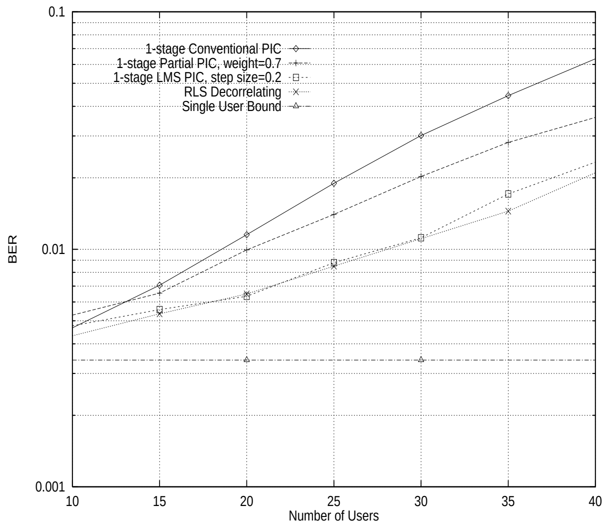
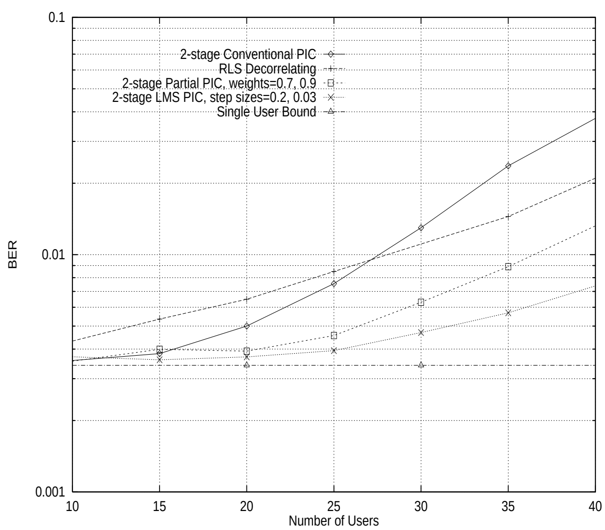
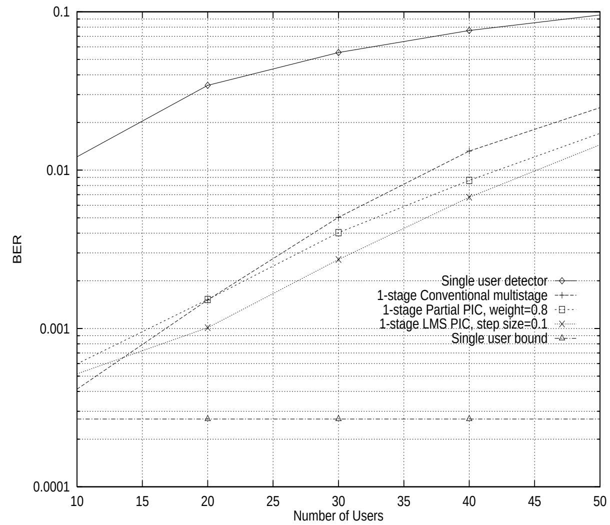


(a) single stage

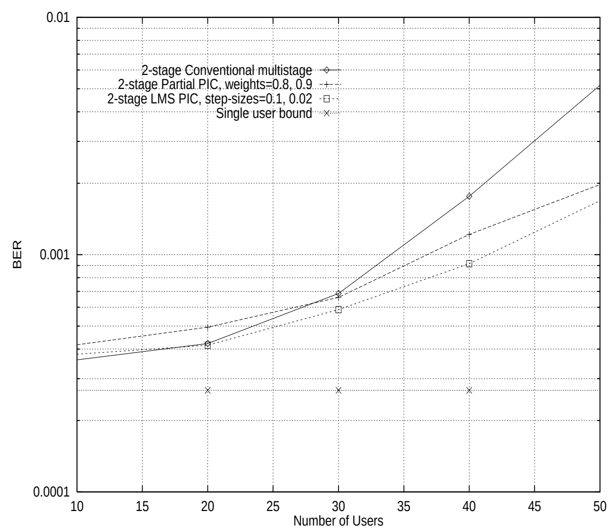


(b) two-stage

Figure 2: Performance comparison of various interference cancellation methods over a single-path Rician fading channel (processing gain=64, $E_b/N_o = 7$dB)



(a) single stage



(b) two-stage

Figure 3: Performance comparison of various interference cancellation schemes over a 2-path Rayleigh fading channel (processing gain=64, E_b/N_0 =17dB)